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	Note: this model was developed jointly with Bill DeLuca		
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2.2	Model assessment and climate niche model added	W. DeLuca	7/7/12
2.3	Minor editorial changes for consistency	K. McGarigal	7/18/12

1 Index

1 Index 1
2 Background 2
2.1 Wood Thrush as a Representative Species 2
2.2 Key Resources and Habitat Needs 2
2.3 Conceptual Model of Habitat 3
2.4 Distribution in States of the North Atlantic LCC 4
3 Habitat Capability Model 4
3.1 Summary 4
3.2 Local Resource Availability 5
4 Home Range Capability 9
5 Results 11
5.1 Location of Ecological Systems Suitable for Breeding 11
5.2 Examples of Model Results 11
6 Model Assessment 13
7 Climate Niche Envelope Model 13
7.1 Model Building 13
7.2 Model Validation 13
8 Literature Cited 14
9 Appendix A – Tables and Figures 16
10 Appendix B – File Names and Brief Descriptions 36

2 Background

2.1 Wood Thrush as a Representative Species

Wood Thrush was selected as a representative species at all three workshops of the North Atlantic LCC (NALCC) in May-June 2011. The habitat clusters (ecological systems) and associated wildlife species that it represents differ in the three subregions (northern New England and New York; southern New England and New York; mid-Atlantic), but generally comprise moist hardwood forests. In the northern subregion, the cluster of seven ecological systems includes northern hardwood forests (both Laurentian-Acadian and Appalachian) and pine-hemlock-hardwood forest. In the middle subregion, it is associated with a large cluster of 13 ecological systems that included all seven of the northern subregion systems plus more southerly systems. In the mid-Atlantic, it includes three ecological systems shared with the other subregions plus southern piedmont mesic forest. Other species chosen to represent these clusters consist of Blackburnian Warbler (n. subregion), Chestnut-sided Warbler (n. and mid), Eastern Red Bat (n. and mid), Eastern Whip-poor-will (s.), Eastern Box Turle (s.), Louisiana Waterthrush, Ovenbird (n. and s.), Red-shouldered Hawk (s.) Ruffed Grouse (n.), and Worm-eating Warbler (s.)

2.2 Key Resources and Habitat Needs

I. Breeding season (James et al. 1984, Roth et al. 1996)

a) Diet and foraging locations. Feeds primarily on invertebrates found in moist, shaded, decaying leaf litter. Physical structure must allow access to leaf litter; avoids dense woody cover (such as thickets) or dense herbaceous cover (such as turf). Needed resources are available under mostly closed canopies of deciduous forests with an intermediate range of understory shrubs or saplings.
b) Breeding (nest) sites. Most nests are placed in low shrubs or small trees; flexible in the species used.
c) Cover. Mostly closed canopies with at least moderate understory development provide protection from predators and brood parasites (namely Brown-headed Cowbird, *Molothrus ater*).
d) Spatial requirements. Defend territory approximately 0.5 to 4 ha, though smaller and larger sizes have been reported. Presumably, territories are composed primarily of areas that (i) provide needed foraging locations and cover and (ii) do not include or straddle large areas of unsuitable space such as roads or open water (Weinberg and Roth 1998).

II. Postbreeding season (Anders et al. 1998, Vega Rivera et al. 1998, Vega Rivera et al. 1999)

a) Diet and foraging locations. Diet shifts following the breeding season to include an increasing amount of fruits. Fruits are more available in early successional forests than closed canopy mature forests.
b) Cover. Birds prefer areas with dense cover, which presumably provide protection from predators. For adults, this may be advantageous while they molt.
c) Spatial requirements. Postbreeding individuals that leave territories tolerate or seek conspecifics and will use areas considerably smaller than breeding territories.

Individuals can move 2 km or more from breeding territories to postbreeding habitat, but presumably postbreeding habitat in close proximity to breeding territories is advantageous in reducing energy costs and predation risk compared to more distant postbreeding habitat. Some adults appear to remain on breeding territories until migration commences.

2.3 Conceptual Model of Habitat

Key resources and habitat needs are illustrated in **figure 1**, along with factors that are major determinants of the availability and quality of these resources. Important considerations from the conceptual model include the following:

- Mesic, mature, closed-canopy deciduous forests provide the volume of deciduous leaves and moisture conditions that support the invertebrate food supply of the Wood Thrush. They also provide protection from predators and cowbirds. Suitability decreases with increasing coniferous component of the canopy, decreasing canopy closure, or increasingly xeric conditions.
- Climate, soils, and topography combine to determine the location of potential deciduous forests. On the breeding grounds, climate is presumed to affect habitat suitability for Wood Thrush through its indirect effects in determining the occurrence of mesic deciduous forests rather than through direct effects on Wood Thrush (e.g., via temperature limitation).
- Disturbance history, including human activities such as harvesting forests or clearing lands for agriculture, influences the structure, composition, and extent of forests at specific locations over time and therefore affects habitat quality. The scale of disturbance effects ranges from microhabitat changes on the scale of meters to changes on the scale of tens of kilometers or greater that affect regional populations of predators and brood parasites. Disturbance affects both breeding and postbreeding habitat, though in different ways.
- Although not explicitly illustrated in the figure, the conceptual model also assumes that landscapes that contain mixtures of breeding and postbreeding habitat provide superior conditions to landscapes where habitats are widely separated (farther than a few km).

2.4 Distribution in States of the North Atlantic LCC

State	Distribution	Source
Maine	In 1978-1983 Atlas, evidence for breeding in 370/543 blocks	On-line Atlas results
New H.	Throughout state south of mountains; rare above 2,000 feet	(Elkins 1994)
Vermont	Widely distributed across all regions of state	(Schwenk in press)
Mass.	Common throughout state except Cape Cod, other coastal areas	(Dowd 2003)
Rhode I.	In 1982-1987 Atlas, evidence for breeding in 125/165 blocks	On-line Atlas results
Conn.	In 1982-1986 Atlas, evidence for breeding in 565/596 blocks	On-line Atlas results
New York	Widely distributed, missing only from parts Adirondacks & NYC	(Hames and Lowe 2008)
New Jersey	Widespread and fairly common	(Boyle 2011)
Penn.	Widely distributed throughout state (91% of blocks)	(Leberman 1992)
Delaware	In 2008-2012 Atlas, evidence for breeding in 191/265 blocks	On-line Atlas results
Maryland	Common and widespread, except barrier islands & parts Baltim.	(Ellison 2010)
Virginia	In 1985-89 Atlas, evidence for breeding in 685/768 priority blks.	On-line Atlas results

Index

3 Habitat Capability Model

3.1 Summary

The Wood Thrush model involves assessment of local resource availability for both breeding and postbreeding habitat. The amount and accessibility of breeding and postbreeding local resources in the neighborhood of each focal cell are then evaluated to compute a single value of home range capability. Given home range capability, the number of home ranges expected to be supported by the landscape can be estimated (landscape capability). The structure of the model is summarized in **figure 2** and described in more detail below.

3.2 Local Resource Availability

Local resource availability for Wood Thrush is determined separately for the breeding season and postbreeding (premigration) season.

LRA-B. Local resource availability for breeding

Local resource availability for the breeding season is comprised of four local resource indices, as follows:

LRB1: Ecological System for Breeding – Categorical index; assign weights (0 to 1) to each ecological system.

Input data – Modified Ecological Systems (ESM+)

Ecological systems that are characterized by mesic deciduous forests are considered to have the potential to represent high quality habitat for Wood Thrush and were assigned a value of 1. Habitat quality was reduced for a) deciduous (hardwood) forest systems containing a substantial pine or hemlock component (such as Laurentian-Acadian Pine-Hemlock Hardwood Forest), b) deciduous forest systems potentially with a wetland component (such as Laurentian-Acadian Floodplain Forest), c) dry but not xeric deciduous forest systems (such as Southern Ridge and Valley / Cumberland Dry Calcareous Forest), and d) forest systems that are both dry and contain a substantial conifer component (such as Central Appalachian Dry Oak-Pine Forest). All other ecological systems, including nonforested systems, swamps, and primarily coniferous systems, were assigned a value of 0 (unsuitable for breeding). **Table 1** lists systems found in North Atlantic LCC area considered to be potential Wood Thrush breeding habitat and their weights.

Primary uncertainties: the Wood Thrush has been studied at many locations across its range and the general types of forests it uses are well-established. However, how its occurrence relates to the relatively new ecological system classification has not yet been established. Furthermore, habitat quality for different ecological systems has not yet been determined. Uncertainties include which systems are too dry, too wet, or contain too much pine to serve as breeding habitat. Therefore, **Table 1** may reflect errors of commission (table contains systems that should not be listed) and omission (systems are missing from the table).

LRB2: Forest Structure and Development – Continuous increasing logistic function of forest biomass, an index of forest structure and development (**Fig. 3**).

Input data – Forest Structure Data: Biomass

The index is intended to reflect the suite of structural changes that occurs as a forest develops, including an increase in canopy height, average tree size, biomass, and dead wood (standing and downed) and a decrease in tree density. Once forest reaches a mature stage, it is also expected that scattered canopy gaps will occur that allow development of shrubs and saplings in the understory. Mature deciduous forest is considered to be highest quality forest habitat for Wood Thrush. We used the results of Brown et al. (1997) and the range of biomass values in the dataset to scale the function. Brown et al. reported that for eastern hardwood stands, aboveground biomass is generally in the range of 100-125 metric tons (Mg)/ha for poletimber stands, 125-185 Mg/ha for saw timber stands, and 220-260 Mg/ha for old growth stands. The average biomass for all sites classified as forest within the LCC area by the 2006 NLCD was approximately 94 Mg/ha, with a range of 0 to 333. Our function assumes that quality increases with increasing biomass until a plateau is reached at approximately 125 Mg/ha. Our approach is similar to a Habitat Suitability Index (HSI) model developed for Wood Thrush for the Central Hardwoods and West Gulf Coastal Plain regions (Tirpak et al. 2009), which classified suitability as increasing from shrub-seedling to saw timber stages.

Primary uncertainties: what stage of forest development is most favorable for Wood Thrush? Although mature forest is frequently cited as Wood Thrush habitat, some sources have argued that mid-successional forests are more favorable than late successional forests. For example, Holmes and Sherry (2001) proposed that loss of Wood Thrush from a northern hardwoods study area in New Hampshire over 30 years may be related to maturing forest and a corresponding loss of understory foliage. They noted, however, that much understory change was related to consequences of beech bark disease, not simply forest maturation. Driscoll and Donovan (2004) reported (without quantification) that Wood Thrush appear to prefer to situate their nests along forest edges, where vegetation is denser. The lack of consensus about most favorable forest stages is reflected in the HSI developed by Rittenhouse et al. (2007) for Wood Thrush in the Central Hardwoods Region, which in contrast to our approach implemented high suitability at young tree ages (low biomass) followed by a decline in suitability in mid-successional forest (intermediate biomass).

An additional consideration not reflected in this local resource measure is that in areas of high density of white-tailed deer (*Odocoileus virginianus*), deer browse may substantially reduce suitability of the understory for Wood Thrush (McShea and Rappole 2000).

LRB3: Small Extent Development Intensity – Continuous estimate of the intensity of development.

Input data – Modified Ecological Systems (ESM+)

This index is intended to measure short-distance edge effects: changes in microclimate, vegetation structure, and access by predators (McCollin 1998) that occur on a scale of a few to tens of meters from a developed or agricultural edge. Edge effects have been reported for many species of forest songbirds, including Wood Thrush (e.g., Driscoll and Donovan 2004). Specifically, the index calculates the density of anthropogenic cover types within 100 m of a focal cell, with the effect of cover types declining as a negative logistic function of distance from a focal cell. Consequently, suitability increases with distance from developed areas. Agricultural areas are included because microclimate and predator access are expected to change near such areas. **Table 2** lists the weights assigned to each land cover category. **Figure 4** depicts an example of the effect of this function. Clearcut or early successional forests are not classified as developed areas even though forest succession may have some effects on microclimate of adjacent forests. The rationale is that clearcut forests in forested areas do not appear to increase predation and parasitism risks to forest songbirds to the degree caused by edges with agricultural and developed sites (Duguay et al. 2001, Rodewald and Yahner 2001).

Primary uncertainties: one uncertainty is that the relative effects of different types of human development are unclear, particularly the relative influence of housing, road development, and agriculture because they involve different risks. Road traffic may cause direct mortality for birds crossing roads. Housing may increase domestic predators (cats, dogs) as well as provide food sources for wild predators such as Blue Jays (*Cyanocitta cristata*). Cultivated crops such as corn may provide food sources for omnivores that prey on Wood Thrush, such as skunks and crows. Additionally, complex interactions among factors that vary depending upon the extent of human development could exist (Driscoll and Donovan 2004). A second uncertainty is the functional relationship between development and habitat suitability; there is strong support for a negative relationship, but the magnitude of change and distance of penetration into forest are not clearly established.

LRB4: Large Extent Development Intensity – Continuous kernel estimate as for LRB3 but at a coarser scale (i.e., larger bandwidth). The maximum distance at which the kernel is evaluated for this index is 1 km, compared to 100 m for LRB3.

Input data – same as for LRB3

This index is intended to reflect effects of human-mediated landscape change that accumulate over a larger geographical area and that may penetrate more deeply into the forest than the processes of LRB3. In particular, large-scale transformation of the landscape to agriculture and residential areas may lead to population increases of cowbirds and generalist predators (such as raccoons, crows, and Blue Jays). Such increased abundance of brood parasites and predators has the potential to affect reproductive success and survival of Wood Thrush at a scale of hundreds of meters from forest edges. In a study replicated at 30 sites across 17 states, Lloyd et al. (2005) documented an approximately 50% lower annual fecundity of female Wood Thrush in the most developed landscapes (developed land cover within 10 km) compared to the least developed landscapes. Among the many other studies that have documented reduced reproductive success of Wood Thrush in landscapes where forests have been fragmented are Hoover et al. (1995) and Driscoll & Donovan (2005). LRB4 also reflects consideration that many forest songbirds, presumably including Wood Thrush, appear to evaluate and utilize spatial areas much larger than their defended territories in making settlement decisions and carrying out breeding activities (Whitaker and Warkentin 2010).

Figure 5 illustrates an example of how the function relates to the proportion of development in the landscape surrounding potential breeding habitat. This function is similar to a suitability index in the Wood Thrush HSI developed by Tirpak et al. (2009), although their function decreased to a suitability of 0 at maximum extent of development.

LRB3 and LRB4 differ in their consideration of cowbirds/predators in that LRB3 focuses on local structural features that allow an individual animal more ready access to a Wood Thrush territory (edge proximity) whereas LRB4 is designed as an indicator of abundance of cowbirds/predators that impact Wood Thrush. Land cover types are given the same weights as for LRB3 (**Table 2**).

Primary uncertainties: although studies have generally documented reduced reproductive successes, such as reduced nest success and female fecundity, in relation to intensity of development in the landscape and size of forest patches, several uncertainties remain. Regional differences appear to exist, with cowbird predation more severe in the Midwest than Northeast (Hoover and Brittingham 1993), but few reproductive studies have been conducted within the North Atlantic LCC area. Uncertainty over which aspects and scales of landscape composition and fragmentation are most important is also an issue.

Calculation of LRA-B

LRA-B is computed as the geometric mean of LRB1 and LRB2 (with LRB1 weighted three times LRB2 due to uncertainty in the biomass values used to calculate LRB2) multiplied by LRB3 and LRB4:

$$LRA\text{-}B = \exp\left(\frac{3\ln(LRB1) + \ln(\mathrm{LRB2})}{4}\right)\mathrm{LRB3\ LRB4}$$

LRA-P. Local Resource Capability for Postbreeding

Local resource capability for the postbreeding (premigration) season is comprised of two local resource indices, as follows:

LRP1: Early Successional Forests – Unimodal function of forest biomass, an index of forest structure and development.

Input data – Modified Ecological Systems (ESM+), Forest Structure Data: Biomass

Early successional forests capable of providing postbreeding habitat for Wood Thrush are identified by a combination of ecological system classification and biomass. All ecological systems considered breeding habitat (**Table 1**) are also considered suitable for postbreeding when in an early successional condition and assigned weight = 1. Additionally, several ecological systems with a substantial deciduous tree component that are not considered suitable for breeding (due to conifer or wetland components) are classified as potential postbreeding habitat (**Table 3**). We applied a Gaussian function to biomass values for these systems based on the results of Brown et al. (1997); they found that for eastern hardwood stands, aboveground biomass for seedlings and saplings is generally in the range of 20-50 Mg/ha. We used a mean value of 25 Mg/ha and a standard deviation of 15 for the function, which we rescaled such that the maximum suitability = 1 (**Figure 6**).

Primary uncertainties: Wood Thrush postbreeding habitat use is much less documented than breeding habitat, and the relative preference for and quality of different ecological systems is uncertain. Also, although vegetation differences between breeding and postbreeding sites have been documented (Vega Rivera et al. 1998) and are consistent with lower forest biomass at postbreeding sites, to our knowledge the functional relationship between forest structure and postbreeding habitat suitability has not been formally assessed.

LRP2: Forest/Open Area Edges – Continuous decreasing logistic function of distance from edge between forest and nonforested land, implemented on the forest side of the edge.

Input data – Modified Ecological Systems (ESM+)

This index is intended to identify edges between forests and open areas that result in shrubby, dense vegetation used by Wood Thrush following the breeding season. Juvenile Wood Thrush have been documented to use forests at the edges of roads, fields, and streams (Anders et al. 1998, Vega Rivera et al. 1998). A steep shape to the function is used because shrubby conditions are expected to occur only on a scale of meters to a few tens of meters. For the purposes of the index, an edge occurs only where a land cover type from the first of the following two categories is juxtaposed with a land cover type from the second category:

1) Forested ecological systems potentially suitable for postbreeding. These systems are identified in **Table 1** (all receive a weight of 1) and **Table 3** (weights apply).
2) Open land cover types and ecological systems listed in **Table 4**. Note that certain portions of the Modified Ecological Systems are mapped as shrublands or grasslands (NLCD designations, not natural systems) even though potentially they could succeed to forested ecological systems.

Primary uncertainties: the uncertainties noted for LRP1 apply to LRP2 as well.

Calculation of LRA-P

LRC-P is computed as the maximum of LRP1 and LRP2.

Index

4 Home Range Capability

Home range capability for Wood Thrush is determined separately for the breeding season and postbreeding (premigration) season, and then combined into a single measure of home range capability.

HRC-B. Home Range Capability for Breeding

Home range capability for the breeding season is comprised of a single index, as follows:

HRC-B: For each focal cell with LRC-B>0, build a resistant kernel scaled to breeding territory size, with resistance weights (costs) for land cover types based on expected tolerance of Wood Thrush for the land cover type within its home range.

Input data – LRC-B and Modified Ecological Systems.

Nesting success and adult return rates in subsequent seasons have been reported to be reduced in forest fragments <2 ha (Weinberg and Roth 1998) and we therefore used 2 ha as the breeding territory scale. All ecological systems considered breeding habitat (**Table 1**) are assigned the lowest possible resistance (weight = 1). Certain forested systems with a substantial deciduous tree component that are not considered breeding habitat but that might be tolerated within a home range (**Table 3**) are also assigned a resistance of 1. Streams (open water – lentic) were assigned a resistance of 1 so that narrow streams would not strongly interrupt home ranges. All other systems, including developed land types, were considered absolute home range barriers. LRC-B is used to identify focal cells and to weight the HRC-B values (cells associated with low resistance and large LRC-B values receive the greatest HRC-B values, all other factors being equal).

Primary uncertainties: uncertainty specific to this metric is considered relatively low, but it may not adequately reduce the suitability of medium-sized forest fragments (e.g., 10-50 ha), which have been reported to have lower occurrence of Wood Thrush than patches >100 ha (Robbins et al. 1989).

HRC-P. Home Range Capability for Postbreeding

Home range capability for the postbreeding (premigration) season is comprised of a single index, as follows:

HRC-P: an index that increases linearly as proportion of postbreeding habitat in the surrounding landscape increases, bounded by lower and upper thresholds (**Fig. 7**).

Input data: LRC-P

The basis for this index is that landscapes containing sufficient postbreeding habitat are expected to be of higher quality for Wood Thrush breeding than landscapes without access to such resources. The index is based on evaluating quantity and quality of postbreeding habitat within a 3 km radius, a distance within which fledgling and adult Wood Thrush are often found to disperse after breeding. A minimum threshold is set at 0.25 under the assumption that even if no postbreeding habitat (early successional forest) is available within 3 km, Wood Thrush may be able to remain within breeding habitat or disperse farther than 3 km in search of postbreeding habitat (Vega Rivera et al. 1999). A maximum threshold of 1 occurs when 5% or more of the landscape is in high quality (LRC-P ≥ 0.9) postbreeding habitat (or at least 15% of the landscape is of a LRC-P value ≥ 0.4). Habitat quality increases linearly between the upper and lower thresholds (**Fig. 7**), with quality increasing most rapidly for highest quality postbreeding habitat (LRC-P ≥ 0.9). Values of 5% and 15% were chosen based on assumptions that space needs are less for postbreeding than breeding (smaller areas used and presence of conspecifics tolerated) yet sufficient quantity must be available to be readily located by dispersing individuals and provide adequate food resources. Schwenk and Donovan (in press) reported that Wood Thrush occupancy is greatest within landscapes containing an intermediate percentage of forest within 1 km, which could indicate preference for areas with access to early successional postbreeding habitat.

Primary uncertainties: although use of early successional forests during postbreeding by both juvenile and adult Wood Thrush has been demonstrated, the implications for landscape-level habitat suitability are not yet well-established. In their Wood Thrush HSI for the Central Hardwoods Region, Rittenhouse et al. (2007) postulated a minimum suitability threshold of 0.1 for postfledging habitat and postulated that maximum suitability occurred when 20% of the landscape (within 1 km) consisted of forest stands of age 11-40 years old.

Calculation of HRC

Home range capability is computed as the product of HRC-B and HRC-P. Because HRC-B is zero for any cells not containing breeding season habitat value, HRC is also zero for those cells. Thus, the final result can be interpreted as the suitability of cells as breeding home ranges, modified by the availability of postbreeding habitat. Because HRC-P has a positive lower threshold (0.25), HRC is always >0 if HRC-B >0.

Index

5 Results

5.1 Location of Ecological Systems Suitable for Breeding

Figures 8 and **9** depict the location of ecological systems classified as suitable for Wood Thrush breeding (LRB1) based on current conditions (time step = year 0 = approx. 2000), as well as other major land cover categories such as developed land.

5.2 Examples of Model Results

We illustrate results of applying the model to the Kennebec Watershed in Maine. **Figure 10** and **11** shows the location of a portion of the watershed approximately 10 km by 12 km in the vicinity of the towns of Anson and Madison. **Figures 10** and **11** depict model results for this sample area.

For detailed spatial results of the current time step for the full study area extent see:

Kennebec River watershed:

- Kenbec_species_current.zip

Middle Connecticut River watershed:

- Conn_species_current.zip

Pocomoke-Nanticoke River watershed:
- Pocnan_species_current.zip

For detailed spatial results for 2030 and 2080for the full study area extent see:

Kennebec River watershed:
- Kenbec_species_future.zip

Middle Connecticut River watershed:
- Conn_species_future.zip

Pocomoke-Nanticoke River watershed:
- Pocnan_species_future.zip

Index

6 Model Assessment

See the Species documentation for details regarding the model assessment process.

http://jamba.provost.ads.umass.edu/web/lcc/NALCC_documentation_species.pdf

eBird data was used to assess the Wood Thrush HABIT@ model. The Wood Thrush Habit@ model associates higher habitat capability (HRC) values with locations of known Wood Thrush presences compared to locations where Wood Thrush were not detected (**Figs. 12** and **13**).

Index

7 Climate Niche Envelope Model

7.1 Model Building

A detailed description of the methods used to define the climate niche envelope (CNE) model can be found here NALCC_documentation_species.pdf. Briefly, we used logistic regression to build species' CNE models from downscaled climate data and independent species' occurrence data (e.g., eBird) for the period 1985-2010. All possible combinations of predictor variables were considered and the final model was selected between models that minimized false positive rates at model sensitivities of 95%, 97.5%, and 99%. The distribution of the CNE for each sensitivity level was compared to Wood Thrush's geographic distribution and the sensitivity level that best approximated its range, was selected.

For Wood Thrush, the logistic regression model that was ultimately selected had a delta (compared to candidate models) false positive value of 0.00 and a total false positive error rate of 0.66 with model sensitivity of 95%, and Deviance explained (D^2) = 0.10. The cutpoint that minimized the false positive rate was 0.018. The model selected with a specified sensitivity of 95% best approximated the species current geographic distribution compared to models that minimized false positive rates with model sensitivities of 97.5% or 99%. See **Table 5** for climate variables and parameter estimates that were included in the final model.

7.2 Model Validation

The Monte Carlo randomization tests confirmed that the observed false positive rate was significantly different from that under the null distribution (**Fig. 14**). Therefore, we conclude that the Wood Thrush CNE model is a relatively accurate representation of the spatial distribution of suitable climate conditions for Wood Thrush throughout its range in the Humid Temperate Domain.

Index

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Index

9 Appendix A – Tables and Figures

Table 1. Ecological systems and weights for ecological systems considered to be potential breeding habitat for Wood Thrush. All other systems were assigned a weight of 0. Larger weights indicate greater habitat value.

Ecological System Code	Ecological System Description	LRB1 (breeding habitat value)	Basis for LRB1 <1	Map Value
201.563	Laurentian-Acadian Pine-Hemlock-Hardwood Forest (all variants)	0.5	Pine-hemlock component	5630, 5639
201.564	Laurentian-Acadian Northern Hardwood Forest (typic, red oak, and moist-cool variants)	1		5640, 5644, 5649
201.564	Laurentian-Acadian Northern Hardwood Forest (high conifer variant)	0.5	Conifer component	5642
201.587	Laurentian-Acadian Floodplain Forest	0.5	Wetland component	587
202.029	Southern Appalachian Northern Hardwood Forest	1		90029
202.323	Southern Piedmont Small Floodplain and Riparian Forest	0.75	Wetland component	90323
202.324	Southern Piedmont Large Floodplain Forest	0.75	Wetland component	90324
202.339	Southern Piedmont Dry Oak-(Pine) Forest	0.75	Dryness and pine component	90339
202.342	Southern Piedmont Mesic Forest	1		90342
202.373	Southern and Central Appalachian Cove Forest	1		90373
202.457	Southern Ridge and Valley / Cumberland Dry Calcareous Forest	0.5	Dry conditions	90457
202.591	Central Appalachian Dry Oak-Pine Forest	0.5	Dryness and pine component	591, 90591
202.592	Northeast Interior Dry-Mesic Oak Forest (all variants)	1		5920, 5929, 90592
202.593	Appalachian Hemlock-Hardwood Forest (all variants)	1		5930, 5938, 5939, 90593
202.596	Central and Southern Appalachian Montane Oak Forest	0.5	High elevation, stunted	90596
202.608	Central Appalachian River Floodplain	0.5	Wetland component	90608
202.609	Central Appalachian Stream and Riparian	0.5	Wetland component	90609

202.700	North-Central Interior Wet Flatwoods (all variants)	0.5	Wetland component	7000, 7008, 7009
202.706	South-Central Interior Small Stream and Riparian	0.5	Wetland component	90706
202.886	Southern Appalachian Oak Forest	1		90886
202.997	Glacial Marine and Lake Clayplain Forest: wet	0.5	Wetland component	997
202.998	Glacial Marine and Lake Clayplain Forest: mesic	1		998
203.241	Southern Atlantic Coastal Plain Dry and Dry-Mesic Oak Forest	0.5	Dry conditions	90241
203.242	Southern Atlantic Coastal Plain Mesic Hardwood Forest	1		242, 90242
203.475	Northern Atlantic Coastal Plain Dry Hardwood Forest	0.75	Dry conditions	475
203.999	Northeast Coastal and Interior Pine-Oak Forest	0.5	Pine component	999

Table 2. Land cover types, and associated weights, used to calculated development indices LRB3 and LRB4. Larger weights indicate more detrimental effects on habitat quality.

Land cover type	Weight	ESM+ code*
Primary road	1	1
Secondary road - ramp	1	2
Local neighborhood road – rural road/city street/service drive	0.95	3
Private roads, logging roads, 4-wheel drive roads	0.90	4
Active trains	0.95	5
Developed, open space (<20% impervious surface)	0.8	21
Low intensity residential development (20-49% impervious)	0.9	22
Medium intensity development (50-79% impervious)	0.95	23
High intensity, commercial and industrial development (80-100% impervious)	1	24
Pasture/hay	0.2	81
Cultivated crops	0.2	82
All natural ecological systems	0	

*Human modified systems used in the index were derived from the 2006 NLCD, except for roads, which were derived from U.S. Census roads network data.

Table 3. Ecological systems considered to constitute potential postbreeding habitat but not breeding habitat. Larger weights indicate greater habitat value. Weights apply only when the system is in an early successional stage of development. (Ecological systems suitable for breeding listed in **Table 1** are also considered suitable for postbreeding and are assigned a weight of 1 when early successional.)

Ecological System Code	Ecological System Description	LRP1 (post-breeding habitat value)	Basis for LRP1 <1	Map Value
103.588	Eastern Boreal Floodplain	0.5	Coniferous component	588
201.565	Acadian Low Elevation Spruce-Fir-Hardwood Forest	0.5	Coniferous component	5650
201.566	Acadian-Appalachian Montane Spruce-Fir-Hardwood Forest	0.5	Coniferous component	566
201.574	Northern Appalachian-Acadian Conifer-Hardwood Acidic Swamp	0.5	Coniferous component	5740, 5747, 5748, 5749
201.575	Laurentian-Acadian Alkaline Conifer-Hardwood Swamp	0.5	Coniferous component	5750, 5757, 5758, 5759
202.023	Southern Piedmont Dry Oak-Heath Forest	0.5	Dry conditions	90023
202.331	Southern Appalachian Montane Pine Forest and Woodland	0.5	Coniferous component	90331
202.332	Southern Appalachian Low-Elevation Pine Forest	0.5	Coniferous component	90332
202.336	Piedmont Upland Depression Swamp	1		90336
202.347	Eastern Serpentine Woodland	0.5	Open conditions	347
202.600	Central Appalachian Pine-Oak Rocky Woodland	0.5	Coniferous component	800, 90600
202.602	Central Appalachian Alkaline Glade and Woodland	0.5	Open conditions	602
202.604	North-Central Appalachian Acidic Swamp	0.5	Coniferous component	6040, 6047, 6048, 6049
202.605	North-Central Interior and Appalachian Rich Swamp	1		6050, 6057, 6058, 6059
202.607	North-Central Appalachian Seepage Fen	0.5	Open conditions	6070
203.282	Northern Atlantic Coastal Plain Tidal Swamp	0.5		282, 90282
203.302	Northern Atlantic Coastal Plain Maritime Forest	0.5	Dry conditions	302, 90302
203.304	Central Atlantic Coastal Plain Nonriverine Swamp and Wet Hardwood Forest	1		90304
203.520	Northern Atlantic Coastal Plain Basin Swamp and Wet Hardwood Forest	1		5200, 5207, 5208, 5209, 90520

Table 4. Open land cover types considered to result in postbreeding habitat for Wood Thrush when juxtaposed with suitable forested ecological systems (**Tables 1** and **3**).

Ecological System or NLCD Code	Ecological System or Land Cover Description	Map Value
11	Open water (lotic , lentic, estuarine, or marine)	100, 200, 300
21	Developed, open space (<20% impervious surface)	21
22	Low intensity residential development (20-49% impervious)	22
31	Barren land	31
32	Unconsolidated shore	90321
52, 71	Shrublands, grasslands, herbaceous*	5271, 95271
81	Pasture/hay	81
82	Cultivated crops	82
103.581	Boreal-Laurentian Bog-- Saco Heath	581
201.019	Laurentian Acidic Rocky Outcrop	19
201.569	Laurentian-Acadian Acidic Cliff and Talus	569
201.570	Laurentian-Acadian Calcareous Cliff and Talus	570
201.571	Northern Appalachian-Acadian Rocky Heath Outcrop	571
201.572	Laurentian-Acadian Calcareous Rocky Outcrop	572
201.573	Acadian-North Atlantic Rocky Coast	573
201.578	Acadian Coastal Salt Marsh	578
201.579	Acadian Estuary Marsh	579
201.580	Acadian Maritime Bog	580
201.583	Boreal-Laurentian-Acadian Acidic Basin Fen	583, 5830, 5839
201.585	Laurentian-Acadian Alkaline Fen	5850, 5859
201.594	Laurentian-Acadian Freshwater Marsh	5940, 5947, 5948, 5949
201.721	Great Lakes Alvar	721
202.330	Southern Appalachian Montane Cliff and Talus	90330
202.386	Southern Piedmont Cliff	90386
202.601	North-Central Appalachian Acidic Cliff and Talus	601
202.603	North-Central Appalachian Circumneutral Cliff and Talus	603, 90603
202.606	North-Central Interior and Appalachian Acidic Peatland	6060, 6067, 6068, 6069
202.690	Central Interior Calcareous Cliff and Talus	90690
203.267	Atlantic Coastal Plain Peatland Pocosin and Canebrake	90267
203.516	Northern Atlantic Coastal Plain Fresh and Oligohaline Tidal Marsh	90516
203.893	Atlantic Coastal Plain Northern Bog	8930, 8937, 8938, 8939
203.894	Northern Atlantic Coastal Plain Brackish Tidal Marsh	99
203.895	Northern Atlantic Coastal Plain Heathland and Grassland	895

*For a minority of areas classified as grasslands or shrublands by the NLCD, the TNC ecological system map adopted the NLCD classification rather than assigning an ecological system. This is particularly true in the southern portion of the LCC.

Table 5. Parameter estimates for variables included in the final logistic regression model for Wood Thrush's climate niche envelop model. Wood Thrush presence/absence data were obtained from eBird. The selected model minimized the false positive rate with a model sensitivity of 95%.

Variable	**Estimate**
β	-1.08e+01
GDD	3.916e-03
GDD^2	-1.37e-06*
May-Sept precip.	1.66e-03*
May-Sept $precip.^2$	-7.11e-08*
Avg. annual $temp.^2$	2.64e-06*
Avg. July $temp.^2$	-1.18e-06

*$P \leq 0.05$

Figure 1. Conceptual model of Wood Thrush habitat requirements.

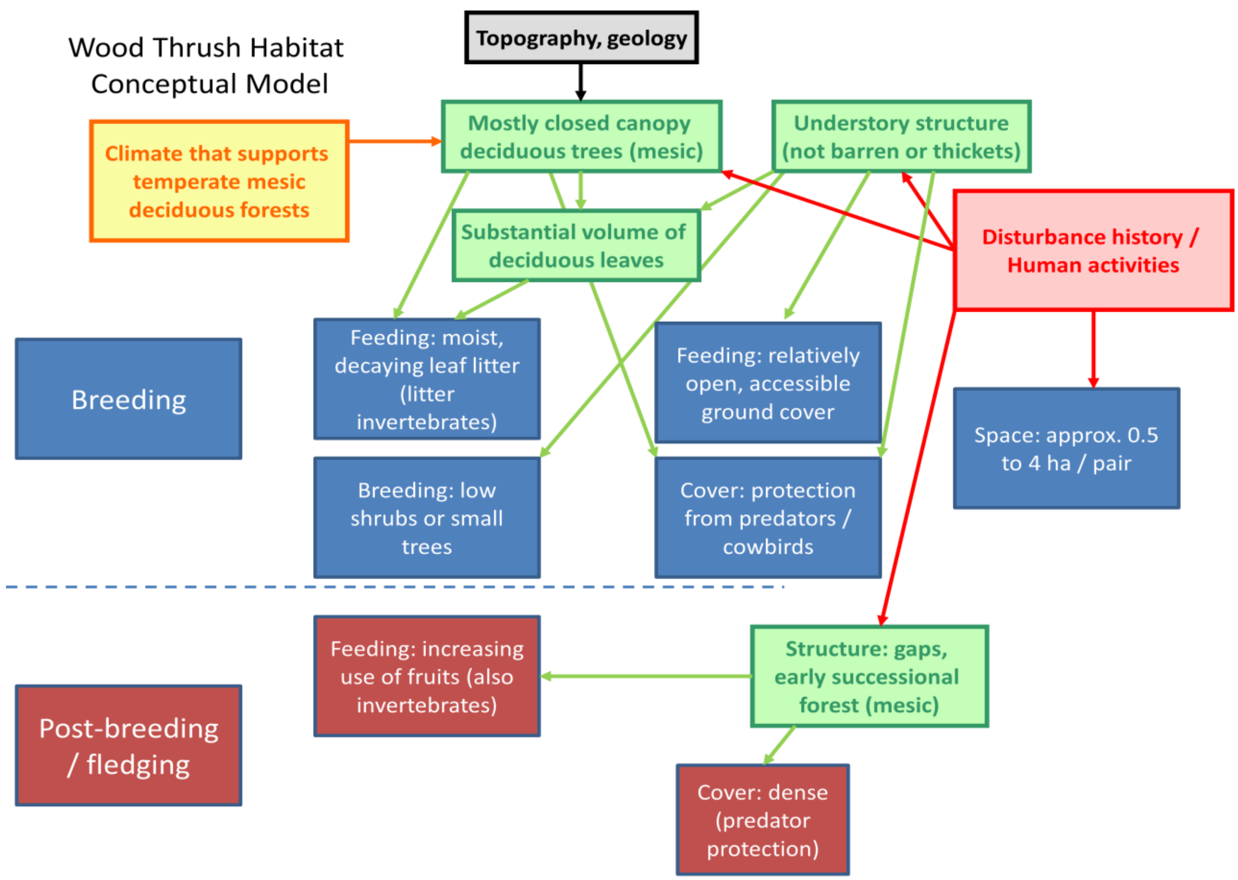


Figure 2. Summary of the steps in computing overall Wood Thrush home range capability (HRC) and landscape capability (LC), taking into account both breeding and postbreeding habitat availability and quality.

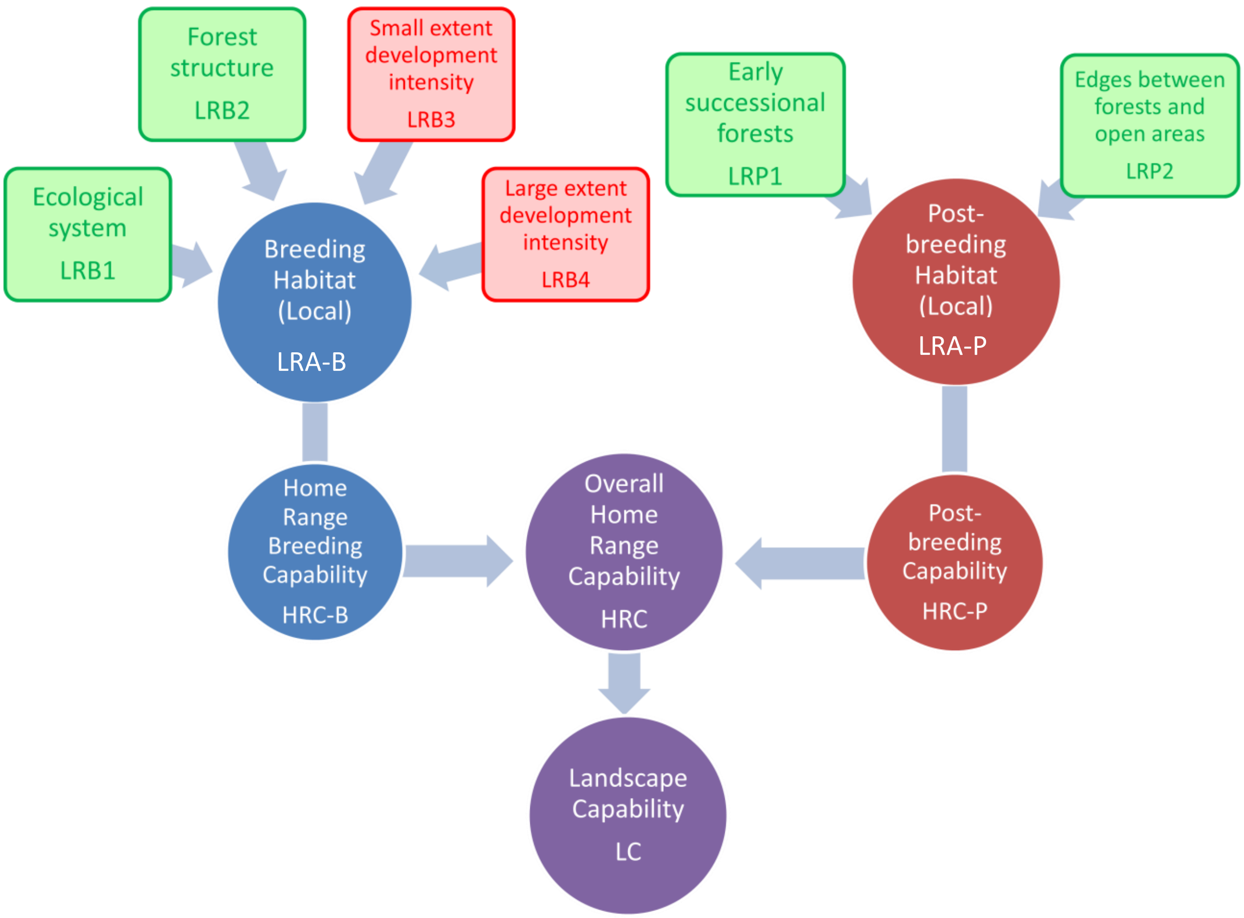


Figure 3. Quality of Wood Thrush habitat as a function of aboveground forest biomass, an index of forest structure and development (inflection point at 80 Mg / ha).

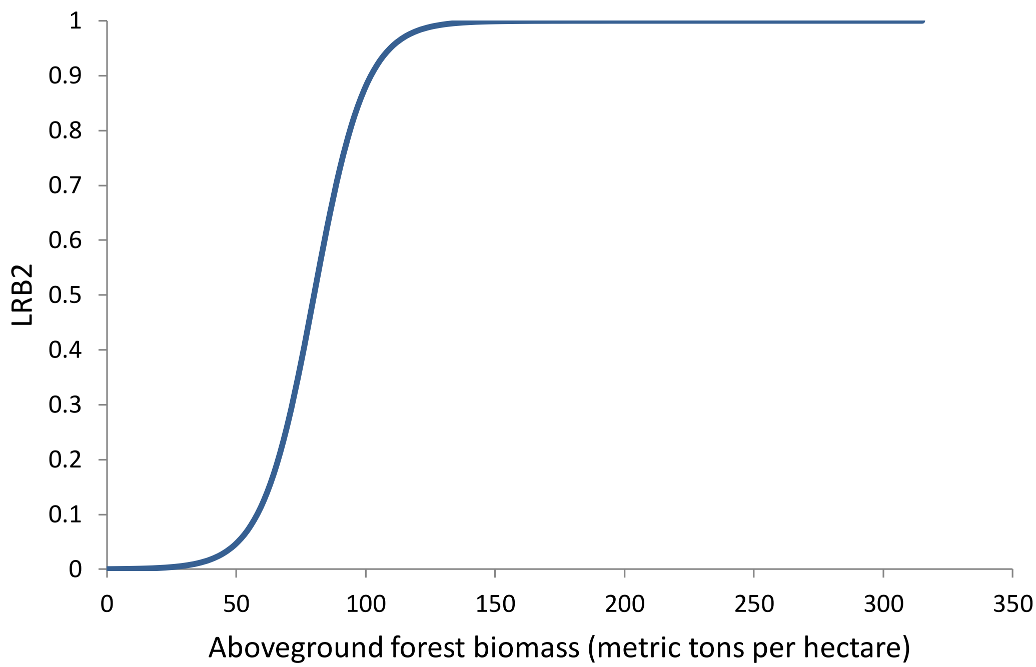


Figure 4. An example of application of the function of LRB3 to an idealized landscape consisting of a forested patch surrounded by development of weight = 1 (see **Table 2**). The response observed on actual landscapes varies depending on the spatial configuration and extent of breeding areas and developed areas.

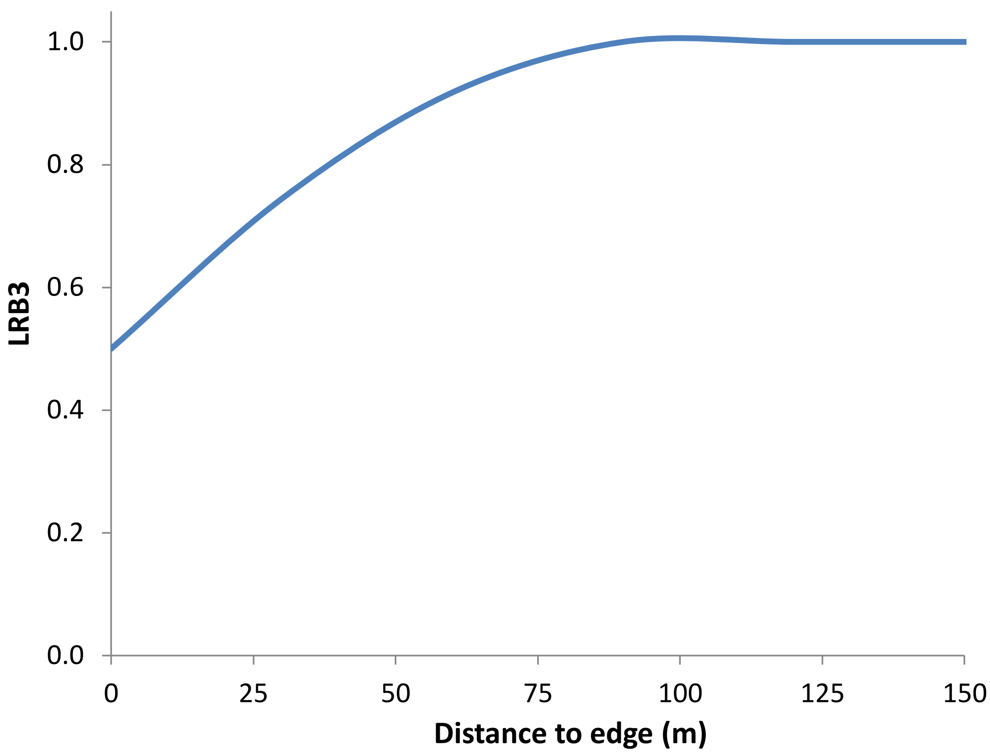


Figure 5. An example of realized suitability for LRB4 applied to several sample breeding habitat patches within developed landscapes, based on proportion of the landscape that is developed within 1 km. The response observed on actual landscapes varies depending on the spatial configuration and extent of breeding areas and developed areas.

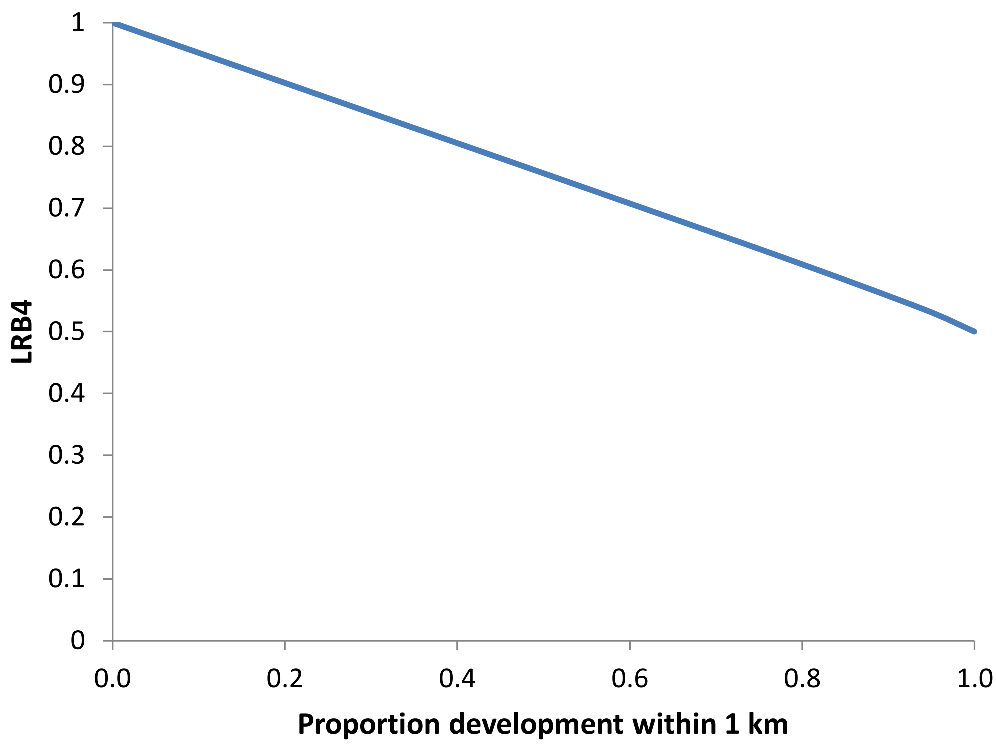


Figure 6. Capability of forest to provide postbreeding habitat for Wood Thrush as a function of biomass; low biomass, early successional forests are considered most suitable.

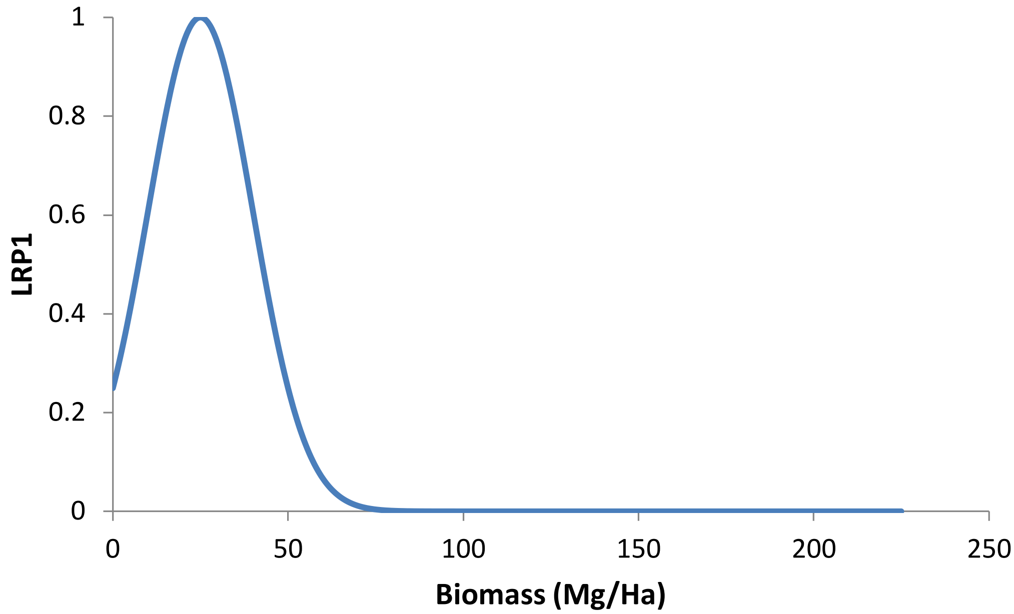


Figure 7. Quality of Wood Thrush habitat as a function of the availability of postbreeding (early successional) habitat within 3 km.

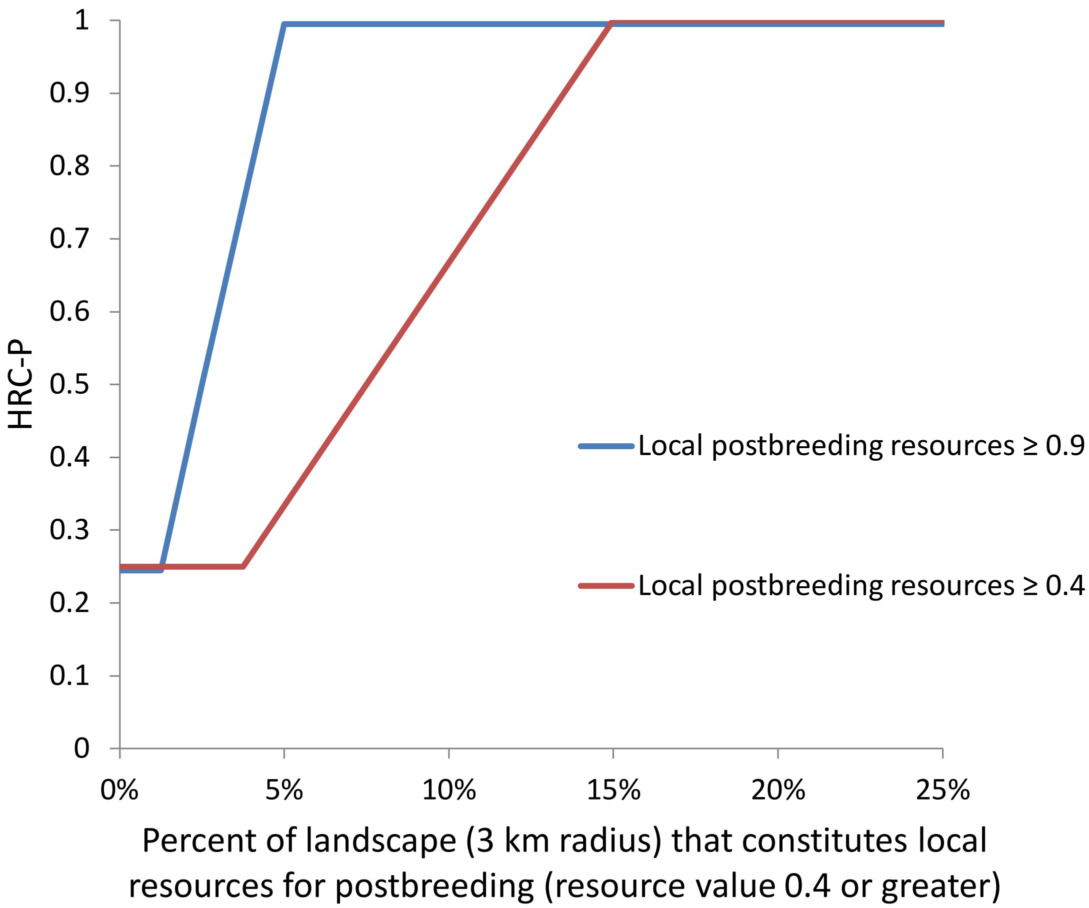


Figure 8. Patterns of occurrence of ecological systems in the northern half of the North Atlantic LCC identified as potentially suitable for breeding (LRB1) by Wood Thrush; water, developed land, and agriculture are also illustrated.

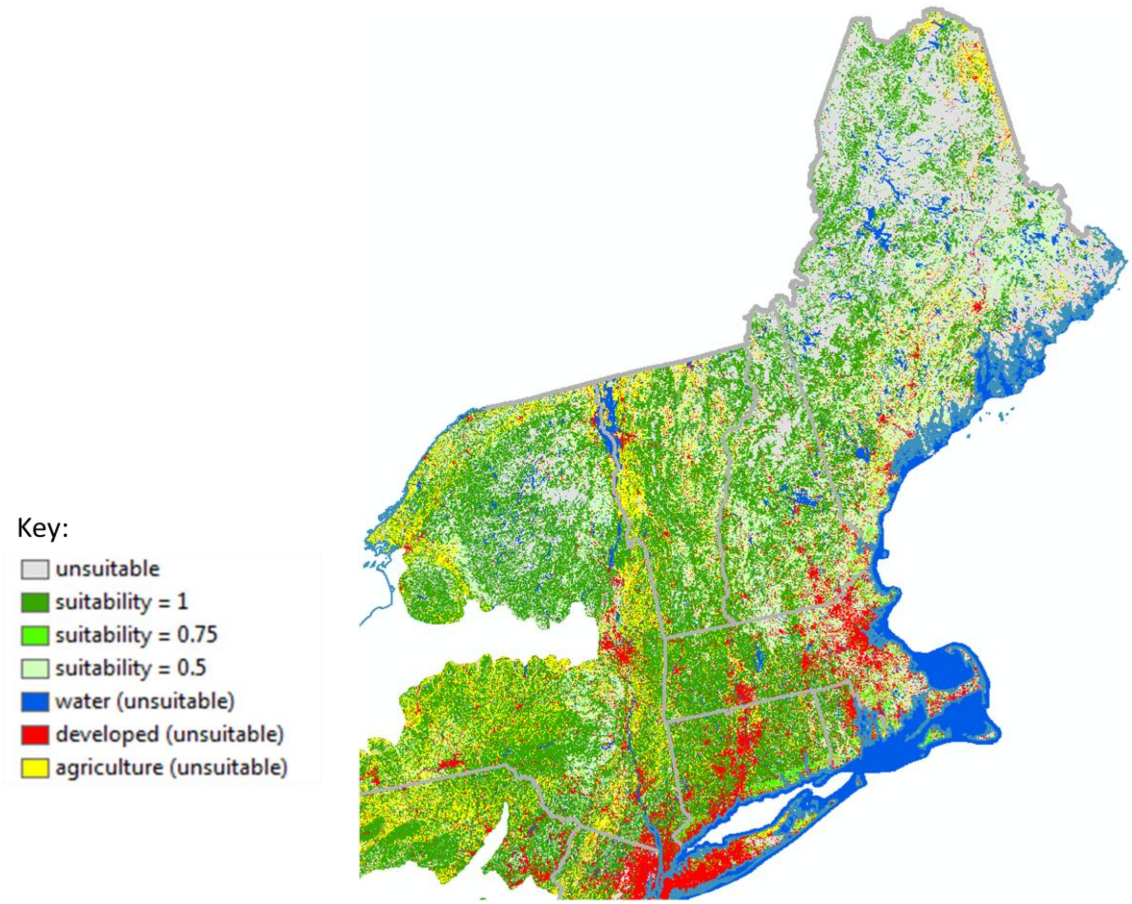


Figure 9. Patterns of occurrence of ecological systems in the southern half of the North Atlantic LCC identified as potentially suitable for breeding (LRB1) by Wood Thrush; water, developed land, and agriculture are also illustrated.

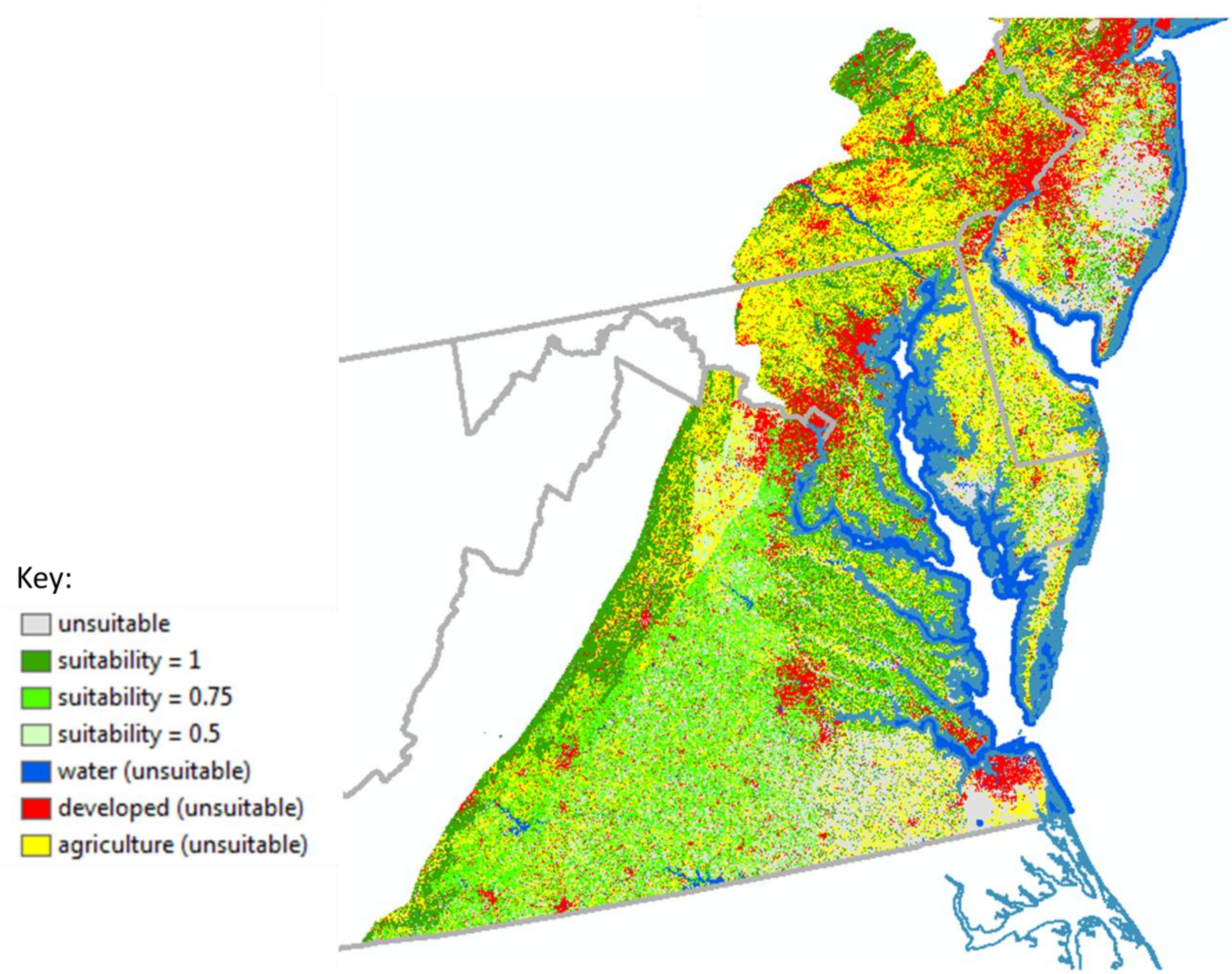
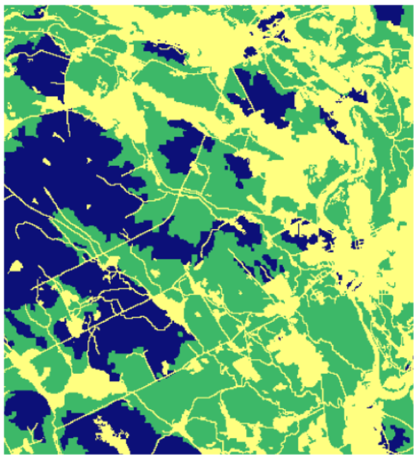
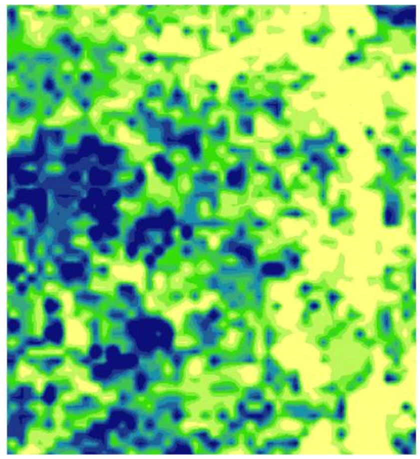


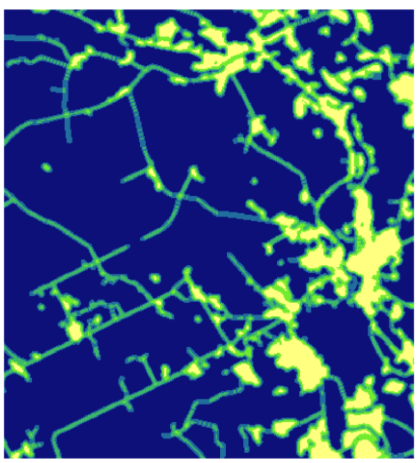
Figure 10. Examples of model results for an area in the Kennebec River watershed, with resource values increasing from yellows to greens to darkest blue: a) LRB1 (ecological systems weighted by breeding value), b) LRB2 (forest structure), c) LRB3 (fine-extent development), d) LRB4 (coarse-extent development) , e) LRA-B (combined local resources for breeding), f) HRC-B (home range capability, breeding).

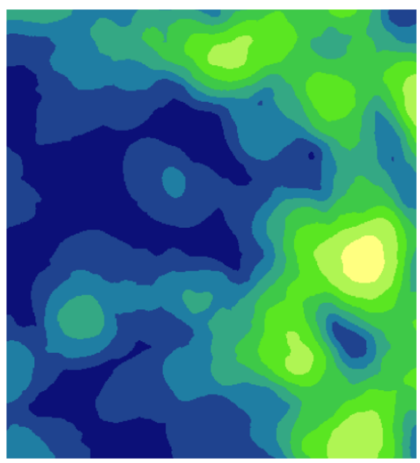
a) b)



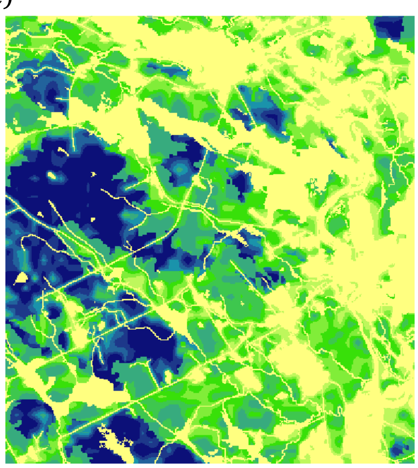


c) d)





e) f)



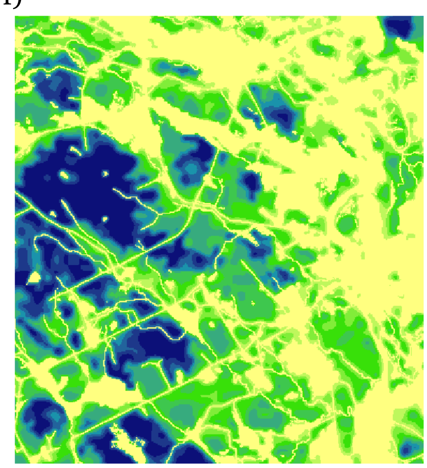


Figure 11. Additional examples of model outputs for the region described in Figure 10 (suitability increasing from yellow to blue): a) LRP1 (early successional forests, b) LRP2 (forest edges), c) LRA-P (combined postbreeding local resources), d) HRC-P (home range capability for postbreeding), e) HRC (overall home range capability).

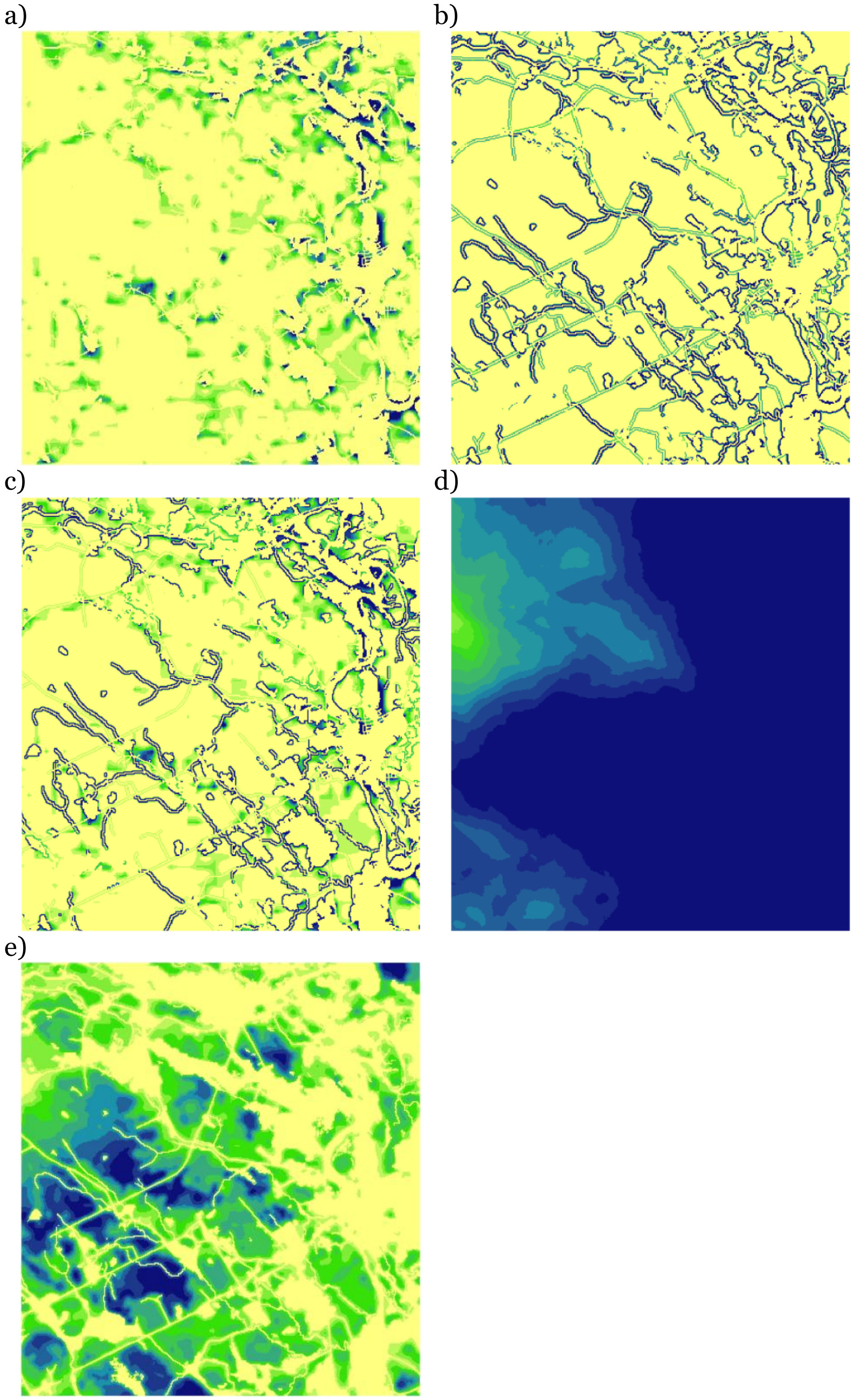


Figure 12. Statistical assessment of HABIT@ model performance for Wood Thrush in the Kennebec River and Connecticut River study areas. The example shown here is for wood thrush in both the Connecticut and Kennebec Rivers study areas. Solid lines are kernel density estimates of the maximum Home Range Capability (HRC) index within 100, 200, 400, and 800 m of the survey location for sites where wood thrush were present (green, n=38) and absent (red, n=682). Dashed lines are the mean of the maximum HRC values and solid black lines are the 95% confidence intervals on the mean. A *p*-value is reported for the model with the greatest Kappa and is based on a Monte Carlo randomization test (Figure 11); delta Kappa's (difference between observed Kappa and the Maximum Kappa) are reported for the other three scales. Kappa values are based on logistic regression models that also contain two detection covariates (Julian date, time of day) to account for detection probabilities and an offset term (survey hours) to account for varying survey effort.

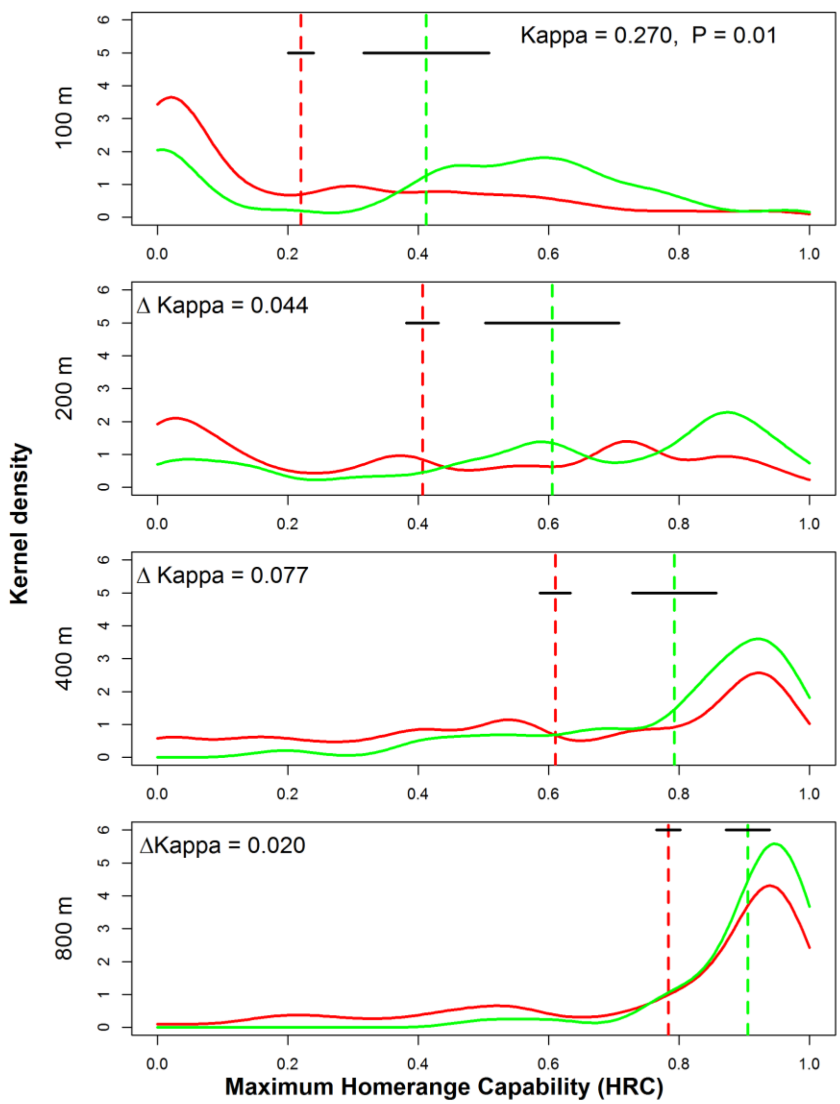


Figure 13. Monte Carlo randomization test (1,000 replications) of the observed Kappa for the logistic regression model predicting Wood Thrush presence from Habit@-derived maximum HRC values at a spatial extent that maximized Kappa (100 m); shown here for wood thrush. The null distribution of Kappa is given by the frequency distribution, while the observed Kappa (0.27) is shown as a vertical dashed line. The *p*-value (0.01) is computed as the proportion of the null distribution greater than or equal to the observed Kappa.

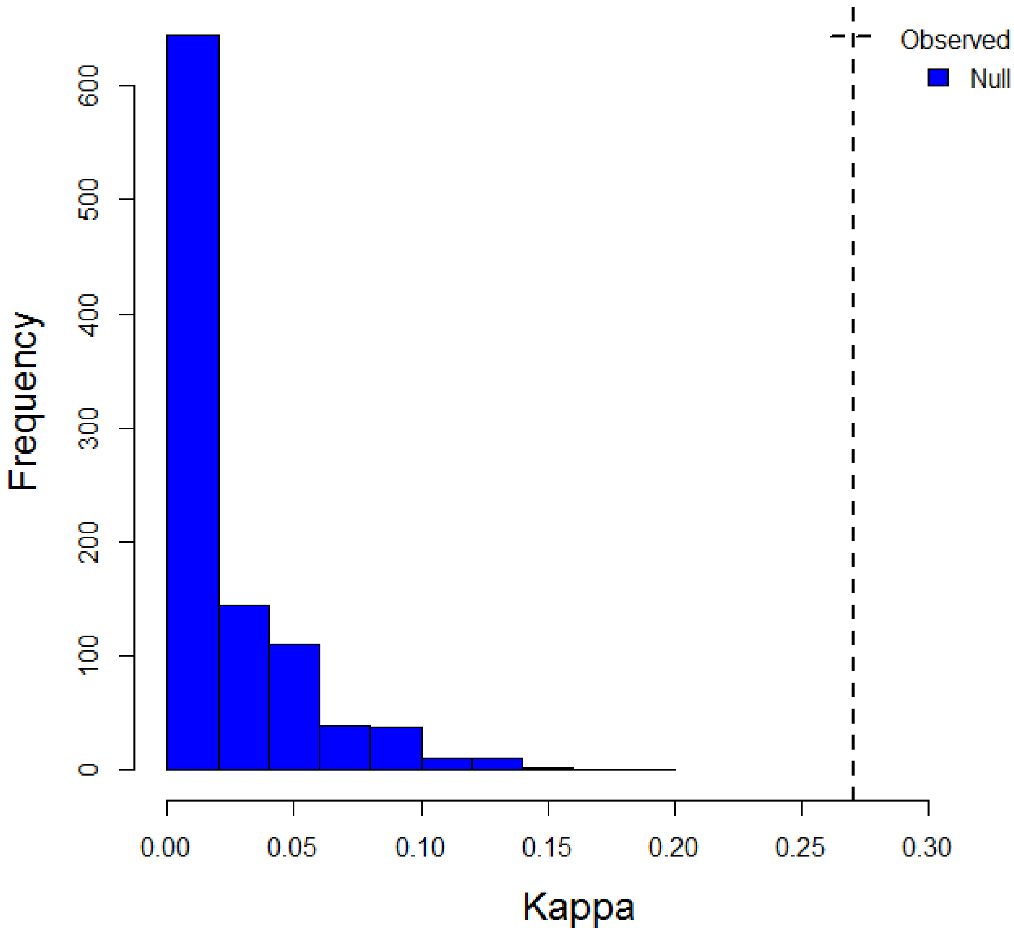
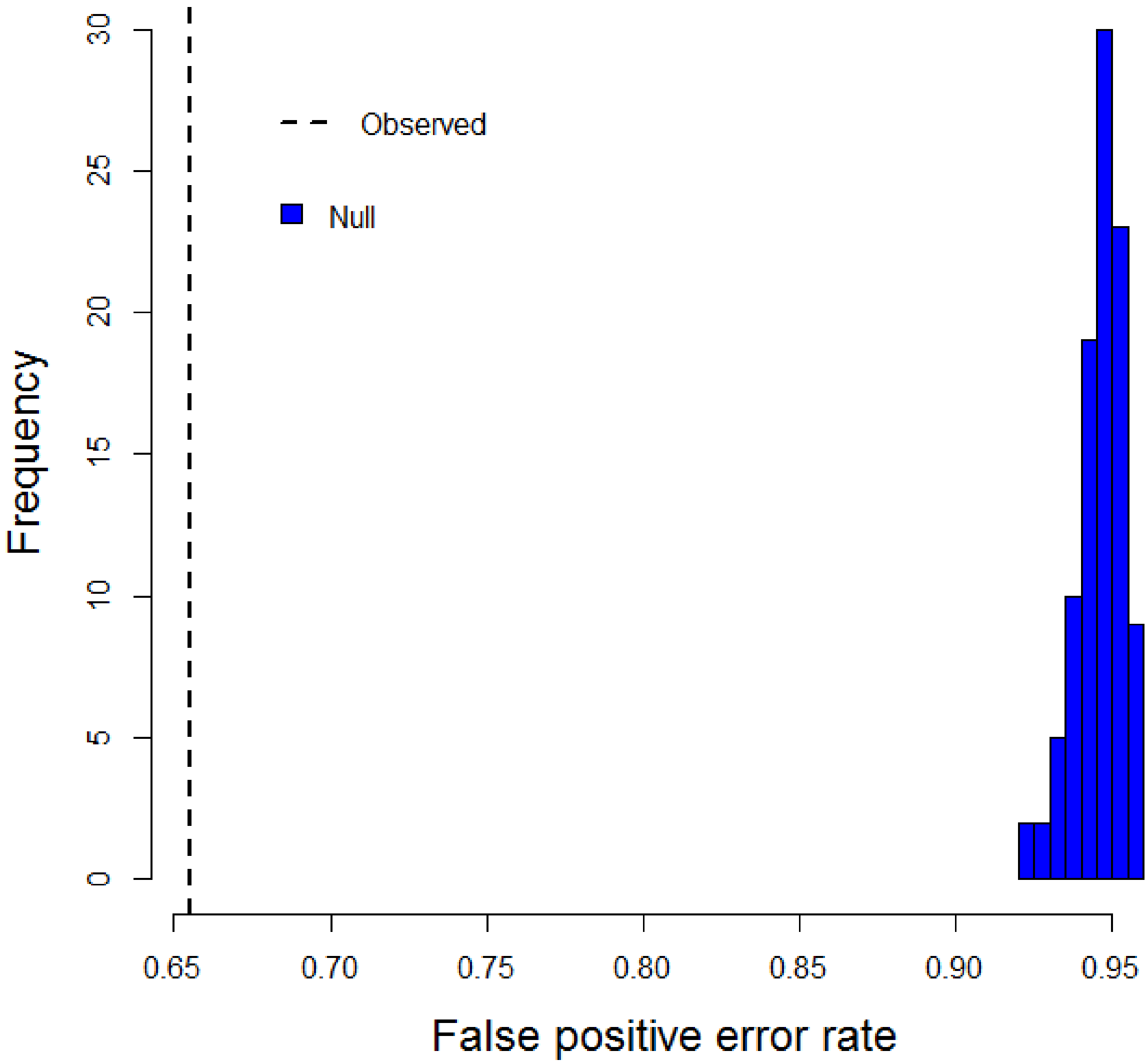


Figure 14. Monte Carlo randomization test (1,000 replications) of the observed false positive rate for the logistic regression model predicting Wood Thrush presence from climate variables. The null distribution of the false positive rate is given by the frequency distribution, while the observed false positive rate (0.66) is shown as a vertical dashed line. The *p*-value (0.01) is computed as the proportion of the null distribution greater than or equal to the observed false positive rate.



Index

10 Appendix B – File Names and Brief Descriptions

Parameter files:
X:\LCC\Parameters\habitat

Parameter files include:

- habit@.par - used by Anthill (cluster software) to run Habit@
- woth.txt - contains the specific Habit@ functions
- wothdev.txt - scales effects of development type for lrb3 and lrb4
- wothlrb1.txt - defines breeding habitat suitability based on ES map
- wothlrp1b.txt - defines post-breeding habitat suitability based on ES map
- wothlrp2a.txt - identifies open ecological systems
- wothmask.txt - creates a mask of suitable habitats used in obtaining HRC
- wothcost.txt - defines ecological resistance for the ES map used in obtaining HRC
- wothhr.txt - defines homeranges for running resistance kernels

Resulting grids created by Habit@ are located here:
X:\LCC\GISdata\DataFinal\species

Grids include (See woth.txt for interpretation):

- lrb1
- lrb2
- lrb3
- lrb4
- lrcb
- lrp1
- lrp1a
- lrp2
- lrp2a
- lrcp
- hrb1
- hrc
- hrp1
- hrp1a
- forestedge
- mask
- x

Index