BARRIERS TO DISPERSAL AND THE CHALLENGES FACING THE SOUTHERN EXPANSION OF BOBCATS IN NEW JERSEY

by

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ABSTRACT

In urban environments, the threats of habitat fragmentation and loss, barriers to dispersal, and anthropogenic causes of mortality affect the recolonization potential of extirpated species. One such species, the bobcat (*Lynx rufus*), historically occurred throughout the state of New Jersey, but due to increased urbanization and agricultural expansion has been confirmed to occur almost exclusively in the northern portions of the state since the 1960's. In this study I examine current barriers to bobcat dispersal and the possibility of the establishment of central and southern New Jersey bobcat populations. First, I developed a statewide habitat suitability index for bobcats and validated it with known bobcat locations. I then identified discrete suitable habitat patches and calculated landscape resistance values across the state from the inverse of the habitat suitability values with some adjustment for road-based metrics. To evaluate landscape connectivity throughout New Jersey, I applied circuit theory using the program Circuitscape within a GIS framework. I ran "current," representing movement potential, through the resistance landscape between each pair of previously identified habitat patches. Using circuit theory in combination with least-cost path analysis, I next identified bottlenecks to bobcat movement throughout New Jersey. I identified barriers to movement using the change in least-cost path value based on a hypothetical barrier reduction. Finally, I repeated all these analyses for a case study in central New Jersey, where all stream crossing structures under roadways were assigned the lowest resistance value of 1, representing the ideal scenario that all structures had been modified to allow bobcat passage. I found that habitat patches were connected with some redundancy in the north, but with less redundancy throughout central New Jersey. The regions of high cumulative current flow around

the Trenton area indicate that dispersing bobcats would have to pass through west central New Jersey to move from northern to southern habitat patches. Of the four least-cost paths connecting northern patches to southern patches, the shortest was approximately 25 km in length. While bobcats can easily disperse that distance, the movement corridors I identified cross through a highly urbanized landscape and contain several potential barriers. The resultant maps I produced will allow state managers to target specific areas for connectivity maintenance and improvement work within the CHANJ framework that are important for bobcat movement.

I next used spatially explicit agent-based simulation models to examine the possibility of the establishment of central and southern New Jersey bobcat populations. The simulations consisted of a primary population model using life history statistics as well as two spatially explicit sub-models that examined dispersal and home range formation through a rasterized landscape representing movement resistances for bobcats. I evaluated the impacts of the following management actions: 1) status quo, 2) barrier reduction, and 3) single translocation event. I ran each scenario ten times to project population size and distribution at the end of 1, 5, 10, and 25 years. There was no significant difference in population size at the 1-, 5-, 10-, and 25-year time intervals for both the status quo and barrier reduction scenario. The translocation scenario revealed that the model needs further refinement as the population decreased between the 1- and 5-year time intervals, with no differences found between any other time interval pairs. Results from all scenarios indicated high probability of bobcat occupancy in habitat north of Route 80 over the course of 25 years. Bobcats more consistently occupied territories south of Route 80 but north of Interstate 95 under the barrier reduction scenario than either the status quo or translocation scenarios. The translocation scenario revealed higher probabilities of occupancy in the south at the 5-year time step likely due to the continued presence of translocated bobcats in their original territories. However, this high probability decreased by the 10-year time step and occupied territories largely disappeared by year 25. The surprising results of the translocation scenario highlighted the need to refine how the model identifies reproducing females, as it is currently too strict. Additionally, the impact of multiple small translocations on the persistence of a southern bobcat population should be evaluated before any decisions are made regarding translocation. Overall, my results suggested that bobcats are unlikely to recolonize central and southern New Jersey under current conditions within the next quarter century. Mitigation of barriers, through the implementation of modified culverts and crossing structures appropriate for bobcat movement, may allow for more reliable establishment of bobcat presence in the region south of Route 80, but still little occupation of territory south of Interstate 95. Given limitations in the model and its need for further refinement, no conclusions can be made regarding the translocation scenario. Translocation, especially in conjunction with barrier mitigation and the conservation of corridor habitat, may still be a viable management opportunity for NJDFW as it has previously been successful with bobcats in both in Georgia and northern New Jersey. However, further research should be pursued before any decisions are made. Once properly calibrated, spatially explicit agent-based models can be useful tools for wildlife managers to evaluate the potential impacts and results of different management actions. Overall, this research has expanded the scientific understanding of species-specific connectivity in an increasingly urban world, thus informing the implementation of mitigation methods to maintain and increase permeability within the landscape.

Chapter 1

HABITAT SUITABILITY INDEX AND CONNECTIVITY ANALYSIS FOR NEW JERSEY BOBCATS

Introduction

Of the six species of felids native to North America, the bobcat (*Lynx rufus*) is the most broadly distributed (Anderson 1987). Within the United States, 47 of the 48 contiguous states report the presence of bobcats, including New Jersey (Roberts and Crimmins 2010). Within New Jersey, bobcats historically occurred throughout the state (Schantz and Valent 2003). However, in the 17th and 18th centuries, bounties were offered for bobcats and by 1757 accounts indicate that the bobcat was rare in Cape May county (Fowles, *in prep*). Bobcat populations continued this decline during the late 19th and early 20th centuries, possibly due to unregulated harvest, increased urbanization, and agricultural conversion of the landscape (Schantz and Valent 2003, Fowles 2020). By the 1960's, there were limited reports of bobcats in the northern portions of New Jersey and none in the southern portions. In 1972, they were declared a game species with a closed season which allowed for improved protection compared to unregulated harvest, however, they were likely extirpated by the late 1970s (N.J.A.C § 7:25-5.1 et seq.). Between 1978-1982, the New Jersey Division of Fish and Wildlife (NJDFW) translocated 24 bobcats from Maine into northern New Jersey in an attempt to restore the species to available habitat (Turbak 1994, Fowles 2020). The bobcat was classified as Endangered in New Jersey in 1991 because there appeared to be little change in bobcat abundance and distribution since the translocation effort

(N.J.A.C. § 7:25-4.13). Since then, increased bobcat sightings and road mortalities in northern New Jersey suggest that their population has increased (Fowles 2020).

In 2016, the bobcat population in northern New Jersey was estimated to be ~276 individuals (Fowles 2019, Fowles 2020), and, in March 2017, a bobcat was captured on a trail camera in central New Jersey north of Princeton in the Sourlands region, but no other verified reports have been documented since at least 2007 in central or southern New Jersey (Fowles 2018). While it is assumed that suitable habitat patches exist for bobcats throughout central and southern New Jersey, roads and urbanization may serve as barriers to recolonization of these areas (Fowles 2020).

Urban environments present numerous challenges for bobcats such as habitat fragmentation, habitat loss, barriers to dispersal, and anthropogenic causes of mortality. The construction and presence of roads contributes to many of these challenges as they degrade habitat quality, fragment existing habitat patches, and expose crossing wildlife to the threat of being hit by vehicles (Riley et al. 2014). Based on the probability of occurrence in relation to fragment area and isolation, bobcats were more likely than cougars (*Puma concolor*) and less likely than coyotes (*Canis latrans*) to exist in smaller, more isolated habitat fragments (i.e. cougars typically existed in large, unfragmented sites, bobcats could be found in small fragments with little isolation, and coyotes were likely found in all fragments except the smallest and most isolated) in southern California (Crooks 2002). Further, the risk of death while crossing busy thoroughfares is considerable for carnivores such as bobcats because of their large home range sizes and can represent large proportions of observed deaths (Grilo et al. 2015). One study summarized mortality statistics for bobcats from studies conducted throughout the United States revealing that 38% of bobcat deaths (n=16 bobcats) resulted from collisions with motor vehicles with no differences between urban and rural areas (Bateman and Fleming 2012). In a study of bobcat mortality over a five-year period in southern Illinois, 52% (n=19) of deaths were caused by collisions with cars (Nielsen and Woolf 2002). In northern New Jersey, a total of 77 road mortalities have been reported for bobcats from 2005 to 2017 with an average of 6.4 mortalities per year (Fowles 2018). While road mortalities in New Hampshire appear to be compensatory in nature for the statewide population, collisions models indicate that bobcat-vehicle collisions can increase mortality rates in regions with suitable habitat that are also severely fragmented, potentially creating demographic sinks (Litvaitis et al. 2015).

Beyond mortality and habitat loss, increasing urbanization and the construction of roads can alter bobcat behavior and reduce gene flow. Bobcats may modify their movement behaviors, both spatially and temporally, to avoid roads and urban areas which affects their home ranges. Spatial effects include decreased bobcat occurrence closer to urban regions and as urban intensity increases (Ordeñana et al. 2010), increased home range size in regions with greater urbanization (Riley et al. 2003), establishment of home ranges with lower densities of primary and secondary roads (Poessel et al. 2014), and restrictions by female bobcats to establish home ranges in regions with little urban association (Riley et al. 2003). Additionally, bobcats will rarely cross roads and freeways, leading to these roads serving as boundaries for bobcat home ranges (Riley et al. 2003, Riley et al. 2006). Temporal effects are seen in modified bobcat activity in urban-associated fragmented landscapes in which bobcats reduced their activity during daylight hours, likely to avoid humans (Tigas et al. 2002). The behavioral modifications elicited by roads and urbanization on carnivore temporal and spatial activity can reduce gene flow across such barriers, impacting the genetic structure of populations, e.g., European wildcat (*Felis silvestris silvestris*) population in Germany (Hartmann et al. 2013) and bobcats and coyotes in California (Riley et al. 2006). In New Hampshire, Litvaitis et al. (2015) found evidence that urban development and roads, such as major highways and interstates, served as barriers to gene flow in bobcats.

Even with these challenges, some studies have shown that bobcats can adjust to urbanization. In southern California, bobcats persisted in developed landscapes given sufficient connectivity among habitat patches (Crooks 2002). Additionally, bobcats have recently been described as "urban tolerant," being able to live in urban regions at low population densities (Riley and Gehrt 2014). In certain urban regions, bobcat populations have even been able to persist at high population densities. This is demonstrated by an estimated density of 1.28 bobcats/km^2 in a highly developed area of the Dallas-Forth Worth metropolis in Texas (Young et al. 2019*a*). Finally, bobcats have shown incredible behavioral plasticity by using riparian corridors within urban matrices and by hunting in urban habitat at night to avoid humans (Young et al. 2019*b*; Dunagan et al. 2019).

To address the potential challenges wildlife invariably face in an urban environment dominated by roads, in 2012 the State of New Jersey initiated the Connecting Habitat Across New Jersey (CHANJ) effort, with the goal of making the landscape more permeable for terrestrial wildlife by conducting analyses to determine essential habitat "cores" and corridors for connectivity and offering tools and resources to guide land protection, habitat restoration and management, and the mitigation of road barriers (New Jersey Division of Fish and Wildlife 2019). This effort has begun the implementation of solutions to promote connectivity with the possibility of incorporating measures such as wildlife under- and overpasses (New Jersey Division of Fish and Wildlife 2019). With the advent of the CHANJ initiative in conjunction with the endangered status of bobcats in New Jersey, the NJDFW has requested further information regarding barriers to bobcat dispersal and the possibility of the establishment of central and southern New Jersey bobcat populations.

To assist the NJDFW with their connectivity and landscape questions, I employed habitat suitability and landscape connectivity models to evaluate current conditions for bobcats in New Jersey. One of the commonly used habitat models by wildlife managers is the habitat suitability index (Brooks 1997). These models quantify the capacity of habitat to support specific species and typically score habitat on a scale from 0 (least suitable) to 1 (most suitable; US Fish and Wildlife Service 1981). They can be developed from habitat relationships described in the literature or from empirical evidence such as collar data (Brooks 1997). Such models have been used to quantify bobcat habitat in Mississippi (Connor and Leopold 1998), the southeast United States (Boyle and Fendley 1987), and New Hampshire (Reed et al. 2017b).

Beyond habitat modeling, wildlife biologists use spatial modeling techniques to evaluate animal movement through landscapes. Previously, researchers have used graph theory (Urban and Keitt 2001) and least-cost paths (Adriaensen et al. 2003) to predict how species-specific behaviors and decisions, within the context of landscape attributes, affect movement among patches in a matrix. Recently, circuit theory has been applied to several ecological topics including wildlife corridors, landscape genetics, movement ecology, and connectivity (McRae et al. 2016). Circuit theory has been used to assess landscape connectivity specific to bobcats in the northeastern United States (Farrell et al. 2018) and the impact of roads and habitat suitability on landscape connectivity for bobcats in New Hampshire (Reed 2013, Litvaitis et al. 2015).

Circuit theory borrows from the science of electrical resistance and uses graphs to represent connections (McRae et al. 2008). Within a graph, nodes are connected by edges or resistors which are assigned a resistance value (McRae et al. 2008). When voltage is applied from one node to another, the current flowing through the resistor increases as resistance decreases (McRae et al. 2008). Current is also dependent on the number of resistors and in what combination (see McRae et al. 2008 for more information on circuit theory). One of the benefits of using circuit theory in lieu of least-cost paths is that it allows for redundancy within the landscape (McRae et al. 2008). Least-cost paths (LCPs) only reveal the path of least resistance (Adriaensen et al. 2003), whereas circuit theory maps reveal multiple paths that may contribute to the connectivity of the landscape giving a clearer picture of the possible routes a given individual might take (McRae et al. 2008). However, LCPs and circuit theory can be utilized together to also inform our understanding of pinch points or bottlenecks in a landscape (McRae et al. 2013).

Additionally, current flow centrality can be used to determine what paths and habitat patches are most important to maintain connectivity throughout a network (Carroll et al. 2012; McRae 2012*b*). Conversely, instead of locating paths and patches important for conservation, barriers, regions of high resistance that prevent effective movement through the landscape, can be identified using the Barrier Mapper (McRae 2012*a*). The Barrier Mapper tool calculates a least-cost path under a hypothetical scenario where barriers are mitigated; if less than the existing cost-weight distance of the LCP, then reduction of the barrier would improve the quality of the LCP (McRae et al. 2012).

In this study, I used the techniques described above to assess the habitat and connectivity landscape for bobcats in New Jersey. Specifically, I sought to 1) develop a habitat suitability index for bobcats throughout New Jersey to determine whether there is suitable habitat to support range expansion through the central and southern portions of the state, 2) identify potential pinch points and barriers to dispersal throughout New Jersey, among both known and potential bobcat territory, and 3) determine how culvert and stream crossing structures located under roadways that permitted unrestricted safe passage of bobcats affect identified pinch points and barriers. The results from this study will inform the NJDFW recovery plan for bobcats.

Methods

Study Site

I roughly divided New Jersey into three regions: north, central, and south (Appendix A). I derived these from five regions delineated by the CHANJ initiative but combined the three most southern ones into one large region. The northern and southern regions are separated by a diagonal swath of largely urbanized landscapes running from southwest to northeast across the state (Appendix B). This central band includes the New Jersey portion of the Philadelphia metropolitan area, the capital city of Trenton, and a portion of the New York City metropolitan area. This highly metropolitan, central band is comprised of 51% urban land cover, whereas the northern and southern regions contain 20% and 19% urban land cover, respectively

(Table 1). Additionally, the connectivity assessment developed through CHANJ mapping reports that generalized core habitat comprises 45% of the northern Skylands region and 62% in the southern Pinelands region, while only 15% in the central Piedmont region (New Jersey Division of Fish and Wildlife 2019).

Land cover in New Jersey consists of eight categories: urban, agricultural, grassland, forest, shrub/scrub, water, wetland, and barren (see Appendix B for distributions among the three regions). New Jersey is dominated by urban and forest land cover type, followed by wetlands and agriculture, respectively (Table 1). As previously discussed, these cover types are not distributed equally throughout the three CHANJ regions and change with increasing urbanization (Table 1). From 1986 to 2007, the rate of urbanization increased 7%, adding 130,817 hectares of developed land throughout New Jersey (Hasse and Lathrop 2010). Currently, there is more forest cover type in the northern and southern regions of the state than in the central band where over half of the land cover is dominated by urban structures.

While large areas of forest can be found in the north (approximately 2,657 km^2, Appendix B) and in the south (approximately 2,331 km^2, Appendix B), these regions are not composed of the same forest types. The north is dominated by deciduous forests located on the leeward side of the Appalachian mountain range, while the south consists of mainly coniferous and mixed forest types in a region known as the Pine Barrens (Appendix C). The Pine Barrens are comprised of mostly pitch pine (*Pinus rigida*) forest with short-leaf pine (*P. echinata*) and oak (*Quercus* spp.) interspersed throughout (Connor 1953). Finally, brush and shrubland are scattered throughout the state.

Habitat Suitability Index (HSINJB)

I developed a weighted Habitat Suitability Index for New Jersey Bobcats (HSINJB) based on information from a literature review of bobcat habitat requirements. While using a subset of known bobcat locations to quantify habitat variables for the development of an index is often preferred, I conducted a literature review as described in Brooks (1997) since there were no known bobcat locations in southern New Jersey and I wanted to capture any differences presented by the Pine Barrens. Bobcats, being widely distributed throughout the United States and Mexico, are found in a multitude of varying habitats (Anderson 1987). Given that the deciduous forests of the eastern United States are vastly different than the shrub, grasslands, and evergreen forests of the central and western United States, I focused on habitat relationships reported for bobcats in the eastern portion of their range (Dewitz 2019).

Generally, abiotic factors, such as elevation, hydrology, and land cover; anthropogenic factors, such as roads and population density; and biotic factors, such as prey density and populations of interspecific competitors, affect the presence of bobcats in an area (Litvaitis et al. 1986, Anderson 1987, Litvaitis and Harrison 1989, Broman et al. 2014). In Maine, dense understories, and less sloped areas positively affected bobcat presence, whereas sparse understories and steep areas negatively affected bobcat presence (Litvaitis et al. 1986). Another study in western Maine revealed that bobcats selected against hardwood and for clear cut and mixed forest habitats in all seasons, but that selection of softwood, and ericaceous wetland habitats was dependent on season (Major and Sherburne 1987). In New Hampshire, bobcats were associated with areas of lower elevation and road density and with areas of higher stream density, ruggedness, slope, and higher proportions of wetland and scrubland (Broman et al. 2014). Using known bobcat locations in New Hampshire, a logistic regression model indicated a positive relationship between beech/oak forest and a negative relationship with slope and mean annual snowfall (Litvaitis et al. 2006). A more recent examination of bobcat habitat in New Hampshire using a third-order habitat selection model revealed positive relationships with shrub/scrub, wetland, south aspect, vector ruggedness measurement, and slope and negative relationships with open water, flat aspect, distance to forest edge, road density, distance to stream, snow depth, and developed land cover (Reed 2013, Reed et al. 2017a). In Vermont, Donovan et al. (2011) found that bobcats preferred regions with higher proportions of shrub, deciduous forest, wetlands, and coniferous forests and with lower proportions of mixed forest and road density. In an examination of bobcat movement habitat, Abouelezz et al. (2018) found that bobcats preferred forest and scrub/rock cover types and selected for forest edge, wetland edge, and high stream density for movement, while development and agriculture were the least preferred cover types and selected against deep forest core and high road density. A Mahalanobis distance analysis on bobcat locations in Vermont also highlighted the importance of edge as a habitat covariate (Farrell et al. 2018). In New York, cover type use varied by individual bobcats, but generally they used areas of low elevation and, in the winter, forest stands with conifers present (Fox 1990). Additionally, higher deer densities increased bobcat habitat use, whereas road density had a negative impact on it (Fox 1990). A winter study in Massachusetts indicated that bobcats selected for road, cliff, spruce plantation, and hemlock hardwood cover types and against hardwood, exposed shore, abandoned field, pine, pine-hardwood, and reservoir ice cover (McCord 1974). In

Pennsylvania, male and female bobcats selected broadleaf deciduous forest cover type but avoided other cover types depending on sex and season (Lovallo 1999).

These habitat relationships are most representative of expected relationships in the northern half of New Jersey as this region is dominated by deciduous forests on the leeward side of the Appalachian Mountains (Appendix C). Since the Pine Barrens are largely dominated by coniferous and mixed forest types, I have included bobcat habitat associations in Mississippi as bobcat use of pinelands in the state provides important insight for identifying suitable habitat in southern New Jersey. Chamberlain et al. (2003) found that pine stands of different maturity were important bobcat habitat for first, second, and third order selection of resources. Another study in Mississippi found that the probability of female bobcat occurrence was negatively associated with distance to sapling stand, distance to paved road, distance to maintenance road, distance to creek, and distance to hardwood stand, and was positively associated with distance to pine stand (Conner and Leopold 1998). Additional studies in Mississippi indicate contrasting use of agricultural areas, dependent on whether composition of the home range was compared to the study or whether core use within home ranges was examined (Conner and Leopold 1996, 1999). Regardless of type of analysis, classifications such as pine plantation, pine (≥70% dominated regions with mean dbh >5.0 cm), and pine saplings (mean dbh ≤ 5.0cm) appeared more important for bobcat habitat use than hardwood (Conner et al. 1992, Conner and Leopold 1996, 1999). See Appendix D for a synthesis of habitat associations.

HSINJB Development

I considered covariates at both local and landscape scale iterations; local-level resolution was a single 30x30 m pixel while landscape-level resolution utilized a moving-window of the average home range size for female bobcats to calculate summary statistics centered on each pixel of the raster layer. Using a land cover raster as an example, the local-level covariate was the land cover category (e.g. urban) found in that individual grid cell, and the landscape-level covariate was the percentage of each land cover type within the average home range size for female bobcats surrounding that center grid cell (Table 2). Since females typically have smaller home ranges than males (Hall and Newsom 1976, Berg 1979), I used the average female home range size for landscape-level analyses. As female bobcat home ranges are highly variable, I used the home ranges reported for eastern bobcats from northern New Jersey, New York, Pennsylvania and other Northeastern states with similar habitats (Table 2). I also included home ranges from Mississippi in regions with pinelands as southern New Jersey contains potential habitat patches consisting primarily of coniferous forests.

I acquired data from publicly available sources and the NJDFW to create rasterized datasets of land cover (National Land Cover Database 2016, USGS), elevation (National Elevation Dataset 2017, USGS), hydrology (National Hydrography Dataset 2019, USGS), and roads (TIGER database 2018, US Census Bureau) in ArcMap 10.6.1 (ESRI 2018). From these datasets I calculated the following covariates: percent cover of agriculture, barren land, coniferous forest, deciduous forest, grassland, mixed forest, shrubland, urban land, water, and wetland within the average home range of a female bobcat; edge density, primary and secondary road density, tertiary road density, minimum distance to water, and Shannon's Diversity Index (SHDI) of agriculture, forest, and wetlands within the average home range of a female bobcat; and vector ruggedness measure (vrm; Sappington et al. 2007). I calculated the percent cover, road density, and minimum distance to water statistics using ArcMap 10.6.1 (ESRI 2018) and used the Terrain Ruggedness (VRM) (Sappington et al. 2007) from the Terrain Tools toolbox to calculate VRM. To calculate edge density, I used the 'landscapemetrics' package (Hesselbarth et al. 2019) in RStudio (RStudio Team 2020) to create a binary raster of forest edge which I then imported into ArcMap to calculate the edge density within the average home range of a female bobcat. I calculated the SHDI for the landscape classes of agriculture, forest, and wetland using the following equation:

$$\mathrm{SHDI} = -\sum_{i=1}^{m}(P_i * \ln P_i) \tag{1.1}$$

where Pi is the proportion of a given class divided by the total area of landscape classes considered excluding background (McGarigal 2015).

I generated spatial points every 30 m across New Jersey and extracted the covariates to each point. I then scaled covariates that did not range from 0 to 1 with min-max normalization using the equation:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{1.2}$$

Following scaling, I scored each covariate using five gamma distributions which approximated the predicted relationship between the scaled covariate value and the suitability index score of a bobcat occupying a habitat cell with that value (Figure 1). For example, a proportion of deciduous landcover of 0.25 would receive a suitability index value of 0.2038 while a scaled distance to water value of 0.25 would receive a probability value of 0.3232. I multiplied the landscape-level covariate values of shrubland, coniferous forest, and deciduous forest by two to emphasize their importance for bobcats based on their often positive association with bobcat presence reported in the literature (Table 3, Appendix A). I also weighted binary landscape values to reflect their relative importance to bobcats based on associations reported in the literature (Table 3, Appendix A). Without this weighting, every habitat type would receive an additional value of 1 (e.g. a cell of agriculture would add the same amount to the model as a cell of deciduous forest). Thus, by multiplying binary values by a coefficient <1, the relative contribution of a cell consisting of agriculture, grassland, mixed forest, and wetland is deemphasized in the overall HSINJB value (e.g. a cell of shrubland maintained its full contribution of 1 to the index value, while a cell of agricultural cover only contributed 0.4). After weighting, I summed all covariate index values and then rescaled the resultant total HSINJB values using min-max normalization (Formula 1.2). Since the moving window technique used for landscape-level covariates allowed for >0 values for unsuitable bobcat habitat (i.e. a lake), I assigned any raster cell classified as water a value of 0. To account for the possibility that bobcats could occasionally use the outer most urban cells for travel or hunting, such as in residential backyards, I used the 'landscapemetrics' package to create a binary raster of urban edge and then multiplied the total HSINJB value for these cells by 0.5. This reduced the total HSINJB value for these cells without creating a hard boundary between potentially highly suitable habitat and unsuitable urban land cover. I, then, assigned the remaining urban cells not classified as urban edge a value of 0 to remove them from being identified as suitable habitat. Finally, I converted the TIGER lines for primary and secondary roads into a binary raster layer and assigned cells classified as primary and secondary roads a value of 0 to ensure that any roads missed by the binary urban land cover layer were not reflected as suitable habitat in the model.

Validation

To validate the model, I compared the HSINJB values of random locations outside of estimated current bobcat range to those of known bobcat locations. Bobcat locations were collated from 2013-2019 and included: collar locations, camera traps identifications, live individual sightings, physical evidence such as scat, and legal by-catch data. Known bobcat locations originally consisted of 24,260 collar points from five individuals and 387 points from unknown individuals of other data types. I randomly subsampled 387 collar locations to avoid overemphasis in calculating known bobcat range, then combined this subsample with the 387 points from other sources (e.g. camera trapping, scat, etc.) resulting in 774 bobcat locations used during HSINJB validation.

I calculated a 95% ad hoc kernel utilization distribution of these 774 bobcat locations and excluded this area from subsequent random point generations. I then generated 774 random points throughout the rest of New Jersey (excluding areas within the kernel boundary) to compare bobcat-selected HSINJB values to total habitat availability that was unselected by bobcats (i.e. statewide locations). Since I hypothesize that bobcats experience a significant dispersal barrier through human transportation corridors in central New Jersey, I generated an additional 774 random points north and west (i.e. northern locations) of the following road segments: I-95, New Jersey Turnpike, and NJ-440. I extracted HSINJB values to bobcat locations and both the statewide and northern random locations and used Mann-Whitney-Wilcoxon tests with an alpha level of 0.05 to evaluate whether HSINJB values for bobcat points were greater than those of randomly generated points.

Connectivity Analyses

Development of Resistance Map

I developed a raster layer representing the resistance to bobcat movement throughout the landscape with final values ranging from 1 to 120 and infinite resistance for water bodies. I first took the inverse of the HSINJB and scaled it from 1 to 100. Large water bodies were given infinite resistance values for appropriate usage with connectivity tools. I incorporated road specific Average Annual Daily Traffic into the resistance layer, by combining data from the 2014 and 2016 AADT layers from New Jersey (NJ Fish and Wildlife 2014, NJ Bureau of GIS 2016) and selecting the highest average value for each road. I scaled these values to range from 0-20 and summed them with their corresponding raster cell values in the scaled, inverse HSINJB layer. This allowed each primary and secondary road with AADT data to vary from 100 to 120, the highest values possible in the resistance landscape.

Habitat Core Generation

I defined habitat cores as patches ≥ 27.2 km^2 (weighted average female bobcat home range, Table 2) and stepping stones as patches between 0.98 and 27.2 km^2. The minimum patch area for stepping stones was based on the smallest published home range average for female bobcats (Hall and Newsom 1976). While Hall and Newsom (1976) calculated the average female home range for bobcats in Louisiana bottomland hardwoods, a habitat very different from those present in New Jersey, I selected this value as a minimum size necessary for stepping stone patches. While smaller than habitat cores which could likely support several bobcats, stepping stones still contain suitable habitat for New Jersey bobcats which could be utilized by both male and females within their home ranges or alternatively as patches large enough for stop-overs during dispersal events. Since I used the weighted average of a female bobcat home range as the minimum value for a core, it is likely that more than one bobcat would be willing to establish home ranges in that region since roughly half of female home ranges should be less than the mean value. Additionally, I selected these conservative threshold values for both cores and stepping stones to attain a more detailed picture of habitat patches to examine connectivity among them in subsequent analyses. Large threshold values would have resulted in a few large, cores thus not permitting connectivity analyses among patches in northern or southern New Jersey. Including stepping stone patches as small as one cell (30 m x 30 m) would have been too detailed resulting in a unmanageable number of patches for subsequent connectivity analyses.

I delineated both habitat cores and stepping stone patches using the Core Mapper in the Gnarly Landscape Utilities toolbox (version 0.1.9) for ArcMap (Shirk and McRae 2013). For a cell to be included as part of a habitat patch it must meet certain thresholds on both landscape and local levels. To maintain consistency with the HSINJB, landscape-level requirements used the weighted average female home range for any circular moving window used to calculate threshold parameters. First, the average HSINJB value within the moving window is calculated. All cells ≥ the minimum average habitat value of 0.491 are classified as suitable habitat with the remaining classified as unsuitable. I chose a threshold of 0.491 because it was one standard deviation below the mean HSINJB value for known bobcat locations, which according to statistical theory should be representative of 84% of all known bobcat locations. Since this average habitat value could still identify cells that actually have unsuitable habitat as part of a patch (e.g. a cell of value 0.2 that is adjacent to a small patch of forest with very high values), the tool then removes any cells < a local-level threshold. I set this threshold, the minimum habitat value per cell, as the mean HSINJB value for known bobcat locations of 0.653 for the delineation of all patches. To combine nearby patches only separated by low resistance that bobcats could travel to within their daily movements, patches were expanded by a cost-weight distance (CWD) of 6163.2 m. I estimated this expansion threshold from the mean speed of travel for female bobcats in Vermont of 4.28 m/min to reflect the average number of meters a female bobcat could travel in a 24-hour period (Abouelezz et al. 2018), thus combining any patches that a female could reasonably travel to within a day. This was a conservative estimate for expansion of patches, since Abouelezz et al. (2018) used the total Euclidean distance of movement paths to calculate this rate. Since the expansion process incorporates the resistance landscape to calculate CWD, this threshold value potentially underestimates the possible Euclidean distance a female bobcat could travel to within a day unless resistance is negligible. Since the expansion process could incorporate unsuitable habitat, patches were then trimmed back by the elimination of raster cells less than the minimum average habitat value (0.491 as in the first step) but still leaving some patches previously unconnected as a one patch. Finally, all patches less than 0.98 km^2 were deleted (see Shirk and McRae 2013 for further details on how the Core Mapper tool functions).

Since the expansion by CWD process incorporated roads with high resistance, I bisected all patches by primary and secondary roads and then deleted any resulting patches that were now less than 0.98 km^2. To create a layer with only core habitat, I deleted patches less than 27.2 km^2. As a final step, I calculated how much area within each patch was protected using the Protected Areas Database of the United States (USGS 2019) and State, Local and Nonprofit Open Space of New Jersey (NJDEP 2020). Of note, these data contain easements, farmland preservation, ball fields and other areas of less permanent or tenuous protection.

Connectivity Analyses

To analyze landscape connectivity, I used the Linkage Mapper toolkit in ArcMap and Circuitscape for Julia (Anantharaman et al. 2020). First, I calculated least-cost paths (LCPs) using the Build Network and Map Linkages tool (McRae and Kavanagh 2011) between all patch pairs, regardless of classification of core or stepping stone, to incorporate patches that could be suitable for dispersal or representative of smaller home ranges. Least-cost paths between adjacent patches and those that passed through patches were removed. The maximum Euclidean distance (EucD) for a corridor was set to 182 km, the longest dispersal distance recorded for a bobcat (Knick and Bailey 1986) and corridors were trimmed at a CWD value of 40 km, which is the upper end of common dispersal distances for transients (reviewed in Hansen 2007). This allows a bobcat to wander away from the least-cost path by 40 weighted-km when generating corridors. I used two different metrics to represent the quality of each corridor connection identified by the tool: a ratio of CWD to EucD and a ratio of CWD to LCP (Dutta et al. 2016). The CWD:EucD represents how much resistance a bobcat would experience controlling for linear distance. Large CWD:EucD values indicate high resistance within a corridor compared to the linear distance a bobcat would have to travel. The CWD:LCP is a similar metric, but incorporates the shortest, least-energy expensive path a bobcat would have to travel between patches (Dutta et al. 2016). According to Dutta et al. (2016) it is representative of the average resistance along an ideal path.

I ran current pairwise through the least-cost paths corridors using Circuitscape within the Pinchpoint Mapper Connectivity Analysis Software to identify pinch points within the corridors (McRae 2012*c*). Using Circuitscape for Julia which allows for running landscape-wide analyses without using bounding corridors, I ran current pairwise through the entire resistance landscape (McRae et al. 2008). Since current flow has high accumulations in habitat patches (habitat patches have low resistances due to high quantity of suitable habitat, thus more current flows through these regions), I assigned all patch cells a value of zero for better interpretation of current flow in the landscape matrix between patches. To analyze connectivity within and outside of cores, I developed a resistance layer in which cells outside of New Jersey were assigned random resistance values based on the normal distribution of the resistance raster ($\bar{x}$ = 0.362, sd = 0.290). This reduced the effect of the New Jersey boundary when running current pairwise from a strip 60 m wide on each side of the map extent from west to east and from north to south (Koen et al. 2010, McClure et al. 2017). Both pairwise maps (east-west and north-south) were summed and currents beyond the New Jersey boundary were removed to produce an omnidirectional cumulative current map. I used the Centrality Mapper to calculate the current flow centrality of habitat patches and links (Carroll et al. 2012; McRae 2012*b*). I used the Barrier Mapper to identify barriers within corridors using moving windows every 30 meters from 60 to 90 meters (McRae et al. 2012, McRae 2012*a*). This assumes that the minimum distance that can be restored or mitigated is 120 m and the maximum is 180 m, roughly the range in widths of primary thoroughfares in New Jersey. I did not use a minimum distance of 60 m as the minimum value because it would require a radius of 30 m which matches the resolution of the resistance raster, thus potentially incorporating rounding errors (McRae 2012*a*). I calculated both maximum (i.e. selects the largest improvement score across all patch pairs) and summed (i.e. adds all scores across all patch pairs) improvement scores (McRae 2012*a*). Finally, I calculated the difference between summed and maximum value improvement scores to determine where individual barrier mitigation could have the greatest impact on multiple corridors (McRae 2012*a*).

Case Study

To disperse from northern habitat cores to the southern habitat cores, bobcats need to traverse a highly urban landscape surrounding Interstate Highway 95. To explore the landscape connectivity in this region, I selected the five cores in closest proximity to each other across the urban landscape around Interstate Highway 95. Specifically, there were two northern cores in the Sourland Mountain region and three southern cores around Perrineville Lake Park, Colliers Mills Wildlife Management Area, and the western end of Brendan T. Byrne State Forest, respectively. To analyze how stream crossing structure improvements under roadways could impact landscape connectivity in this region, I conducted a focused analysis among these cores using the original resistance layer and an alternate "restored" resistance layer. I cropped the resistance raster to central New Jersey and calculated LCPs, pinch points, centrality, and barriers using the same methods as above. I then developed the alternate "restored" resistance layer where all cells corresponding to a stream crossing structure received a resistance value of 1 and repeated the same analyses. Omnidirectional analyses were omitted for the case as I was primarily interested in movement between patches instead of through the entire landscape.

Results

Habitat Suitability Index

I calculated unique HSINJB values for 22,334,804 30 m grid cells covering the state of New Jersey. HSINJB values ranged from 0 to 1 with the best inferred habitat suitability represented by 1 (Figure 2). The mean and standard deviation for all cells were 0.3625 and 0.2904, respectively. Using a threshold value of 0.491 as indicative of suitable bobcat habitat, the HSINJB correctly classified 88.8% of known bobcat locations as occurring in suitable habitat. Only 43.8% of statewide random points and 35.5% of northern random point occurred in suitable bobcat habitat.

The mean HSINJB value for known bobcat locations was 0.6527 ± 0.1615 (n = 774) and, excluding locations corresponding to an HSINJB value of zero, was 0.6638 ± 0.1382 (n = 761). For statewide random locations, the mean HSINJB value was 0.3688 ± 0.2763 (n = 774) and, excluding locations corresponding to an HSINJB value of zero, was 0.5125 ± 0.1799 (n = 557; Figure 3). For northern random locations, the mean HSINJB value was 0.3141 ± 0.2679 (n = 774) and, excluding locations corresponding to an HSINJB value of zero, was 0.4758 ± 0.1781 (n = 511; Figure 3). One-sided Mann-Whitney-Wilcoxon tests comparing known bobcat HSINJB values to randomly generated point HSINJB values showed significant difference for both northern and statewide comparisons ($P < 0.001$ and $P < 0.001$, respectively; Table 4). One-sided Mann-Whitney Wilcoxon tests drawing the same comparisons but excluding locations corresponding to an HSINJB value of zero were also significant (north: P < 0.001, statewide: P < 0.001; Table 4). These results indicate that HSINJB values for known bobcat locations were shifted to the right of HSINJB values for randomly generated points, both statewide and in northern New Jersey.

Connectivity Analyses

I identified 34 habitat cores which covered a total area of 5463.95 km^2 (Figure 4). The mean area was 160.70 km^2 (sd: 185.74 km^2, range: 27.88 – 972.60 km^2). I identified 39 stepping stones, covering a total area of 235.31 km^2 (mean ± sd: 6.03 ± 6.52 km^2, range: 1.00 – 25.75 km^2). The total protected area within all patches was 2828.89 km^2 with 2711.58 km^2 located in cores and 117.31 km^2 located in stepping stones. Overall, 49.64% of core and stepping stone area is under some form of protection. The proportion of protected land within all patches was 0.4964, ranging from 0 – 1 for individual patches. For cores, the proportion of protected land was 0.4963, ranging 0.1738 – 0.9694 for individual cores. The proportion of protected land for all stepping stones was 0.4985, with individual stepping stones ranging from 0 – 1 (Appendix E).

I identified 140 total least-cost paths among all patches. Of these, 53 connected cores to other cores, 65 connected cores to stepping stones, and 22 connected stepping stones to stepping stones. Euclidean distances ranged from as little as 0.03 km to as long as 56.37 km, with a mean of 4.60 km (sd: 8.82 km) and several links (N = 56) that spanned small distances mostly crossing one or two roads (~30 m). The longest Euclidean distance was between stepping stones 14a and 21a traversing central New Jersey, and the shortest, excluding those crossing only one or two roads, was between core 27 and stepping stone 26a in southern New Jersey (Figure 5).

Least-cost path (LCP) distances varied widely from 0.042 to 63.79 km (Figure 5). The mean distance was 5.27 km (sd: 9.94 km) indicating that several links (N=53) mostly crossed distances roughly equivalent to one or two roads. The longest LCP was 63.79 km between stepping stones 14a and 21a (Figure 5). Excluding LCPs only crossing a single thoroughfare, the shortest was 0.09 km connecting core 22 and stepping stone 24a (Figure 5).

Cost-weighted distances (CWDs; i.e. distances that incorporate landscape resistance and represent a total travel cost) ranged from 1.06 to 3509.81 weighted km, with a mean of 273.82 weighted km (sd: 524.18). The highest CWD was between stepping stones 14a and 21a, and the lowest was between core 5 and stepping stone 5a (Appendices G and H).

As for corridor quality metrics, the three greatest values for CWD:EucD (i.e. resistance to movement controlled for linear distance) were in corridors connecting southern patches between core 33 and stepping stone 33b (6851.62), between cores 30 and 33 (4427.45), and between stepping stones 34b and 34c (3900.36, see Appendices F, G, and H). The three greatest values for CWD:LCP (i.e. average resistance along an ideal path) were between cores 23 and 24 (78.36), between core 29 and stepping stone 29b (77.37), and between core 26 and stepping stone 26a (76.50, see Appendices F, G, and H

Current flow centrality (i.e. relative importance to maintain connectivity in the network) for LCPs ranged from 4.51 to 1096.81 Amps with higher amperage representative of greater importance for maintaining the overall connectivity among habitat patches (Figure 6). The three largest values, identifying LCPs most important to the network, were located in southern New Jersey between core 29 and stepping stone 29d (1096.81 Amps), stepping stones 29d and 31c (1029.52 Amps), and core 31 and stepping stone 31c (961.61 Amps, Figure 6, see Appendices E, F, and G). Current flow centrality for all habitat patches ranged from 72.00 to 1525.98 Amps network. The three largest values, essentially identifying "hubs" (McRae 2012*b*), were located in southern New Jersey in cores 29 and 31 and stepping stone 31c (1525.98, 1404.87, and 1217.72 Amps, respectively; Figure 6; Appendix E). When corrected for area, the three largest current flow centrality values were found in stepping stones 15a, 7a, and 6a highlighting their importance to maintaining connectivity within the network of patches and links (208.05, 145.95, and 144.95 Amps/km^2, respectively; Figure 6; see Appendix E).

Running current using Circuitscape through the corridors calculated by the LCP analyses identified several pinch points, or bottlenecked regions, within corridors. While pinch points were calculated among all patches pairwise, those within longer corridors highlighted 3 constrictions in the north, 23 in the south, and 14 across the central portion of the state (Figure 7). Several of the southern pinch points appeared wherever a corridor had to traverse large rivers and streams, which are abundant in southern coastal New Jersey. Using Circuitscape to run current pairwise across the entire resistance landscape resulted in a minimum cumulative current value of 0 Amps and a maximum of 34.477 Amps with current values from habitat patches excluded (Figure 8). Regions with higher amperage identify cells with a higher probability of bobcats passing through them while navigating the landscape (McRae et al. 2008). The cumulative current flow map among patches reveals that there is redundancy in current paths throughout the landscape, but these are shifted to the western portion of central New Jersey away from urbanization around the greater New

York metropolis and towards the Delaware river running along the western region of the state (Figure 8). Cumulative current appears more concentrated in central and southern New Jersey, suggesting greater redundancy in paths among northern habitat patches. The omnidirectional cumulative current flow map revealed that when examined holistically movement through the landscape was more likely to occur within identified habitat patches (Figure 9).

The barrier analysis revealed regions within each corridor where barriers exist and where reduction of the barrier would improve connectivity (Figure 10). The analysis identified barriers where corridors crossed roads or large rivers and streams. It also highlighted the barrier effect that urbanization can have within corridors as some barriers appear to be associated with urban landcover where few natural landcover patches are available (see corridor between cores 19 and 23 in Figure 10). The difference between summed and maximum improvement scores revealed corridors with barriers where mitigation actions would have the greatest impact on multiple corridors (Appendix I).

Case Study

For the "restored" resistance layer, 6024 pixels were converted to the lowest resistance value of 1 at the locations of culverts. Since the number of habitat patches was restricted to include only 5 cores, only 6 corridors were identified. All metrics between cores using the original, unmodified resistance layer were the same except for centrality which is dependent on the size of the network and the corridor connecting cores 22 and 23 (Appendices F and J). In the New Jersey-wide analysis, no corridor was identified between cores 22 and 23 due to the presence of stepping stone 24a.

Since stepping stone 24a was removed for simplicity in the case study, a hypothetical corridor was calculated.

In general, the incorporation of low-resistance culverts reduced the CWD of the corridors. The greatest change occurred between cores 19 and 22 with a difference of 29.01 weighted km. Surprisingly, there was either no change in LCP or a small increase in LCP distance when culverts were incorporated into the analysis (Appendices J and K). This can be attributed to the LCP taking a slightly longer path to cross through the low resistance found at culverts (Figure 11). For metrics relating CWD to distance, both CWD:EucD and CWD:LCP decreased with the incorporation of culverts with the exception of the corridor linking cores 21 and 22 (Appendix K). The greatest reduction for both metrics occurred in the corridor connecting adjacent cores 19 to 20, presumably because the incorporation of 6 culverts across NJ Route 31 N separating them resulted in ~70% reduction in CWD (Appendix L).

When running current pairwise through the corridors using Circuitscape to identify pinch points, the addition of culverts decreased the current flow density from 0.087 to 0.082 suggesting that the addition of culverts more evenly distributed current throughout the landscape (Appendix M). Closer examination also revealed that culverts themselves did not necessarily become pinch points, but rather increased the pinch point effect of certain habitat patches (Figure 12). When compared to a map of landcover, these bottleneck regions seem to correspond with landcover types that are more suitable for bobcat movement, such as wetland, forest, and even agriculture (Figure 13). To verify that this observation was not an artifact of display, I examined a pixel value of the center habitat patch (8 pixels to the right and 7 down from the northwest culvert in the central circle in Figure 13) and found that the value increased from 0.0224 to 0.0362 Amps/cell when culverts were included. In contrast, when running current pairwise through the entire case study landscape the incorporation of culverts increased the maximum cumulative current flow density from 0.066 to 0.165 Amps/cell. This might be due to higher current density in localized regions where current was funneled through low resistance culverts (Appendix N). Culverts appear to have the greatest impact on the barrier analyses (Appendix O). While the maximum improvement score of 101.024 ΔLCD per m restored remained the same for both the original resistance and culvert scenarios, there exist notable localized reductions in barriers, especially along primary and secondary roads (Figure 14).

Discussion

Fortunately for the recovering bobcat population in New Jersey, apparently suitable habitat in deciduous, mixed, and coniferous forests exists throughout the state, with most concentrated along the leeward side of the Appalachian Mountains in the north and in the Pine Barrens in the south. However, suitable habitat becomes increasingly patchy closer to the urban corridor connecting Philadelphia to New York City along Interstate 95. No core or stepping stone patches were identified along the urban corridor surrounding Interstate 95 due to low HSINJB values and insufficient suitable habitat area.

While habitat itself does not exist in sufficient quantities within this highly urbanized central region, connectivity analyses indicated that habitat patches may be connected. Bobcats would have to traverse approximately 25 km from core 19 to core 21 to disperse from northern to southern patches, a feasible distance as the longest know bobcat dispersal was 182 km (Knick and Bailey 1986). Additionally, this is a reasonable distance for female bobcats to disperse, as evidenced by a female bobcat in

Minnesota which dispersed a 136 km (Berg 1979). The dispersal of female individuals is a critical component for the recolonization of bobcats in southern New Jersey and for the establishment of a reproducing, resident population.

While the distance is reasonable for a dispersing bobcat, crossing the highly urbanized landscape of central New Jersey becomes more challenging due to barriers such as roads. The corridors connecting northern core 19 with southern cores 21-23 was composed of 21.6% urban and 36.5% agricultural cover, with large blocks of urbanization almost completely bisecting the corridors in some locations. Previous bobcat studies have shown that roads and urbanization greatly impact their interaction with the landscape by reducing their occurrence in urban regions (Ordeñana et al. 2010), increasing the size of their home ranges (Riley et al. 2003), and affecting establishment of home ranges (Riley et al. 2003, Poessel et al. 2014). Large thoroughfares are known to serve as boundaries for home ranges as bobcats seem to rarely cross roads and freeways (Riley et al. 2003, Riley et al. 2006) and previous studies have indicated that these linear features can reduce and serve as barriers to gene flow (Riley et al. 2006, Litvaitis et al. 2015). Additionally, vehicular collisions on roads are known to kill bobcats across their range (see Nielsen and Woolf 2002, Bateman and Fleming 2012, Grilo et al. 2015, Litvaitis et al. 2015, Fowles 2018). As of 2019, approximately 62,683 km of public roads crossed New Jersey, with primary and secondary roads known to serve as potential barriers to bobcat movement and as sources of mortality (NJDOT 2019; Fowles 2020, Fowles, *in prep.*). Indeed, barrier analyses revealed that several roads are barriers within potential bobcat movement corridors. The most notable in central New Jersey are US Highways 1, 130, and 206; the New Jersey Turnpike (I-95); and Interstate 195. However, the case study revealed that improvements to existing culverts and stream crossing structures could effectively reduce the barrier effect of roads within these corridors.

While these challenges are real threats to bobcat movement, increasing evidence suggests that bobcats may be quite tolerant to urbanization. Crooks' (2002) study in southern California indicated that the bobcat had intermediate sensitivity to fragmentation and was capable of living in developing regions when there is suitable connectivity among habitat patches. More recently, Riley and Gehrt (2014) classified the bobcat as an "urban tolerant" species, having the ability to survive and live in urban areas but not in high densities. They also emphasize that classifying whole species in reference to their relationship with urbanization can change and that individuals and populations within a species may respond differently (Riley and Gehrt 2014). Some bobcat populations have proved to have high population densities, even in highly urban areas. In a region of high urban development in the Dallas-Fort Worth metropolis in Texas, a spatially explicit capture-recapture model estimated a density of 1.28 bobcats/km^2 which the authors attributed to abundant prey and little harvest of bobcats from the population (Young et al. 2019*a*). Bobcats in urban areas demonstrate remarkable behavioral plasticity, having been shown to utilize natural landcover such as riparian corridors within developed areas and to adjust temporally to utilize urban habitat at night likely to avoid humans while hunting (Young et al. 2019*b*; Dunagan et al. 2019).

My results suggest that the implementation of mitigation methods, such as the adaptation of steam crossing structures to permit bobcat movement could effectively reduce the effect of road barriers on the connectivity landscape. Reducing the resistance of roads to movement, thus reducing mortality due to roads, could be critical for bobcats to successfully disperse from northern to southern New Jersey. Mitigation methods to combat the significant obstacles that roads and urbanization present to the expansion and continued heath of wildlife populations have been proposed and implemented, to varying success, throughout the world (Smith et al. 2015). To mitigate the obstacles roads present for animal movement, crossing structures, such as overpasses and underpasses, and fences are often implemented (Smith et al. 2015). Existing structures such as drainage culverts can be modified with catwalks or the addition of cover to make them suitable for wildlife movement (Smith et al. 2015). In fact, New Jersey law mandates that culvert installations and replacements incorporate suitable crossing structures for terrestrial wildlife use in many circumstances (N.J.A.C. § 7:13). In conjunction with the mitigation of barriers, state managers and land protection groups should prioritize the conservation of suitable habitat within the corridors identified. Loss of existing suitable habitat for bobcat movement within corridors could reduce the connectivity between habitat cores and stepping stones. If bobcats are unable to traverse the landscape matrix within corridors up to identified barriers, any mitigation of these road barriers would be rendered moot.

Even though my results are suggestive that increasing landscape connectivity through barrier mitigation actions could benefit bobcats in New Jersey, there are inherent limitations to the analyses due to its statewide scope and lack of bobcat data from southern New Jersey. I based the HSINJB on habitat associations documented in the literature, however these varied greatly depending on state, analyses, and in selected variables. This resulted in largely subjective assumptions and the collapse of variables into broad classifications such as agriculture and coniferous forest. Studies from Mississippi seemed to indicate that the age of coniferous forest stands affected bobcat use of habitat, which the authors thought was due to increased availability of prey (Conner et al. 1992, Conner and Leopold 1996, 1998, 1999). My HSINJB is not able to make any distinctions based on forest stand age since it collapsed any differences into a singular, simplified coniferous forest land cover class. If bobcats were to recolonize southern New Jersey, either naturally or through management actions, state managers should evaluate the age composition of coniferous forests in the Pine Barrens as increasing pine saplings could potentially improve habitat for bobcats (Conner and Leopold 1996). I compromised specificity for generality of analyses by using the weighted average female bobcat home range to define my moving window for HSINJB development and as a threshold for core generation. Home ranges from Mississippi bobcats were considerably smaller than those reported in the northeast United States (Table 2). Excluding the home ranges of these Mississippi bobcats would have increased the weighted average home range to ~43.6 km^2 which would have affected the landscape-level covariates such a road density and proportion of land cover type and would not have been necessarily representative of how these covariates would be perceived by bobcats in the largely coniferous Pine Barrens. Future models could be developed for northern and southern New Jersey independently, thus incorporating covariates and parameters that would be more representative of the distinct areas. This was not possible within in the scope of my study as I was interested in evaluating connectivity throughout all of New Jersey which necessitated a cohesive statewide model to delineate habitat patches and develop resistance layers. Additionally, larger minimum core and stepping stone thresholds would have resulted in few large, cores thus preventing CWD corridors from being calculated between several habitat patches in both northern and southern New Jersey which are useful for evaluating connectivity within these regions. For similar regions, I restricted the smallest patches (stepping stones) to those greater than ~1 km^2 to avoid overwhelming the system with an unmanageable number of small patches for subsequent connectivity analyses. Finally, the resolution of my analyses (30 m x 30 m cells) could have diluted the importance of riparian corridors for connectivity bobcats by collapsing them into a different land cover type.

While northern bobcat locations were used to validate the HSINJB, it is currently impossible to validate habitat use in southern New Jersey as no verified bobcat sightings have been reported south of I-95. Continued monitoring of identified southern habitat patches, using scat-scenting dogs and camera traps, could result in previously unknown bobcat occupancy and provide further data to validate this model. Additionally, all subsequent steps of the connectivity analyses were intrinsically based on this model so any new information regarding bobcat presence in New Jersey could affect their reliability. I recommend that these models are used to prioritize regions for continued monitoring for bobcat presence, rather than an explicit indication that bobcat can and will persist in identified habitat patches. While beyond the scope of my study, connectivity models can be validated for northern New Jersey using movement analyses of collar data and camera trapping with in identified corridors. Additionally, roadkill data of bobcats in the north and of other species (e.g. coyotes and fox) could be used to validate the locations of corridors that cross roads. I recommend their use in conjunction with CHANJ mapping initiatives in prioritizing sections of roads where initial mitigation efforts could be implemented and in identifying patches of natural landcover to conserve that are important for maintaining connectivity across the landscape.

TABLES

Table 1 Percent total land cover type calculated from the 2016 National Land Cover Database (USGS) in each of the three regions delineated in this study and the overall percent total cover for the state of New Jersey, USA. The north and central regions are the same as identified by the Connecting Habitat Across New Jersey (CHANJ) initiative, however the remaining three southern regions were combined into one larger southern patch.

Cover Type	North (%)	Central (%)	South (%)	New Jersey (%)
Urban	20.1	50.8	19.3	29.6
Agriculture	16.8	16.9	8.1	13.2
Grassland	0.4	0.6	0.8	0.6
Forest	49.2	14.7	28.5	29.6
Shrub/Scrub	0.4	0.5	0.9	0.7
Water	2.3	1.9	8.5	4.7
Wetland	10.5	14.2	33.0	20.9
Barren	0.3	0.3	1.0	0.6

Table 2 Reported average female bobcat home ranges in Mississippi and throughout the Northeast, USA with corresponding sources. Weighted average was calculated by summing the product of the number of individuals (N) by the mean corresponding home range and then dividing by the total number of individuals.

State	Home range (km^2)	N	Source
New Hampshire	29.7	1	Broman et al. 2014
	23.8	5	Reed 2013; Reed et al. 2017a
Vermont	22.9	4	Donovan et al. 2011
New York			
Adirondacks	86.4	4	Fox and Brocke 1983; Fox 1990
Catskills	31.0	1	Fox and Brocke 1983; Fox 1990
Maine	27.5	1	Major and Sherburne 1987
Coastal	32.5	6	Litvaitis et al. 1986
Mountains	33.2	2	Litvaitis et al. 1986
New Jersey	73.67	6	NJDFW, unpublished data
Pennsylvania	41.2	17	Lovallo 1999
Mississippi	5.9	3	Shiflet 1984
	8.63	38	Chamberlain et al. 2003
AVERAGE	34.7		
WEIGHTED AVERAGE	27.2		

Table 3 Variables used to calculate the Habitat Suitability Index for New Jersey Bobcats (HSINJB) values and their corresponding resolution, scored value range, and weighting coefficient. Local- level resolution was a single 30x30 m cell while landscape-level resolution was calculated using a moving-window technique based on the average female bobcat home range size. Scored values could be either binary (0 or 1) or range from 0 to 1. The products of the weighting coefficients and the scored values were summed to calculate the HSINJB values for bobcats for each cell across New Jersey, USA.

Variable	Resolution	Scored Value	Weighting Coefficient
Binary agricultural cover	Local	0 or 1	0.4
Binary grassland cover	Local	0 or 1	0.2
Binary shrubland cover	Local	0 or 1	1
Binary coniferous forest cover	Local	0 or 1	1
Binary deciduous forest cover	Local	0 or 1	1
Binary mixed forest cover	Local	0 or 1	0.8
Binary wetland cover	Local	0 or 1	0.2
Proportion of agricultural cover	Landscape	0 – 1	1
Proportion of barren cover	Landscape	0 – 1	1
Proportion of grassland cover	Landscape	0 – 1	1
Proportion of shrubland cover	Landscape	0 – 1	2
Proportion of coniferous forest cover	Landscape	0 – 1	2
Proportion of deciduous forest cover	Landscape	0 – 1	2
Proportion of mixed forest cover	Landscape	0 – 1	1
Proportion of urban cover	Landscape	0 – 1	1
Proportion of wetland cover	Landscape	0 – 1	1
Minimum distance to water	Landscape	0 – 1	1
Primary and secondary road density	Landscape	0 – 1	1
Tertiary road density	Landscape	0 – 1	1
Forest edge density	Landscape	0 – 1	1
SHDI of agriculture, forest, and wetland cover	Landscape	0 – 1	1
Vector Ruggedness Measure	Local	0 – 1	1
Slope	Local	0 – 1	1

Table 4 Results from the one-sided Mann-Whitney-Wilcoxon tests used to identify significant differences between the mean Habitat Suitability Index for New Jersey Bobcats (HSINJB) values for known bobcat locations (i.e. mean bobcat) and randomly generated locations (i.e. mean random). Mean HSINJB values for bobcat locations were compared to those of random locations both statewide and restricted to the north since bobcats likely experience a dispersal barrier into southern New Jersey, USA. Tests were repeated with the exclusion of HSINJB values corresponding to values of zero. All the one-sided Mann-Whitney-Wilcoxon tests indicate a significant difference and that bobcat HSINJB values are shifted to the right (i.e. have greater means) of random HSINJB values.

Region	Include zeros?	Mean bobcat	Mean random	W	p-value
Statewide	No	0.6638	0.5125	320035	<2.2e-16*
Statewide	Yes	0.6527	0.3688	486583	<2.2e-16*
North	No	0.6638	0.4758	314841	<2.2e-16*
North	Yes	0.6527	0.3141	516694	<2.2e-16*

* indicates significant test

FIGURES

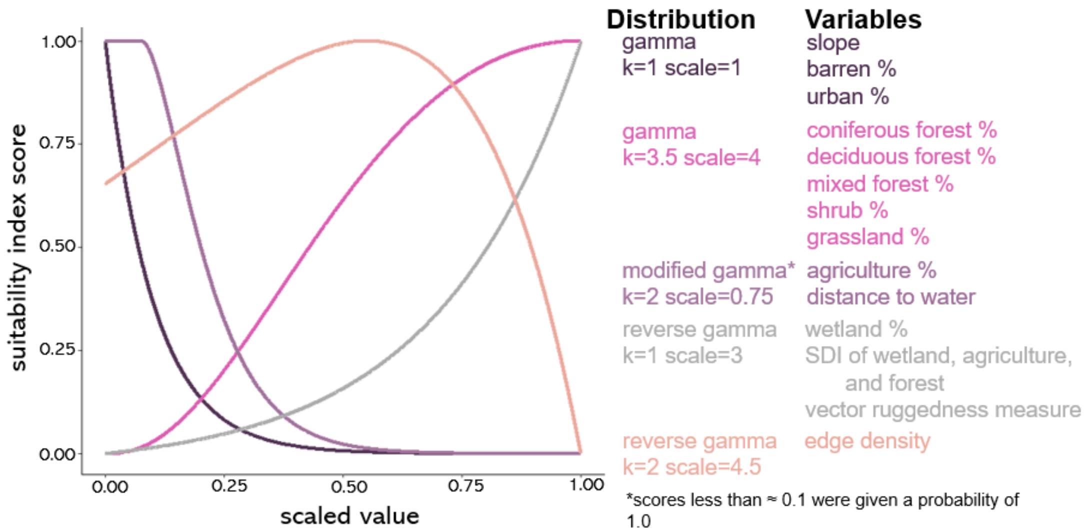
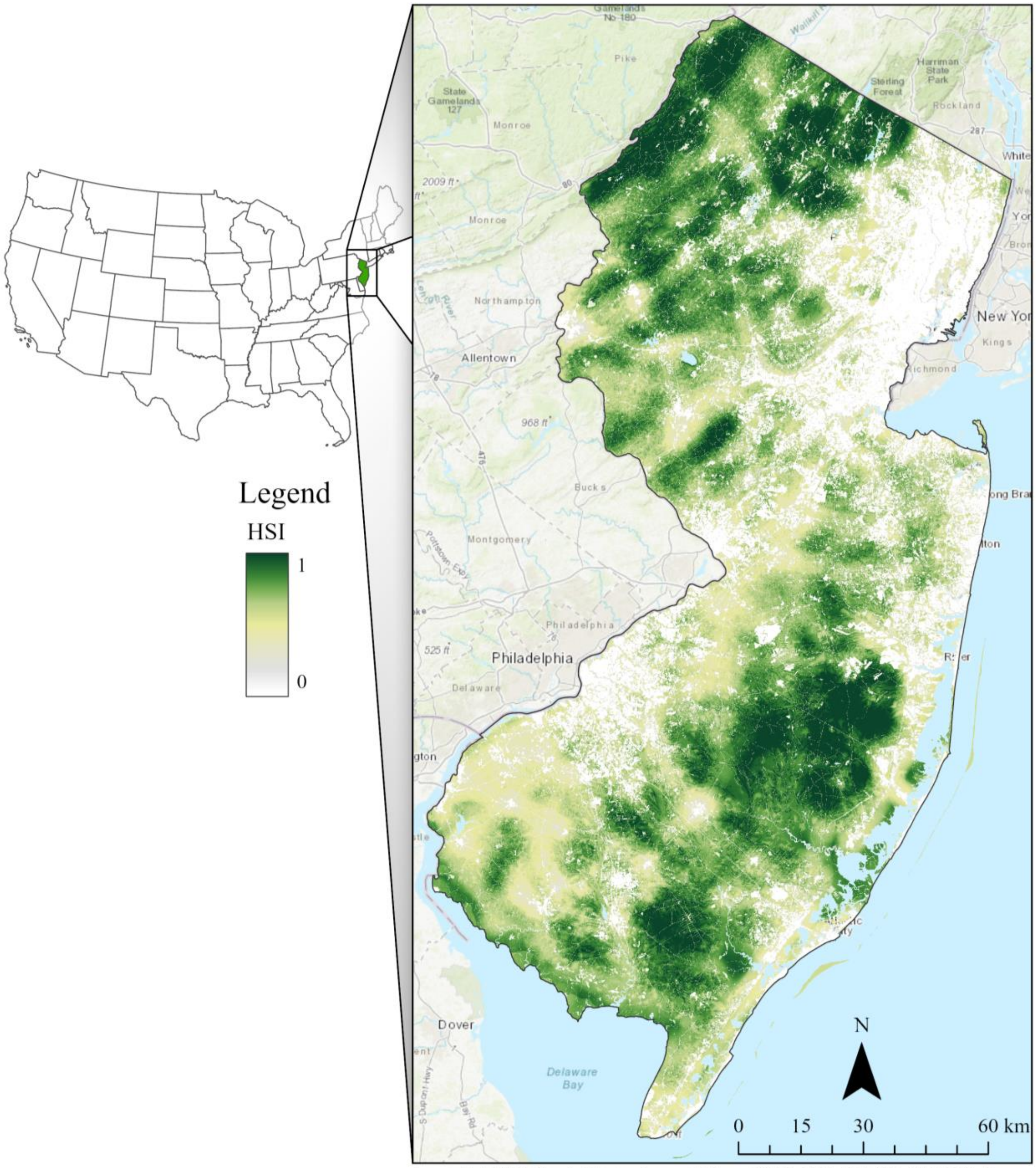


Figure 1 Gamma distributions used to calculate Habitat Suitability Index for New Jersey Bobcats (HSINJB) values. The gamma distributions are based on predicted habitat relationships with bobcats in New Jersey, USA. The distribution was used to determine suitability index scores (i.e. HSINJB values) from the scaled values of different habitat variables. The color of the variable corresponds to the gamma distribution used to calculate its suitability index score. For example, a proportion of 0.25 for deciduous forest cover would receive a suitability index score of 0.2038 while a scaled distance to water value of 0.25 would receive an index score of 0.3232.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 2 Habitat suitability index for bobcats in New Jersey, USA. The index ranges from 0 to 1 with higher values represented by a dark green color indicating better predicted habitat quality or higher likelihood of supporting bobcats.

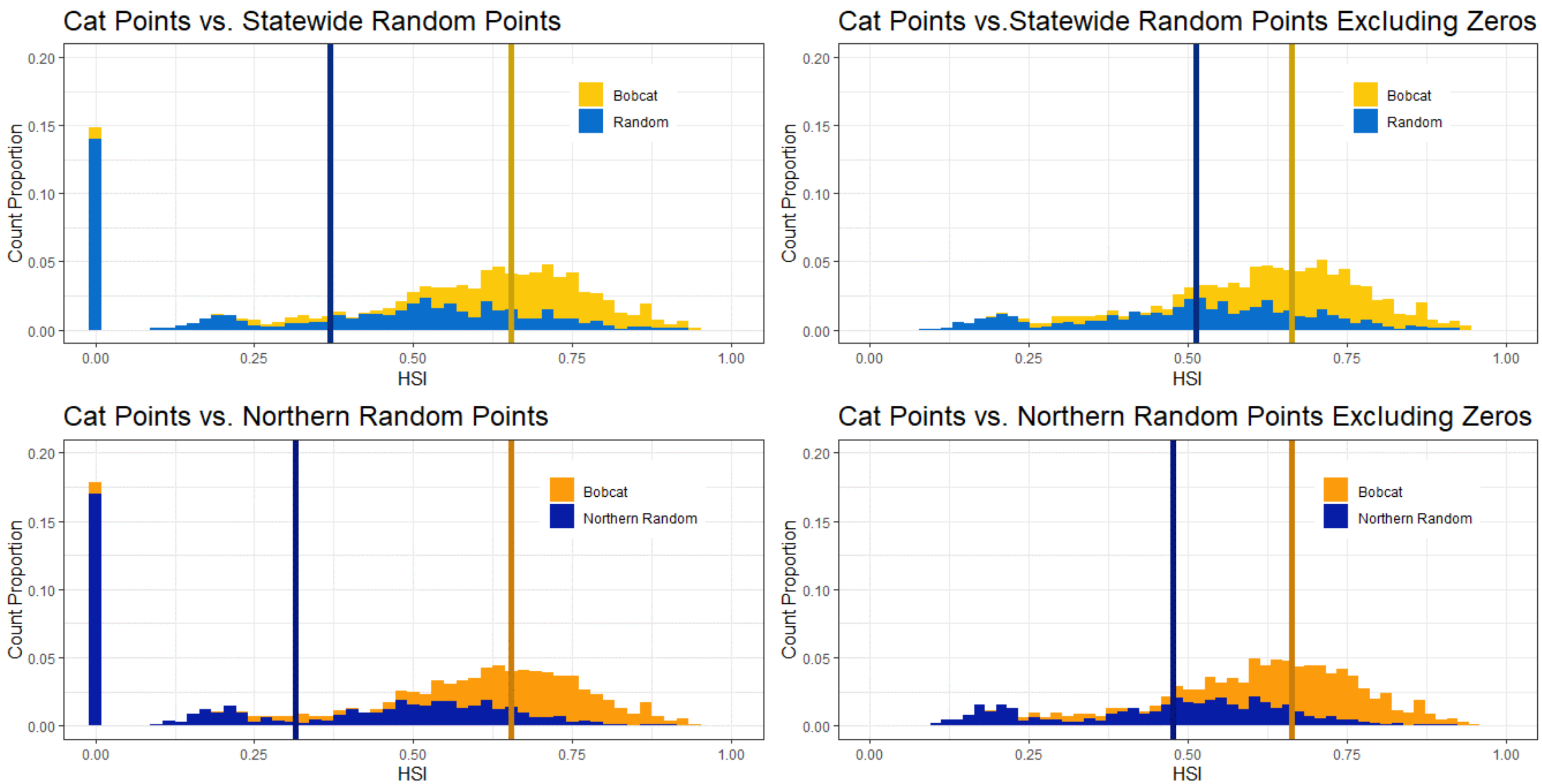
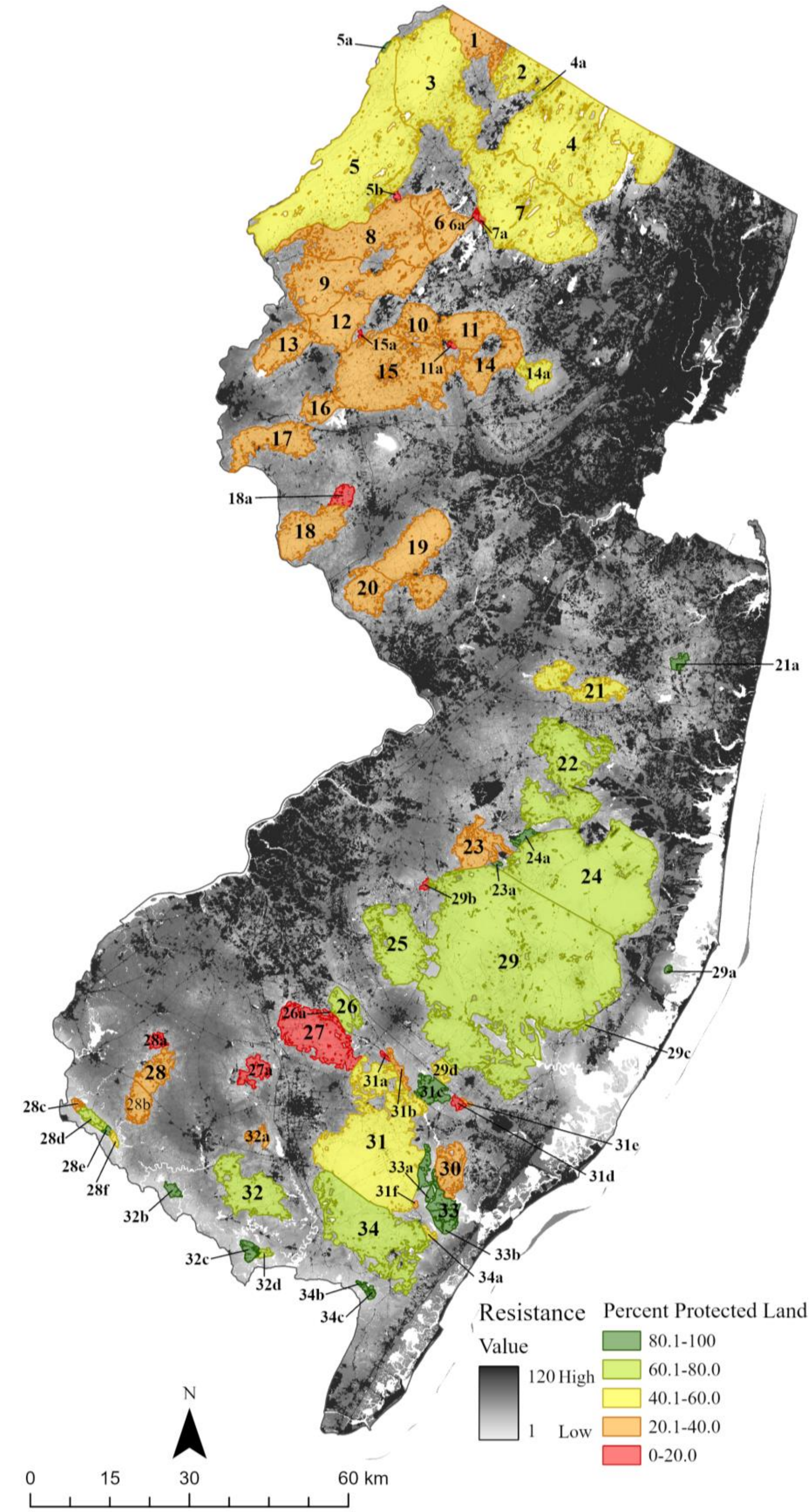


Figure 3 Comparison of Habitat Suitability Index for New Jersey Bobcats (HSINJB) values for randomly generated points to known bobcat points in New Jersey, USA. Random points were generated throughout New Jersey outside of 95% ad hoc kernel utilization distribution. Additional random points were generated for New Jersey north and west of the following road segments: I-95, New Jersey Turnpike, and NJ-440. Bobcat locations were obtained from collar data, scat, camera traps, legal trapping by-catch, and confirmed sightings from 2013 to 2019.



Resistance
Value
120 High
1 Low
Percent Protected Land
80.1-100
60.1-80.0
40.1-60.0
20.1-40.0
0-20.0
N
0 15 30 60 km

Figure 4 Resistance landscape with bobcat habitat cores and stepping stones in New Jersey, USA. Bobcat cores were defined as regions with areas ≥ 27.2 km^2 and numbered beginning in the north from 1-34 for easier reference. Stepping stones were defined as regions with areas between 0.98 and 27.2 km^2 and given an ID number corresponding to the closest core and a unique letter starting with the letter “a.” Even if there was only one stepping stone adjacent to a core, it still received a letter to denote its stepping stone status (e.g. stepping stone 4a). Colors represent the percent protected land area of each core or stepping stone patch.

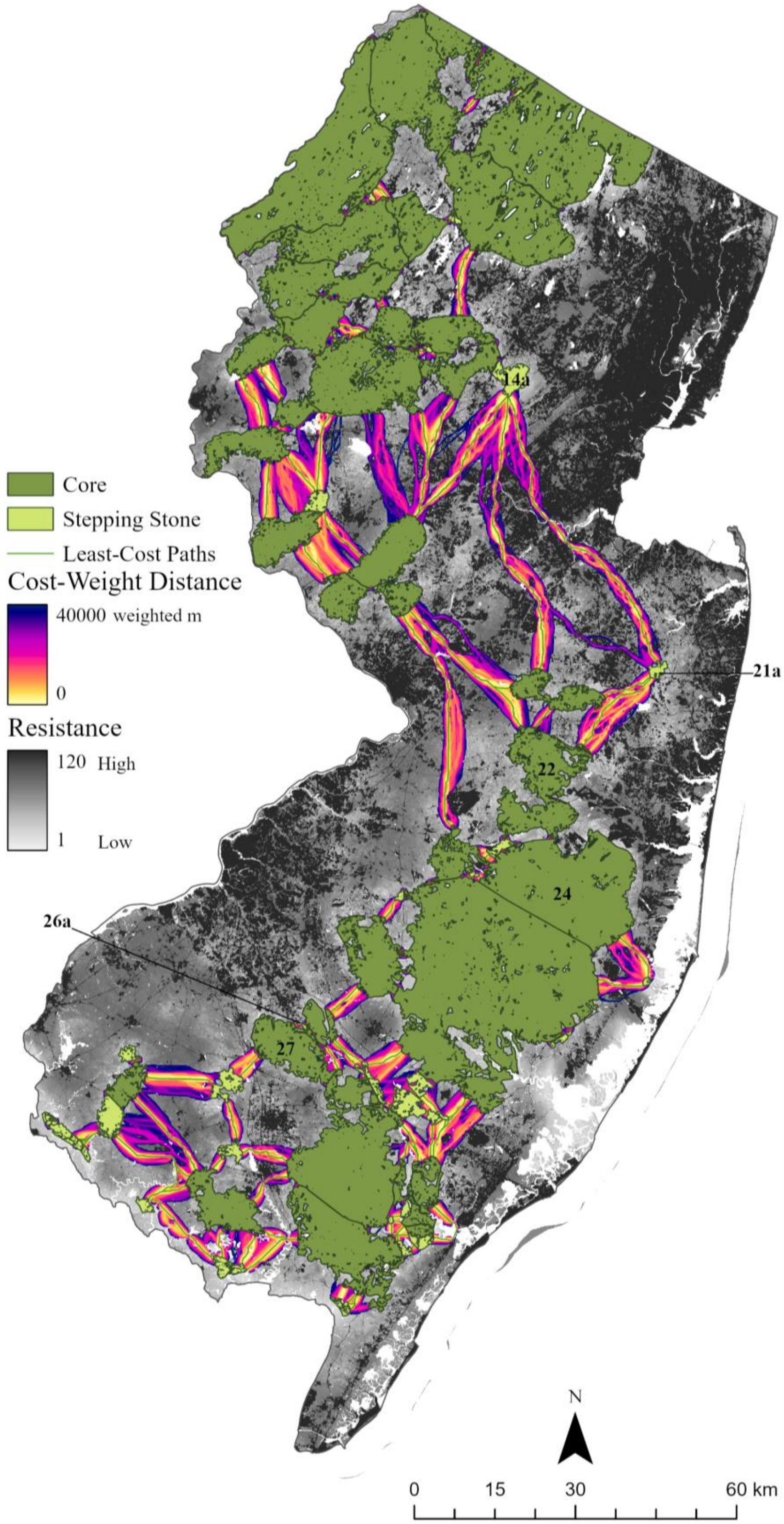
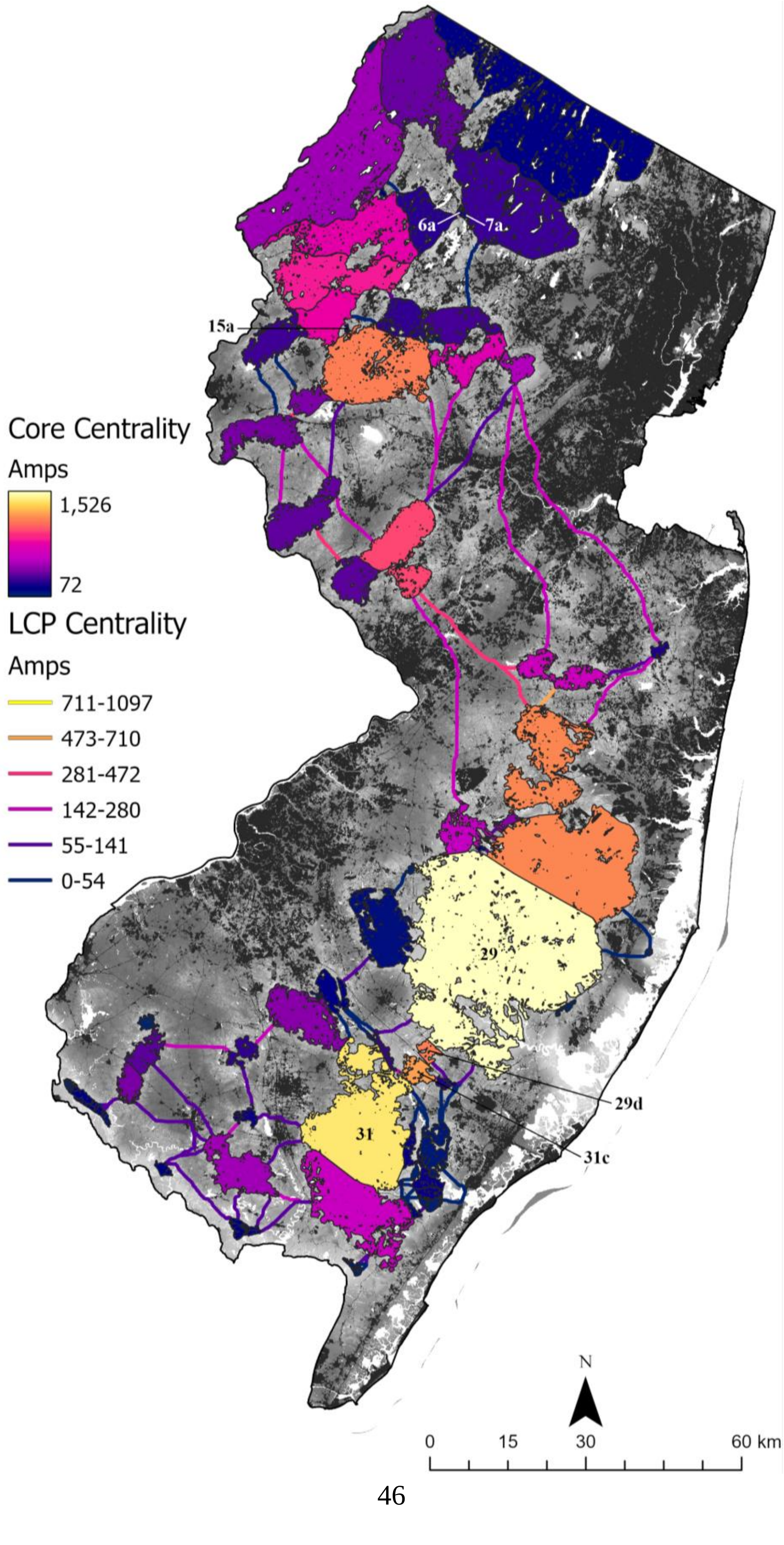
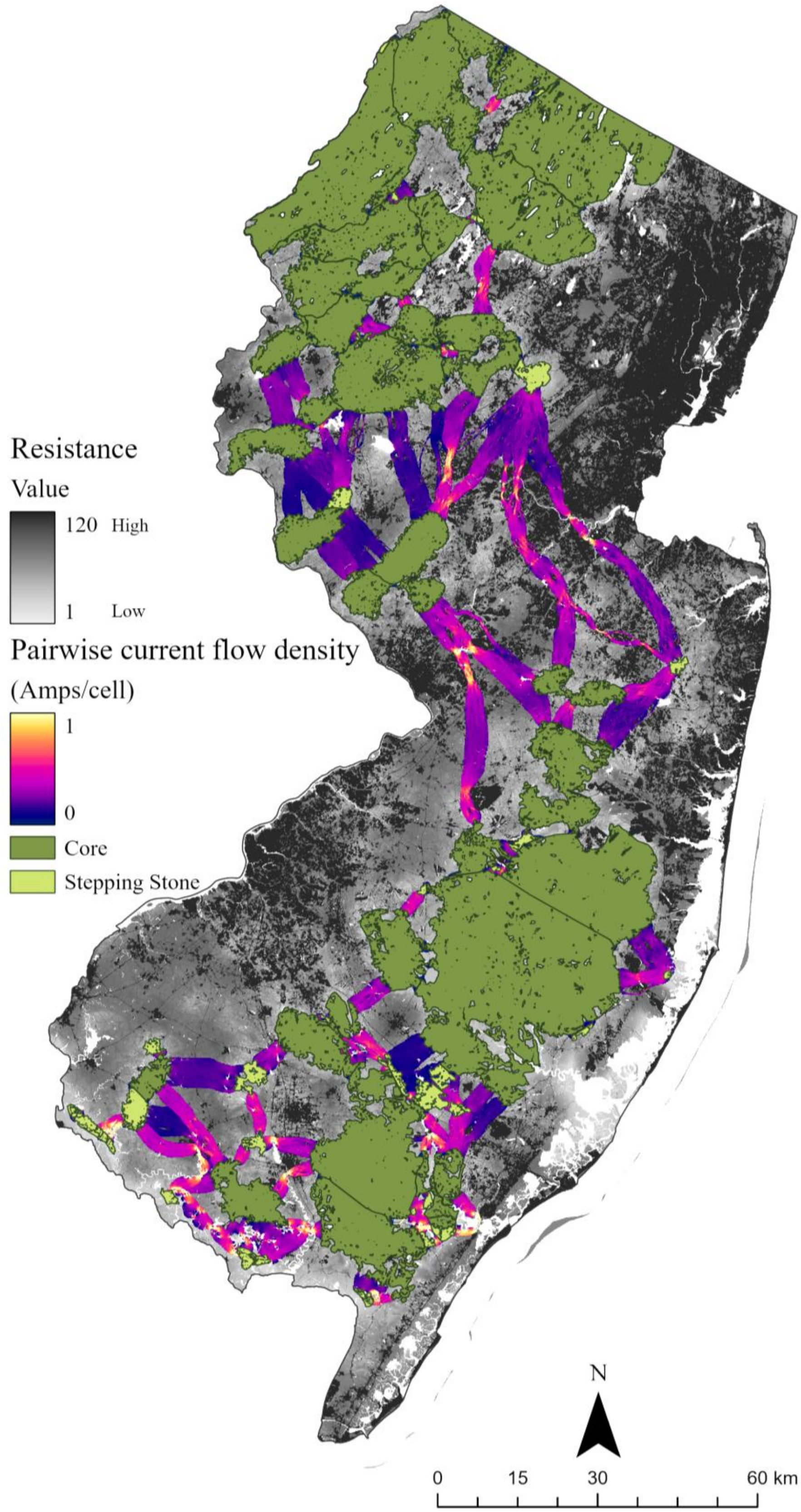

Core
Stepping Stone
Least-Cost Paths
Cost-Weight Distance
40000 weighted m
0
Resistance
120 High
1 Low
14a
21a
22
24
26a
27
N
0 15 30 60 km

Figure 5 Corridors with least-cost paths (LCPs) connecting all bobcat habitat patches in New Jersey, USA. Corridors were truncated at a cost-weight distance (CWD; i.e. distances that incorporate landscape resistance and represent a total travel cost) of 40 km. Green lines represent the LCPs and lower CWD for bobcat movement is represented by yellow and orange with higher CWD values indicated by purple and dark blue.



Core Centrality
Amps
1,526
72
LCP Centrality
Amps
711-1097
473-710
281-472
142-280
55-141
0-54
6a
7a
15a
29
29d
31
31c
N
0
15
30
60 km

Figure 6 Bobcat least-cost path (LCP) and habitat patch current flow centrality (i.e. relative importance to maintain connectivity in the network) measured in amps. Least-cost paths and patches in yellow and orange shades represent habitat patches and corridors more important in the network to maintain connectivity for bobcats across New Jersey, USA.



Resistance
Value
120 High
1 Low
Pairwise current flow density
(Amps/cell)
1
0
Core
Stepping Stone
N
0
15
30
60 km

Figure 7 Pairwise current flow density (amps/cell) between every bobcat core and stepping stones across New Jersey, USA. Bright yellow regions of high current flow density indicate pinch points, or constrictions, within corridors and are suggestive of narrow regions where bobcats would likely have to pass to travel from one patch to another. Not pictured is current flow density between patches separated by small distances (i.e. the width of a highway).

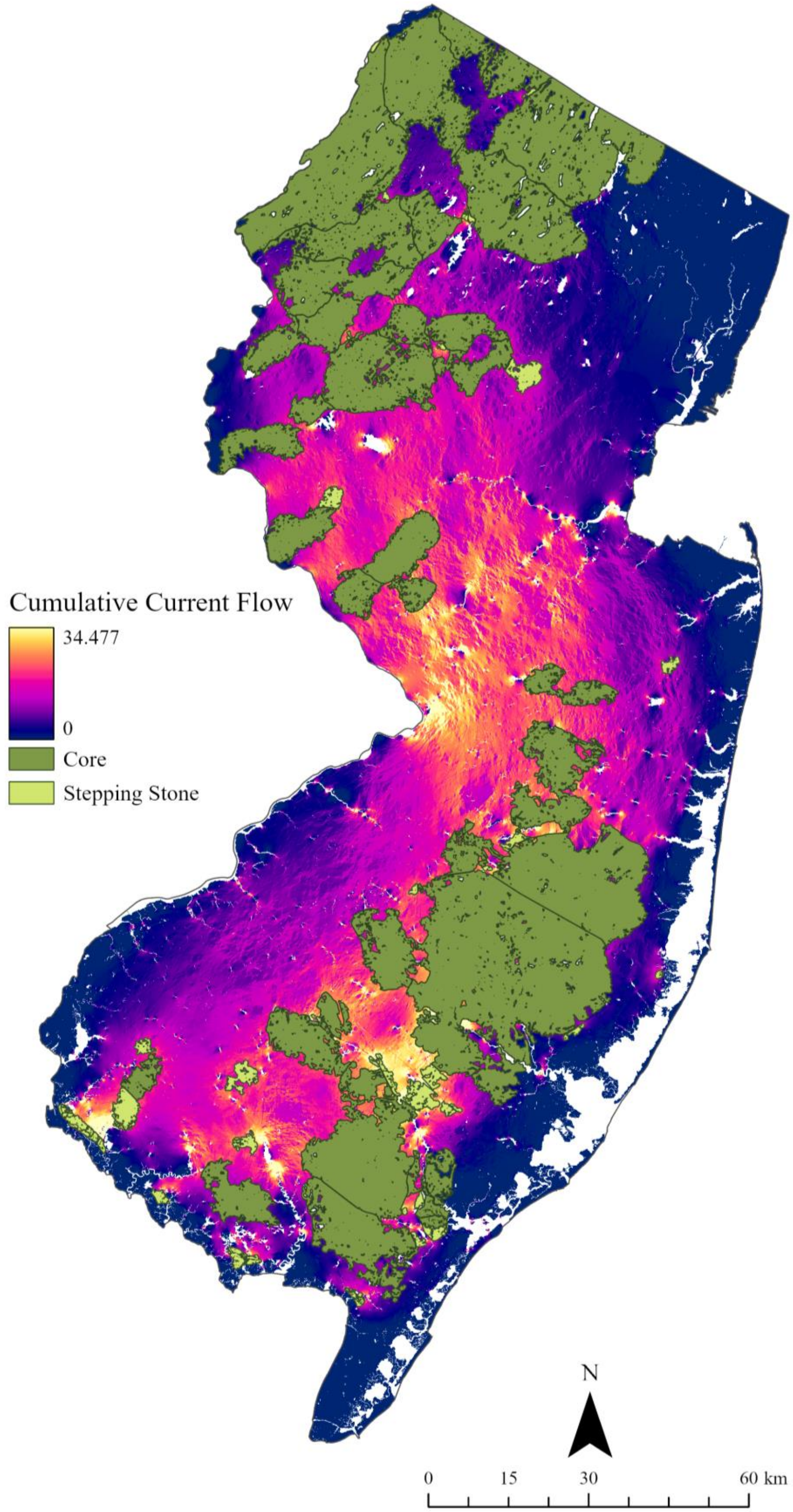

Cumulative Current Flow
34.477
0
Core
Stepping Stone
N
0
15
30
60 km

Figure 8 Pairwise cumulative current flow density is shown among cores and stepping stones for bobcat connectivity in New Jersey, USA. Higher amperage (shades of yellow) indicates cells with a higher probability of bobcats passing through them while navigating the landscape and also suggests less redundancy in possible pathways.

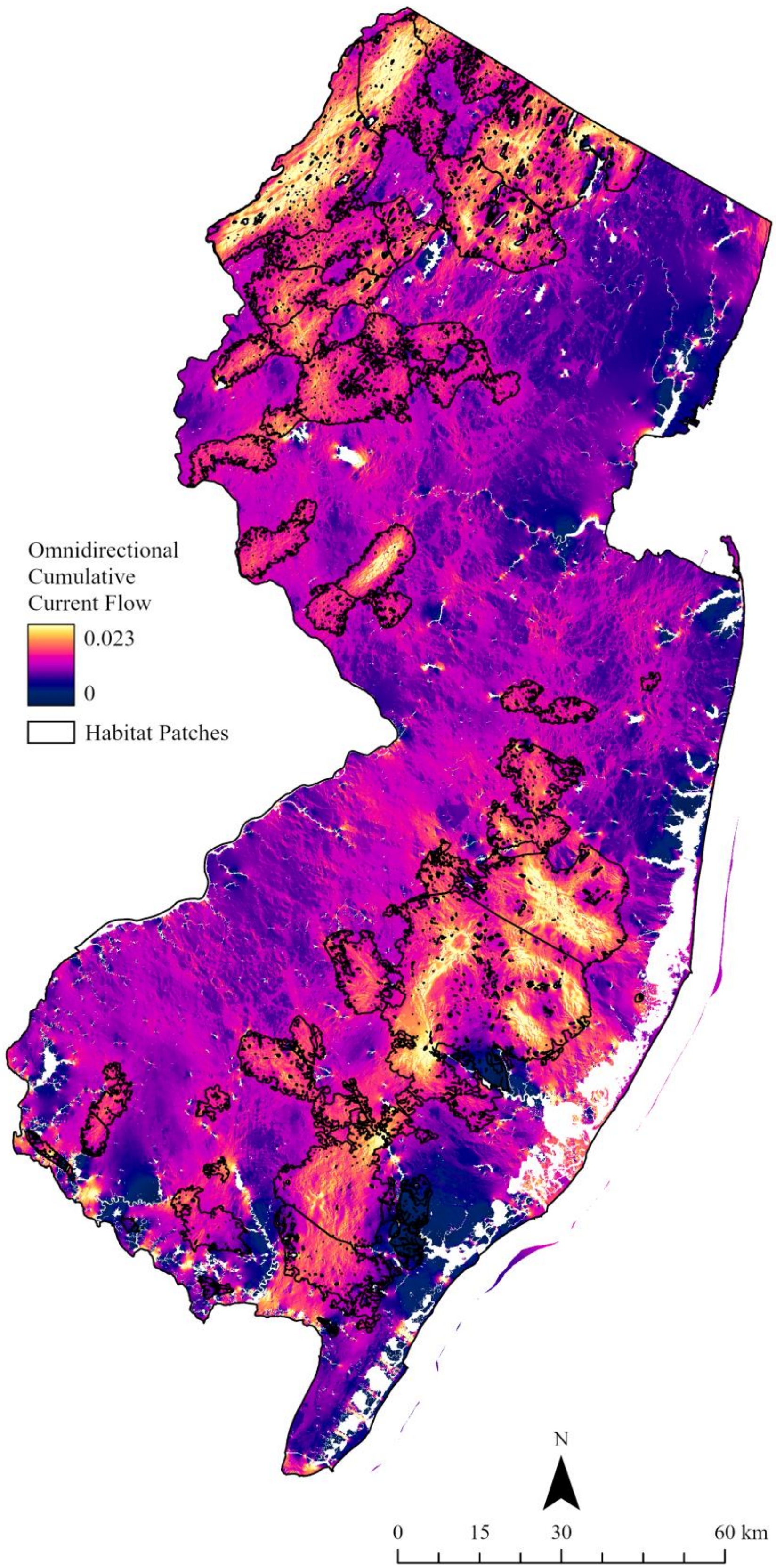

Omnidirectional
Cumulative
Current Flow
0.023
0
Habitat Patches
N
0
15
30
60 km

Figure 9 Omnidirectional cumulative current flow map use to model bobcat movement through New Jersey, USA. Yellow represents regions of high current flow from all four cardinal directions indicating that bobcat movement would likely be funneled through existing habitat patches (outlined in black)

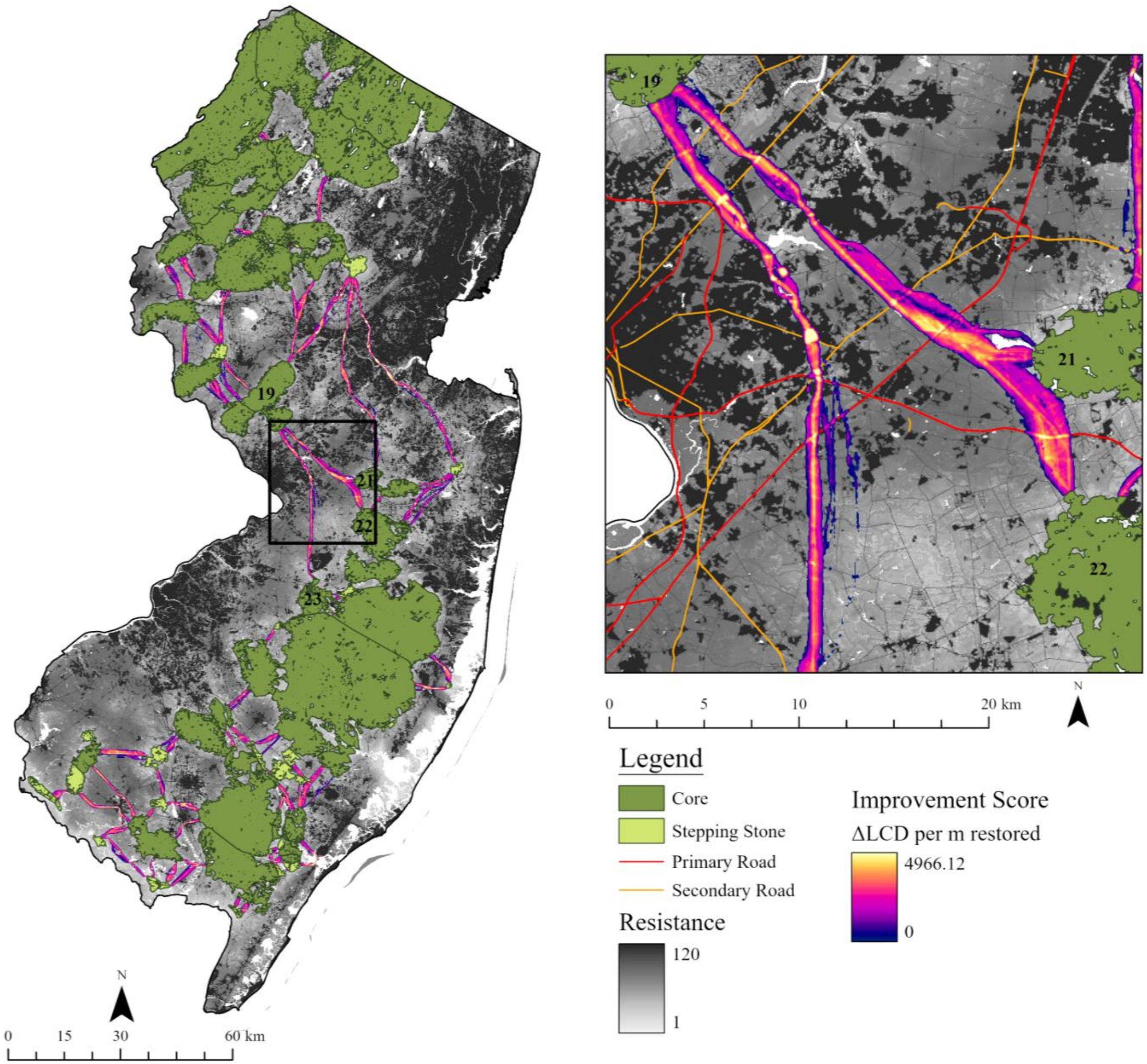

19
21
22
23
N
0
15
30
60 km
0
5
10
20 km
Legend
Core
Stepping Stone
Primary Road
Secondary Road
Resistance
120
1
Improvement Score
ΔLCD per m restored
4966.12
0

Figure 10 Map of maximum improvement score values revealing barriers within corridors connecting bobcat habitat patches in New Jersey, USA. Yellow regions indicate pixels where restoration of habitat or reduction of barrier would have the greatest impact on improving connectivity within the corridor. The zoomed extent demonstrates how primary and secondary roads that cross corridors are identified as barriers and are opportunities for mitigation.

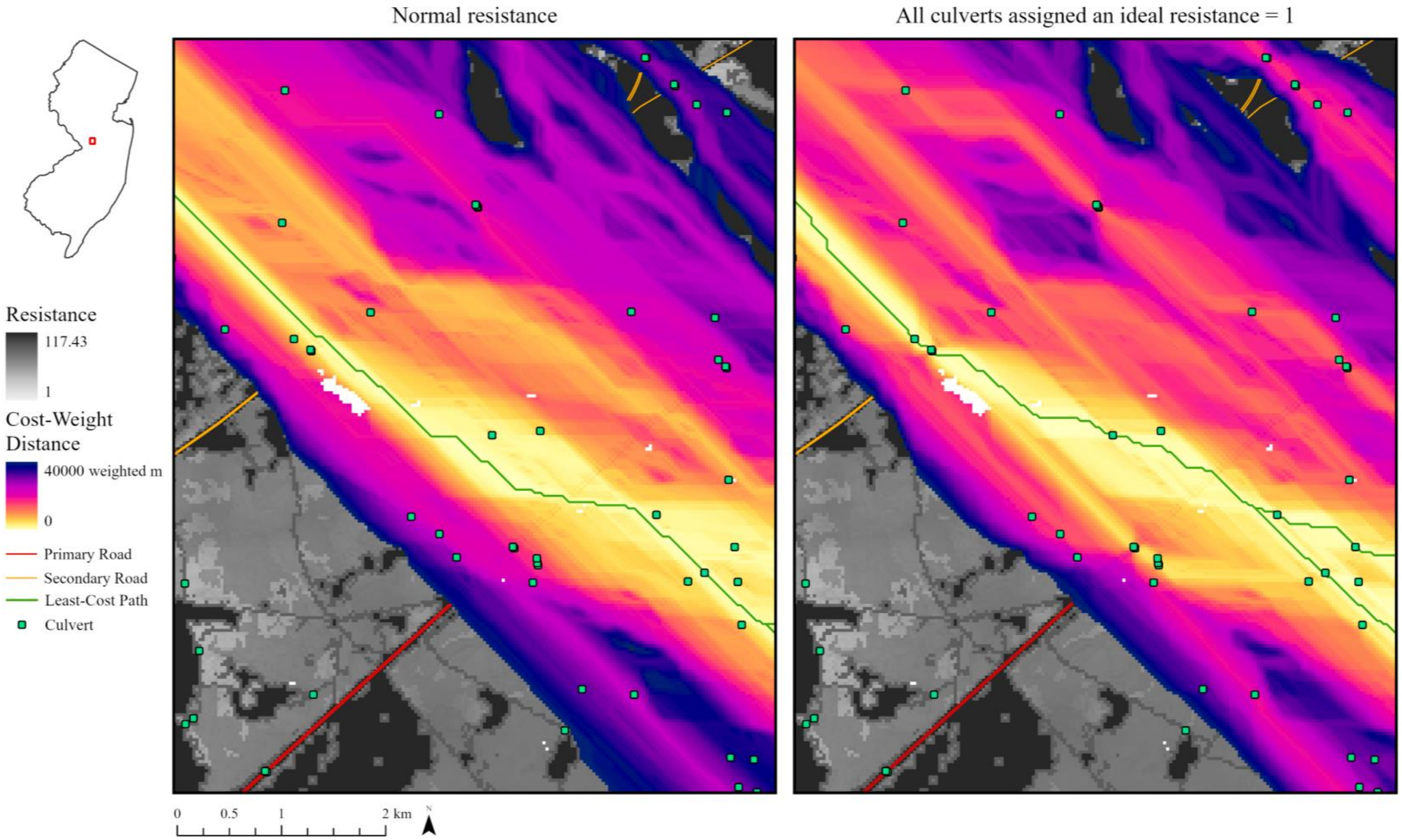

Normal resistance
All culverts assigned an ideal resistance = 1
Resistance
117.43
1
Cost-Weight Distance
40000 weighted m
0
Primary Road
Secondary Road
Least-Cost Path
Culvert
0
0.5
1
2 km
N

Figure 11 Zoomed in comparison of least-cost paths (LCPs) between bobcat habitat patches in central New Jersey, USA for both normal resistance and for an alternate resistance with culverts assigned an ideal resistance of 1. Corridors were truncated at a cost-weight distance (CWD, i.e. distances that incorporate landscape resistance and represent a total travel cost) of 40 km. Green lines represent the LCPs for bobcat movement and lower CWD is represented by yellow and orange with higher CWD values indicated by purple and dark blue. The LCP is directed through culvert locations in the alternate resistance scenario.

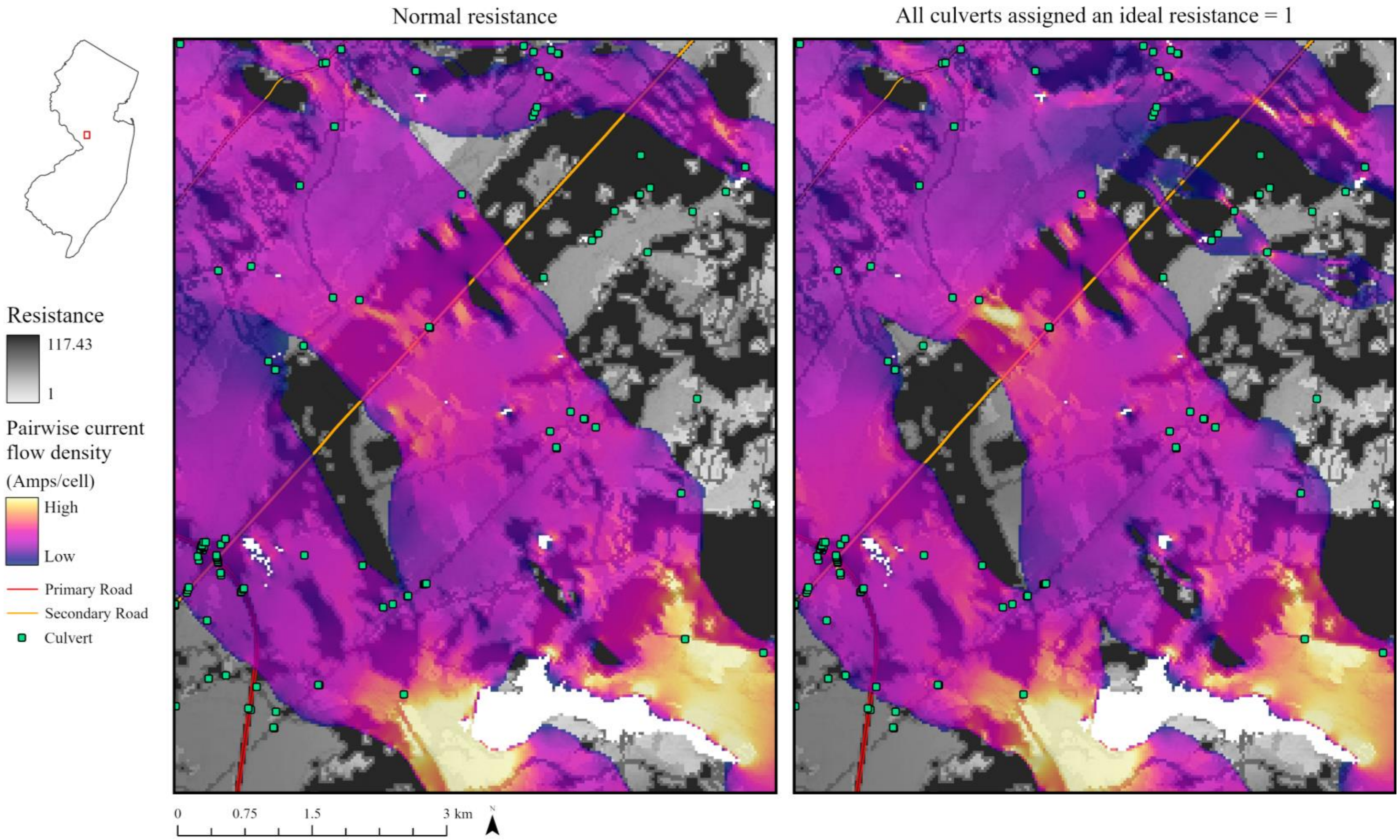

Normal resistance
All culverts assigned an ideal resistance = 1
Resistance
117.43
1
Pairwise current flow density
(Amps/cell)
High
Low
Primary Road
Secondary Road
Culvert
0
0.75
1.5
3 km
N

Figure 12 Maps showing a zoomed in comparison of pinch points (indicated with yellow) within a corridor connecting bobcat habitat patches in central New Jersey, USA. Differences can be seen between the map with normal resistance and the one with the alternative resistance which incorporates an ideal resistance of 1 for all culverts. In the alternative resistance scenario, current flow was directed through culverts resulting in higher flow density over certain landscape features within the resistance landscape and is represented by an increased intensity of yellow on the map.

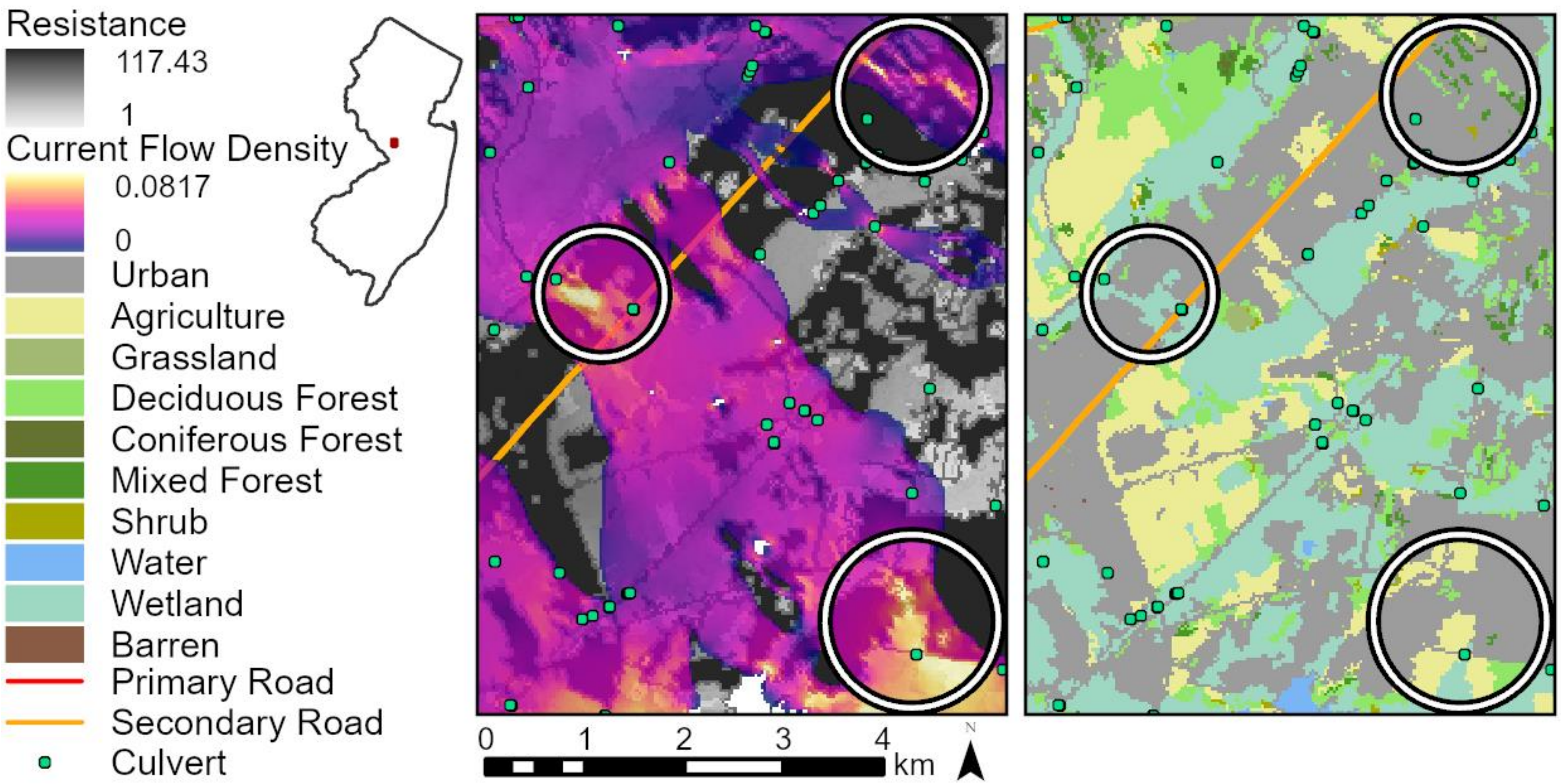


Figure 13 Maps showing pinch points (indicated with yellow) within a corridor connecting bobcat habitat patches in central New Jersey, USA under an alternative resistance scenario in which all culverts were assigned the lowest resistance of 1 and their underlying land cover classes (2016 National Land Cover Database, USGS). Underlying patches of low resistance near culverts received higher current flow density (yellow) indicating pinch points through these patches which correspond to underlying regions of wetland, forest, and agriculture in an urban matrix.

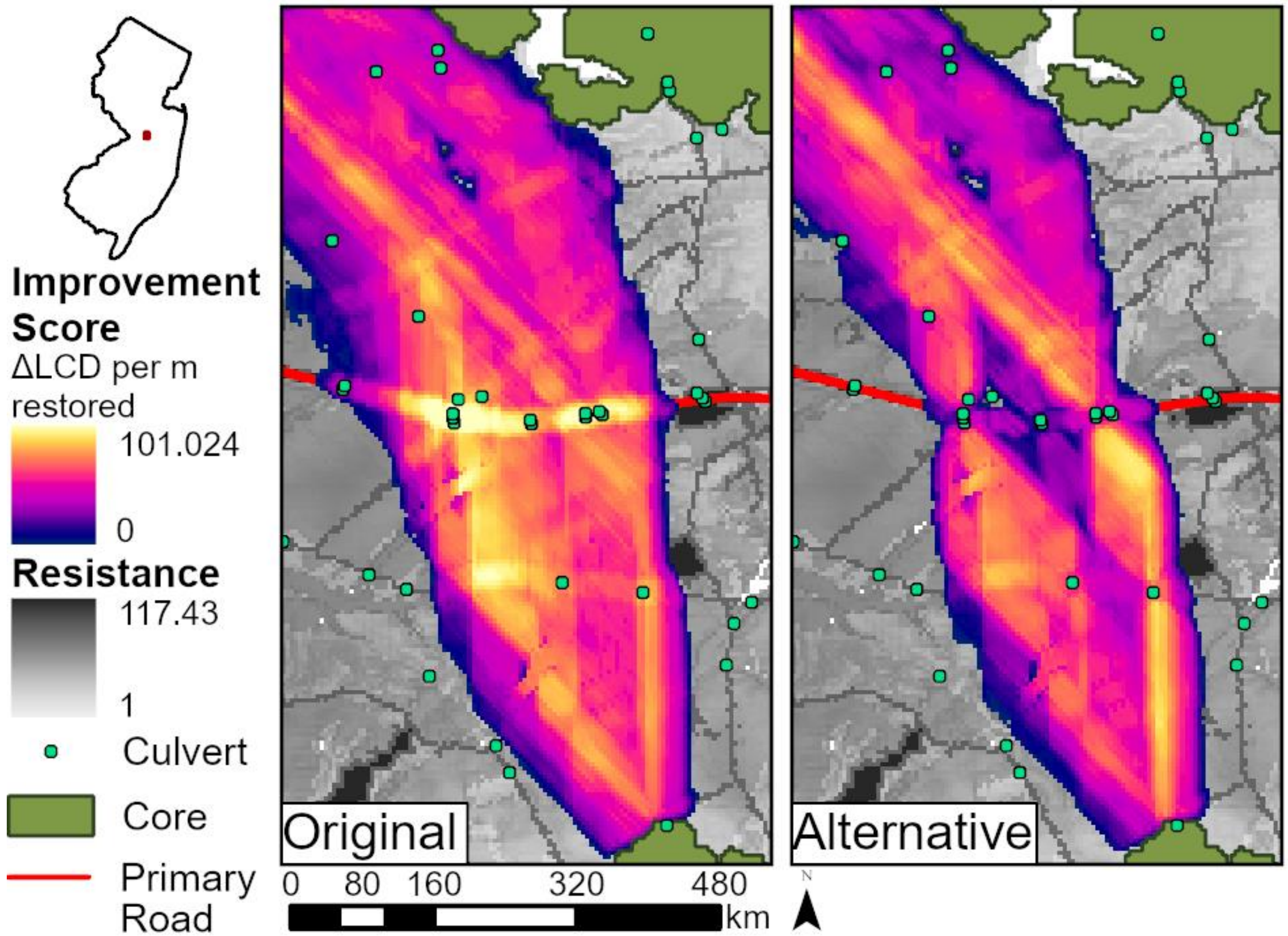

Improvement Score
ΔLCD per m restored
101.024
0
Resistance
117.43
1
Culvert
Core
Primary Road
Original
Alternative
0
80
160
320
480
km
N

Figure 14 Maps with zoomed in extents comparing maximum improvement scores for the original resistance and an alternative resistance in which all culverts were assigned the lowest resistance of 1. Maximum improvement scores indicate barriers within corridors connecting bobcat habitat patches in New Jersey, USA. High improvement scores in shades of yellow indicated barriers within corridors where mitigation could be implemented. Culverts appear to reduce barriers across secondary roads. In the alternative resistance analysis, the barrier across Interstate 195 (in red) was greatly reduced.

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Chapter 2

SCENARIO MODELING TO EXAMINE RECOLONIZATION POTENTIAL OF BOBCATS IN CENTRAL AND SOUTHERN NEW JERSEY

Introduction

In North America, carnivore species historically extirpated from much of their range are now recolonizing many previously occupied habitats. Most notable is the recovery and expansion of wolves which has been occurring in the Midwest states of Minnesota, Wisconsin, and Michigan (US Fish and Wildlife Service 2011). Cougars (*Puma concolor*), which have been historically extirpated from the central and eastern regions of the United States, have also been expanding into the Midwest with increased reports of dispersing individuals moving eastward (LaRue et al. 2012). Bobcats (*L. rufus*) are recolonizing regions or increasing in population in Illinois, Ohio, Iowa, Indiana, and Connecticut (Woolf and Hubert 1998, Johnson et al 2010, Roberts and Crimmins 2010, Beattie 2020). Additionally, some carnivore species are colonizing regions where they historically did not occur, potentially creating new sources of human-carnivore conflict and changing ecosystem dynamics. Expansion of coyotes (*C. latrans*) into the eastern United States and golden jackals (*C. aureus*) from southeast Europe into northern and western regions of the continent are two modern examples of how carnivore colonization can generate ecological and management issues (Gompper 2002, Trouwborst et al 2015).

The bobcat is the most widely distributed native felid in North America (Anderson 1987). Bobcats currently occur in all states of the conterminous United States except Delaware, and their populations have been increasing nationally (Roberts and Crimmins 2010). In line with the national trend, New Jersey bobcat populations are currently increasing after extirpation from most of the state by the

1970s (Schantz and Valent 2003). Within the past decade, there has been anecdotal evidence of increasing bobcat populations and the recolonization of historically occupied habitat by bobcats in New Jersey. The most recent population estimate for bobcats in northern New Jersey indicated a population of 276 individuals in 2016 (Fowles 2019, Fowles 2020). Suggestive of an increasing population, road mortalities have increased in recent years with the highest number on record occurring in 2019 with 15 documented deaths due to vehicular collisions (Fowles 2020). Recolonization is evidenced by bobcats being increasingly found between Interstates 80 and 78 in northern New Jersey and, in 2017, by a bobcat being confirmed south of Interstate 78, suggesting that dispersal and potential recolonization southwards is occurring (Fowles 2018).

The ongoing recovery of this population was made possible through extensive management actions, which continue through today. In 1972, the New Jersey Game Code identified the bobcat as a game species and established a closed season, providing the species protection from unregulated harvest (N.J.A.C § 7:25-5.1 et seq.). State managers translocated 24 bobcats from Maine into northern New Jersey from 1978-1982 to bolster the dwindling population (Turbak 1994, Fowles 2020) and the species was declared state-endangered in 1991 granting it further protections (N.J.A.C. § 7:25-4.13). In 2012, state policymakers introduced the Connecting Habitat Across New Jersey (CHANJ) effort to beginning addressing the difficulties wildlife, including bobcats, face navigating a highly urbanized environment. Through this initiative, the state is working towards improving landscape connectivity for terrestrial wildlife through research to inform land protection, habitat restoration, and barrier mitigation decisions (New Jersey Division of Fish and Wildlife 2019).

To begin addressing the complex issues the recolonization or colonization of carnivores presents, simulation models can be an effective tool. Such models can be used to predict potential recolonization or colonization, future population demographics, species' extinction risk, and genetic flow. Some of the most common models used are population viability analyses (PVAs; Boyce 1992), spatially-explicit PVAs (Akçakaya et al. 1995), and spatially-explicit agent-based models (e.g. Kramer-Schadt et al. 2004, Marucco and McIntire 2010, Kanagaraj et al. 2013). Spatially-explicit agent-based models are additionally useful for predicting where future human-wildlife conflict might occur (e.g. Marucco and McIntire 2010) and may be utilized to examine differing management scenarios through the manipulation of inputs.

In this study, I use simulation modeling to examine the recolonization potential of bobcats into previously occupied habitat in New Jersey. Specifically, I developed a spatially-explicit agent-based model to examine three scenarios: status quo (i.e. natural recolonization), barrier reduction, and a single translocation event. Through these scenarios I will address the potential for bobcats to naturally recolonize central and southern habitat in New Jersey, or whether intervention will be required, either through improvements to landscape connectivity or through translocation events. This information can be used to inform a bobcat recovery plan for the state within the CHANJ framework.

Methods

Study Area

My study area encompassed the entire state of New Jersey, USA. At the time of analyses in 2020, bobcats were only known to consistently occur in northern New

Jersey, a region dominated by deciduous forests. While suitable bobcat habitat, primarily composed of coniferous and mixed forest, existed in the southern region of the state known as the Pine Barrens, no verifiable bobcat presences have been documented there for over a decade (see Chapter 1; Fowles 2018). The bobcat-occupied northern habitat was separated from this potential habitat in the south by a swath of largely urbanized landscapes running from southwest to northeast across the state connecting the greater Philadelphia area, through the capital city of Trenton, to the New York City metropolitan area.

Model Development

Model Structure

I created a spatially explicit agent-based model (SEABM) to predict bobcat demographics, dispersal, and territory establishment across a 25-year time span in the state of New Jersey (Figure 15). I built upon a model presented in SpaDES (R package), which was previously ported to R from the Spatially Explicit Landscape Event Simulator (SELES; Fall and Fall 2001) by Bauduin et al. (2016). The original model framework was developed to examine the dispersal and territory establishment of wolves in the Italian Alps (Marucco and McIntire 2010).

My SEABM is composed of three sub-models, one each for bobcat demographics, bobcat dispersal, and bobcat territory establishment. Of the three sub-models, only the demographic model is not spatially based. For bobcat dispersal and territory establishment the model required six different spatial inputs including, five independent raster datasets representing habitat quality, female locations, male locations, female territories, male territories, and movement blocks and one vector dataset of primary and secondary roads. The habitat raster is used to determine what cells are eligible for bobcat movement and could be incorporated into territories in both dispersal and territory establishment sub-models (Appendix P). I developed this habitat raster by resampling the previously developed New Jersey Bobcat Habitat Suitability dataset (Chapter 1) to a raster consisting of 1.2 km x 1.2 km cells through bilinear interpolation. I assigned cells beyond the boundary of New Jersey a value of negative one. Due to the resampling process, the highest index value became 0.966 (suitable habitat) while the lowest habitat value remained as 0 (unsuitable habitat, Appendix P).

To develop the bobcat location and territory rasters, I incorporated the intrasexual exclusivity through which bobcats organize themselves throughout potential habitat. In this system, females typically maintain home ranges with little overlap with those of other females, while males will usually establish home ranges that overlap several different females while maintaining minimum overlap with other males (Bailey 1974; Berg 1979). While this is the general understanding of how bobcats are socially organized in space, different populations with unique habitat circumstances may result in deviations from this model (Miller and Speake 1979, Zezulak and Schwab 1979, Riley et al. 2006). To accommodate this system of intrasexual exclusivity, I separated rasters depicting either territories or individual bobcat locations by sex, thus allowing for overlap between sexes while maintaining exclusivity of territories within them.

Based on the 2016 regional bobcat population size in northern New Jersey, I randomly generated 276 bobcat locations, i.e., simulated individual bobcats, within the northern habitat patches (see Chapter 1, Fowles 2019, Fowles 2020). Of these 276 locations, I placed 250 (125 M, 125F) north of I-80, resulting in an approximate density of 0.08 bobcats/km^2 which is similar to densities calculated by NJDFW for the region (Fowles 2019). I placed twenty-five (13F, 12M) of the total locations in habitat patches south of I-80 and north of I-78 and the final one location (1M) in the central NJ patch where a known bobcat was documented in 2017 (Fowles 2018). I generated all bobcats locations within habitat cells the met the minimum habitat requirement (0.491, see Table 5) and at least 1.2 km apart from the same sex. I then transformed the bobcat locations into raster datasets with the same extent and cell size as the habitat raster (Appendix P). While not a perfect approximation, the higher density north of I-80 should be reflective of anecdotal and qualitative evidence that there is a higher density of bobcats in that region. To evaluate translocation as a management alternative, I generated ten random bobcat locations for each sex (20 total) in the second largest habitat core (#24, see Chapter 1 and Appendix E) in the New Jersey Pine Barrens using the same methods as above. I avoided the largest habitat patch (#29, see Chapter 1 and Appendix E) to increase the probability that male and female bobcat territories would overlap. This ensured that a least some of the translocated female bobcats would be classified as reproducing females (i.e. their territories have overlap with at least one male) according to model rules.

I generated the initial territories for the starting population of simulated male and female bobcats using the model rules outlined in the territory establishment sub-model resulting in two raster datasets (Appendix P). First, the territory establishment sub-model removes any intrasexual territory and unsuitable habitat cells. It then removes cells that are too far from the bobcat. If sufficient cells of suitable habitat exist, the simulated bobcat establishes a territory, and the sub-model identifies overlap between male and female territories (Figure 16). I drew 276 random samples, with replacement, from an age distribution of mortality dataset for bobcats in New Jersey (NJDFW 2018, unpublished data) to enumerate bobcats of each age in the population. I gave bobcats without territories an age of zero and randomly assigned the remaining ages to bobcats with territories. Since there were not enough randomly generated ages of zero, the random age assignment occasionally assigned an age >2 to a bobcat without a territory, violating the model assumptions that dispersing animals either establish a territory or die by age 2. This required randomly switching these bobcats with younger bobcats assigned a territory during the initialization of territory inputs (i.e. occasionally a bobcat without a territory would be assigned an age >2, so this would be exchanged with a territorial bobcat assigned the age of 1 or 2). Regardless of any required exchanges in ages, the same number of individual classes was retained. For the simulated translocated bobcats, each individual established a territory following the same methods as above and were randomly assigned an age >2 using a random sample with replacement from the age distribution of mortality dataset, truncated to exclude yearlings and juveniles with the assumption that translocation efforts would include only adults.

Finally, the dispersal sub-model required a roads dataset and patchwork raster of “bounce patches” to incorporate the mortality risk of road crossings and the barrier effects of highly trafficked roads. I derived the roads layer by filtering the 2018 TIGER lines dataset (U.S. Census Bureau) to include only primary and secondary roads (Appendix P). To develop the patchwork raster, I first identified the highest value from 2014 and 2016 Average Annual Daily Traffic (AADT) layers from New Jersey (NJ Division of Fish and Wildlife 2014, NJ Bureau of GIS 2016) and depicted roads with an AADT > 10,000, as roads with this level of traffic intensity appear to be impermeable barriers for wildlife (Seiler 2003, Clevenger and Huijser 2011). I then used this AADT reference and the locations of primary and secondary roads to simplify a previously developed map of patches bounded by roads with >10,000 AADT from NJDFW in 2017 (Gretchen Fowles, unpublished data) by combining smaller patches into larger ones to accommodate the computational limitations of the model (Appendix P). Specifically, I collapsed patches in eastern NJ around the New York metropolis into four patches, patches in central NJ around Trenton and the I-95 corridor into seven patches, and patches in southern NJ in the greater Philadelphia area into one patch. I combined smaller dispersed patches throughout New Jersey with nearby larger patches. Overall, this simplification resulted in 33 larger "bounce patches" which are used in the dispersal sub-model to simulate a dispersing individual balking at crossing highly trafficked roads, instead "bouncing" within the patch by opting to stay in the region bounded by roads.

During the demographic sub-model, all bobcats age by one year. Individuals over 16 years old die (i.e. age 17+) as ages greater than 16 are rarely seen in wild bobcats (Anderson and Lovallo 2003, Hansen 2007). Then, yearlings and adults undergo a mortality risk and dispersing bobcats are identified. Both the dispersal and territory establishment sub-models use the HSINJB raster input, but the dispersal model also incorporates information from the primary and secondary roads layer and the "bounce patch" raster dataset. During the dispersal sub-model, first potential dispersal cells are identified using step parameters. Cells occupied with bobcats of the same sex or consisting of unsuitable habitat are removed from the eligible dispersal cell list. If the individual remains within the "bounce patch," cells outside of the current patch are removed. Each remaining cell is given a probability of moving to that given cell based on the current heading of the bobcat. Finally, the next location is selected, and the bobcat is moved to that cell. Using the straight-line movement of the bobcat from its previous location, the number of primary and secondary roads crossed is determined and the individual experiences a mortality risk for each road crossed (Figure 17). If the dispersing individual survives its dispersal event, it then enters the territory establishment sub-model which follows the steps outlined in the generation of initial bobcat territories (Figure 16). In the event that a dispersing bobcat did not establish a territory, it undergoes a mortality risk

While bobcats are known to disperse from northern New Jersey into and out of New York and Pennsylvania and vice versa (Fowles, *in prep.*), this model does not take into account emigration or immigration in and out of northern New Jersey and could be expanded to incorporate this in future studies. For this model, I assumed that that immigration is equal to emigration, thus negating a net gain or loss to the population.

Parameter Selection

I used eleven parameters in the three sub-models of the SEABM to define the behavior of individual bobcats and describe mortality risk (Table 5). I derived litter size from mortality necropsy data from the state of New Jersey in which they counted placental scars found in the uterine horns of adult female bobcats (N = 14). I calculated mortality rates for adults (>2 years old), yearlings (1-2 years old), and juveniles (<1 year old) from rates reported in the literature from other states, prioritizing unharvested populations when possible (Appendix Q). However, only one study was available excluding harvest for juveniles, so I also included results from harvest data. Finally, mortality rates for yearlings were only available from harvest data, requiring adjustment. To adjust yearling mortality rates, I implemented a calibration run of 5 years and calculated yearling death rate due to road crossings and dispersal mortality (no bobcats died from dispersal mortality). I then subtracted this road crossing specific death rate from the original mortality rate calculated for yearlings. I next adjusted the standard deviation so that it maintained the same proportion of the mean as in the original parameter. This provided a yearling mortality rate adjusted to account to for death rates due to road crossing and dispersal mortality rate per move (Table 5). I verified that this adjusted mortality rate, in combination with the other mortality parameters, resulted in an average annual yearling mortality rate comparable to the original rate calculated from the literature by using a final calibration run of 10 years. Additionally, all bobcats older than 16 underwent a 100% mortality event upon age up, thus restricting the maximum age to less than 17 years old (Anderson and Lovallo 2003, Hansen 2007).

For mortality rates based on dispersal, I calculated the road mortality rate per cross event from Bencin et al. (2019). Using the rates they reported for different road types, I calculated the mean and standard deviation of the probability of an individual being killed per cross event for state, US, and interstate road types, thus approximating an average mortality rate for crossing a road in the primary and secondary roads layer. I adjusted the mean dispersal mortality rate from reported cause-specific mortality rates of transient bobcats killed by natural causes in Texas for 0.01-year time steps (0.247±0.152 annually, Blankenship et al 2006). To account for expected differences in mortality rates between Texas and New Jersey, I increased the standard deviation of the mean. I averaged dispersal distances reported in studies from Illinois, Iowa, Kansas, and Indiana (Appendix Q; Kamler et al 2000; Nielsen and Woolf 2003; Johnson et al 2010; Hughes et al 2019). I defined the probability of a bobcat leaving a "bounce patch" as 0.05 ± 0.001, which approximates 1 out of 20 dispersing bobcats successfully leaving a "bounce patch." This estimate is generous as previous studies indicated that ~12% of the population crossed a freeway over the course of 7 years (i.e. approximately 1 in 60; Riley et al 2006).

To arrive at the minimum total territory quality (MTTQ), used in the territory establish sub-model, I used the following equation:

$$\left(\frac{T}{A}\right) * Q = MTTQ \tag{2.1}$$

where T is the total area of the territory, A is the area of an individual raster cell, and Q is the habitat quality threshold value. I based the total area of the territory on studies reporting that larger core areas within home ranges were ~8 km^2 (Tucker et al 2008, Prange and Rose 2020). The overall average from these studies was 9.01 km^2 and for females was 5.43 km^2. Additionally, the mean female home range for Mississippi bobcats was 8.63 km^2 (Chamberlain et al 2003). While bobcat home ranges are larger than this in New Jersey (range 23 km^2 to 168 km^2; Fowles, *in prep.*), I selected the value of 8 km^2 as an approximation of core territory usage so that the current population estimate of bobcats in New Jersey could fit within suitable habitat in the northern portion of the state. I selected a minimum habitat threshold of 0.491 based on my previously selected minimum average habitat value from connectivity analyses (see Chapter 1). This value is one standard deviation below the mean Habitat Suitability Index value for New Jersey bobcat locations, encompassing 84% of the total population of bobcat habitat index values. Home ranges generally include both optimal and sub-optimal habitat, but since the threshold was 0.491, this would exclude less desirable habitat that could possibly be included in a real bobcat's home range.

Management Scenario

I examined three management scenarios using the SEABM: 1) status quo, 2) barrier reduction, and 3) translocation. I ran each scenario 10 times for 25 years and analyzed results at 5-, 10-, and 25-year time steps. For all scenarios, I assumed that all existing habitat patches are maintained throughout all years (i.e. no conversion to agriculture throughout time or changes in landcover due to climate change). In the status quo scenario I examined what would happen to the population within the landscape given current conditions. In this scenario, I assumed that there are no changes to connectivity and that the starting population consists of the 2016 estimated northern population. In the barrier reduction scenario, I assumed that the implementation of terrestrial passages through culverts or crosswalks would decrease the mortality rate per cross event and increase the probability that a dispersing bobcat would be willing to leave a "bounce patch" and cross a busy throughfare. To account for these assumptions, I doubled the probability that a bobcat would be willing to leave the patch to 1 in 10 bobcats and decreased the mortality rate per cross event to 0.025 (Table 5). I adjusted the standard deviations to maintain the same proportion in relation to their respective means. I kept all remaining parameters and inputs constant for this scenario. Finally, in the translocation scenario I examined the fate of the population when 20 additional bobcats (10M, 10F) were introduced into the Pine Barrens over an area of 385.64 km^2 (Patch #24, Appendix E). I selected the translocation number of 20 individuals as managers from NJDFW felt this was a feasible goal (Gretchen Fowles, *pers. comm.*). Additionally, the translocation effort from 1978-1982 resulted in the insertion of 24 bobcats into northern New Jersey and I wanted to use a value that was comparable to efforts that had previously been successful in the state (Turbak 1994, Fowles 2020). I decided to introduce an even sex ratio of male to female bobcats for translocation as a previously successful bobcat translocation effort in Georgia used a founding population with a roughly even sex ratio of 15M:17F (Diefenbach et al. 2009). Additionally, mortality data for bobcats in northern New Jersey suggest that the population has a roughly even sex ratio (53M:48F from 2007-2018, NJDFW, unpublished data). Assuming random capture of individuals from northern New Jersey, this would result in approximately equal numbers of male and female bobcats being captured for translocation. Under this scenario, I assumed there were no changes to landscape connectivity through barrier mitigation. To simplify changes to the model, no bobcats were removed from the northern population as I assumed that the removal of 20 bobcats for translocation would be compensatory. The translocation of 20 bobcats within a single year would be a difficult achievement, but I made this assumption due to the computational constraints of adding additional bobcats to the Pine Barrens over the course of a few years. Future models could incorporate the gradual translocation of bobcats.

Results

Based on the three different management scenario models, bobcats will not likely colonize central and southern New Jersey without intervention. There was no significant difference in population size at the 1-, 5-, 10-, and 25-year time intervals for the status quo scenario (Kruskal-Wallis $\alpha = 0.05$, $\chi^2 = 2.895$, df = 3, p = 0.408; Figure 18). The loess regression across all ten simulations suggested that the population should remain relatively stable over the course of 25 years (Figure 19). The barrier reduction scenario also revealed no significant difference in population for the same time steps (Kruskal-Wallis $\alpha = 0.05$, $\chi^2 = 2.118$, df = 3, p = 0.548; Figure 20). The loess regression across all ten simulations for the barrier reduction scenario also suggested that the population should remain relatively stable or slightly increase over the course of 25 years (Figure 21). Finally, the translocation scenario revealed a significant difference in population size between the 1- and 5-year time intervals (Wilcoxon rank sum test with Bonferroni correction, $\alpha = 0.05$, p = 0.039; Table 6), with no differences found between any other time interval pairs (Kruskal-Wallis $\alpha = 0.05$, $\chi^2 = 9.717$, df = 3, p = 0.21; Figures 22). The loess regression across all simulations suggests a slight decrease in population over the course of 25 years (Figure 23).

Based on the probability of occupancy for any cell across the landscape for all years across all simulations, bobcats more consistently occupied territories south of Route 80 but north of Interstate 95 under the barrier reduction scenario than both the status quo and translocation scenarios (Figure 24). Additionally, the barrier reduction and translocation scenarios suggested that more territory establishment occurred in central and southern New Jersey (Figure 24). When considering the locations and probability of occupancy for territories at different time intervals (i.e. all the simulations considering only one year), the status quo scenario indicates that bobcat territories have a high probability of maintaining establishment in the region north of Interstate 80 at 5-, 10- and 20-year time intervals. The 10- and 25- year time intervals suggest that there was likely moderate expansion into the area between Interstates 78 and 80 and little to no establishment south of Interstate 95 (Figure 25). The probability of occupancy at 5-, 10-, and 25-year intervals for the barrier reduction scenario indicated maintenance of territories north of Interstate 80 and increasing occupancy probability in the region between Interstates 78 and 80 (Figure 26). Even with barrier reduction, the probability of occupancy did not greatly improve for southern habitat patches (Figure 26). More cells appeared to be occupied occasionally in the south under the barrier reduction scenario than under the status quo, but probability of occupancy still remained low (Figure 26). The translocation scenario also maintained high probability of occupancy in the region north of Interstate 80 (Figure 27). Most notably, there were higher probabilities of occupancy in the south at the 5-year time step likely due to the continued presence of translocated bobcats in their original territories (Figure 27). However, this high probability had decreased by the 10-year time step and occupied territories had largely disappeared by year 25 (Figure 27).

Discussion

Overall, this research suggests that using spatially explicit agent-based models can be useful tools for wildlife managers to evaluate the potential impacts and results of different management actions. My results suggest that bobcats are unlikely to recolonize central and southern New Jersey under current conditions over the course of 25 years. Under the status quo scenario, bobcats remained largely concentrated north of Interstate 80 with a reduced presence in the region between Interstates 78 to 80 and rare dispersal into southern New Jersey. These results were in line with observations by NJDFW of fewer incidental captures, road-kills, hair snare efforts south of Interstate 80 which suggest a lower density of bobcats than in the region north of the highways (Fowles, *in prep.*). Additionally, the first bobcat sightings south of Interstate 78 only occurred as recently as 2017 and no reports have been verified for bobcats south of Interstate 95 (Fowles 2018; Fowles, *in prep.*).

The barrier reduction scenario suggested more reliable establishment of bobcat presence in the region south of Interstate 80, but still little occupation of territory south of Interstate 95. Increased occupancy is seen in regions south of Interstate 80 in Warren County, especially in the western area around Merrill Creek Reservoir near Scotts Mountain and in habitat near Pohatcong Township. Additionally, increased probability of occupancy was noticeable in the region around Great Swamp National Wildlife Refuge and along the western border of Hunterdon county near the Wescott Preserve. Increased connectivity through barrier reduction could aid in increasing bobcat populations south of Interstate 80 and across other major thoroughfares. As recently as 2020, a bobcat was killed on a road near Great Swamp National Wildlife Refuge (Fowles, *in prep.*), thus any reduction in road crossing mortality may aid in the establishment of bobcats in this region west of Interstate 287. The barrier reduction scenario appeared to also increase the number of bobcat territories south of Interstate 95, but the low probabilities suggest that these were dispersing individuals which failed to establish a reproducing population of permanent residents.

Barrier reduction efforts, often by mitigating road obstacles through overpasses, underpasses, or culvert modification, have been proposed and implemented, to varying success, throughout the world (Smith et al. 2015). Wild felids will use available crossing structures to traverse busy roads. Cougars have been documented using wildlife crossing structures in Banff National Park and researchers in southern Texas recorded 54 complete crossings by bobcats through culverts (Gloyne and Clevenger 2001, Cain et al. 2003). This suggests that culverts and crossing structures appropriate for bobcat movement could be successful mitigation methods within the state. In fact, New Jersey law mandates that installation of new or replacement culverts under roads incorporate suitable crossing structures for terrestrial wildlife use in many cases (N.J.A.C. § 7:13), making these results salient for informing the implementation of mitigation methods suitable for bobcats.

Finally, the translocation scenario was the only one to show a significant difference in population size between the 1- and 5-year time step, seeming to decease during the first five years and then stabilize. This is likely due the stochastic nature of the model and low number of simulation runs (N= 10) computationally possible in this study. With more runs, I predict that population size results would be more similar to the status quo scenario since the only change was an insertion of 20 additional bobcats in the south and all the remaining parameters were maintained. The translocation of 20 bobcats in a sex ratio of 1M:1F appeared to maintain bobcats in southern New Jersey through the first five years, but by the 10-year time step occupied territory was becoming sparser and territories had mostly disappeared by 25 years. I hypothesize that this is partly due to how the model identifies a reproducing female, in which territory overlap with a male is a prerequisite for reproduction. Territories in this model were more representative of core area usage than total area used by a bobcat. This was more restrictive than what occurs in nature since male and female home ranges are commonly known to overlap (Bailey 1974; Berg 1979). The results from the translocation scenario highlight that I need to further refine this model before it is used to inform any management or policy decisions. However, the status quo and barrier reduction scenarios show that spatially explicit agent-based models can serve as useful tools in examining management scenarios once properly calibrated.

Even though my model needs further refinement to be able to properly assess the efficacy of a bobcat translocation into southern New Jersey, bobcat translocations have historically been successful, restoring bobcat populations in both New Jersey and Georgia. Over the course of four years beginning in 1978, the New Jersey Division of Fish and Wildlife (NJDFW) translocated 24 bobcats from Maine into northern New Jersey (Turbak 1994, Fowles 2020). Based on recent genetic analyses, there was likely a remnant population of New Jersey bobcats at the time of the translocation that subsequently bred with translocated bobcats from Maine and immigrants from New York and Pennsylvania (Pilgrim et al. 2018; Fowles, *in prep.*). Researchers translocated 32 bobcats from coastal Georgia to Cumberland Island, a barrier island designated as National Seashore, from 1988 to 1989 (Diefenbach et al. 1993). Twenty-three years after translocation, the population of bobcats on the island was estimated to be ~14 individuals and genetic analyses suggested that allelic diversity on the island had been lost but showed low levels of inbreeding (Diefenbach et al. 2015). Given this evidence, translocation may still be a viable management opportunity for NJDFW, but further research should be pursued. The barrier reduction model suggests that immigration from northern habitat patches into southern New Jersey is possible by dispersing individuals which could maintain allelic diversity in a newly established southern population.

While my results are suggestive that barrier reduction is important for the expansion of bobcats south of Interstate 80, I only expect this positive effect on expansion to become more prominent with further refinement of the model. As with most models, the SEABM is a simplification of the complexities of the natural world and is subject to computational limitations of current technology. It was also limited by the parameters available to define the rules by which it functioned. For example, mortality rates for both juvenile and yearling bobcats were largely calculated from harvest data, thus potentially overestimating the actual mortality rate if harvest has additive instead of compensatory effect on the mortality rate of the population. To reduce model complexity, the dispersal distance parameter incorporated data from both male and female bobcats which may not be reflective of reality or the specific dynamics observed in New Jersey. While female bobcats have been documented dispersing distances as large as 136 km, it appears that males typically disperse farther than females and that females remain closer to their natal home range (Berg 1979, Hansen 2007). At its current state, the SEABM is too restrictive in how it identifies reproducing female bobcats, thus potentially limiting population growth for all scenarios evaluated.

Based on these limitations, I recommend model refinements to the identification of reproducing females, a static minimum dispersal distance, and separation of both dispersal distance and territory size parameters by sex. Specifically, reproducing females could be identified as adults that have overlap with males or are within a certain distance from an adult male, thus resolving the underestimation of the number of breeding females in the population. The dispersal sub-model could also incorporate an affinity metric, increasing the likelihood of male dispersal to cells near already established female territories. In the current version of the model, the dispersal ring is defined by two randomly selected values from the distribution of dispersal distances (Table 5), with the lowest value serving as the inner ring and the largest as the outermost. To permit a wider range of dispersal distances, the minimum value could be fixed at a much lower value thus allowing dispersers to settle in unoccupied habitat closer to their natal range. This would also reduce the pile-up of territories along boundaries more evenly distributing them within bounce blocks where suitable habitat is available (Figure 24). Pile-up of home ranges along freeways has been documented for bobcats in California (Riley et al. 2006), so if this observation persists even after changes have been implemented it could be suggestive that this phenomenon may also be occurring in the population of New Jersey bobcats. Additionally, if computational constraints allow, the minimum and maximum dispersal distances and territory sizes could be separated for both sexes. These changes, in addition to more simulation iterations (i.e. ~100), have the potential to change the distribution of territories and population growth observed. Thus, they should be successfully implemented before any concrete management decisions regarding bobcats are made.

Beyond the changes outlined above, variations of each scenario and additional scenarios could aid in management decisions for bobcats in New Jersey. Under each scenario, different starting population sizes (e.g. the highest estimated population size) may affect the distribution and expansion of bobcats throughout the state. Specific to the translocation scenario, I recommend that further iterations of the model examine different numbers of individuals translocated and whether multiple translocations (e.g. insertion of ~5-10 individuals each year for 5 years) could affect the results. This should be done as a single translocation may not be practical within the span of a year and it is possible that there were not enough individuals translocated in my model to establish a southern population. In addition to varying the number of individuals translocated, the ratio of males to females could also be examined. For example, it may be prudent to translocate more females than males, as bobcats are polygynous, and a single male is capable of mating with several females (Anderson 1987, Hansen

2007). Finally, a scenario examining the effects of combining translocation with barrier reduction will further help explore whether translocation may be feasible.

The incorporation of immigration and emigration into and out of New Jersey from adjacent populations could improve this model in future studies. However, this would largely only affect the population north of Interstate 80 as New Jersey is mostly a peninsula and movement into central and southern New Jersey would have to originate from the north. Additionally, most of the parameters used were sourced from the literature; future population studies and collaring studies, especially examining the specific factors that affect bobcat dispersal in New Jersey, could provide more informative parameters specific to this population in the state. Beyond bobcat-specific research, genetic flow analyses for other terrestrial wildlife could also be informative to parse out the degree that genetic exchange is happening between northern and southern populations. In summary, at this stage in the SEABM model development I recommend that New Jersey managers continue their efforts to reduce barriers to bobcat dispersal and improve landscape connectivity in general for terrestrial wildlife. Translocation is still a viable option, but further model iterations after refinements should be executed before any final decisions regarding this management action are made. If managers do decide to translocate bobcats into southern New Jersey, I recommend that it is implemented in conjunction with the conservation of habitat patches within corridors and the mitigation of barriers such as roads to maintain connectivity between northern and southern bobcat populations and allow for genetic exchange.

To my knowledge, this is one of the first spatially explicit agent-based models that seeks to model the expansion of a species with intrasexual exclusivity of territory establishment. Tracey et al. (2014) used an agent-based model to investigate the transmission of feline immunodeficiency virus in a population of bobcats. However, they did not incorporate any metric for discrete territory establishment or intrasexual exclusion, rather opting for movement behavioral rules which were more appropriate for modeling disease transmission based on individual movements within territories and by dispersers (Tracey et al. 2014). Spatially explicit agent-based models can be implemented in other states where bobcat populations are expanding and recolonizing new territory to inform management decisions and making population predictions (Woolf and Hubert 1998, Johnson et al 2010, Roberts and Crimmins 2010). They are also likely applicable to the expansion of other carnivore species throughout the world with the incorporation of locally relevant habitat layers and species-specific parameters and could be useful to examine territory establishment in a transboundary network.

TABLES

Table 5 Table showing parameter values used in the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA and their corresponding sources. Three different management scenarios were examined: 1) status quo (natural recolonization), 2) barrier reduction, and 3) single translocation event. Parameter values were identical for both the status quo and single translocation scenarios. The barrier reduction scenario, which assumed improved connectivity and reduced mortality due to barrier mitigation, replaced the leave "bounce patch" rate and the road mortality rate per crossing event with the parenthetical values listed for those paraments. All remaining parameter values for the barrier reduction scenario were kept the same as the status quo and translocation scenarios.

Parameter	Value (Alternative)[a]		Sources
Habitat threshold	0.491		Unpublished data, this project
Minimum total territory quality	2.73		Tucker et al 2008; Prange and Rose 2020
	Mean	*SD*	
Adult mortality rate	0.261	0.090	Knick 1990; Chamberlain et al 1999; Fuller et al 1995; Nielsen and Woolf 2002; Riley et al 2003
Juvenile mortality rate	0.407	0.260	Bailey 1979; Blankenship and Swank 1979; Hoppe 1979; Lovallo 2007; Landry 2017
Yearling mortality rate[b]	0.198	0.079	Bailey 1979; Hoppe 1979; Landry 2017
Dispersal mortality rate per move	0.00247	0.00215	Blankenship et al 2006
Dispersal Step (km)	45.48	26.51	Kamler et al 2000; Nielsen and Woolf 2003; Johnson et al 2010; Hughes et al 2019
Litter size (kittens)	3.07	1.38	NJ Division of Fish and Wildlife, unpublished data
Leave "bounce patch" rate	0.05 (0.1)	0.001 (0.002)	Riley et al 2006
Road mortality rate per cross event	0.0357 (0.0250)	0.04550 (0.03186)	Bencin et al 2019

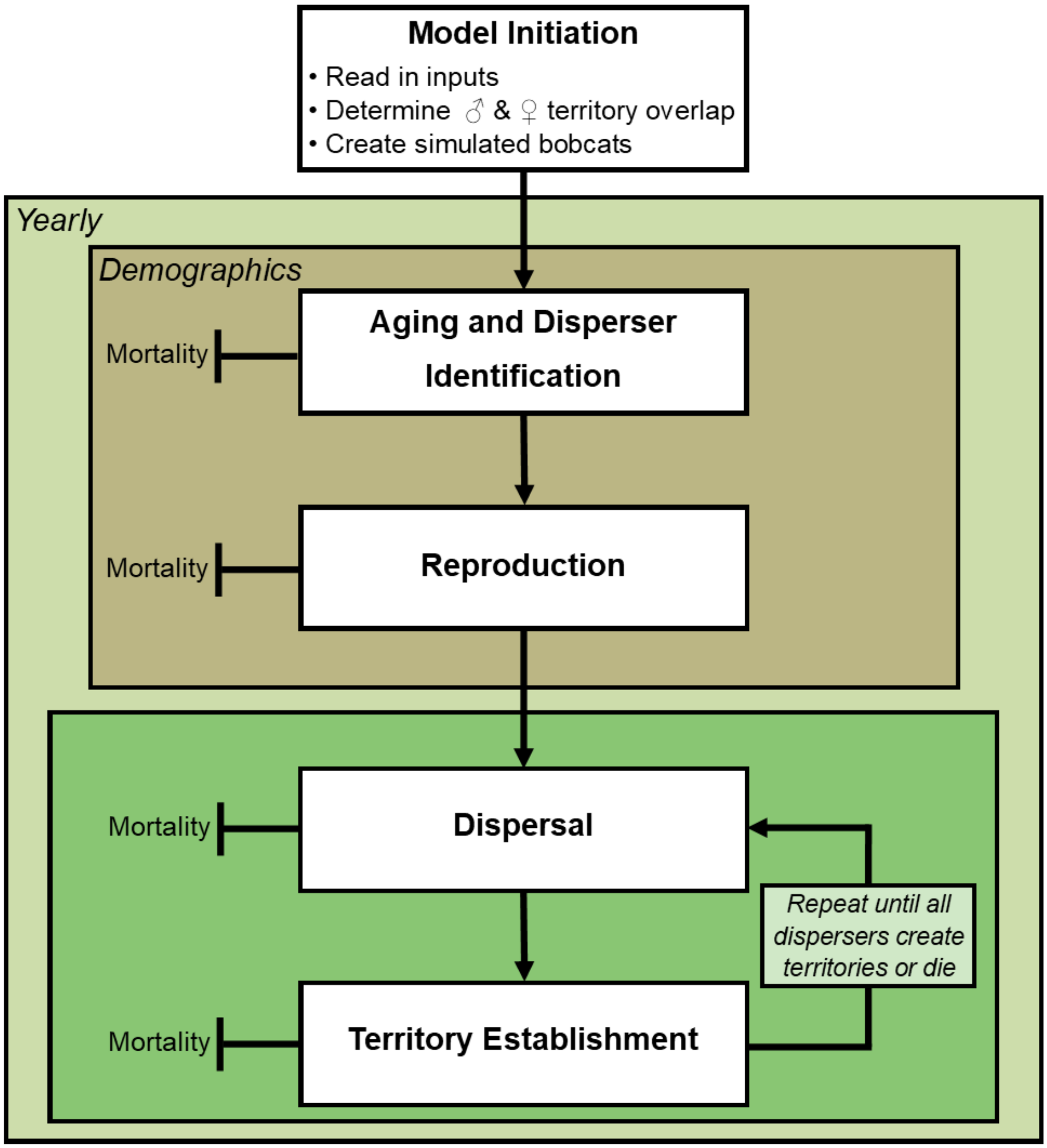
[a] for improved connectivity scenario

[b] adjusted to account for mortality during dispersal and crossing roads; see Table 8 for original mean and standard deviation

Table 6 Results from the pairwise comparisons of bobcat population size at 1-, 5-, 10-, and 25-year time intervals using Wilcoxon rank sum test with Bonferroni correction for the translocation scenario examined using a spatially explicit agent-based model (SEABM). The translocation scenario SEABM examined bobcat recolonization potential in New Jersey, USA under the translocation of 20 bobcats into a southern habitat patch in the state. P-values are displayed for each year interval pairs and an asterisk denotes a significant difference in population size between years 1 and 5.

	Year 1	**Year 5**	**Year 10**
Year 5	0.039*	-	-
Year 10	0.296	1.000	-
Year 25	0.205	0.631	1.000

FIGURES



Model Initiation
• Read in inputs
• Determine ♂ & ♀ territory overlap
• Create simulated bobcats
Yearly
Demographics
Mortality
Aging and Disperser Identification
Mortality
Reproduction
Mortality
Dispersal
Repeat until all dispersers create territories or die
Mortality
Territory Establishment

Figure 15 Concept map for the spatially explicit, agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA. After initiation of the SEABM, the model passes to the demographic sub-model where individual bobcats are aged up, dispersers are identified, and reproducing females have litters. Each of those steps within the demographic sub-model incorporate mortality risk for individual bobcats. The model then passes to the spatially explicit sub-models of dispersal and territory establishment, which are repeated on a loop until all dispersers either create territories or die. Both the dispersal and territory establishment sub-models incorporate mortality risk for dispersing bobcats.

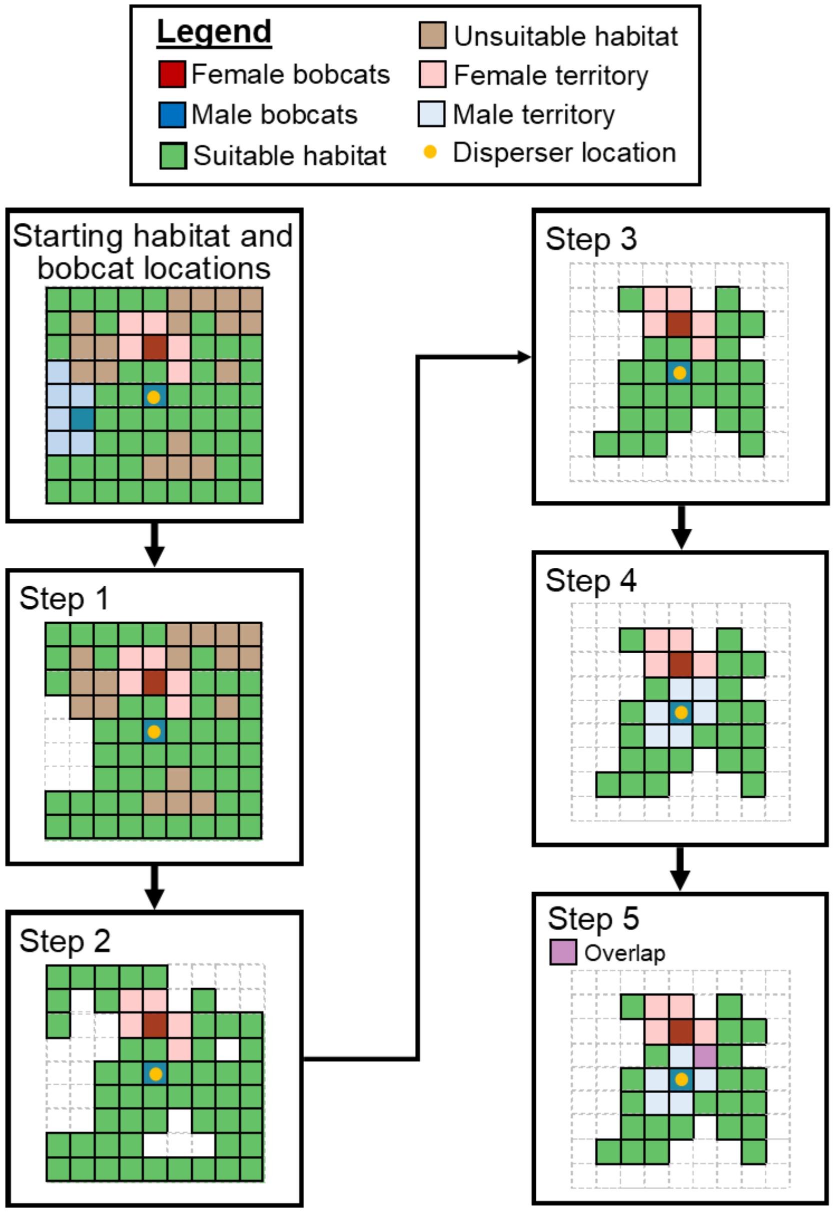

Legend
Female bobcats
Male bobcats
Suitable habitat
Unsuitable habitat
Female territory
Male territory
Disperser location
Starting habitat and bobcat locations
Step 1
Step 2
Step 3
Step 4
Step 5
Overlap

Figure 16 Concept map of the territory establishment sub-model in the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA. This follows the fate of an individual male bobcat as the SEABM determines the extent and location of its territory. The territory establishment sub-model follows these steps: 1) remove existing bobcat (of the same sex) territories from potential territory area, 2) remove cells with unsuitable habitat, 3) remove cells that are too far from the bobcat, 4) determine if sufficient cells of suitable habitat exist and establish a territory, and 5) determine male and female territory overlap after all dispersers have established territories. If a dispersing bobcat did not establish a territory, it undergoes a mortality risk event.

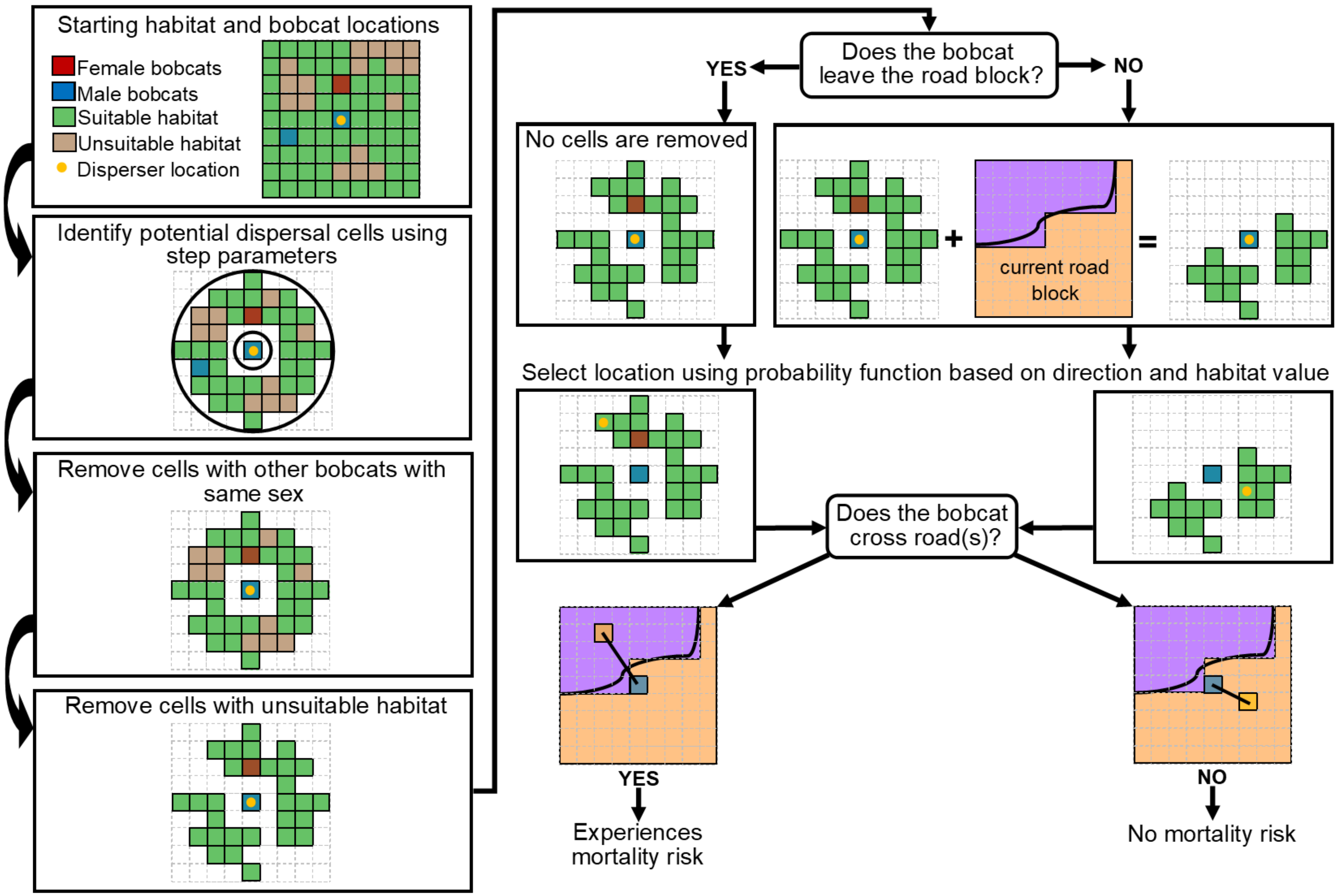

Starting habitat and bobcat locations
Female bobcats
Male bobcats
Suitable habitat
Unsuitable habitat
Disperser location
Identify potential dispersal cells using step parameters
Remove cells with other bobcats with same sex
Remove cells with unsuitable habitat
Does the bobcat leave the road block?
YES
NO
No cells are removed
+
current road block
=
Select location using probability function based on direction and habitat value
Does the bobcat cross road(s)?
YES
Experiences mortality risk
NO
No mortality risk

Figure 17 Concept map of the dispersal sub-model for the spatially explicit agent-based model used to examine bobcat recolonization (SEABM) potential in New Jersey, USA. This follows the fate of an individual male dispersing bobcat (yellow dot) as the SEABM determines its dispersal location. First, potential dispersal cells are identified using the dispersal distance parameter (i.e. step parameter) and then removes cells of bobcats of the same sex (in this case the other males) from the list of eligible cells. Then, cells with unsuitable habitat are removed and the model determines in the bobcat leaves its road block (i.e. "bounce patch") using a probability function. If it remains in the block, then cells outside of the are removed. If it can leave the block, all cells remain available to the disperser. Finally, the model tallies the number of roads the disperser crossed and creates a mortality risk for each crossing event. If the dispersing bobcat survives, it moves on to the territory establishment sub-model within the SEABM. If there is no eligible dispersal location, then the bobcat remains in its current location.

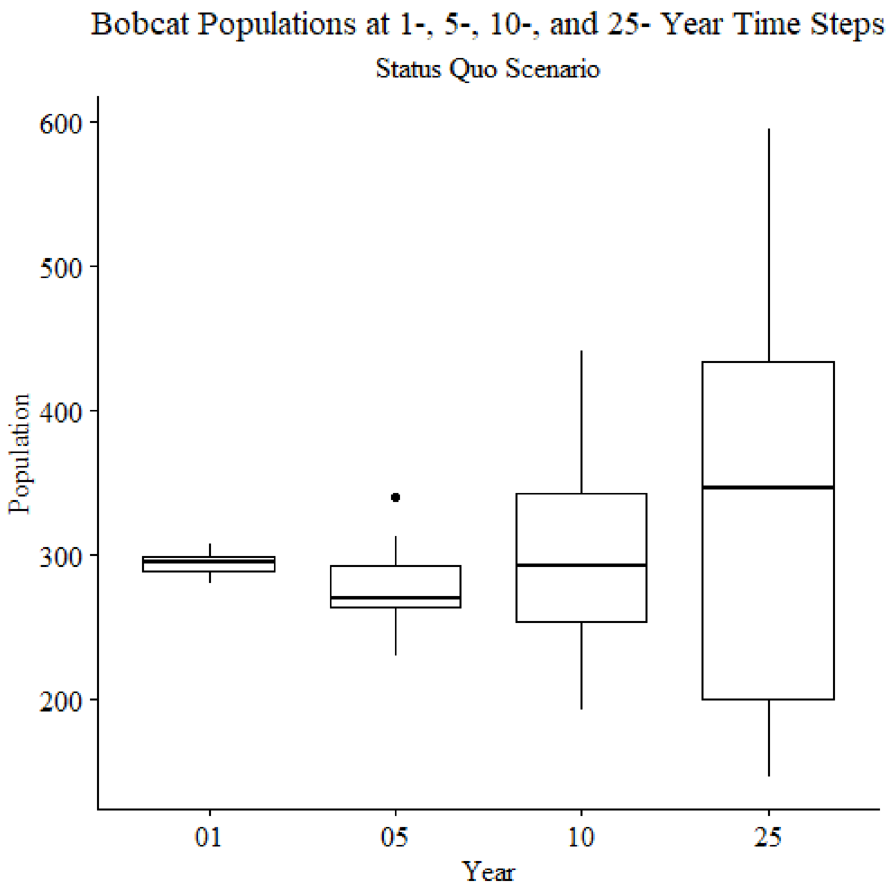


Figure 18 Boxplot depicting simulated bobcat populations in New Jersey, USA at 1-, 5-, 10-, and 25- year time steps from 10 runs of the status quo scenario (i.e. natural recolonization) using the spatially explicit agent-based model (SEABM). Bobcat populations were not significantly different between any time interval under this scenario, suggesting that the population is expected to be maintained over the course of 25 years.

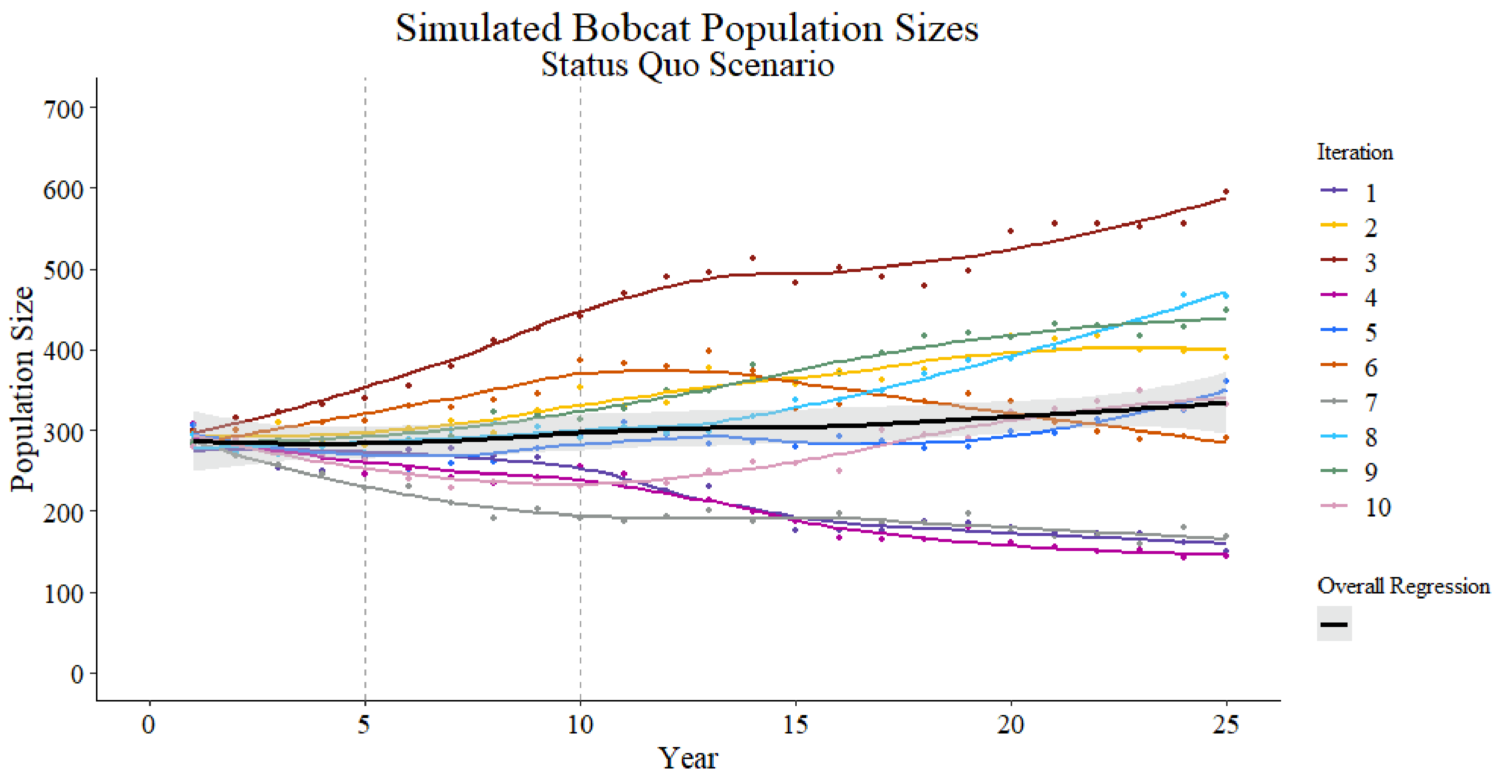


Figure 19 The loess regression for simulated bobcat population sizes under the status quo (i.e. natural recolonization) scenario using the spatially explicit agent-based model (SEABM) indicates that bobcat populations should remain stable for the next 25 years in New Jersey, USA. Each iteration is represented by a different color and the gray region surrounding the overall regression line represents a 95% confidence interval.

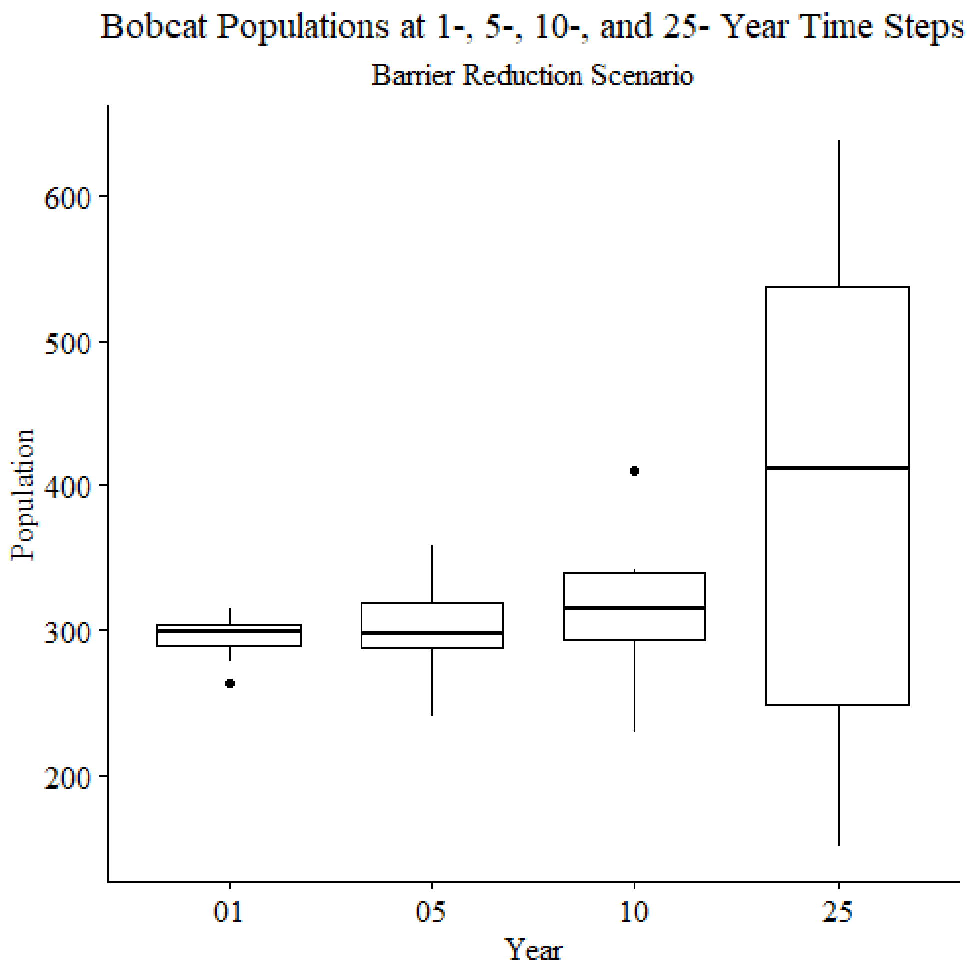


Figure 20 Boxplot depicting simulated bobcat populations in New Jersey, USA at 1-, 5-, 10-, and 25- year time steps from 10 runs of the barrier reduction scenario (i.e. increased connectivity through barrier mitigation) using the spatially explicit agent-based model (SEABM). Bobcat populations were not significantly different between any time interval under this scenario, suggesting that the population is expected to be maintained over the course of 25 years.

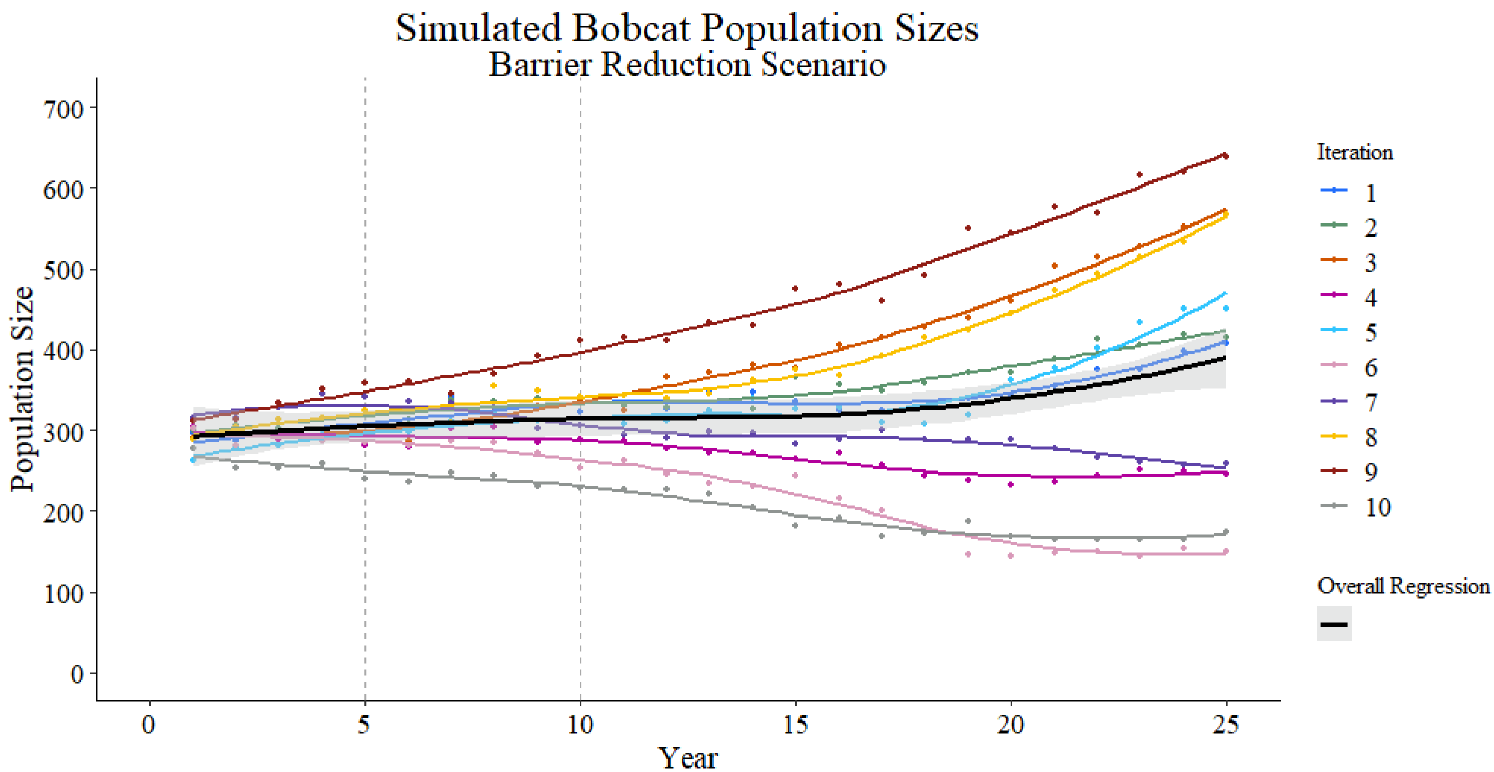


Figure 21 The loess regression for simulated bobcat population sizes under the barrier reduction (i.e. improved connectivity through barrier mitigation) scenario using the spatially explicit agent-based model (SEABM) indicates that bobcat populations should remain stable for the next 25 years in New Jersey, USA. Each iteration is represented by a different color and the gray region surrounding the overall regression line represents a 95% confidence interval.

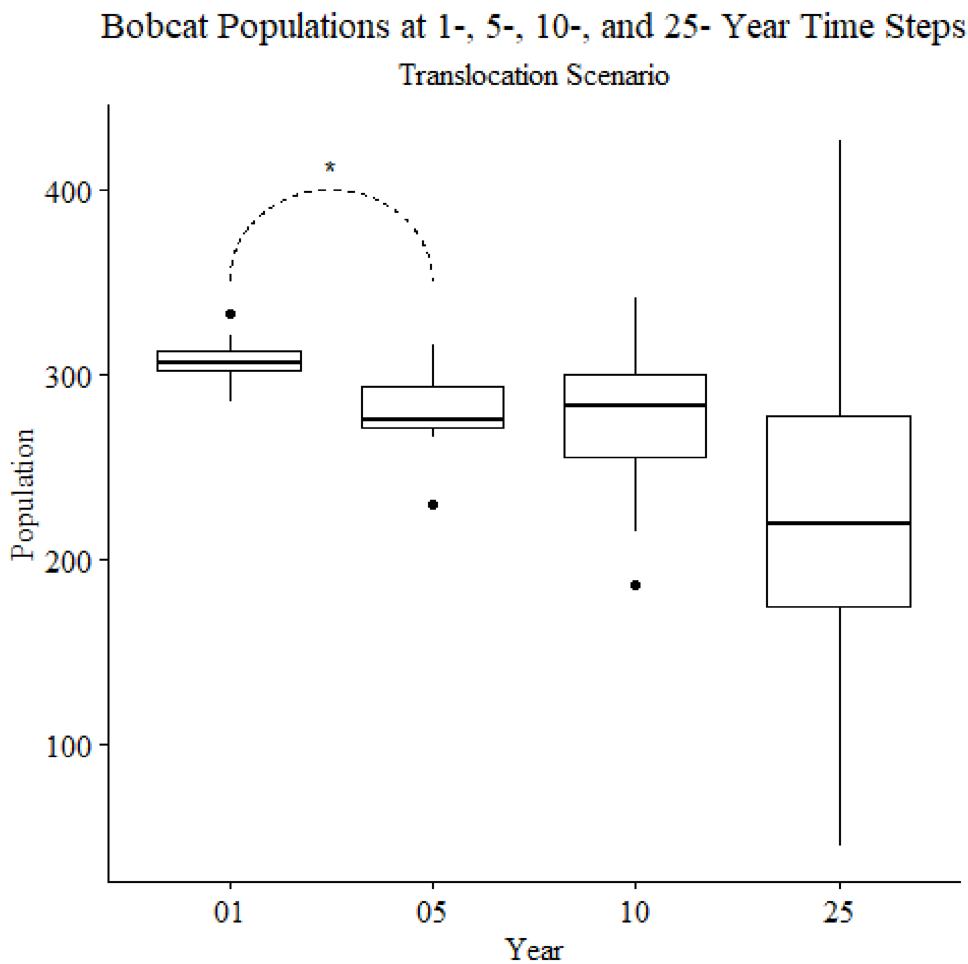


Figure 22 Boxplot depicting simulated bobcat populations in New Jersey, USA at 1-, 5-, 10-, and 25- year time steps from 10 runs of the single translocation scenario (i.e. 20 bobcats translocated into southern New Jersey) using the spatially explicit agent-based model (SEABM). This scenario showed a significant difference ($p = 0.039$; denoted by asterisk) in bobcat population size between year 1 and 5, suggesting that bobcat populations decrease during the first five years and then stabilized.

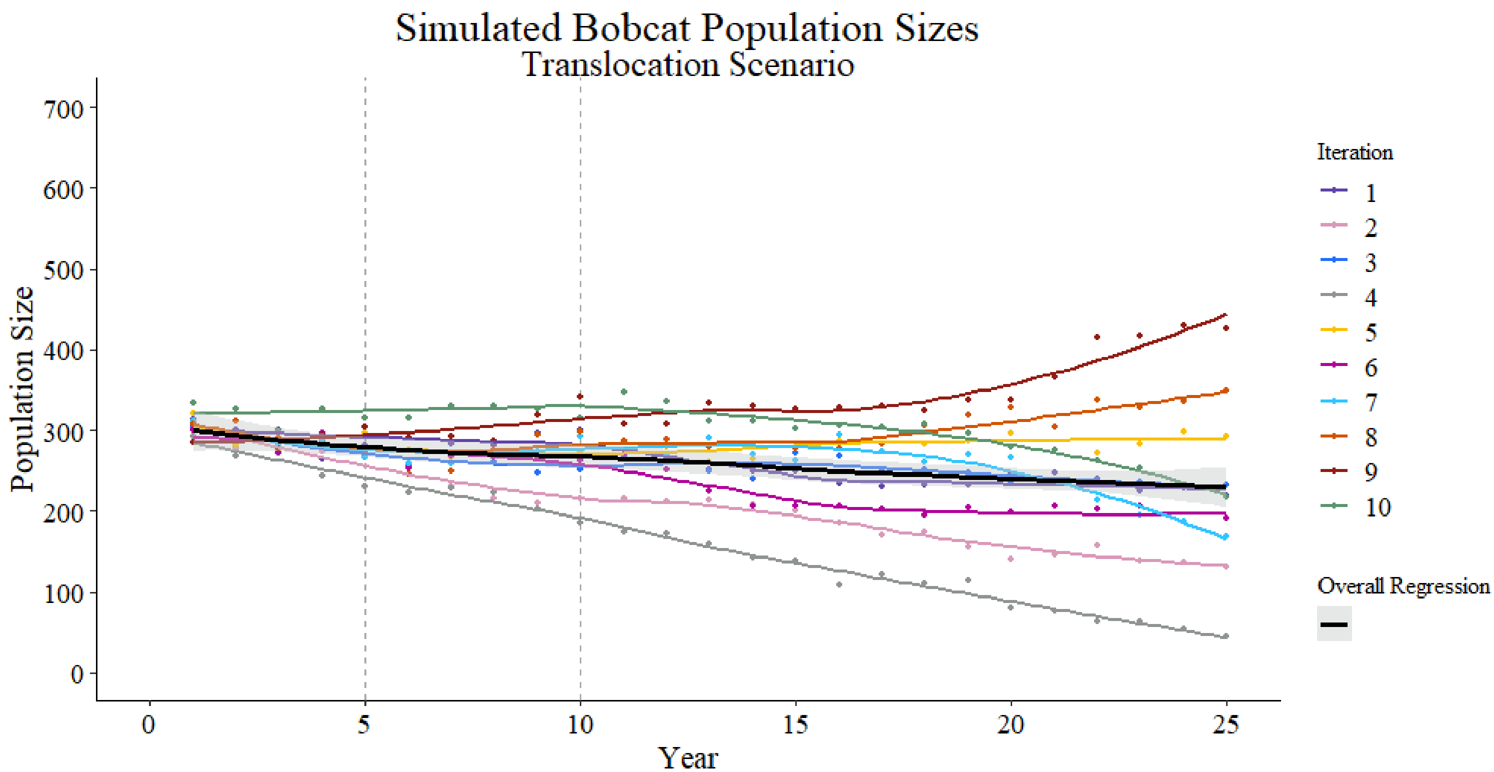
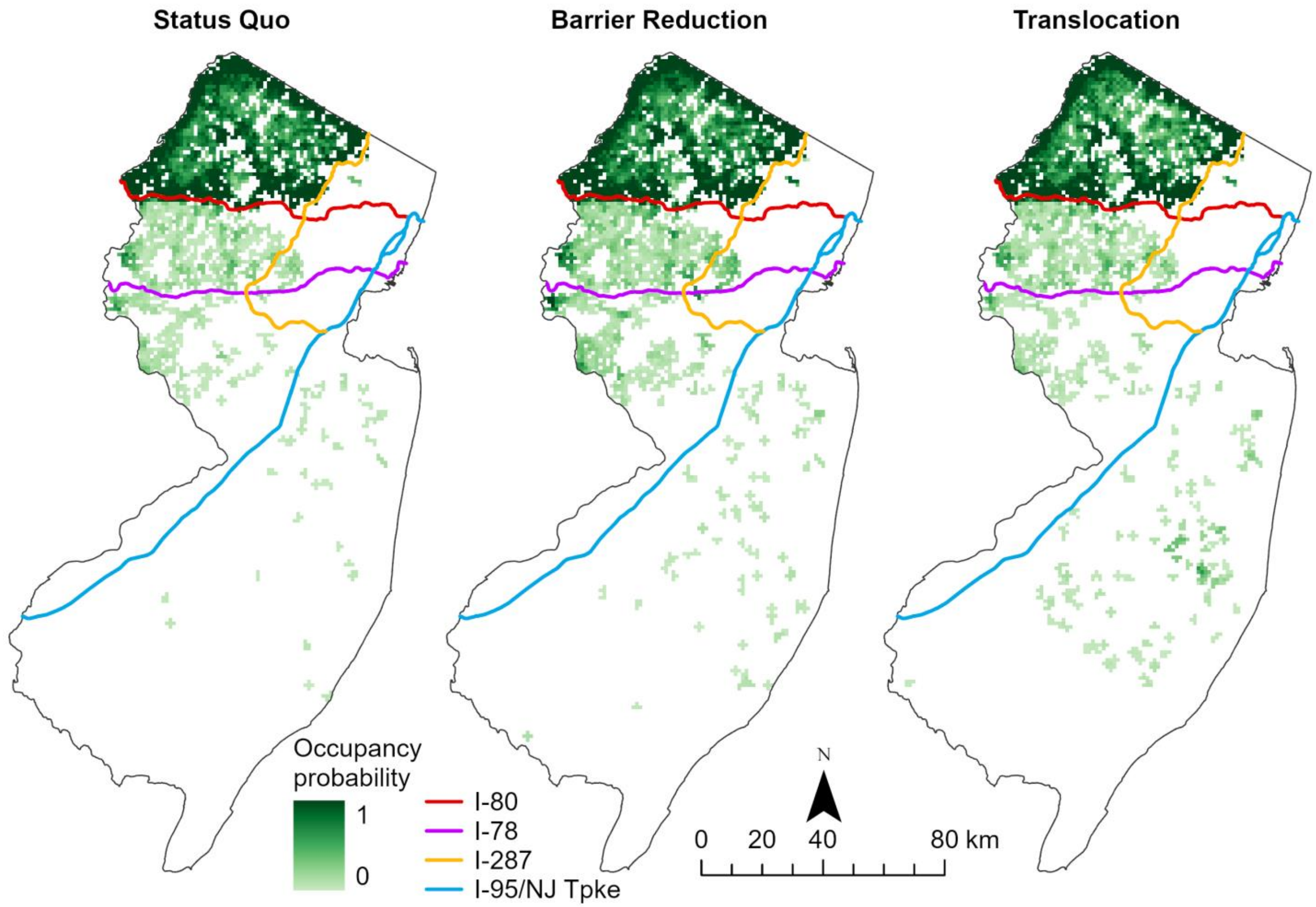


Figure 23 The loess regression for simulated bobcat population sizes under the translocation scenario (i.e. 20 bobcats translocated into southern New Jersey) using the spatially explicit agent-based model (SEABM) indicates that bobcat populations decrease slightly over the next 25 years in New Jersey, USA. Each iteration is represented by a different color and the gray region surrounding the overall regression line represents a 95% confidence interval.



Status Quo
Barrier Reduction
Translocation
Occupancy probability
1
0
I-80
I-78
I-287
I-95/NJ Tpke
N
0
20
40
80 km

Figure 24 Maps depicting the probability that a cell will be occupied by bobcats over the course of 25 years and for all 10 simulations within each of three management scenarios in New Jersey, USA. The three management scenarios were as follows: status quo (i.e. natural recolonization), barrier reduction (i.e. increased connectivity and reduced road crossing mortality through barrier mitigation, and translocation (i.e. 20 bobcats translocated into southern New Jersey). Probabilities were calculated for each year and all simulations from bobcat distribution territory maps resulting from the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA. Major interstates a superimposed on the map, revealing a high probability of occupancy north of I-80 for all scenarios.

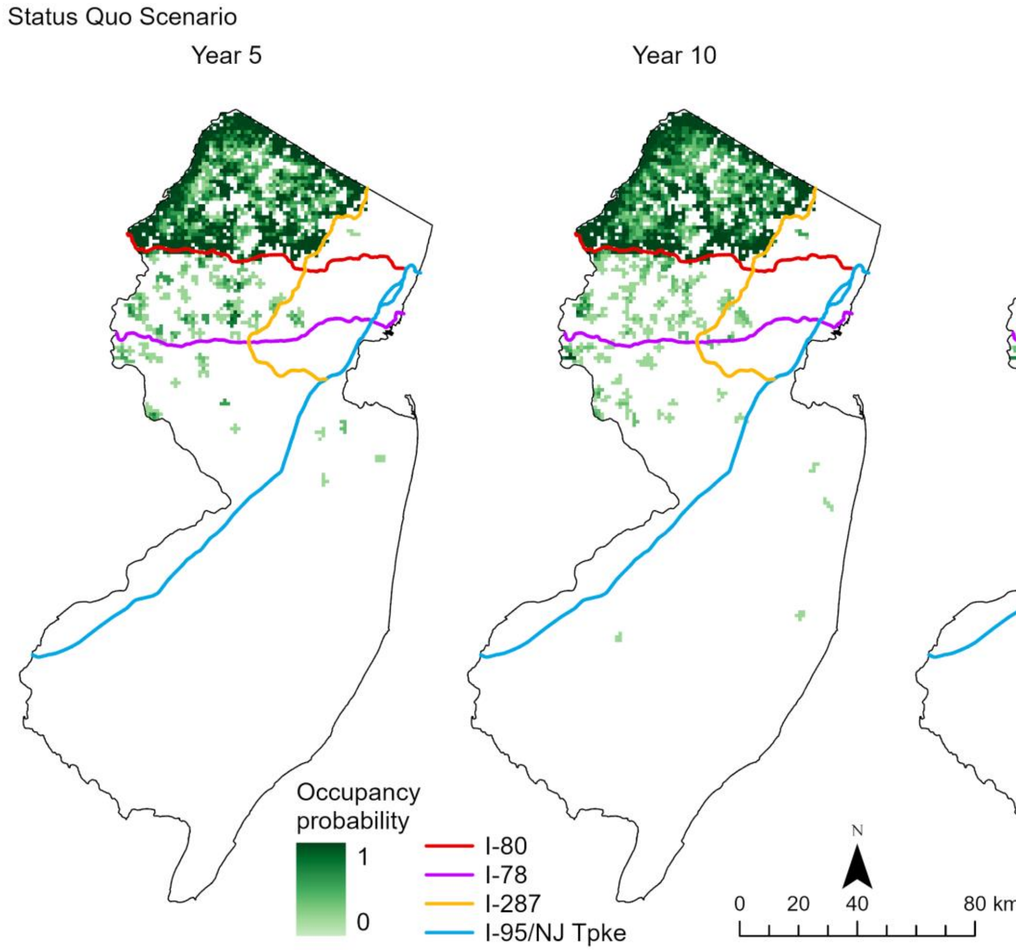

Status Quo Scenario
Year 5
Year 10
Year 25
Occupancy probability
1
0
I-80
I-78
I-287
I-95/NJ Tpke
N
0
20
40
80 km

Figure 25 Maps depicting the probability that a cell will be occupied by bobcats at years 5, 10, and 25 in New Jersey, USA under the status quo scenario (i.e. natural recolonization) evaluated using the spatially explicit agent-based model (SEABM). The simulations (N=10) for this scenario suggest that bobcats remain largely concentrated in northern New Jersey north of I-80 with occasional transient bobcat presence in central and southern New Jersey in years 10 and 25.

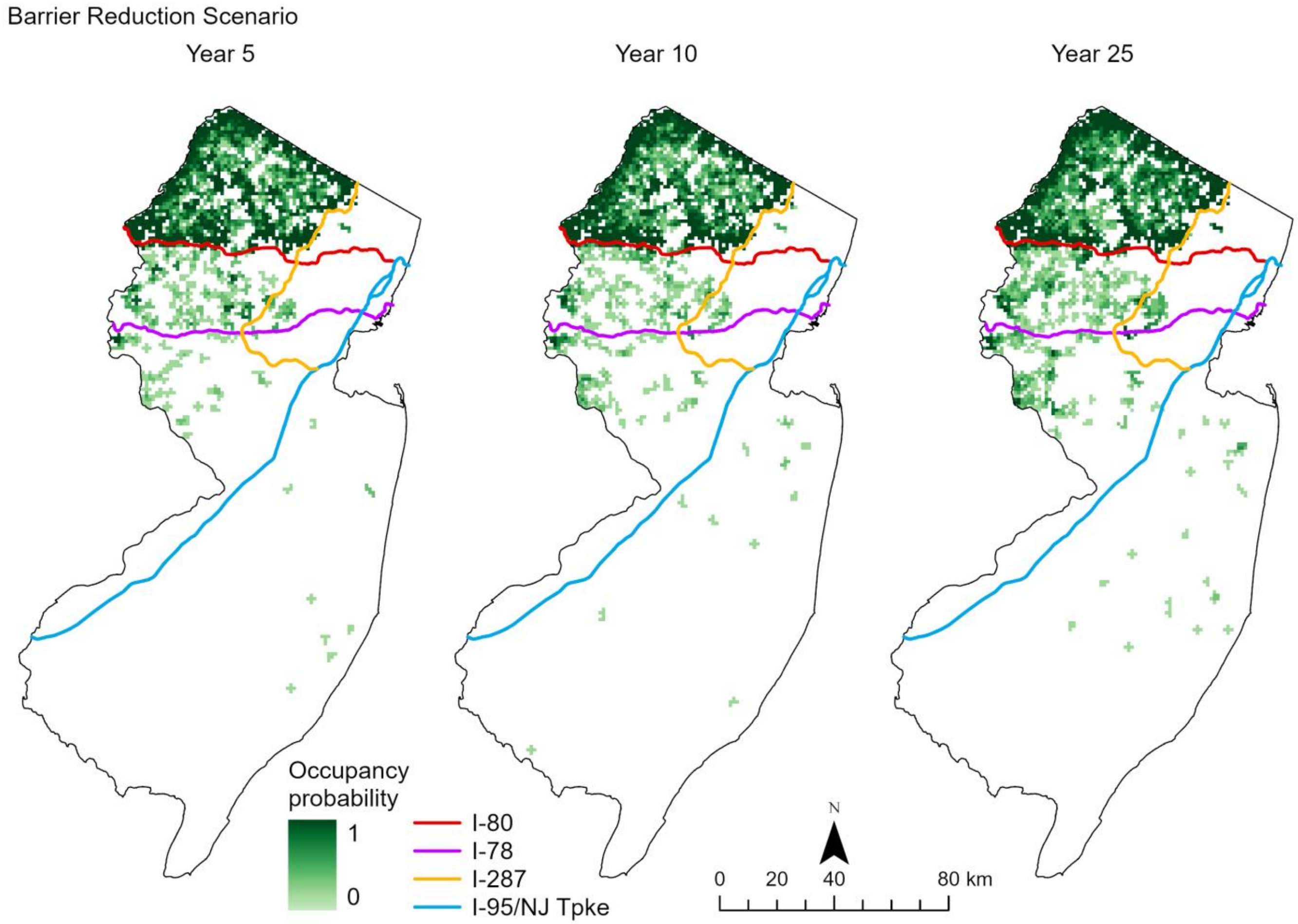

Barrier Reduction Scenario
Year 5
Year 10
Year 25
Occupancy probability
1
0
I-80
I-78
I-287
I-95/NJ Tpke
N
0
20
40
80 km

Figure 26 Maps depicting the probability that a cell will be occupied by bobcats at years 5, 10, and 25 in New Jersey, USA under the barrier reduction scenario (i.e. improved connectivity and reduced mortality due to barrier mitigation) evaluated using the spatially explicit agent-based model (SEABM). The probabilities resulting from the barrier reduction simulations (N=10) suggest that bobcats remain largely concentrated in northern New Jersey north of I-80, but with greater presence in the region between I-80 and I-78 and occasional transient bobcat presence south of I-95 in southern New Jersey during years 10 and 25.

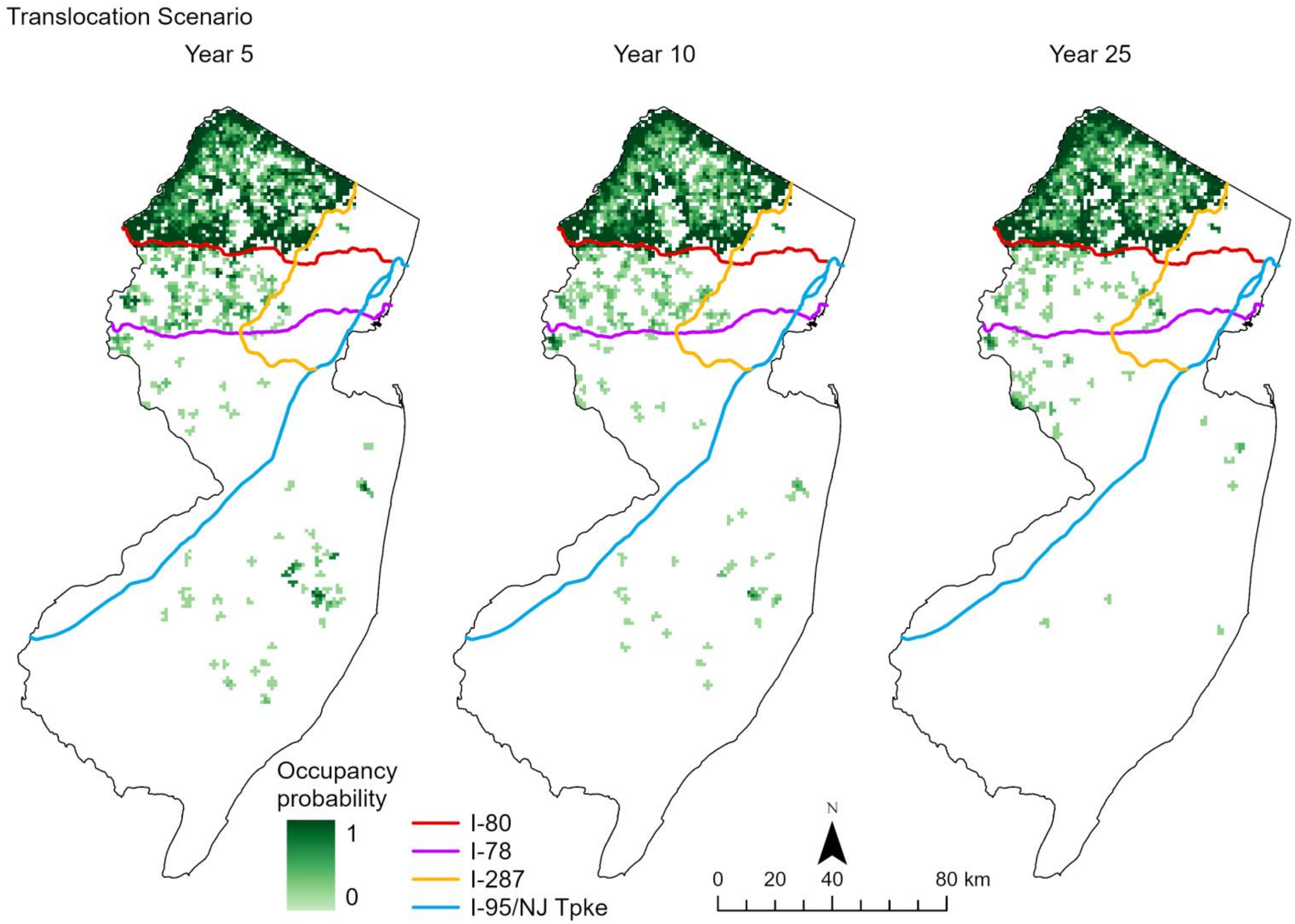

Translocation Scenario
Year 5
Year 10
Year 25
Occupancy probability
1
0
I-80
I-78
I-287
I-95/NJ Tpke
N
0
20
40
80 km

Figure 27 Maps depicting the probability that a cell will be occupied by bobcats at years 5, 10, and 25 in New Jersey, USA under the translocation scenario (i.e. 20 bobcats translocated into southern New Jersey) evaluated using the spatially explicit agent-based model (SEABM). Probability of occurrence across translocation simulations (N=10) suggest that bobcats remain largely concentrated in northern New Jersey north of I-80. However, the translocated population appears to maintain territories south of I-95 through year 5 but these become scarcer by year 10 and have largely disappeared from southern New Jersey after 25 years.

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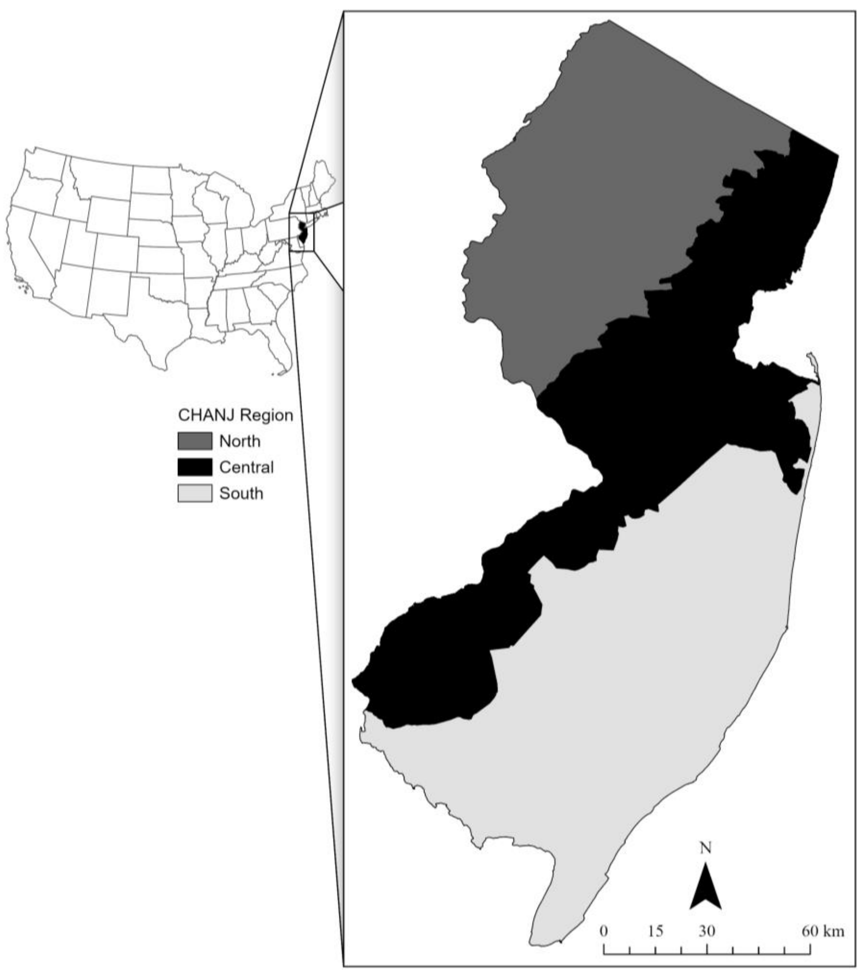
Appendix A

REGIONS OF NEW JERSEY

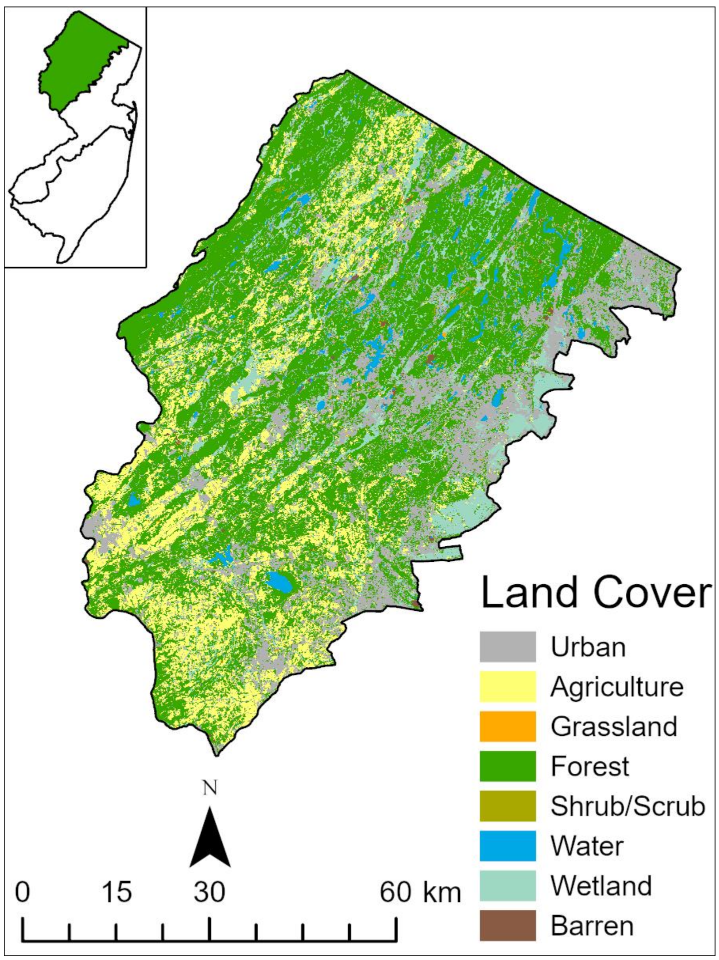
Description: Three ecologically distinct regions in New Jersey, USA as defined in this study. The northern and southern regions are the same as delineated by the Connecting Habitat Across New Jersey effort (CHANJ, New Jersey Division of Fish and Wildlife 2019), whereas the southern region combines three patches identified by CHANJ into one.



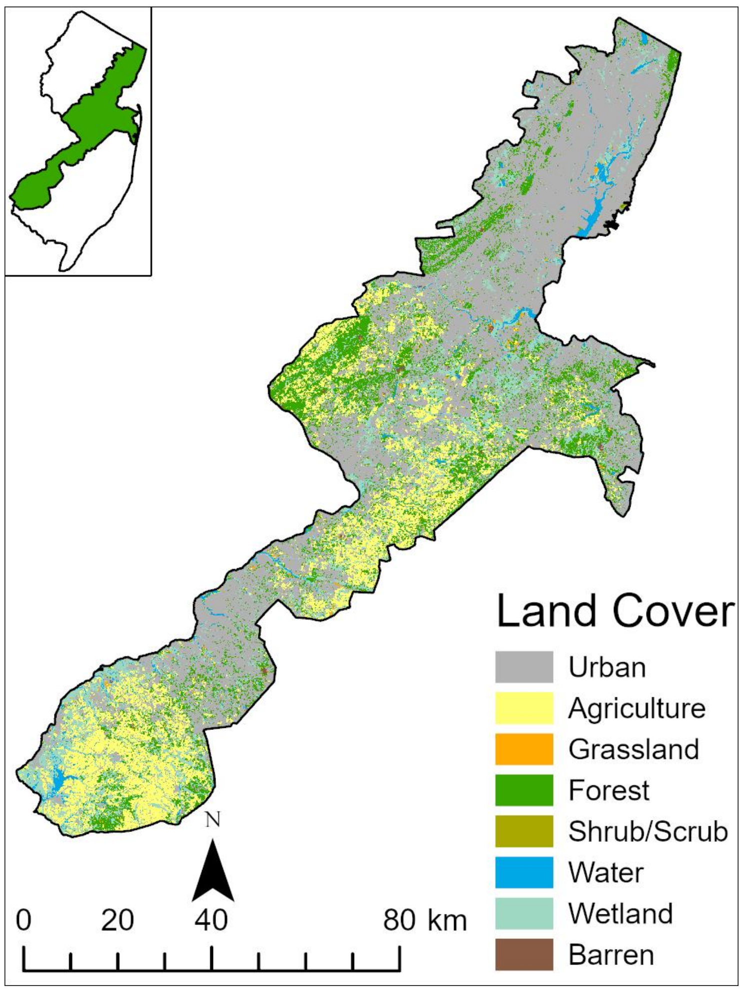
Appendix B

LAND COVER BY REGION

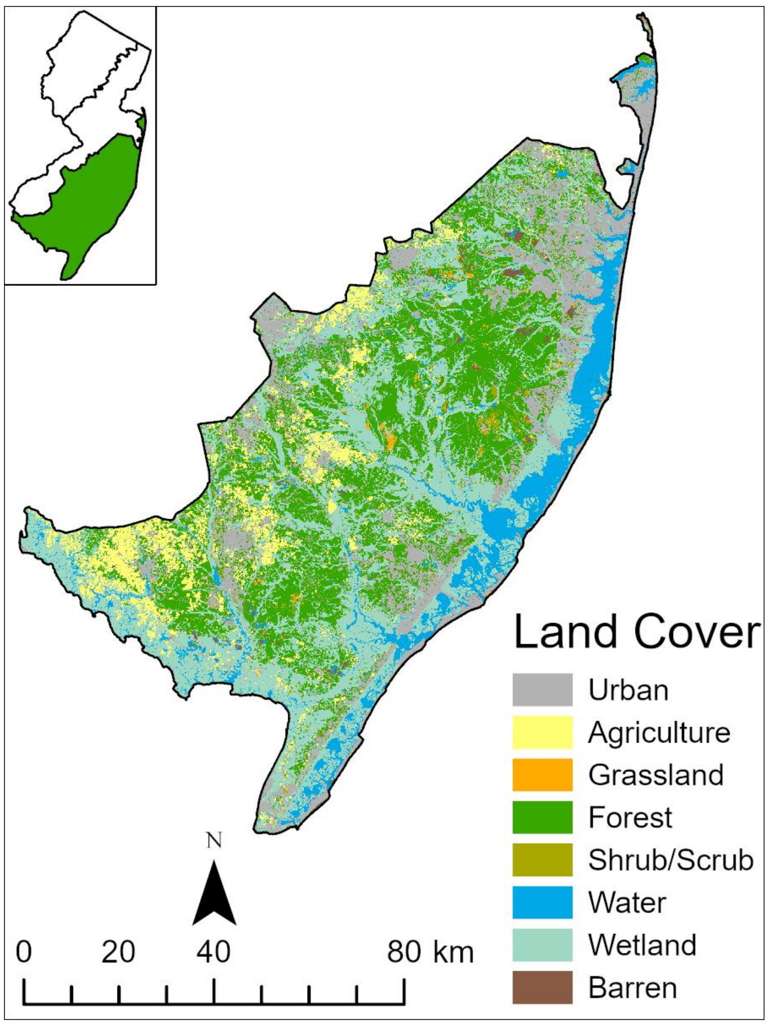
Description: The northern region in New Jersey, USA identified by the Connecting Habitat Across New Jersey initiative, showing eight land cover types from the 2016 National Land Cover Database (USGS).



Description: The central region in New Jersey, USA identified by the Connecting Habitat Across New Jersey initiative, showing eight land cover types from the 2016 National Land Cover Database (USGS).



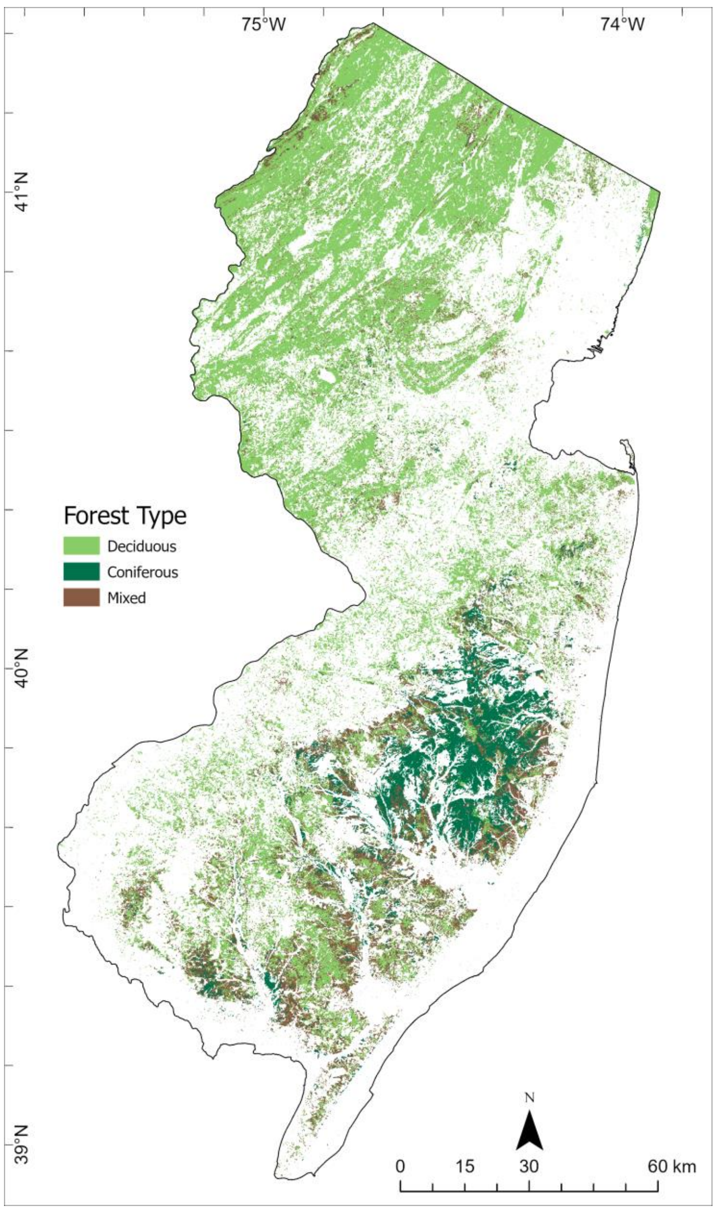
Description: The southern region in New Jersey, USA identified in this study, showing eight land cover types from the 2016 National Land Cover Database (USGS). This region is a combination of the three southern regions identified by the Connecting Habitat Across New Jersey initiative.



Appendix C

DISTRIBUTION OF FOREST TYPES IN NEW JERSEY

Description: The distribution of forest types throughout New Jersey, USA showing the cover types of deciduous, coniferous, and mixed forests from the 2016 National Land Cover Database (USGS). Non-forested area is left blank.



Appendix D

HABITAT COVARIATES THAT AFFECT BOBCAT PRESENCE

Description: Habitat covariates reported in the literature that affect bobcat presences in the northeast US and Mississippi These relationships between bobcats and their habitat was used to inform the development of the Habitat Suitability Index for New Jersey Bobcats (HSINJB).

Positively Associated Covariates	Negatively Associated Covariates	State(s)	Source
• Dense stands (>36,000 stem cover unites/ha) • Flat areas (<2° slope)	• Spare understories (<12,000 stem cover units/ha) • Steep areas (>5° slope)	ME	Litvaitis et al. 1986
• Hardwood-dominated mixed forest • Softwood-dominated mixed forest • Clear cut • Softwood (summer, fall, winter) • Ericaceous wetland (fall, spring)	• Hardwood • Softwood (spring) • Ericaceous wetland (summer, winter)	ME	Major and Sherburne 1987
• Ecotone/edge density • Undeveloped habitat • Water within 300 m • Cover within 300 m • Cover edge 300 m margin	-	ME, NH, VT	Farrell et al. 2018[a]
• Beech/oak forest • Total forest	• Slope • Snow	NH	Litvaitis et al. 2006

Appendix D continued

Positively Associated Covariates	Negatively Associated Covariates	State(s)	Source
• Shrub/scrub • Wetlands • South aspect • Vector ruggedness measurement • Slope	• Developed • Open water • Flat aspect • Distance to forest edge • Road density • Distance to stream • Snow depth	NH	Reed 2013; Reed et al. 2017a
• Stream density • Ruggedness • Wetland • Scrubland • Forest • Slope	• Road density • Elevation • Snow • Development • NW aspect	NH	Broman et al. 2014
• Shrub • Deciduous forest • Wetland • Coniferous forest	• Mixed forest • Road density (1st and 2nd class) • Road density (3rd class)	VT	Donovan et al. 2011
• Forest • Scrub/rock • Forest edge • Wetland edge • Stream density	• Development • Agriculture • Deep forest core • Road densities	VT	Abouelezz et al. 2018[b]

Appendix D continued

Positively Associated Covariates	Negatively Associated Covariates	State(s)	Source
• Stands with conifer component (winter) • Deer densities	• Elevation, • Road density	NY	Fox 1990
• Road • Cliff • Spruce plantation • Hemlock hardwood forest	• Hardwood • Exposed shore • Abandoned field • Pine • Pine-hardwood • Reservoir ice cover	MA (winter only)	McCord 1974
• Broadleaf deciduous forest	• Perennial herbaceous (F both seasons, M winter) • Annual herbaceous (F both seasons, M summer) • Unvegetated (F both seasons, M winter) • Conifer forest (M summer) • Mixed forest (M winter)	PA	Lovallo 1999
• Diversity index of agriculture wetlands, and forest • Wetlands • Distance to wetlands	• Urban • Forested land	NJ	Valent 2013
• Pine plantations • Agricultural areas	• Mature pine stands • Bottomland hardwoods (F)	MS	Conner et al 1992
• Pine (HR vs study area) • Pine sapling (HR vs study area & HR vs HR)	• Agriculture (HR vs study area) • Hardwood (HR vs study area)	MS	Conner and Leopold 1996[c]

Appendix D continued

Positively Associated Covariates	Negatively Associated Covariates	State(s)	Source
• Slope class • Distance to mature pine stand	• Distance to sapling stand • Distance to paved road • Distance to maintenance road • Distance to creek • Distance to hardwood stand • Stand type	MS	Conner and Leopold 1998
• Pine plantations • Agriculture	• Hardwoods	MS	Conner and Leopold 1999[d]
• Mature pine (≥30 years old) • Pine (16-29 years old) • Pine (9-15 years old) • Pine (≤8 years old)	-	MS	Chamberlain et al. 2003

[a] Examined connective habitat

[b] Examined movement habitat; compositional ranking analyses

[c] HR vs study area indicates analyses that considered habitat composition of the home range to availability of the entire study area, where as HR vs HR compared habitat use within the home range to the overall habitat composition of the home range

[d] Examined use within core use areas (regions of high use)

Appendix E

PROTECT AREA AND CENTRALITY METRICS FOR HABITAT PATCHES

Description: Protected area and centrality metrics for each core and stepping stone habitat patch for bobcats in New Jersey, USA. Protected area was calculated from the Protected Areas Database of the United States (USGS 2019) and State, Local and Nonprofit Open Space of New Jersey (NJDEP 2020). The current flow centrality reveals the relative importance of a given patch to the overall connectivity network. The area-corrected current centrality shows the relative importance of a given patch when removing the effect of area.

Patch	Area (km^2)	Protected area (km^2)	Percent Protected	Current flow centrality (Amps)	Area-corrected current centrality (Amps/km^2)
15a	1.00	0.05	5.02	207.07	208.05
7a	1.58	0.29	18.28	230.04	145.95
6a	1.62	0.00	0.00	235.02	144.96
31e	1.39	0.29	20.83	201.68	144.83
23a	1.29	1.23	94.95	182.60	141.28
5b	1.55	0.00	0.00	171.70	110.77
29d	10.83	6.18	57.09	1131.27	104.47
31f	1.05	0.28	26.50	108.32	102.88
28e	1.87	1.63	87.32	168.35	90.03
26a	1.15	0.04	3.52	100.97	87.64
31a	1.42	0.00	0.00	112.97	79.28
11a	1.40	0.02	1.41	106.70	76.14
4a	1.55	1.06	68.37	115.31	74.30
24a	6.79	6.01	88.47	458.63	67.50
31d	4.25	0.81	19.04	246.06	57.95
31c	21.63	17.36	80.29	1217.72	56.31
32d	3.59	2.65	73.91	201.38	56.13
28f	2.66	1.40	52.78	134.24	50.52
5a	1.60	1.60	100.00	72.00	44.88
34a	3.63	1.99	54.97	160.23	44.16

Appendix E continued

Patch	Area (km^2)	Protected area (km^2)	Percent Protected	Current flow centrality (Amps)	Area-corrected current centrality (Amps/km^2)
29a	1.75	1.49	85.14	74.54	42.68
34b	2.56	2.34	91.30	101.15	39.54
31b	8.02	2.46	30.65	312.23	38.94
34c	2.37	2.21	93.23	91.11	38.42
21a	6.74	5.99	88.85	246.87	36.60
29b	2.12	0.00	0.00	74.71	35.28
18a	12.69	0.65	5.12	387.25	30.52
32b	5.54	5.28	95.18	157.51	28.42
33a	3.27	3.27	100.00	80.47	24.60
14a	24.42	12.32	50.46	555.96	22.76
32a	9.26	3.03	32.73	208.01	22.47
28c	3.29	1.06	32.12	72.00	21.90
29c	3.51	2.18	62.14	72.00	20.52
32c	8.79	7.40	84.18	171.68	19.53
28d	10.52	7.03	66.86	192.45	18.30
28b	25.75	7.60	29.51	418.84	16.27
27a	18.14	2.98	16.42	287.33	15.84
16	27.88	8.00	28.71	426.41	15.30
33b	7.84	6.98	89.02	96.17	12.27
14	62.05	17.39	28.03	752.34	12.13
23	51.75	19.01	36.74	605.79	11.71
28	31.56	10.07	31.91	366.70	11.62
12	73.05	22.89	31.33	817.16	11.19
21	59.08	28.59	48.40	655.92	11.10
28a	6.89	0.14	2.06	72.00	10.45
19	131.69	50.01	37.97	978.43	7.43
20	52.60	15.90	30.22	370.99	7.05
26	28.06	18.92	67.41	183.69	6.55
22	183.46	128.27	69.92	1152.55	6.28
10	47.27	12.04	25.47	291.25	6.16
32	88.09	53.25	60.45	517.97	5.88
33	35.16	34.09	96.94	203.31	5.78
17	74.71	15.32	20.50	419.18	5.61
13	59.12	12.56	21.25	319.43	5.40
9	160.74	52.06	32.39	857.37	5.33

Appendix E continued

Patch	Area (km^2)	Protected area (km^2)	Percent Protected	Current flow centrality (Amps)	Area-corrected current centrality (Amps/km^2)
11	66.00	25.13	38.08	329.92	5.00
15	232.12	65.69	28.30	1127.01	4.86
18	78.65	16.43	20.89	373.21	4.75
8	175.80	58.40	33.22	795.77	4.53
27	103.18	17.93	17.38	450.60	4.37
31	336.22	136.59	40.62	1401.87	4.17
6	71.66	15.91	22.20	270.84	3.78
1	52.80	17.46	33.06	190.90	3.62
34	203.42	122.12	60.03	634.10	3.12
2	61.72	30.17	48.88	191.02	3.09
30	37.30	9.65	25.88	114.13	3.06
24	385.64	292.37	75.82	1154.23	2.99
29	972.60	607.48	62.46	1525.98	1.57
3	260.48	124.94	47.97	388.84	1.49
25	113.91	83.17	73.02	139.22	1.22
5	444.04	251.92	56.73	511.42	1.15
7	295.97	138.09	46.65	309.55	1.05
4	406.17	199.75	49.18	195.39	0.48

Appendix F

CONNECTIVITY METRICS BETWEEN EVERY PAIR OF CORE HABITAT PATCHES

Description: Connectivity metrics between every pair of core habitat patches for bobcats in New Jersey, USA. Euclidean distance (EucD) is the shortest straight-line path between each patch while cost-weighted distances (CWD) incorporated landscape resistance developed from the Habitat Suitability Index for New Jersey Bobcats (HSINJB) and is representative of total travel cost. Least-cost path (LCP) is the shortest path of least resistance between two patches. The ratio of CWD:EucD represents resistance to movement controlled for linear distance while the ratio of CWD:LCD represents the average resistance along an ideal path. The current flow centrality reveals the relative importance of a given link between two patches to the overall connectivity network. Links are presented in descending order on the basis of this centrality, since higher amperage indicates greater importance to the overall network.

From Core	To Core	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
24	29	0.03	3.42	0.06	117.80	56.94	794.53
8	9	0.03	4.46	0.07	153.86	61.97	765.52
22	24	0.03	4.05	0.06	139.62	67.48	709.70
12	15	0.03	3.93	0.06	135.60	65.54	636.43
21	22	4.12	189.41	4.51	45.95	41.97	612.07
31	34	0.03	3.57	0.06	123.20	59.55	541.23
9	12	0.03	3.53	0.06	121.72	58.83	511.07
23	29	0.03	3.79	0.06	130.73	63.18	471.88
14	15	0.03	3.91	0.06	134.84	65.17	448.27
15	16	0.03	3.99	0.06	137.43	66.43	399.36
27	31	0.03	3.98	0.06	137.16	66.30	390.92
5	8	0.03	3.81	0.06	131.44	63.53	367.25
16	17	0.59	33.94	0.73	57.23	46.43	367.05
3	5	0.03	3.54	0.06	122.14	59.03	363.43

Appendix E continued

From Core	To Core	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
19	20	0.03	3.94	0.06	135.82	65.65	359.27
19	21	23.21	1379.97	25.61	59.46	53.88	337.52
19	22	29.68	1726.81	31.89	58.18	54.15	329.01
18	20	7.00	358.13	7.68	51.14	46.65	310.71
9	13	0.03	4.08	0.06	140.80	68.06	266.47
11	14	0.03	3.88	0.06	133.70	64.62	265.29
23	24	0.03	4.70	0.06	162.12	78.36	258.97
6	8	0.03	3.77	0.06	129.95	62.81	255.73
12	13	0.03	3.83	0.06	132.17	63.88	250.16
19	23	40.03	2336.11	44.26	58.37	52.79	244.79
10	11	0.03	3.89	0.06	134.25	64.89	236.93
32	34	5.02	325.02	6.73	64.71	48.31	198.11
15	19	18.51	1029.00	20.75	55.60	49.59	179.87
1	3	0.03	3.50	0.06	120.57	58.27	170.15
31	33	0.03	3.79	0.06	130.73	63.19	167.92
4	7	0.03	3.55	0.06	122.47	59.19	167.57
3	7	0.03	4.04	0.06	139.46	67.41	163.50
17	18	9.69	506.55	10.37	52.30	48.86	162.97
10	15	0.03	3.82	0.06	131.88	63.74	160.45
14	19	22.77	1246.23	24.77	54.72	50.32	147.63
1	2	0.03	4.03	0.06	138.92	67.15	139.65
26	27	0.03	4.11	0.06	141.86	68.57	135.65
25	29	0.03	3.88	0.06	133.65	64.60	133.35
31	32	7.60	490.68	9.23	64.60	53.17	132.70
28	32	17.27	1011.17	18.39	58.57	54.99	120.14
9	10	1.09	47.85	1.21	44.02	39.61	99.68
2	4	0.03	3.98	0.06	137.33	66.37	77.20
25	26	6.68	326.68	6.93	48.90	47.17	68.59
29	30	11.73	610.26	13.48	52.03	45.29	35.98
13	17	9.14	474.88	10.31	51.97	46.06	35.83
30	31	2.07	398.20	8.05	192.37	49.48	26.77
30	33	0.09	416.18	8.05	4427.45	51.70	26.62
7	11	12.09	593.75	13.45	49.11	44.14	19.86

Appendix E continued

From Core	To Core	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
33	34	2.58	129.26	2.86	50.08	45.18	17.32
13	16	6.65	340.99	7.33	51.25	46.52	14.42
10	12	4.61	225.76	4.97	49.03	45.41	13.45
2	3	2.59	116.45	2.77	44.94	42.11	8.59
26	31	4.63	231.92	5.03	50.10	46.07	7.88
5	6	2.58	141.18	2.94	54.78	47.97	7.81

Appendix G

CONNECTIVITY METRICS BETWEEN EVERY PAIR OF CORE AND STEPPING STONE HABITAT PATCHES

Description: Connectivity metrics between every pair of core and stepping stone (SS) habitat patches for bobcats in New Jersey, USA. Euclidean distance (EucD) is the shortest straight-line path between each patch while cost-weighted distances (CWD) incorporated landscape resistance developed from the Habitat Suitability Index for New Jersey Bobcats (HSINJB) and is representative of total travel cost. Least-cost path (LCP) is the shortest path of least resistance between two patches. The ratio of CWD:EucD represents resistance to movement controlled for linear distance while the ratio of CWD:LCD represents the average resistance along an ideal path. The current flow centrality reveals the relative importance of a given link between two patches to the overall connectivity network. Links are presented in descending order on the basis of this centrality, since higher amperage indicates greater importance to the overall network.

From Core	To SS	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
29	29d	0.03	5.04	0.07	173.70	69.96	1096.81
31	31c	0.03	4.53	0.06	156.08	75.44	961.61
14	14a	0.08	11.85	0.16	141.04	75.46	533.73
22	24a	0.06	3.89	0.09	64.80	43.20	415.97
24	24a	0.03	3.92	0.06	135.09	65.29	369.89
28	28b	0.03	4.19	0.06	144.53	69.86	279.89
27	27a	4.73	237.77	4.89	50.23	48.65	239.21
31	31b	0.03	4.02	0.06	138.70	67.04	236.49
21	14a	50.80	2937.36	57.42	57.83	51.15	213.36
6	6a	0.11	6.81	0.16	63.02	43.35	206.13
18	18a	0.03	3.95	0.06	136.11	65.79	200.73
17	18a	8.20	409.10	8.69	49.88	47.07	200.51
7	7a	0.03	4.80	0.07	165.42	66.63	196.17
15	15a	0.03	4.01	0.06	138.20	66.80	190.93
28	27a	12.12	693.10	12.77	57.17	54.26	189.38
19	18a	10.55	653.69	11.32	61.98	57.73	172.43
22	21a	17.73	847.89	19.86	47.81	42.69	166.35
32	32a	2.33	117.85	2.53	50.49	46.68	153.91

Table F continued

From Core	To SS	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
34	34a	0.03	4.04	0.06	139.46	67.41	151.86
12	15a	0.30	14.04	0.34	47.59	41.41	151.22
5	5b	0.03	4.18	0.06	144.15	69.67	140.35
8	5b	0.15	8.74	0.20	58.28	42.85	131.06
15	18a	14.11	719.96	15.44	51.03	46.64	128.83
34	32d	9.84	573.59	11.92	58.31	48.11	123.39
29	23a	0.24	13.91	0.28	58.21	49.33	123.29
32	28b	15.26	1016.52	17.36	66.61	58.56	120.08
31	32a	8.26	500.86	9.79	60.63	51.18	116.04
19	14a	28.11	1568.89	30.15	55.82	52.04	114.33
23	23a	0.03	4.10	0.06	141.35	68.32	104.56
31	31f	0.03	4.00	0.06	137.89	66.65	96.47
32	32b	7.08	368.39	8.10	52.05	45.49	95.03
2	4a	0.03	2.27	0.06	75.74	37.87	84.61
34	34b	2.12	95.04	2.18	44.81	43.58	81.37
21	21a	9.13	432.54	10.06	47.38	43.02	76.89
33	33a	0.03	2.61	0.07	89.89	36.21	74.50
32	32c	4.58	245.94	5.67	53.66	43.37	74.36
4	4a	0.03	4.07	0.06	140.26	67.79	74.01
29	29b	0.03	4.64	0.06	160.07	77.37	72.91
29	31e	4.68	230.56	5.20	49.31	44.36	72.66
5	5a	0.03	1.06	0.04	35.34	25.25	72.00
28	28a	0.21	10.15	0.24	48.58	42.31	72.00
29	29c	0.12	11.88	0.19	96.58	61.87	72.00
32	32d	5.50	263.19	6.06	47.86	43.44	69.60
29	31b	6.58	306.60	7.28	46.58	42.14	67.50
26	26a	0.03	5.51	0.07	189.93	76.50	66.52
11	11a	0.03	4.92	0.07	169.76	68.37	65.75
24	23a	0.53	23.65	0.59	44.30	39.89	65.35
27	26a	0.06	9.51	0.22	161.21	43.83	63.41
34	34c	2.52	145.02	3.29	57.52	44.12	61.27
23	24a	0.97	44.11	1.10	45.62	40.10	59.39
31	31a	0.39	18.70	0.46	47.95	40.92	53.69
29	29a	8.20	513.55	8.93	62.62	57.48	39.05
24	29a	8.60	528.17	9.90	61.39	53.35	38.02
15	11a	0.78	40.09	0.90	51.46	44.74	37.89

Appendix F continued

From Core	To SS	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
14	11a	0.67	32.54	0.78	48.27	41.77	37.76
30	31d	5.82	294.49	6.07	50.60	48.49	25.04
30	31e	7.14	358.55	7.79	50.24	46.02	22.58
34	31f	2.01	97.36	2.21	48.44	44.00	21.65
33	33b	0.03	205.55	4.63	6851.62	44.41	20.34
30	33b	3.50	720.27	12.65	206.08	56.93	19.26
33	34a	1.87	164.10	3.49	87.85	47.05	15.84
33	31f	1.35	58.85	1.45	43.53	40.47	12.08
26	31a	5.79	282.56	6.12	48.79	46.15	8.83
26	31b	6.34	308.65	6.76	48.72	45.64	7.92
25	29b	3.66	182.44	4.02	49.81	45.36	4.51

Appendix H

CONNECTIVITY METRICS BETWEEN EVERY PAIR OF STEPPING STONE HABITAT PATCHES

Description: Connectivity metrics between every pair of stepping stone (SS) habitat patches for bobcats in New Jersey, USA. Euclidean distance (EucD) is the shortest straight-line path between each patch while cost-weighted distances (CWD) incorporated landscape resistance developed from the Habitat Suitability Index for New Jersey Bobcats (HSINJB) and is representative of total travel cost. Least-cost path (LCP) is the shortest path of least resistance between two patches. The ratio of CWD:EucD represents resistance to movement controlled for linear distance while the ratio of CWD:LCD represents the average resistance along an ideal path. The current flow centrality reveals the relative importance of a given link between two patches to the overall connectivity network. Links are presented in descending order on the basis of this centrality, since higher amperage indicates greater importance to the overall network.

From SS	To SS	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
29d	31c	0.11	10.98	0.16	101.70	69.96	1029.52
31c	31d	0.33	16.85	0.37	51.07	45.31	223.18
6a	7a	0.03	3.99	0.06	137.75	66.58	191.91
14a	21a	56.37	3509.81	63.79	62.27	55.02	178.50
31d	31e	0.04	5.89	0.08	140.13	70.07	171.91
31b	31c	0.55	27.32	0.63	49.66	43.08	149.13
32c	32d	0.03	1.29	0.04	43.05	30.75	137.77
28d	28e	0.03	1.32	0.04	43.85	31.32	110.25
28b	28e	3.38	172.21	3.78	50.95	45.62	96.52
28b	28f	3.31	164.75	3.56	49.79	46.25	94.17
31a	31b	0.03	4.20	0.06	144.74	69.96	91.42
28b	32b	11.68	1349.57	24.29	115.55	55.56	88.77
28b	28d	3.76	193.34	4.29	51.47	45.06	86.26
33b	34a	0.74	31.51	0.79	42.47	39.74	80.75
27a	32a	6.81	344.21	7.38	50.52	46.64	74.06
28c	28d	0.03	1.35	0.04	45.04	32.17	72.00

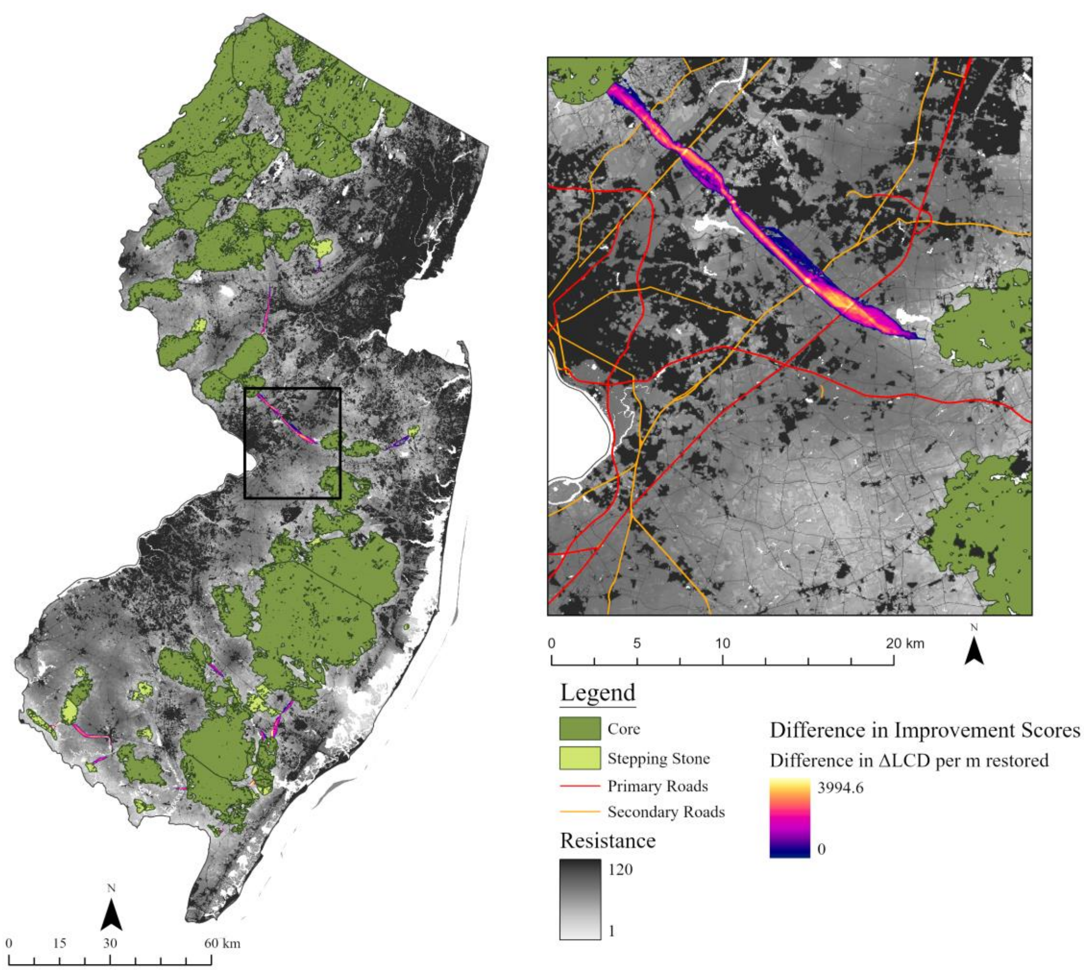
Appendix G continued

From SS	To SS	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Least-cost path (LCP, km)	CWD: EucD	CWD: LCP	Current flow centrality (Amps)
29d	31e	3.90	177.36	4.25	45.45	41.72	64.20
32b	32c	13.67	754.66	18.07	55.21	41.76	59.23
28e	28f	0.03	82.79	1.85	2854.95	44.75	57.93
34b	34c	0.03	113.11	2.61	3900.36	43.39	48.94
28d	28f	1.10	109.39	2.54	99.18	43.07	44.38
31f	33a	1.46	59.56	1.57	40.82	37.84	14.45

Appendix I

DIFFERENCE IN SUMMED AND MAXIMUM IMPROVEMENT SCORES

Description: Map of the difference in summed and maximum improvement scores for corridors connecting bobcat habitat patches in New Jersey, USA. Rather than representative of a corridor, this map highlights regions within the previously identified corridors (Figure 5) where mitigation efforts would have the greatest impact on multiple corridors. Yellow pixels indicate regions where mitigation efforts or improvements to connectivity would be the most effective.



Appendix J

CORRIDOR AND LEAST-COST PATH METRICS FOR CASE STUDY IN CENTRAL NEW JERSEY

Description: Comparison of connectivity metrics for the case study in central New Jersey (NJ), USA which examined landscape connectivity between cores 19-20 in northern NJ to cores 21 to 23 in southern NJ. Two cases were examined: one with the original resistance landscape (i.e. Original) developed from the Habitat Suitability Index for New Jersey Bobcats (HSINJB) and another resistance landscape in which all culverts were assigned an ideal resistance of 1 (i.e. Culvert). Euclidean distance (EucD) is the shortest straight-line path between each patch while cost-weighted distances (CWD) incorporated landscape resistance and is representative of total travel cost. Least-cost path (LCP) is the shortest path of least resistance between two patches. The ratio of CWD:EucD represents resistance to movement controlled for linear distance while the ratio of CWD:LCD represents the average resistance along an ideal path. The current flow centrality reveals the relative importance of a given link between two patches to the overall connectivity network. Links are presented in descending order on the basis of this centrality, since higher amperage indicates greater importance to the overall network. Finally, the difference (Δ) between the original and culvert resistances are reported.

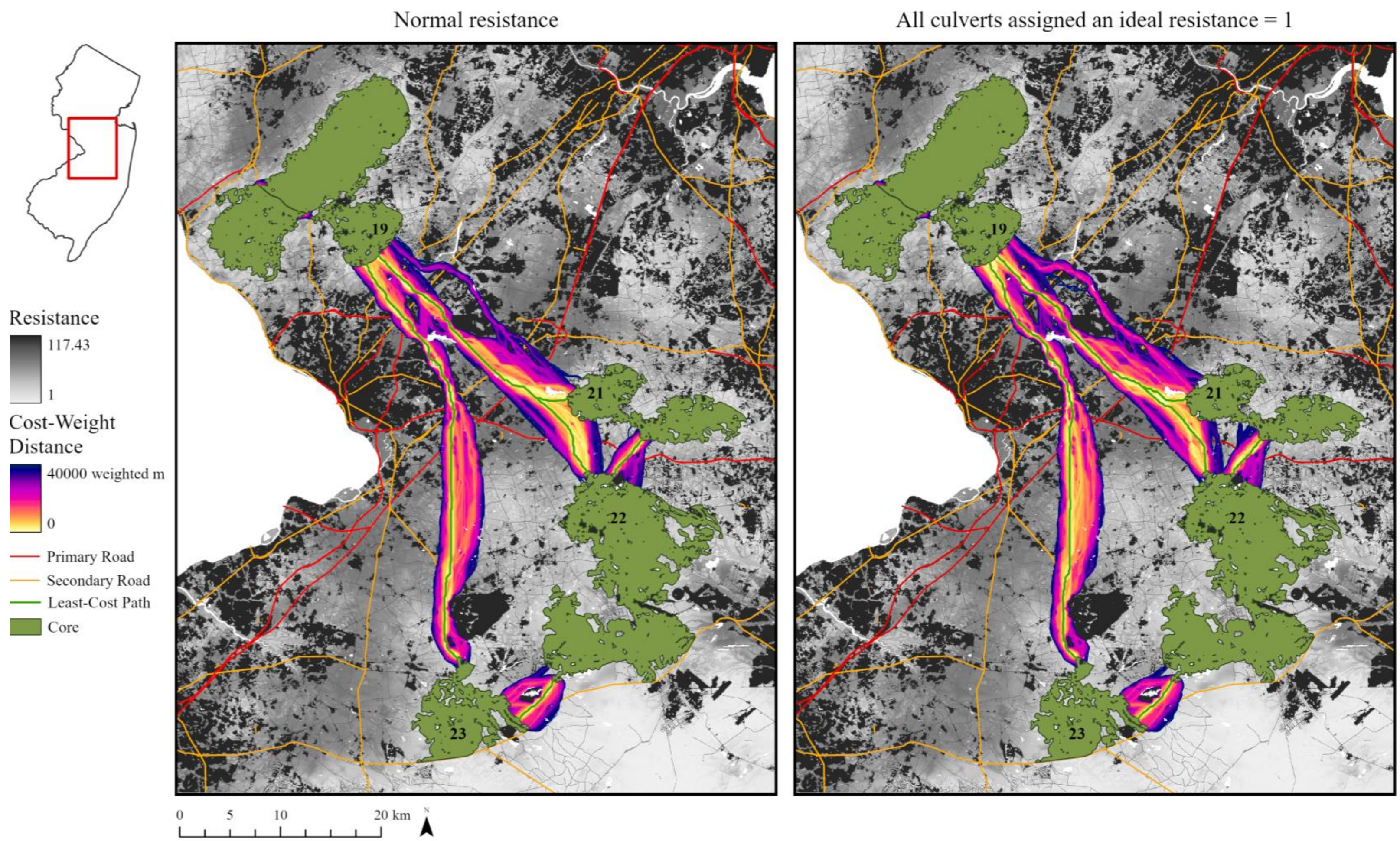
From Core	To Core	Case	Euclidean distance (EucD, km)	Cost-weighted distance (CWD, weighted km)	Δ	Least-cost path (LCP, km)	Δ	CWD:EucD	Δ	CWD:LCP	Δ	Current flow centrality (Amps)
19	20	Original	0.03	3.94		0.06		135.82		65.65		4.000
19	20	Culvert	—	1.18	2.75	—	0.00	40.85	94.97	19.75	45.90	—
19	21	Original	23.21	1379.97		25.61		59.46		53.88		2.665
19	21	Culvert	—	1358.65	21.32	25.87	-0.26	58.54	0.92	52.51	1.37	2.668
19	22	Original	29.68	1726.81		31.89		58.18		54.15		2.101
19	22	Culvert	—	1697.80	29.01	32.40	-0.51	57.21	0.97	52.41	1.74	2.106
19	23	Original	40.03	2336.11		44.26		58.37		52.79		1.706
19	23	Culvert	—	2309.21	26.90	44.62	-0.36	57.69	0.68	51.75	1.04	1.702
21	22	Original	4.12	189.41		4.51		45.95		41.97		4.437
21	22	Culvert	—	—	0.00	—	0.00	—	0.00	—	0.00	4.433
22	23	Original	4.66	198.40		5.21		42.58		38.10		4.194
22	23	Culvert	—	196.13	2.26	—	0.00	42.10	0.48	37.67	0.43	4.192

"Original" indicates analyses conducted with the resistance used for the New Jersey-wide study
"Culvert" indicates analyses using the altered resistance with culverts assigned a resistance of 1.
— indicates same value to nearest 0.001

Appendix K

COMPARISON OF CORRIDORS AND LEAST-COST PATHS IN CASE STUDY

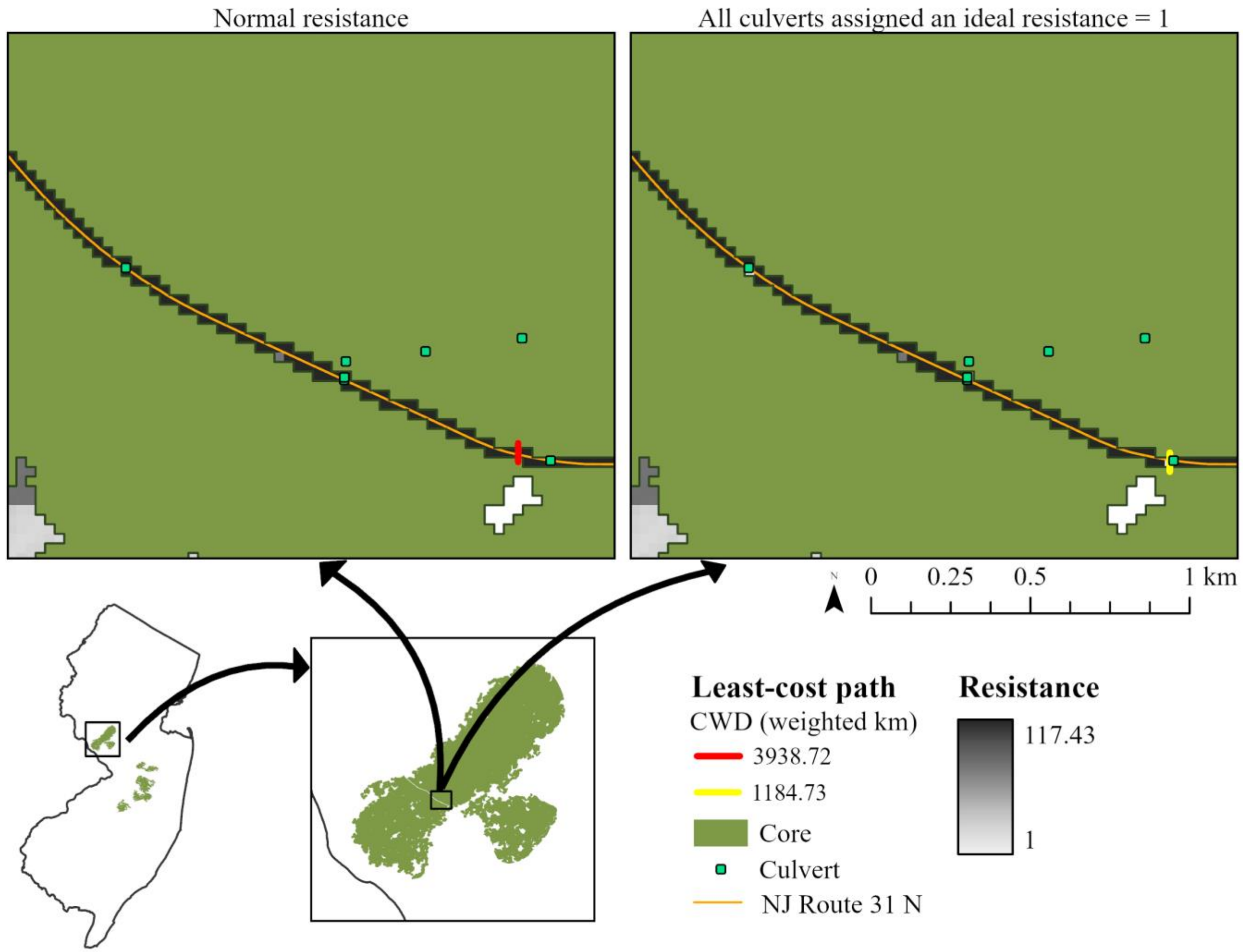
Description: Comparison of corridors between bobcat habitat patches in New Jersey, USA with least-cost paths (LCPs) for both normal resistance and for an alternate resistance with culverts assigned an ideal resistance of 1. Corridors were truncated at a cost-weight distance (CWD, i.e. distances that incorporate landscape resistance and represent a total travel cost) of 40 km. Green lines represent the LCPs for bobcat movement and lower CWD is represented by yellow and orange with higher CWD values indicated by purple and dark blue.


Normal resistance
All culverts assigned an ideal resistance = 1
Resistance
117.43
1
Cost-Weight Distance
40000 weighted m
0
Primary Road
Secondary Road
Least-Cost Path
Core
19
21
22
23
0
5
10
20 km
N

Appendix L

CHANGE OF COST-WEIGHT DISTANCE FOR CASE STUDY

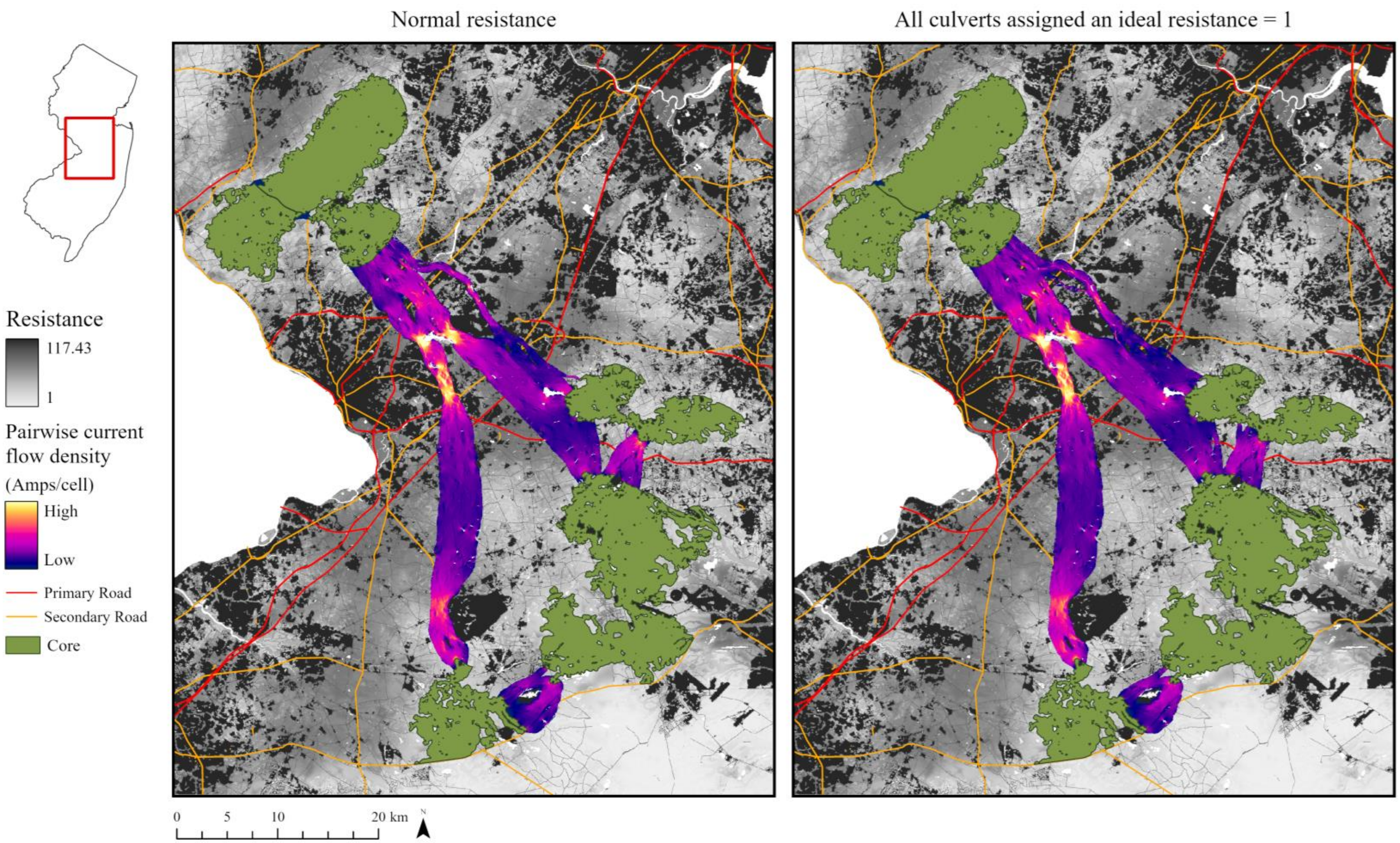
Description: Comparison of the corridor between bobcat habitat cores 19 and 20 across NJ Route 31 N in the Sourland region of New Jersey, USA. The corridor was truncated at a cost-weight distance (CWD, i.e. distance that incorporates landscape resistance and represents a total travel cost) of 40 km. The red line represents the least-cost path (LCP) for bobcat movement and lower CWD is represented by yellow and orange with higher CWD values indicated by purple and dark blue. The incorporation of culverts resulted in a shifting of the LCP across a culvert and an overall reduction in CWD of the LCP (Appendix E).


Normal resistance
All culverts assigned an ideal resistance = 1
N
0
0.25
0.5
1 km
Least-cost path
CWD (weighted km)
3938.72
1184.73
Core
Culvert
NJ Route 31 N
Resistance
117.43
1

Appendix M

PINCH POINT COMPARISON FOR CASE STUDY

Description: Comparison of pairwise current flow density (amps/cell) between bobcat habitat patches in central New Jersey, USA for the original resistance and the alternative scenario where all culverts were assigned an ideal resistance of 1. Bright yellow regions of high current flow density indicate pinch points, or constrictions, within corridors and are suggestive of regions where bobcats would likely have to pass to travel from one patch to another. At a resolution showing all corridors (such as this), minute differences in pinch points are difficult to see.

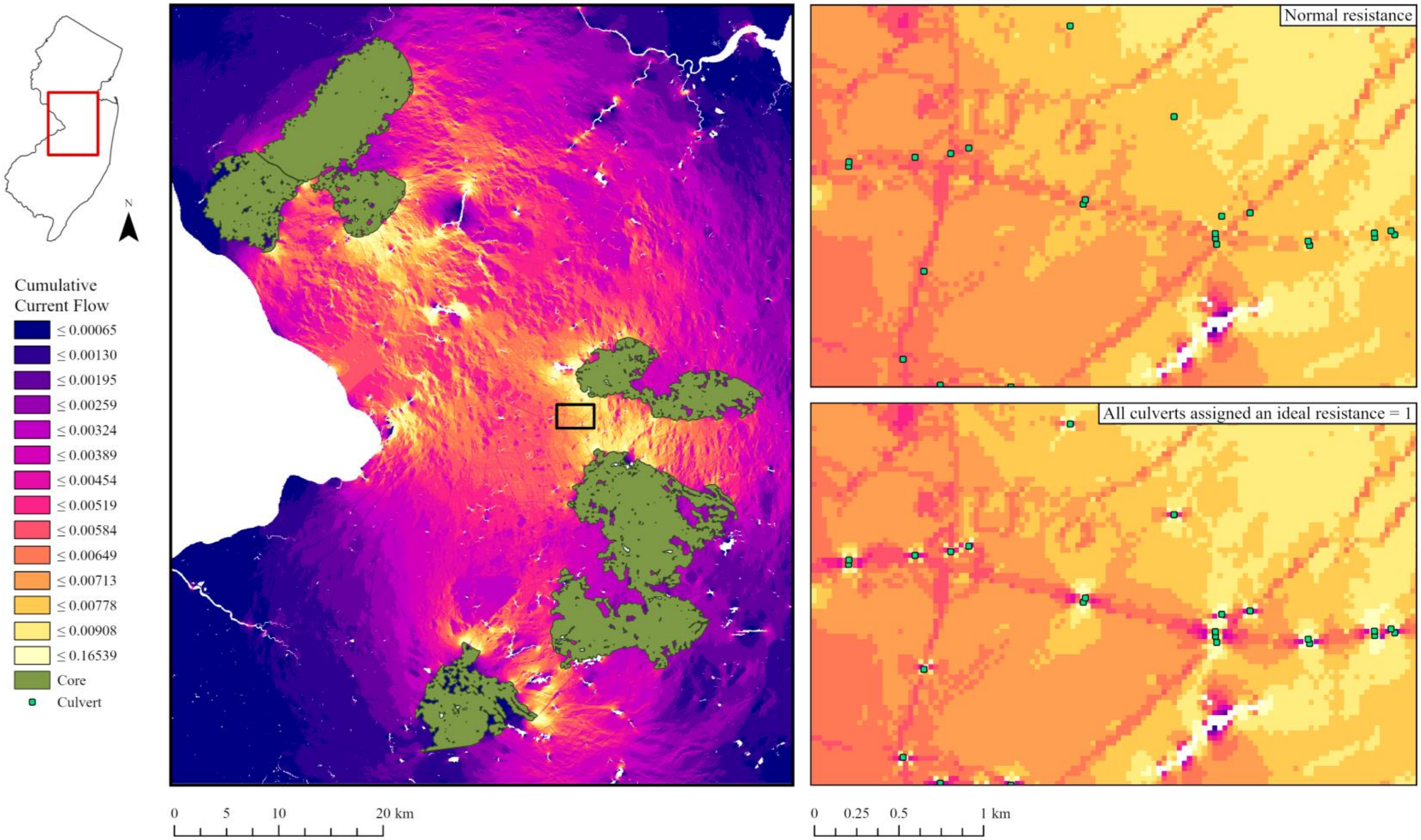


Normal resistance
All culverts assigned an ideal resistance = 1
Resistance
117.43
1
Pairwise current flow density
(Amps/cell)
High
Low
Primary Road
Secondary Road
Core
0
5
10
20 km

Appendix N

COMPARISON OF CUMULATIVE CURRENT FLOW FOR CASE STUDY

Description: Maps comparing the pairwise cumulative current flow among bobcat habitat patches in central New Jersey, USA through the original resistance and an alternative resistance in which all culverts were assigned the lowest resistance of 1. Higher amperage (shades of yellow) indicates cells with a higher probability of bobcats passing through them while navigating the landscape and suggests less redundancy in possible pathways. Both resistance landscapes appear roughly the same at a coarser resolution (current through normal resistance pictured here). At finer resolutions, culverts appeared to divert current through them indicated by lighter shades of yellow.

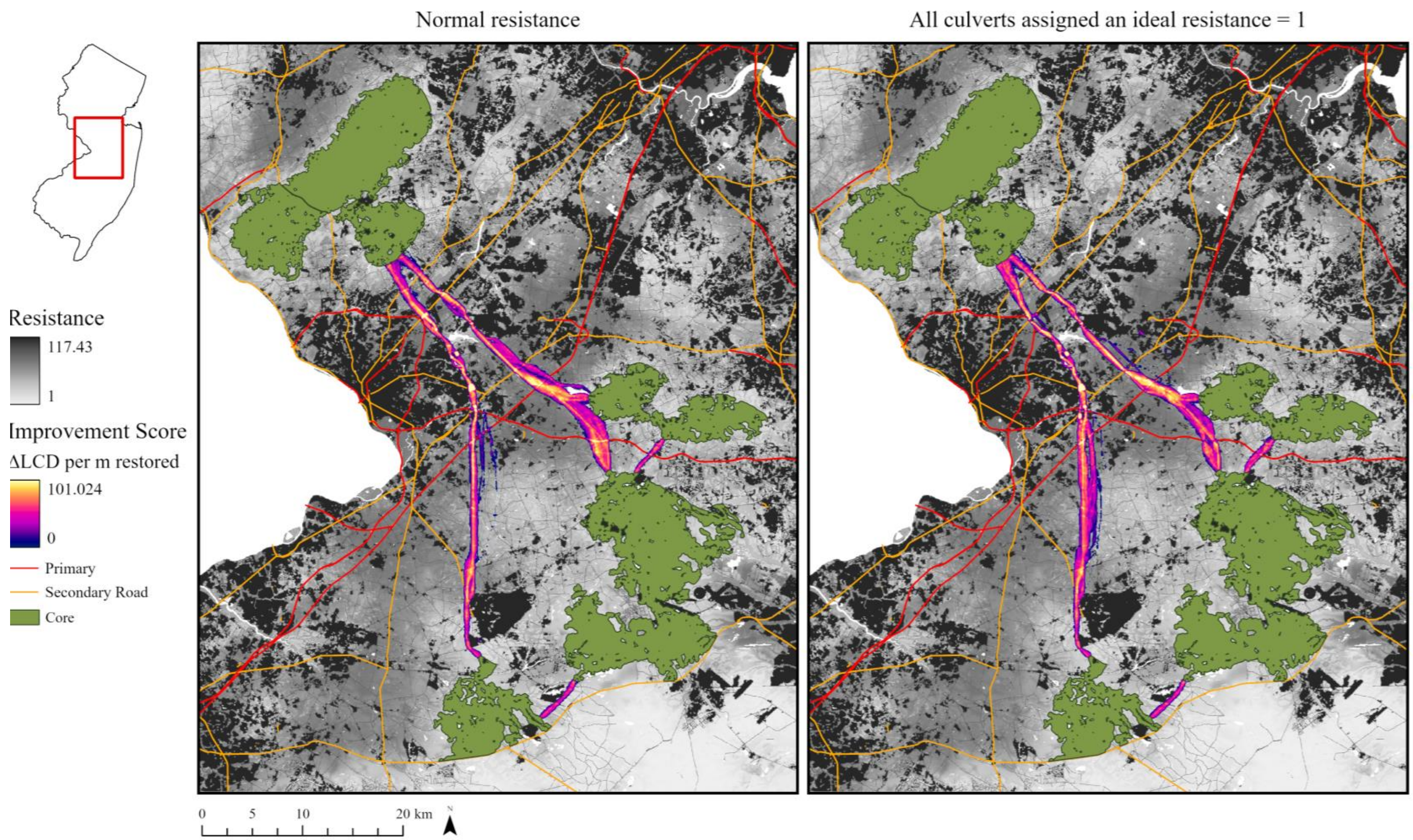


N
Cumulative Current Flow
≤ 0.00065
≤ 0.00130
≤ 0.00195
≤ 0.00259
≤ 0.00324
≤ 0.00389
≤ 0.00454
≤ 0.00519
≤ 0.00584
≤ 0.00649
≤ 0.00713
≤ 0.00778
≤ 0.00908
≤ 0.16539
Core
Culvert
0 5 10 20 km
Normal resistance
All culverts assigned an ideal resistance = 1
0 0.25 0.5 1 km

Appendix O

COMPARISON OF BARRIERS FOR CASE STUDY

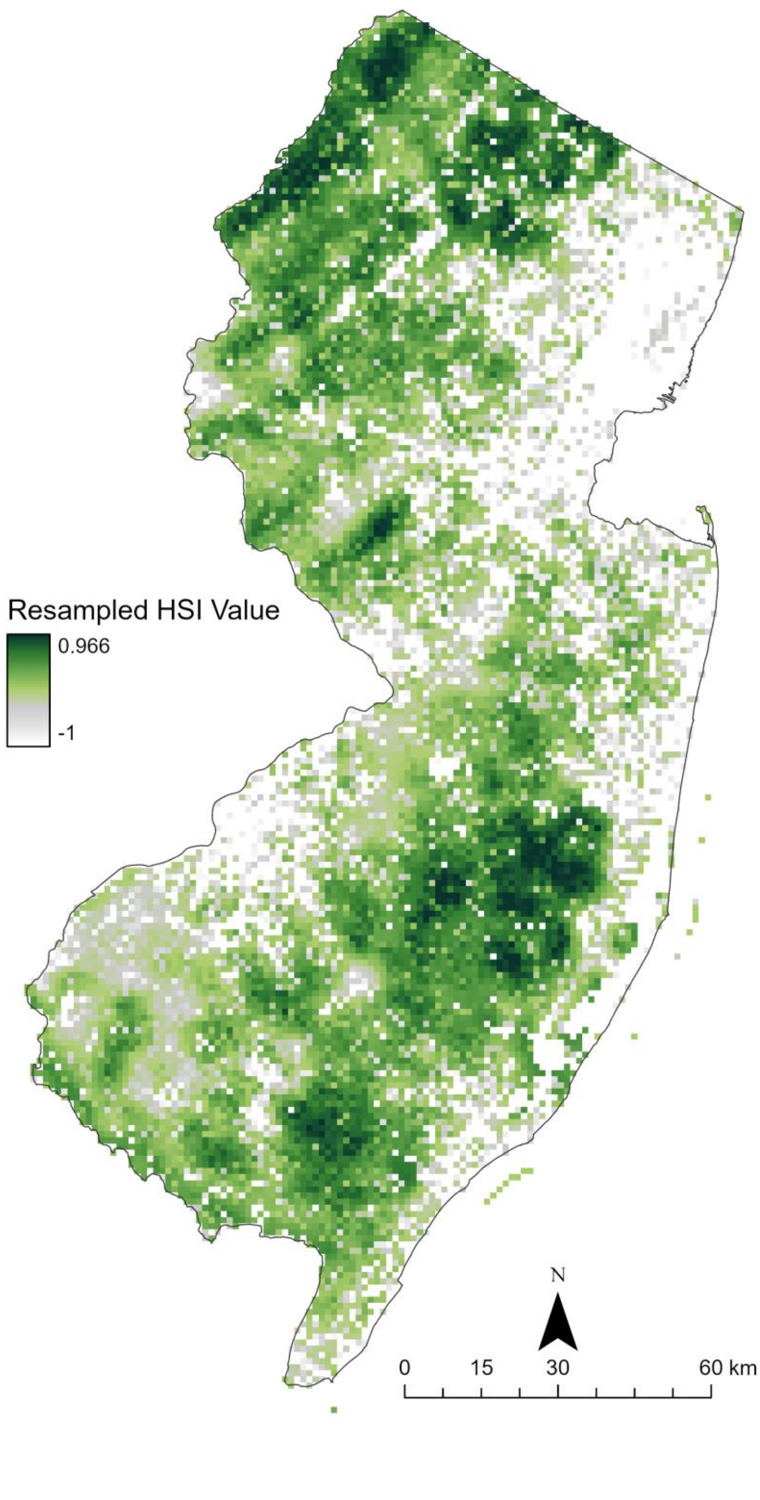
Description: Maps comparing maximum improvement scores revealing barriers within corridors connecting bobcat habitat patches in New Jersey, USA for the original resistance and an alternative resistance in which all culverts were assigned the lowest resistance of 1. Yellow regions indicate pixels where restoration of habitat or reduction of barrier would have the greatest impact on improving connectivity within the corridor. Culverts appear to reduce barriers across primary and secondary roads.


Normal resistance
All culverts assigned an ideal resistance = 1
Resistance
117.43
1
Improvement Score
ΔLCD per m restored
101.024
0
Primary
Secondary Road
Core
0
5
10
20 km
N

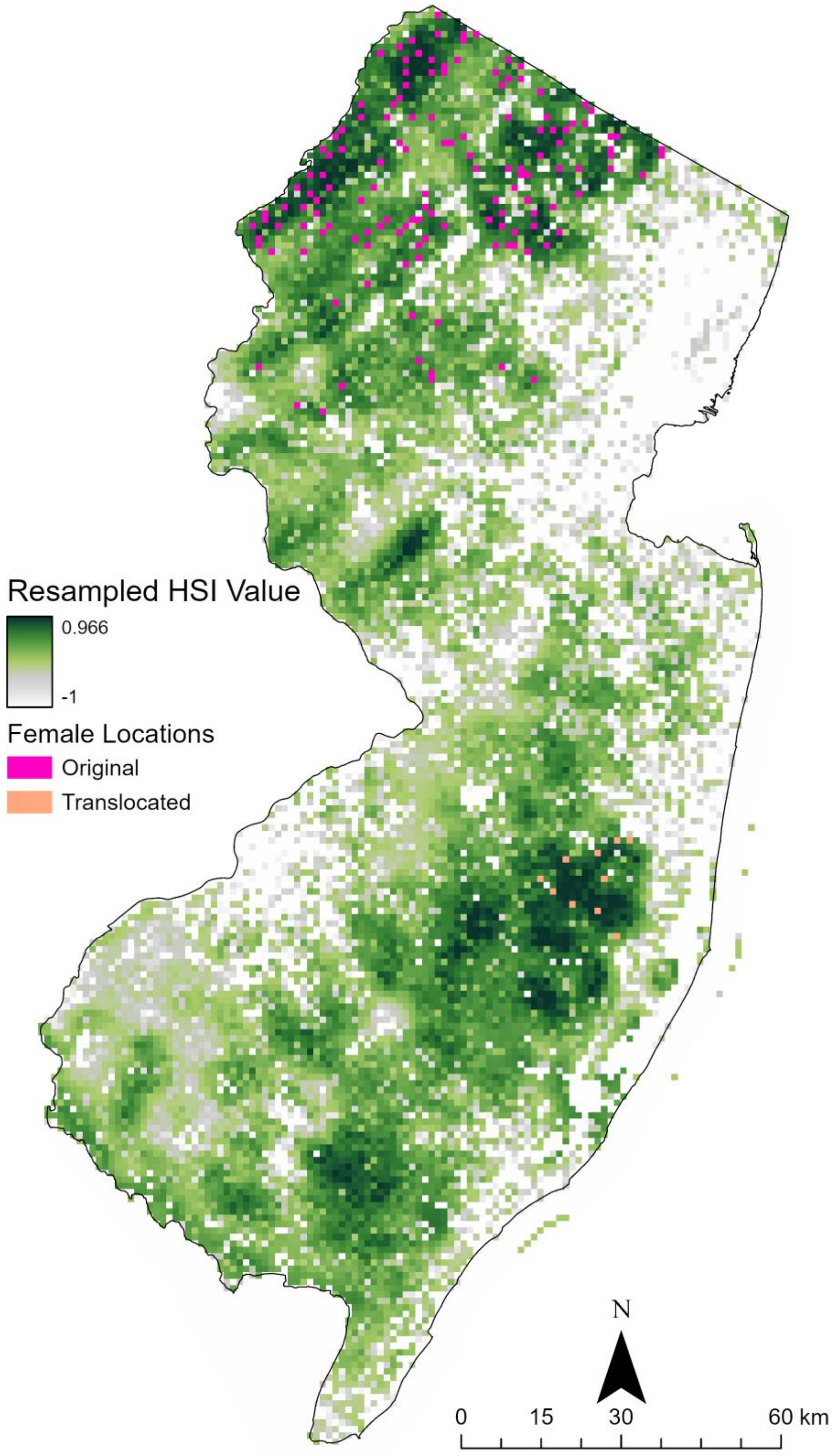
Appendix P

MAP INPUTS FOR SPATIALLY EXPLICT AGENT-BASED MODEL

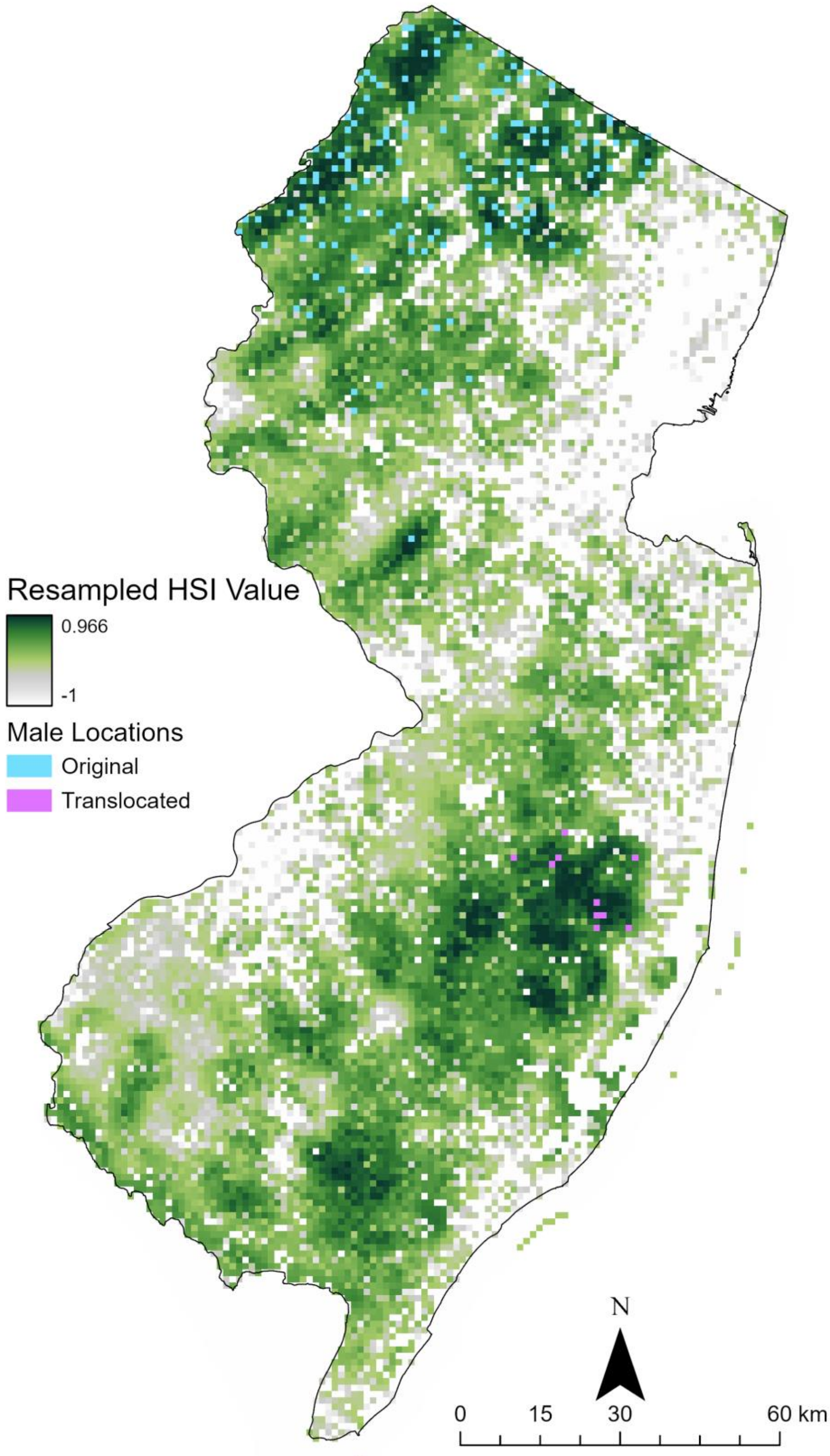
Description: Habitat input raster for the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA. It consists of 1.2 km x 1.2 km cells that were resampled through bilinear interpolation from the Habitat Suitability Index for New Jersey Bobcats presented in Figure 7 (Chapter 1). Higher values, depicted in medium to dark green, represent better predicted habitat quality or higher likelihood of supporting bobcats.


Resampled HSI Value
0.966
-1
N
0
15
30
60 km

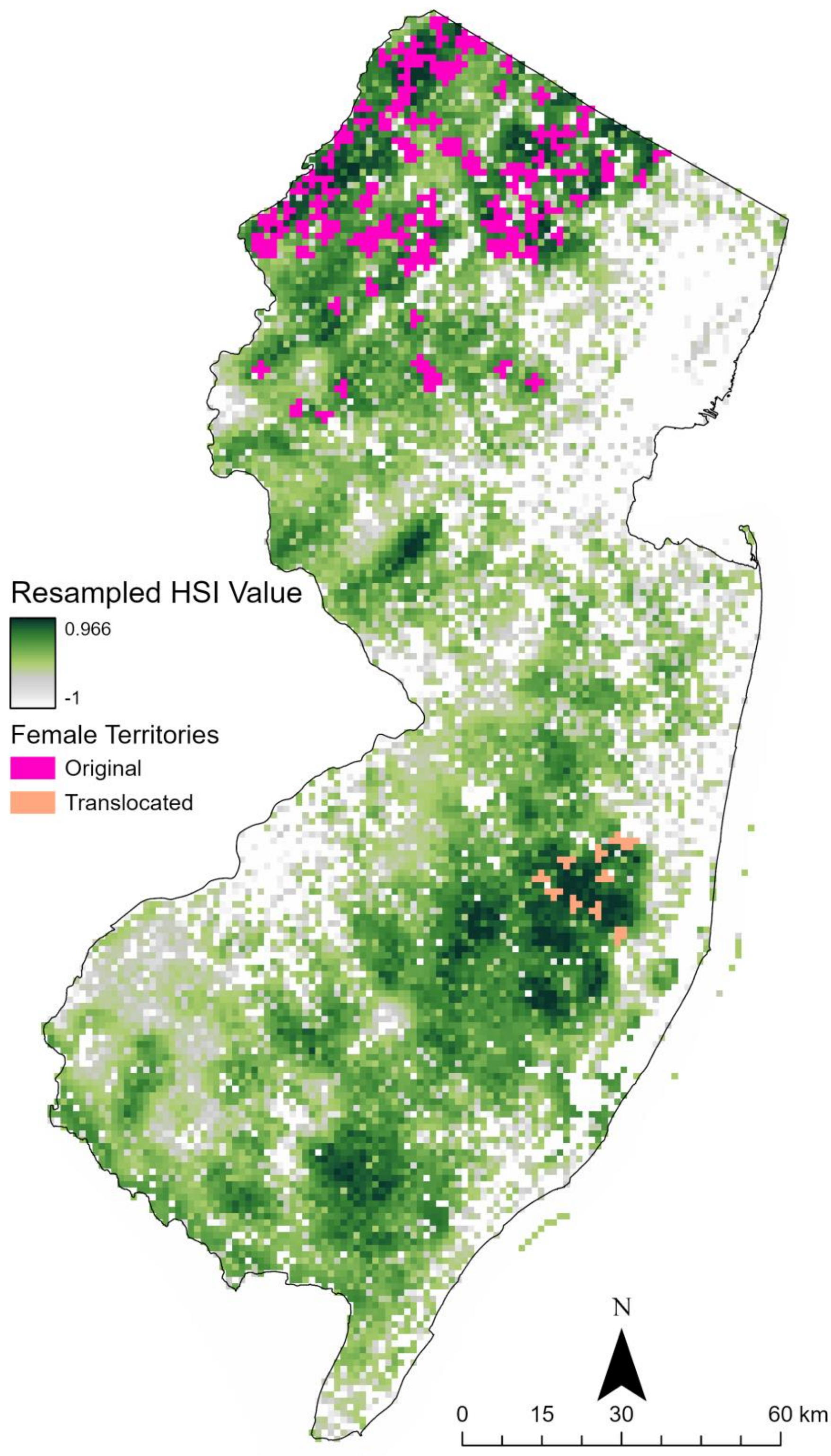
Description: Locations of randomly generated female bobcats within suitable habitat patches in northern and southern New Jersey, USA which were inputs for the spatially explicit agent-based model used to examine bobcat recolonization potential in the state. Pink cells represent the 138 original female bobcat locations used in two different management scenarios which examined natural recolonization (i.e. status quo) and improved connectivity through barrier mitigation (i.e. barrier reduction), respectively. These are representative of the current population of female bobcats in northern New Jersey. The peach cells are locations of 10 translocated female bobcats into southern New Jersey and were used in combination with the original 138 female bobcats locations to examine the viability of translocation to restore bobcats to the south. Locations are superimposed on the habitat input raster with medium to dark green representing better predicted habitat quality or higher likelihood of supporting bobcats.


Resampled HSI Value
0.966
-1
Female Locations
Original
Translocated
N
0
15
30
60 km

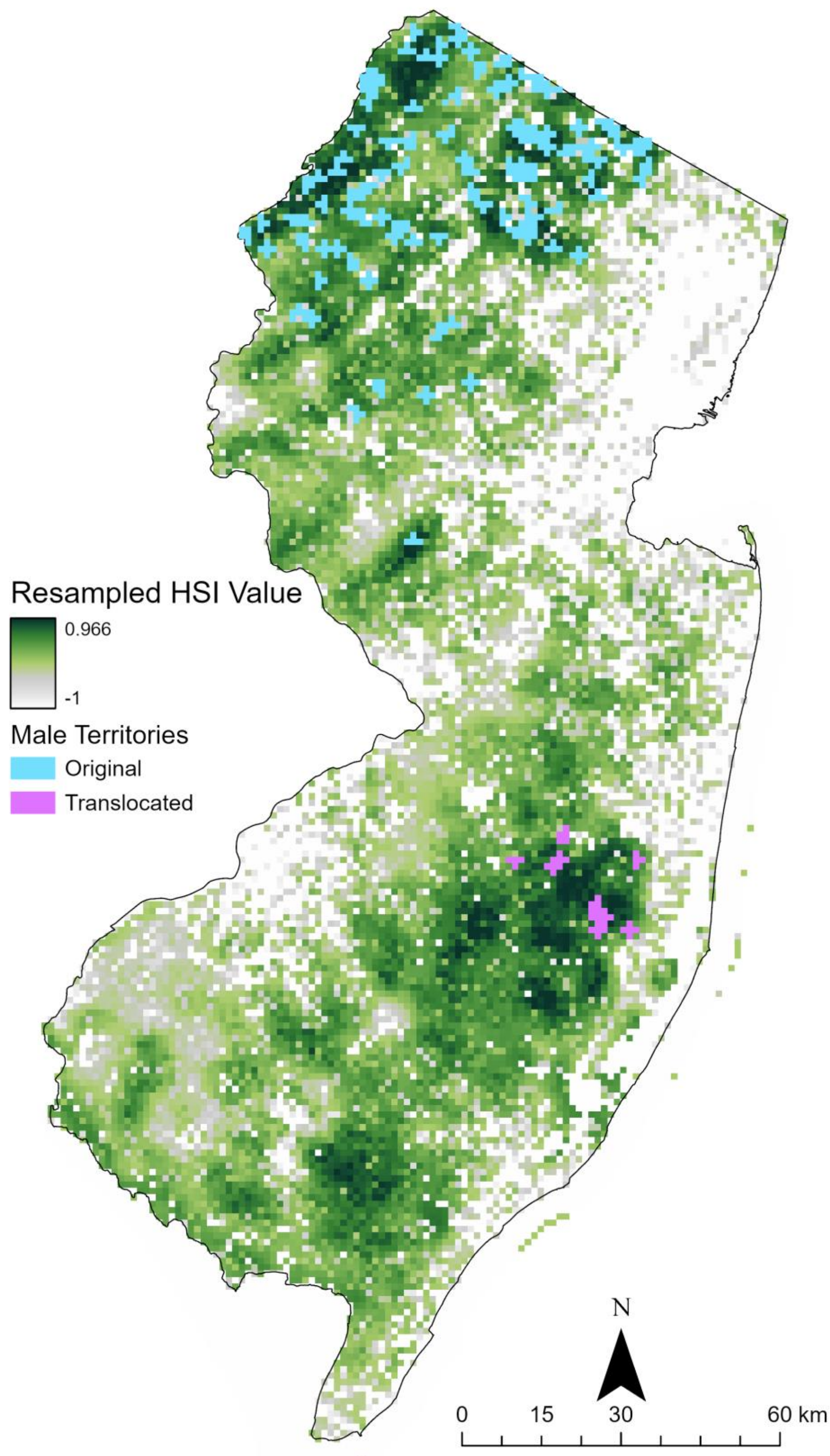
Description: Locations of randomly generated male bobcats within suitable habitat patches in northern and southern New Jersey, USA which were inputs for the spatially explicit agent-based model used to examine bobcat recolonization potential in the state. Blue cells represent the 138 original male bobcat locations used in two different management scenarios which examined natural recolonization (i.e. status quo) and improved connectivity through barrier mitigation (i.e. barrier reduction), respectively. These are representative of the current population of male bobcats in northern New Jersey. The purple cells are locations of 10 translocated male bobcats into southern New Jersey and were used in combination with the original 138 male bobcats locations to examine the viability of translocation to restore bobcats to the south. Locations are superimposed on the habitat input raster with medium to dark green representing better predicted habitat quality or higher likelihood of supporting bobcats.


Resampled HSI Value
0.966
-1
Male Locations
Original
Translocated
N
0
15
30
60 km

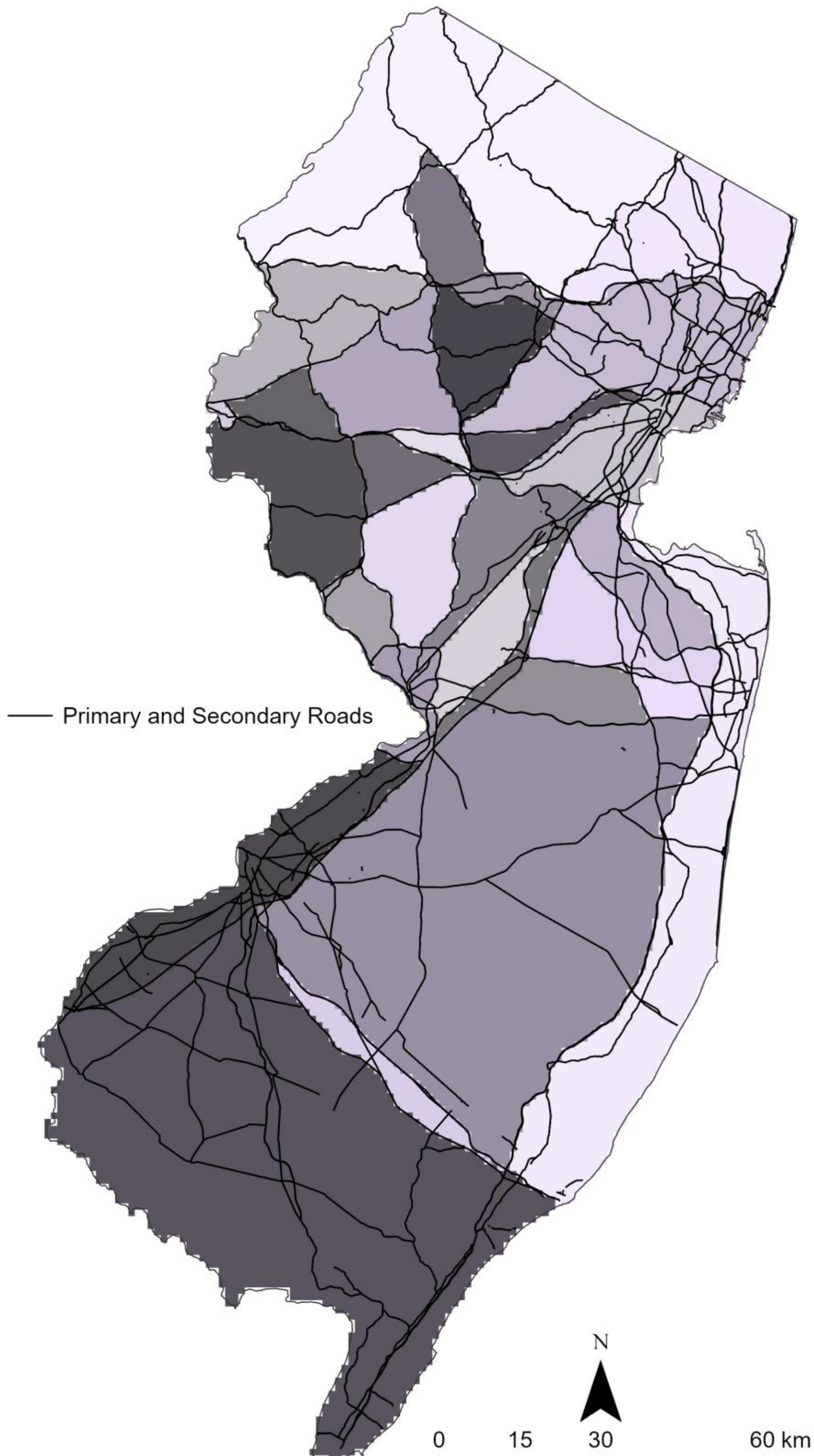
Description: Locations and extent of initial female bobcat territories in northern and southern New Jersey, USA which were inputs for the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in the state. Territories were generated using the territory establishment rules of the SEABM. Pink cells represent the territories corresponding to original female bobcat locations and were used in two different management scenarios which examined natural recolonization (i.e. status quo) and improved connectivity through barrier mitigation (i.e. barrier reduction), respectively. These are representative of the starting distribution of female territories in northern New Jersey. The peach cells represent the territories of 10 translocated female bobcats into southern New Jersey and were used in combination with the starting distribution of female territories to examine the viability of translocation to restore bobcats to the south. Locations are superimposed on the habitat input raster with medium to dark green representing better predicted habitat quality or higher likelihood of supporting bobcats.


Resampled HSI Value
0.966
-1
Female Territories
Original
Translocated
N
0
15
30
60 km

Description: Locations and extent of initial male bobcat territories in northern and southern New Jersey, USA which were inputs for the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in the state. Territories were generated using the territory establishment rules of the SEABM. Blue cells represent the territories corresponding to original male bobcat locations and were used in two different management scenarios which examined natural recolonization (i.e. status quo) and improved connectivity through barrier mitigation (i.e. barrier reduction), respectively. These are representative of the starting distribution of male territories in northern New Jersey. The purple cells represent the territories of 10 translocated male bobcats into southern New Jersey and were used in combination with the starting distribution of male territories to examine the viability of translocation to restore bobcats to the south. Locations are superimposed on the habitat input raster with medium to dark green representing better predicted habitat quality or higher likelihood of supporting bobcats.


Resampled HSI Value
0.966
-1
Male Territories
Original
Translocated
N
0
15
30
60 km

Description: Input map of the patchwork "bounce patch" raster dataset and the primary and secondary roads layer used for the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA. Different "bounce patches" are depicted in differing shades of grey and are used in the SEABM to simulate a dispersing individual balking at crossing highly trafficked roads. The roads layer is used by the SEABM to identify road crossing events during dispersal to incorporate a mortality risk to the dispersing bobcat for each separate crossing.


Primary and Secondary Roads
N
0
15
30
60 km

Appendix Q

DATA USED TO CALCULATE PARAMETERS FOR SPATIALLY EXPLICT AGENT-BASED MODEL

Description: Adult (>2 years old) bobcat mortality rates used to calculate the overall adult mortality rate and standard deviation for the spatially explicit agent-based model used to examine bobcat recolonization potential in New Jersey, USA.

Adult mortality rate	Location	Source
0.161	Illinois	Nielsen and Woolf 2002[a]
0.33	Idaho	Knick 1990[b]
0.2	Mississippi	Chamberlain et al 1999[c]
0.239	California	Riley et al 2003[a]
0.376	Massachusetts	Fuller et al 1995[d]
Mean	0.261	
Standard deviation	0.090	

[a] no harvest in population
[b] unharvested population, but includes one instance of harvest outside of study area
[c] no furbearer trapping during study, but includes instances of incidental harvest
[d] included harvested population, but no harvest was recorded for study bobcats

Description: Juvenile (<1 year old) bobcat mortality rates used to calculate the overall juvenile mortality rate and standard deviation for the spatially explicit agent-based model used to examine bobcat recolonization potential in New Jersey, USA.

Juvenile mortality rate	Location	Source
0.243 [a]	Pennsylvania	Lovallo 2007 [b]
0.233[c]	Idaho	Bailey 1979
0.18[d]	West Virginia	Landry 2017
0.67[e]	Michigan	Hoppe 1979
0.71[e]	Texas	Blankenship and Swank 1979
Mean	0.407	
Standard deviation	0.260	

[a] average of 3 years of reported survival probabilities for a 9 month period and calculated morality
[b] harvested population, but no harvest documented for juvenile deaths
[c] average of reported male and female mortality rates from harvest data
[d] average of two years of reported survival probabilities from harvest data and calculated mortality
[e] calculated from harvest data

Description: Yearling (between 1 and 2 years old) bobcat mortality rates used to calculate the overall yearling mortality rate and standard deviation for the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA. This is the original parameter value before it was adjusted to account for road mortality during the calibration phase of developing the SEABM.

Yearling mortality rate	**Location**	**Source**
0.534[a]	Idaho	Bailey 1979
0.36[b]	Michigan	Hoppe 1979
0.235[c]	West Virginia	Landry 2017
Mean	0.376	
Standard deviation	0.150	

[a] average of reported male and female mortality rates from harvest data
[b] calculated from harvest data
[c] average of two years of reported survival probabilities from harvest data and calculated mortality

Description: Average bobcat dispersal distances used to calculate the overall mean dispersal distance parameter and its standard deviation for the spatially explicit agent-based model (SEABM) used to examine bobcat recolonization potential in New Jersey, USA.

Dispersal Distance (km)	**Location**	**Source**
43	Illinois	Nielsen and Woolf 2003
57.9	Iowa	Hughes et al 2019
71.33[a]	Kansas	Kamler et al 2000
9.7	Indiana	Johnson et al 2010
Mean	45.48	
Standard deviation	26.51	

[a] average of individual distances reported for three dispersing bobcats (1M, 2F)