Designing Sustainable Landscapes: Spotted Turtle Landscape Conservation Tools

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General description

The spotted turtle (*Clemmys guttata*) is considered an at-risk species in the Northeast, with populations thought to be declining across the range. It is listed as Endangered by the IUCN Red List (van Dijk 2011). As with many turtles, spotted turtles are long-lived with delayed maturity, with most of the reproductive value in adult life stages. This makes spotted turtle populations particularly susceptible to even small increases in adult mortality (Condon et al. 1993). Primary threats include mortality from road traffic and agricultural machinery, collection as pets, invasive plants, habitat degradation, loss, and fragmentation, and subsidized predation of eggs and juveniles (van Dijk 2011). Although some of these threads must be managed at the site scale, all are related to landscape context of spotted turtle habitat, and several of these threats must be addressed at a landscape scale, by protecting relatively large, intact complexes of wetlands and uplands with high connectivity to nearby sites, and minimal road crossings.

This project is intended to support proactive conservation for this species at a landscape scale. It represents our first set of species-specific conservation planning tools. The spotted turtle conservation tools are meant to be used by conservationists focusing on conserving land for the spotted turtle. The conservation tools identify sites likely to provide high-quality habitat for spotted turtles that are relatively large and intact, connections among these sites, and potential hot spots of road mortality on these connections. Rather than representing a prescriptive design ("all of these sites must be protected"), these tools are intended to highlight sites with a high potential for spotted turtles at the landscape scale and help guide conservation actions. Its use must be paired with field-based assessments of potential sites and informed assessment at the local scale.

These landscape conservation tools are based on our new (as of 2020) Landscape Capability (LC) model of the spotted turtle (Compton and DeLuca 2020, McGarigal et al. 2017c). As with our other species models, the spotted turtle LC uses GIS data and parameters based on literature review and expert opinion to produce a comprehensive map of LC at each cell in the northeast range. LC is an estimate of the ability of a site to support a population, based on Habitat Capability (HC), a Climate Niche (CN) model, and prevalence (Fig. 1a). Habitat capability is an estimate of the ability of a site to provide local resources (feeding, estivation, and overwintering) in sufficient quantity, quality and accessibility to support a local population. The climate niche model is based on several climate variables sampled at known spotted turtle locations, giving the probability of a population being present at a site given the climate. Finally, prevalence is based on a generalized range map, to restrict modeled locations to where populations occur across the landscape when habitat and climate do not necessarily define range boundaries.

Conservation cores

Given the LC model, we built conservation cores, sites where LC was particularly high across the landscape. Although LC across the landscape gives the most detail as to where spotted turtle habitat is expected to be, it can be overwhelming when trying to select potential conservation sites across large areas. Many small, isolated areas of high LC may not support populations over the long term, and many clusters of high LC are subdivided by busy roads and development. In building cores, our goal was to merge high quality wetland complexes that have high LC into viable sites for conservation, while buffering these sites from roads and development to the extent possible. Cores represent an attempt to capture the best subset of spotted turtle habitat across the region in landscape contexts that might provide for defensible reserves. Cores were developed in a several-step process (Fig. 1):

1. We designated **regional seeds** (Fig. 1b) where LC was in the top 10% of the total LC across the landscape, representing the best modeled sites in the range.
2. We similarly designated **marginal seeds** where LC, stratified by HUC6 watershed, was in the top 1% of total LC in each HUC. This brings in sites that are not among the best in the region, but are among the very highest within a portion of the region (there are 35 HUCs in the Northeast). These seeds bring in more marginal potential populations, which may be important source populations for dispersal in response to climate change, as well as possible sites for evolutionary innovation. HUCs representing < 0.01% of the total LC across the region were dropped to minimize errors from data artifacts.
3. We used both the regional and marginal seeds as initiation sites for **resistant kernels** (Compton et al. 2007; Fig. 1c), using the species LC to determine landscape resistance. This is similar to the process used to create terrestrial ecosystem cores for Nature's Network (McGarigal et al. 2017c). Resistant kernels spread far and retain high values through areas of low resistance (high-quality spotted turtle habitat); are retarded by higher resistance (such as lower-quality habitat or non-habitat) and return lower values; and spread very little if at all through areas of much higher resistance, such as developed areas. In this model, all roads act as absolute barriers. The result for each site is a kernel, or hill, with high values at the seed of high LC, dropping to lower values at the edges, depending on the underlying landscape (Fig. 1c). Tiny seeds of <5 cells (0.45 ha) were dropped, as they tended to produce very small cores. We took this approach (as opposed to simply using the highest LC values as our conservation cores) because we want reasonably large, intact areas that are buffered to the extent possible from roads and development.
4. We then sliced the resistant kernels at a level that gave us a target percent of 20% of total LC across the landscape. We chose parameters that yield a large number of relatively extensive spotted turtle cores, with the expectation that only a subset of these will end up being protected. This produces **preliminary cores** (Fig 1d): fairly large areas of high-quality habitat interspersed with lower-quality habitat and non-habitat, but generally not including developed land. Cores never span roads. These cores don't necessarily represent the best 20% of LC, as areas of lower LC are included, and small areas of high LC are excluded, but they represent contiguous, buffered areas of generally high LC.
5. To create **final cores** (Fig. 1d), we dropped preliminary cores with a total area smaller than 50 ha, as we judged these unlikely to provide sustainable habitat for populations over the long term. Note that this causes us to drop below our target in Step 4. The 2,496 final cores represent 19.2% of total LC in the region.

The resulting cores represent the areas across the range of the spotted turtle in the Northeast that include large areas of high-quality habitat in relatively intact areas.

Connectivity

Although the conservation cores are intended to provide sufficient habitat to support populations, including seasonal within-wetland, nesting, and estivation migrations, connectivity among cores is important for two reasons.

1. Individual turtles sometimes disperse long distances—much farther than typical within-homerange movements. These movements could provide demographic rescue and genetic diversity for recipient populations, and, as females can store sperm for extended periods, potentially represent opportunities to colonize or recolonize vacant habitat. To our knowledge, no long-distance movements by spotted turtles have been recorded, though such movements are difficult to observe, as they are rare, and turtles can easily outrun the range of telemetry transmitters. Rare long-distance movements of 10-20 km have been recorded in other Emydine turtles including wood turtles and Blanding's turtles (B. Compton, pers. obs., M. T. Jones, pers. comm., and F. Beaudry, pers. comm.). Spotted turtles must occasionally make long-distance movements, as their presence in isolated wetlands attests. These long-distance dispersal movements are necessary to maintain populations and evolutionary potential over the long term, and will be critically important in making the species resilient to climate change.
2. We parameterized the model to split conservation cores by roads, no matter the size, as we consider any active road a serious threat to populations. By splitting cores with roads and separately modeling connectivity and road mortality vulnerability, we are able to explicitly represent the threats and conservation opportunity of within-homerange movements that cross roads.

We modeled connectivity among cores using **random low-cost paths** (also used to model connectivity among terrestrial ecosystem cores for Nature's Network, McGarigal et al. 2017c). This approach, described in more detail below, involves creating a large number (e.g., 1000) of paths between each pair of nearby cores, up to a maximum distance of 5.3 km (20 homerange lengths). Random low-cost paths are intermediate between deterministic least-cost paths (which follow the optimal path through a resistant landscape) and a random walk. They allow us to represent the uncertainty in which path an animal will take, while including the animal's estimated preferences in the model. Each path is converted to a probability of connectivity based on the length and total resistance of the path, and is multiplied by the mean LC of the two cores, to represent the increased importance of connecting cores with more, higher-quality habitat. All paths between pairs of cores across the landscape are summed at each cell, yielding **conductance**, a raster representation of connectivity (Fig. 1e). Conductance can be interpreted as the density of paths taken by vary large numbers of animals over many decades, or equivalently, as the probability that a turtle dispersing between cores would pass through each cell.

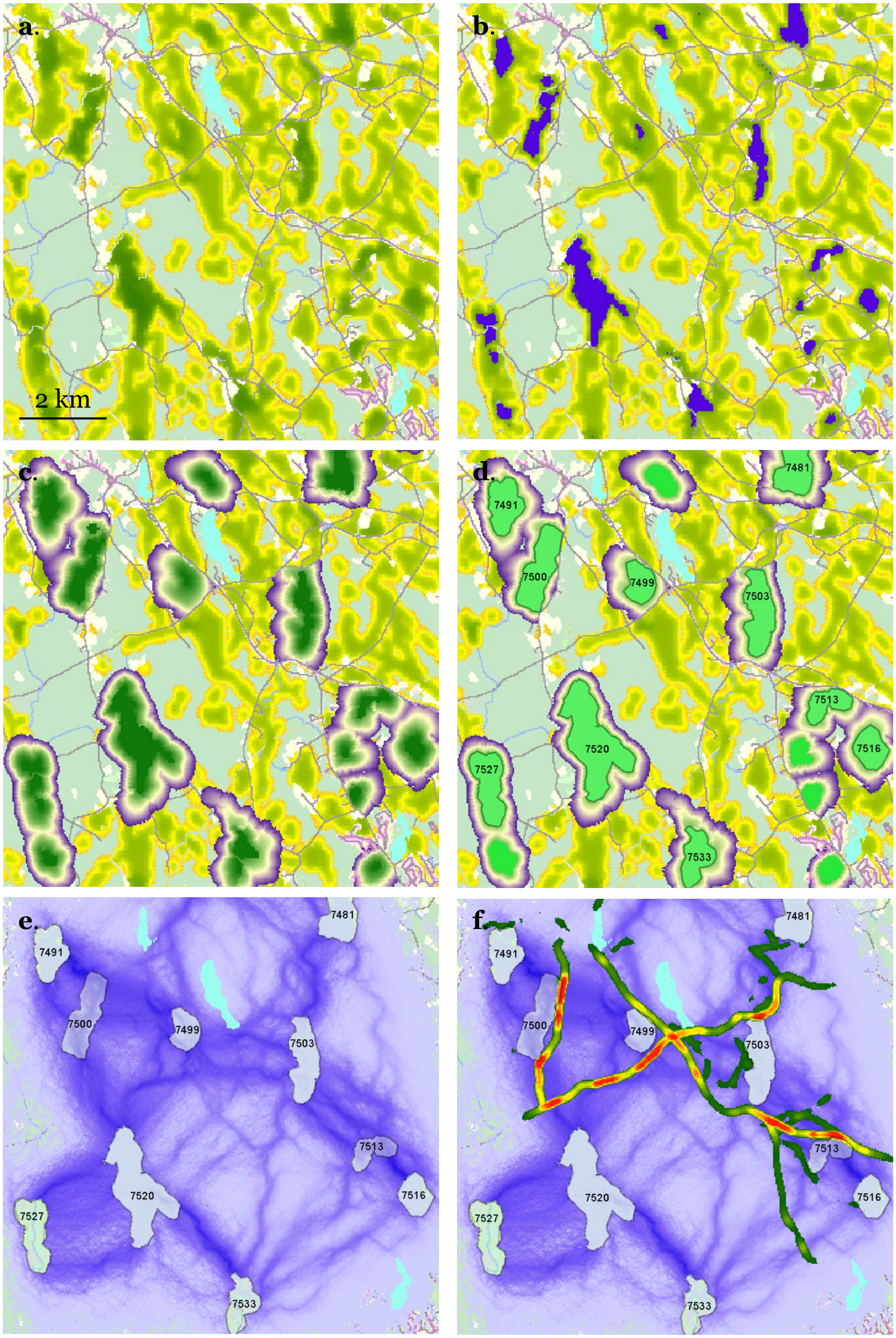

Fig 1. Spotted turtle cores, connectors, and road vulnerability for an area in southeastern Massachusetts: (a) LC (shades of green) on top of landcover; (b) regional and marginal seeds (purple); (c) resistant kernels (dark green [high] to purple [low]); (d) preliminary cores (lime) and final cores (with numeric ids); (e) conductance (light purple [low] to deep purple [high]); and (f) road vulnerability (green [low] to red [high]).

Road vulnerability

Finally, we modeled the vulnerability of spotted turtles to road traffic when moving among cores. We used a road mortality model (also used in generating the spotted turtle LC) based on Gibbs and Shriver (2002) that gives an estimate of the probability of mortality at a given traffic rate (see below for assumptions). We multiplied this probability of mortality by conductance for every road cell, yielding a relative (not absolute) probability of a spotted turtle being killed on a road for each cell. We drop very low values to emphasize areas where potential road mortality is higher. The highest values of road vulnerability will occur on higher-traffic roads run between nearby high-quality spotted turtle wetlands (Fig. 1f). These road vulnerability hotspots may suggest an assessment of bridges and culverts that might provide alternative crossing opportunities, and possible consideration of mitigation measures ranging from turtle crossing signs to the installation of turtle tunnels and fences.

Use and interpretation of this layer

Spotted turtle cores, conductance, and road vulnerability provide estimates of the most important spotted turtle sites for conservation, of the routes turtles are likely to take when moving among cores, and of the threat of road mortality to animals moving among cores. The goal of this suite of models is to provide conservation practitioners tools that will help in conservation planning for spotted turtles. We think these models will be particularly useful in an initial assessment of threats and conservation opportunities in a target area. There are several considerations that should be kept in mind when using these models:

- It is important to acknowledge that these results were derived from a model, and thus subject to the limitations of any model due to incomplete and imperfect data, and a limited understanding of the phenomenon being represented. In particular, the GIS data upon which these products were built are imperfect; they contain errors of both omission and commission. Consequently, there will be places where the model gets it wrong, not necessarily because the model itself is wrong, but rather because the input data are wrong. Thus, these products should be used and interpreted with caution and an appreciation for the limits of the available data and models. However, getting it wrong in some places should not undermine the utility of the product as a whole. As long as the model gets it right most of the time, it still should have great utility. Moreover, the model should lead to new insights that might at first seem counter-intuitive or inconsistent with limited observations. This is so because the model is able to integrate a large amount of data over broad spatial scales in a consistent manner and thus provide a perspective not easily obtained via direct and limited observation.
- Every modeler's favorite quote is George Box's "All models are wrong but some are useful." While we have striven to make these models useful, it is vital to remember that in any conflict between model results and reality, reality is correct. It would be foolish to make major site-level conservation decisions for any species based solely on a habitat model. We expect that anyone making significant decisions such as purchasing land or conservation easements with a goal of protecting habitat for spotted turtles will do due diligence to ensure that a spotted turtle population actually occurs at the site, and that the site is relatively intact and doesn't hold any threats not represented in the model.

- The LC model is constrained by our imperfect knowledge of spotted turtle habitat preferences and inclination/ability to move through various ecological systems and developed land classes. In particular, there is some evidence that spotted turtles in the south of our region use habitat differently from those in the north, but these range-wide differences are not yet well-understood. The LC model assumes that habitat preferences and homerange sizes of turtles southern Maine are the same as those in Virginia. As northern spotted turtles are better studied, the model is likely weaker in the south.
- It's important to emphasize that the LC model was not based on empirical location data; however, see below. High-quality regionally-consistent surveys have only recently been launched, and it will be some time before results are available. Heritage Element Occurrences (EOs) are of limited use in habitat modeling, as they are opportunistic, road- and development-biased, collected inconsistently by state, and often carry large locational error. For this project, Heritage EO data were not directly available to us. We were able to indirectly use EOs for building the climate niche model, thanks to the Spotted Turtle Working Group, who sampled our climate variables at EO locations for us. There are a few known areas where our LC model over- and underpredicts spotted turtles, either because of misspecification of habitat, inadequate GIS data, or site-specific factors we didn't account for. We hope to improve the model in these areas in a future version.
- The production of cores relies on several arbitrary parameters including the percent of LC to capture in regional and marginal seeds and in final cores, the scaling of resistance for kernels, the bandwidth for kernels, and size thresholds for dropping seeds and kernels. These parameters affect the sizes and number of cores, and how much they buffer high-quality habitat. There is no biological justification for selecting values of these parameters; they must be chosen to give "reasonable" results. A different set of parameters might result in many fewer cores, or the inclusion of smaller cores, or other configurations. We chose parameters that produced a very large number of cores, more than could likely be conserved, in the belief that the pruning of cores (and adjustment of boundaries) would best be done by conservationists working at local scales, with access to additional information, including aerial photos, biological records, and field surveys. Cores can be colored in maps by several metrics of quality to prioritize or reduce the set to be assessed (see GIS Metadata, below, for a list of metrics).
- Cores exclude small areas of high LC (<50 ha), even thosugh these areas might have lots of turtles and could potentially support viable populations in some instances. Our assumption is that such small habitat blocks are not likely to be viable in most instances.
- Note that the LC model does not include any representation of nesting habitat, as GIS data representing nesting areas were unavailable, so the model assumes that nesting habitat is available somewhere. The presence of nesting habitat (or opportunities for creating it) should be assessed at a site level.
- Likewise, most vernal pools are not represented in our GIS data. This is a serious drawback for a species that often makes use of seasonal wetlands for feeding. Some larger vernal pools are represented as wetlands.

- The road mortality model assumes that cars arrive following a Poisson distribution (this is likely a good assumption at low to moderate traffic rates), that turtles cross perpendicularly to roads, that turtles move at a constant rate, and that drivers do not react to turtles by trying to miss them, hit them, or move them off of the road. Although these assumptions are problematic (e.g., turtles often retract into their shells in response to danger), this model gives a reasonable approximation of the probability a turtle is killed given it crosses a road having a particular traffic rate.

We envision these tools being used to assist those making decisions about conservation actions for spotted turtles including (but not limited to) land protection and habitat management. Possible scenarios include:

1. In an area where little is known, helping refine areas for initial surveys of spotted turtles with the ultimate goal of protecting promising habitat with defensible populations.
2. In an area with anecdotal information (e.g., Heritage Element Occurrences), helping select sites in the most promising landscape settings for further assessment.
3. In areas where populations are well-documented, helping design a conservation plan that delineates high-quality habitat (assessed from model scores, aerial photography, site visits, and ideally, surveys), land most likely to provide habitat connectivity (again, assessed from the model and in the field), and mitigation measures where road mortality is likely to threaten the population.

In all of these scenarios (others are possible), model results and field work interact to support and challenge each other. The model can "see" issues that might not be obvious in the field, such as enticing wetlands on the other side of a busy road, or a wetland complex with a far more intact landscape setting a few miles away that might be a better conservation target. And, obviously, an experienced turtle biologist in the field can see all sorts of things the model is blind to. Of course the model is wrong—but, if it's doing its job well, it may help provide insights that are of great use. When decisions need to made, particularly those that are preliminary, in the absence of any information regarding the suitability of the landscape for spotted turtles, these conservation planning products will offer at least some baseline information to inform, not determine, those decisions.

We are interested in feedback on our approach from users in the conservation community. Several of the parameters we chose to produce cores (e.g., target percentages of LC, minimum core size) are completely arbitrary and could be chosen differently. It would be feasible for us to produce a second version of this model based on responses from conservationists. If you use (or try to use) this model, please share your thoughts with Brad Compton (bcompton@umass.edu).

Derivation of these layers

Conservation cores

As described above, we built potential conservation cores based on LC, using resistant kernels.

1. We found all cells where LC was in the top 10% of total LC in the landscape and designated these as regional seeds.
2. We found all cells where LC was in the top 1% of LC for its HUC6 watershed and designated these marginal seeds.
3. We combined regional and marginal seeds, and built resistant kernels originating at the seeds. Seeds of <5 cells (0.45 ha) were dropped. Landscape resistance was the complement of negative logistically-scaled LC (inflection point = 0.25; scaling factor = -0.05) times a multiplier of 4, thus the highest LC had a resistance of 1, and the lowest LC approached 4. For nonhabitat cells where LC is zero, resistance is set to the multiplier of 4 + the resistance, thus the resistance for nonhabitat is always ≥5. We used the estimated homerange length × 10, 2,650 m, as the bandwidth. As we used these kernels to select core areas, the scaling didn't matter, so we didn't do Gaussian scaling, as is usually done with resistant kernels.
4. We then found a slices of the kernels that captured a total of 20% of LC across the landscape. This is not necessarily the top 20%, as cores are intended to be contiguous conservation targets, and some smaller areas of high LC values will fall outside of cores. We sliced the kernels at this level to create preliminary cores.
5. We then dropped cores with a total area of <50 ha to create final cores. We calculated several stats for each core: core area (ha), area of nonzero LC in core (ha), sum of LC in core, sum of LC^2 in core, mean LC in habitat area, mean LC^2 in habitat area, and maximum LC in core. These statistics can be used to help prioritize cores if desired.

Connectivity

We assessed connectivity among spotted turtle cores using random low-cost paths. It would be straightforward to connect one or more points in each core to one or more points in each neighboring core with a least-cost path; however, there are a number of drawbacks to using least-cost paths. They typically select unrealistically narrow corridors (e.g., one cell wide—something that would be unlikely to be used by most migrating or dispersing animals). As a result, least-cost paths are sensitive to small GIS errors. They also ignore the number of alternatives, failing to distinguish between situations where there is a single path and situations where there are many alternatives. There are significant limits, therefore, to how usefully one can assess landscape connectivity with least-cost paths.

Our approach is to add some random variation to least-cost paths, making them sub-optimal and variable. We believe this approach, which we call random low-cost paths, more realistically represents the way animals move through the landscape, and more completely and robustly describes the connectivity between two areas. Random low-cost paths have three parameters: one that determines how random they are (ranging from deterministic least-cost paths to random walks), and two momentum parameters that determine the grain of randomness. For this project, we selected parameters that gave "reasonable" paths, as there is no direct biological interpretation of these parameters.

Spotted turtle conductance is derived from random low-cost paths as follows:

1. For each pair of spotted turtle cores within the designated threshold distance of 5.3 km (20 homerange lengths), we selected a fixed number of random points (e.g., 1,000) within each core (the "from-core").
2. For each neighboring core (the "to-core"), we constructed a random low-cost path from each of these points to the first point encountered in the neighboring core. Random low-cost paths are built on a resistant landscape based on the landscape movement resistance used in for the spotted turtle habitat model. This is done by following a resistant kernel built on a number of points in the to-core "uphill" from the from-core. The result was a set of 2,000 random low-cost paths between each nearby pair of cores in the landscape.
3. We measured the functional length of each path (i.e., path length) by adding the landscape resistance along the path's length. This gives path functional distance, which integrates the distance travelled along the path in meters with the resistance of the intervening landscape. The minimum resistance value is 1.0, so a 500 m long path through cells of optimal habitat (such as Laurentian-Acadian Freshwater Marsh) would have a functional distance of 500.
4. We converted path functional distance to path probability of connectivity using a Gaussian density function based on a bandwidth (standard deviation) representing dispersal ability. We used 5.3 km, or 20 homerange lengths. The Gaussian function represents a non-linear decay with distance, such that the probability of connectivity declines slowly at first with increasing functional distance and then declines rapidly as the functional distance increases further, and eventually declines to zero. Any path with a functional distance greater than the bandwidth is dropped.
5. Finally, we multiplied path probability of connectivity by the mean total LC of the two cores, assigned this value to each cell in the path, summed across all paths in the landscape, and let this be the regional conductance index. Total LC is a measure of both size and quality of each core, and is expected to be roughly equivalent to the expected population and thus number of dispersers in each core.

The spotted turtle conductance index is influenced by three major factors. First, the resistance of the intervening landscape between the nearby cores affects the magnitude of conductance; the greater the resistance of intervening landscape between the cores, the lower the probability of connectivity of the paths through the focal cell, and thus the lower the conductance. Second, the proximity of the nearby cores affects conductance, since the probability of connectivity decreases according to a Gaussian function of the functional distance between cores, and cores beyond a functional distance of one bandwidth are considered functionally disconnected. Third, the size and quality of the nearby cores affects conductance, since the path probability of connectivity is weighted by the total LC, thus the size and quality of the two cores connected by the path. Thus, cells with higher values are functionally closer to larger cores and indicate a greater probability that turtles will pass through these cells.

Road vulnerability

The road vulnerability model uses a model of road mortality given a traffic rate (Gibbs and Shriver 2002). The model gives an exact probability of mortality, given the assumptions (See Use and interpretation of this layer, above).

$$P(killed) = 1 - e^{\frac{-traffic \cdot (2 \cdot tirewidth + 2 \cdot turtlelength)}{velocity}}$$

where *tirewidth* = 25 cm, *turtlelength* = 11 cm, and *velocity* = 2 m/min. We reduce the estimated traffic rate by 20%, as 80% of traffic is typically during daylight hours. The probability of mortality is less than 1% with fewer than 50 cars/day, then increases rapidly between 100 and 10,000 cars/day, and rises above 99% at about 25,000 cars/day (Fig 2).

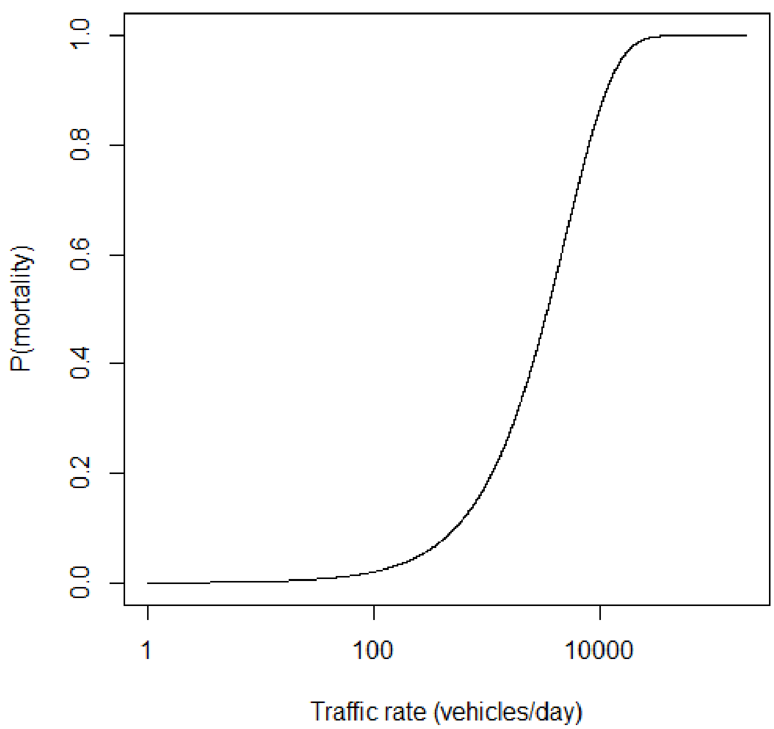

Fig 2. Modeled road-crossing mortality given traffic rate for spotted turtles.

We applied this model to the estimated road traffic rates for the DSL project at each road cell to get estimated probability of road mortality for crossing turtles. This probability is multiplied by conductance (which gives a relative estimate of the number of turtles expected to cross through each cell) to give a relative estimate of road vulnerability. Because conductance is in arbitrary units, road vulnerability does not have an absolute interpretation, but must be interpreted in a relative sense. A road cell with double the vulnerability of another would be expected to kill twice as many turtles. We dropped road vulnerability cells with values < 1. Finally, we took a focal sum in a circle with a radius of 3 cells to expand roads, as single-cell width roads are often hard to see in a GIS viewer.

GIS metadata

Results of this model are available in several GIS data layers that can be found at McGarigal et al (2017a). Spotted turtle Habitat Capability (HC), Climate Niche model (CN), Prevalence, and Landscape Capability (LC) are described in Compton and DeLuca (2020).

- **Spotted turtle cores** (polygon shapefile) of final cores, with the following fields:

1.	coreid	unique core id
2.	x	centriod x
3.	y	centriod y
4.	area	core area (ha)
5.	habitat_area	area of nonzero LC in core (ha)
6.	total_LC	sum of LC in core
7.	total_LC_squared	sum of LC^2 in core
8.	mean_LC	mean LC in habitat area
9.	mean_LC_squared	mean LC^2 in habitat area
10.	max_LC	maximum LC in core

- **Spotted turtle conductance** (connectivity) geoTIFF raster (30 m cells) gives a relative probability of turtles that migrate or disperse among cores crossing each cell. Values range from 0 (no crossings) to an arbitrary high value. This variable has been transformed with a square root for better display.

- **Spotted turtle road-crossing vulnerability** geoTIFF raster (30 m cells) gives a relative probability of traffic mortality for turtles moving among cores. Values range from 1 to an arbitrarily high value. Values have been expanded to adjacent cells to make the results easier to view, such that roads are depicted as 7-10 cells wide. This variable has been transformed with a square root for better display.

Acknowledgements

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