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TECHNICAL ARTICLE

An inventory of continental U.S. terrestrial candidate ecological restoration areas based on landscape context

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Landscape context is an important factor in restoration ecology, but the use of landscape context for site prioritization has not been as fully developed. We used morphological image processing to identify candidate ecological restoration areas based on their proximity to existing natural vegetation. We identified 1,102,720 candidate ecological restoration areas across the continental United States. Candidate ecological restoration areas were concentrated in the Great Plains and eastern United States. We populated the database of candidate ecological restoration areas with 17 attributes related to site content and context, including factors such as soil fertility and roads (site content), and number and area of potentially conjoined vegetated regions (site context) to facilitate its use for site prioritization. We demonstrate the utility of the database in the state of North Carolina, U.S.A. for a restoration objective related to restoration of water quality (mandated by the U.S. Clean Water Act), wetlands, and forest. The database will be made publicly available on the U.S. Environmental Protection Agency's EnviroAtlas website (http://enviroatlas.epa.gov) for stakeholders interested in ecological restoration.

Key words: biodiversity, ecosystem services, landscape ecology, Morphological Spatial Pattern Analysis, NLCD

Implications for Practice

- Site prioritization is an underdeveloped aspect of the science and practice of ecological restoration.
- We developed a continental U.S. database of candidate ecological restoration areas that includes 17 attributes related to site content and context to support site prioritization for a suite of different restoration objectives.
- The database will be posted on a public-facing website (http://enviroatlas.epa.gov) to facilitate stakeholder use.

Introduction

Three inter-related research issues have been important since the emergence of restoration ecology (Bradshaw 1993): (1) the relationship between societal involvement and restoration success (Aronson et al. 2010; Knight et al. 2011); (2) economic costs and benefits of restoration activities (BenDor et al. 2015; Kimball et al. 2015); and (3) the ecological efficacy of restoration activities (Rey Benayas et al. 2009; Suding 2011). There has been less emphasis on the question of where restoration should be located. For example, although it is being evaluated for its currency (Shackelford et al. 2013), the Society of Ecological Restoration (SER) primer (SER 2004) does not mention the importance of location to restoration outcomes, and location is discussed only as an a priori known entity in the SER guidelines for developing and managing restoration projects (SER 2005). Although others have recognized the importance of location to successful ecological restoration outcomes (Holl & Aide 2011; Suding 2011), site prioritization has yet to be incorporated as an element in the restoration ecology paradigm (e.g. SER 2004, 2005; Shackelford et al. 2013; Perring et al. 2015).

Restoration ecologists recognize the importance of landscape context—the set of earth surface features surrounding a particular site and the pattern in which the features are arranged—to successful outcomes (Holl et al. 2003; Shackelford et al. 2013; Perring et al. 2015). Many studies have found that the success of revegetation tends to increase nearby extant vegetation (Bakker & Berendse 1999; Crossman & Bryan 2006; Martin & Kirkman 2009; Meinke et al. 2009; Thomson et al. 2009), suggesting that location, an aspect of landscape context, is important to realizing objectives. In arid and semiarid systems, successful ecological restoration outcomes require an understanding of the interactions between vegetation patterns and rain events (Tongway & Ludwig 2011, 2012; Okin et al. 2015). Improving habitat connectivity for a given species has focused on finding the best locations to remove barriers (McRae et al. 2012; Torrubia et al. 2014). It would be appropriate to classify these ecological restoration studies as site prioritization studies, because they

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focused on the importance of place for the reestablishment of processes. In the same way, site prioritization is becoming a standard of practice for restoring waters identified as impaired under the U.S. Clean Water Act (33 U.S. Code §1251) (Norton et al. 2009; https://www.epa.gov/rps). Identifying where landscape processes should be restored is an important aspect of the science and practice of restoration ecology (e.g. Tongway & Ludwig 2011, p 25).

Our objective is to describe and demonstrate the use of a database of candidate ecological restoration areas for the continental United States that can be used for site prioritization. The database was developed to assist practitioners interested in using geographic data to inform their choice of location for a particular intervention, and researchers interested in evaluating the importance of proximity and connectedness to successful outcomes (Matthews et al. 2009; Grman et al. 2013). The database identifies areas proximal to extant areas of natural vegetation, and includes 17 attributes related to both site content (e.g. soil productivity) and context (e.g. amount of surrounding vegetation) so that it can support site prioritization studies for many different restoration objectives. Database development was based on proximity to extant vegetation because revegetation is a common means of ecological restoration (Young 2000; Perring et al. 2015). The database will be posted on the U.S. Environmental Protection Agency's (EPA) EnviroAtlas website (http://enviroatlas.epa.gov). The purpose of EPA's EnviroAtlas is to provide stakeholders with data and tools for understanding the benefits people receive from nature (Pickard et al. 2015).

Methods

Overview

We analyzed spatial patterns on a raster land cover map to understand how the spatial structure of extant continental U.S. vegetation is related to opportunities for ecological restoration. Candidate areas for revegetation were identified from the existing vegetation patterns. The raster candidate areas were then converted to vector format to better accommodate the common Geographic Information System (GIS) routines and national-scale geographic data that were used to assign attributes values (e.g. road length) to each site. Raster-to-vector conversion was implemented so that the native raster boundary of the candidate ecological restoration areas was maintained when they were converted to polygons (i.e. raster-to-vector conversion did not generate "sliver" polygons). We then generated a null set of ecological restoration areas and compared selected database attributes between the null sites and the candidate sites. Comparison of the null and candidate sites was done to demonstrate how use of location (candidate sites) resulted in differences in characteristics between the two types of sites. Following comparison of null and candidate sites, we used the candidate ecological restoration areas database in combination with geographic data related to conservation and restoration from the state of North Carolina to demonstrate site prioritization.

Table 1. MSPA class descriptions (see Wickham et al. 2010).

Class	*Description*
Core	Foreground surrounded by foreground and greater than the user-specified edge width from background
Edge	Foreground that separates core from background
Perforation	Foreground that separates core from interior areas of background
Bridge	Linearly oriented foreground that connects two disjunct core areas
Loop	Linearly oriented foreground that extends from core and connects back to the same core area (e.g. a handle)
Branch	Linearly oriented foreground that extends from core and terminates in background
Islet (patch)	Area of foreground that is too small to contain core

Data and Processing

We used the 2011 National Land Cover Database (NLCD) for the continental United States as input into Morphological Spatial Pattern Analysis (MSPA), the spatial pattern software. NLCD is a 30 m × 30 m (0.09 ha) land cover product derived from Landsat Thematic Mapper (TM) satellite data and several sources of ancillary data (Homer et al. 2015). The NLCD 2011 16-class legend includes three categories of forest, four categories of urban development, two categories each of agriculture and wetland, and single categories for shrubland, grassland, barren, water, and perennial ice and snow (http://www.mrlc.gov/nlcd11_leg.php). The NLCD 2011 land cover data were reclassified into a binary map of foreground and background to meet MSPA processing requirements. The NLCD forest, shrubland, grassland, and wetland classes were considered to be foreground because those classes represent the vegetation of interest. The urban, agriculture, water, barren, and perennial ice and snow classes were reclassified as background. The producer's accuracies for the NLCD 2011 forest, shrubland, grassland, and wetland classes were 88, 90, 88, and 91%, respectively (Wickham et al. 2017).

MSPA identifies the structural elements of foreground from the binary map of foreground and background (Soille & Vogt 2009). There are two primary, user-specified parameters in MSPA—connectivity and edge width. Connectivity can be either four or eight neighbor, where four defines adjacency as a focal pixel with like-classified immediate neighbors at all four pixel edges (i.e. rook's case) and eight defines adjacency as a focal pixel with like-classified neighbors at all edges and corners (i.e. queen's case). Edge width defines the length (in pixels) that separates background from interior regions of foreground. We set connectivity and edge width parameters to eight and one, respectively. MSPA output includes seven classes (Table 1): core, edge, perforation, bridge (corridor), loop, branch, and islet (patch). The MSPA branch class was used as the basis for identification of candidate ecological restoration areas. The branch class can be thought of as a base or terminus of a potential

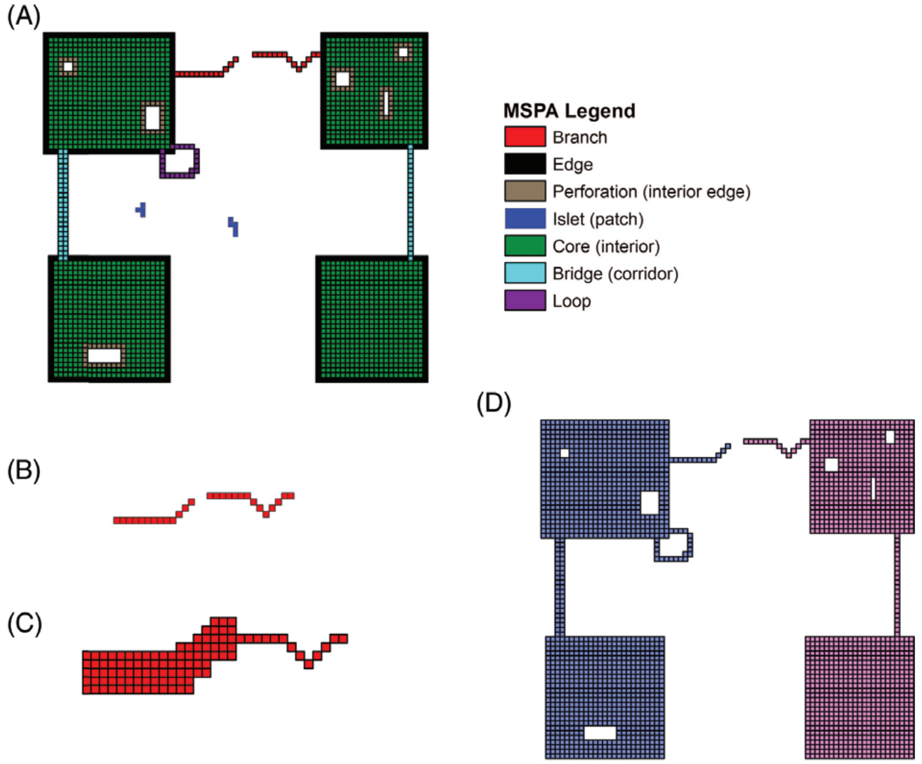

Figure 1. Identification of candidate ecological restoration areas by (A) generation of MSPA output, (B) extraction of MSPA branches, (C) expansion and regionalization of MSPA branches, and (D) regionalization of MSPA output. Overlay of panels C and D was used to identify candidate restoration areas. Expansion of only one branch in panel C is shown for clarity. Expanded branches can also connect directly to a MSPA vegetated region.

corridor that could, if extended (revegetated), connect two spatially disjunct core areas.

Identifying and Describing Candidate Ecological Restoration Areas

Candidate restoration areas were identified using GIS software by (1) extracting the MSPA branch class, (2) expanding (growing) the map of extracted branches, (3) regionalizing the map of extracted and expanded branches and the MSPA map, and (4) overlaying the regionalized map of extracted and expanded branches and the regionalized MSPA map (Fig. 1). Extracted branches (step 1) were expanded (step 2) by two pixels (i.e. 60 m linear distance). We chose a rather small distance to constrain the size of the candidate areas because ecological restoration can be expensive (De Groot et al. 2013). In step 3, we regionalized the expanded branches and the seven-class MSPA output, which assigned a unique numerical identifier to each geographically distinct feature (Wickham et al. 2010). The regionalized expanded branches and MSPA maps were then overlaid (step 4) to determine where, if restored, extension of branches would connect two (or more) MSPA regions. The candidate areas were identified in the tabular output that results from the overlay of the two regionalized maps. Each expanded and regionalized branch that overlays more than one MSPA region will have one record in the table for each MSPA region that it intersects. Summary files of the tabular output were used to extract only the expanded and regionalized branches that intersected two or more MSPA regions, the candidate areas for ecological restoration. This raster map was then converted to a vector format to facilitate database development.

Geographic attributes were included in the candidate ecological restoration areas database if they were (1) available across the continental United States and (2) relevant to ecological restoration. A total of 17 attributes (Table 2) were included in the database. The set of 17 attributes includes information about a candidate site's content (e.g. site area, soil productivity) and landscape context (e.g. number and overall size of MSPA vegetated regions). Common GIS overlay algorithms were used to assign attribute values to the candidate ecological restoration areas. Although our approach for identifying candidate ecological restoration areas emphasizes location and landscape context, which may be more intuitively related to revegetation success (Crossman & Bryan 2006; Martin & Kirkman 2009; Thomson et al. 2009), many of the database attributes can be used to address other ecological restoration goals. For example, roads are a prominent source of water pollution in streams (Trombulak & Frissell 2000). Revegetation of candidate sites with roads and streams may address water pollution issues in addition to potentially improving the likelihood of successful revegetation. Additional information about database design and characteristics, the relationship between database design and landscape connectivity, and the data sources and

Table 2. Candidate ecological restoration area database attributes.

Attribute	*Description*
Area	Size (ha) of candidate restoration area
Number of MSPA regions	Number of MSPA regions connected by candidate area restoration
Conjoined MSPA area	The total area (ha) of MSPA regions potentially connected by candidate area restoration
Net 1	Area (ha) of largest MSPA region connected by candidate area
Net 2	Area (ha) of second largest MSPA region connected by a candidate area
pNet	Net 2/(Net 1 + Net 2)
Road length (RdL)	Candidate area total NAVTEQ road length (km)
Light duty road length (RdL5)	Candidate area total NAVTEQ functional class = 5 road length (km)
Stream length (StrL)	Candidate area total stream length (m)
Impaired stream length (L303d)	Candidate area total impaired stream length (m)
CEC05	Candidate area mean cation exchange capacity, 0–5 cm depth (meq/100 g soil)
CEC0520	Candidate area mean cation exchange capacity, 5–20 cm depth (meq/100 g soil)
Potentially restorable wetland (pPRW)	Proportion of candidate area that may support wetland restoration
Proportion islet (pislet)	Proportion of candidate area classified as MSPA islet class
Proportion urban (purban)	Proportion of candidate area classified as NCLD urban classes
Proportion water (pwater)	Proportion of candidate area classified as NCLD water class
Proportion barren (pbarren)	Proportion of candidate area classified as NCLD barren class

GIS methods used to assign attribute values to the candidate ecological restoration areas are provided as Appendix S1, Supporting Information.

Comparison to Null Model

Using the MSPA background classes of urban, agriculture, and barren, and masking all classes used as MSPA foreground, water, and perennial ice and snow, we randomly selected more than 1,000,000 pixels, expanded the selected pixels by two pixels, and assigned selected attributes to the expanded set. We compared percentile values of selected attributes to show how the candidate ecological restoration areas were different from a null set of sites. The attributes selected for comparison were site area, conjoined MSPA region size, road length, stream length, cation exchange capacity (CEC; 0–5 cm soil depth), and the proportion of a site that had potential for restoring wetlands.

Demonstration

To demonstrate how the database of candidate restoration sites can be queried to prioritize sites whose characteristics are likely to facilitate specified restoration goals, we overlaid the database with an existing conservation planning database from the state of North Carolina (NC), U.S.A. The NC database was developed by the State's Department of Natural Resources (http://portal.ncdenr.org/web/cpt/cpt-report). The NC data includes priority forest lands for urban and rural conservation and restoration (hereafter "NC forest lands"), as well as many other geographic datasets. The NC forest lands dataset is a result of a statewide assessment, in collaboration with the U.S. Forest Service, to identify where U.S. federal restoration investment in counties with either small or large urban areas can help maintain healthy forests that face external threats (e.g. urbanization). It has five priority levels (very low, low, medium, high, and very high). We combined these data (http://data.nconemap.gov/geoportal/catalog/main/home.page) with our candidate ecological areas, specifically focusing on NC forest lands that were identified as high and very high, and the attributes from the candidate ecological restoration areas database that describe the potential for wetland restoration (pPRW) and water impairment (L303d). The focus on impaired waters, which must be restored as mandated by the U.S. Clean Water Act, pPRW, and high and very high priority forest restoration areas has the potential to attract investment from multiple stakeholders, which is an intended use of the NC forest lands dataset (http://portal.ncdenr.org/c/document_library/get_file?uuid=f5a4b6d8-76db-44a2-921c-ca90bf65d340&groupId=5118315).

Results

We identified 1,102,720 candidate ecological restoration areas across the continental United States. Candidate ecological restoration areas were more prevalent east of 100°0′0″ W than to the west. In the east, there were relatively few candidate ecological restoration areas in the extensively forested areas of Adirondack State Park, New York, and northern Maine (Fig. 2) because these areas are extensively forested and relatively unfragmented by agriculture, urban, or barren land cover. Many western watersheds had no candidate ecological areas because the NLCD forest, shrubland, and grassland classes tended to form expansive, uninterrupted polygons in this region when combined into a single class for this pattern analysis. Watersheds with the highest densities of candidate sites ($\geq$1 site/km^2) occurred in Michigan and other areas scattered throughout the eastern United States. Less than 1% of all watersheds (approximately 400) had a density of $\geq$1 site/km^2, and 25% of all

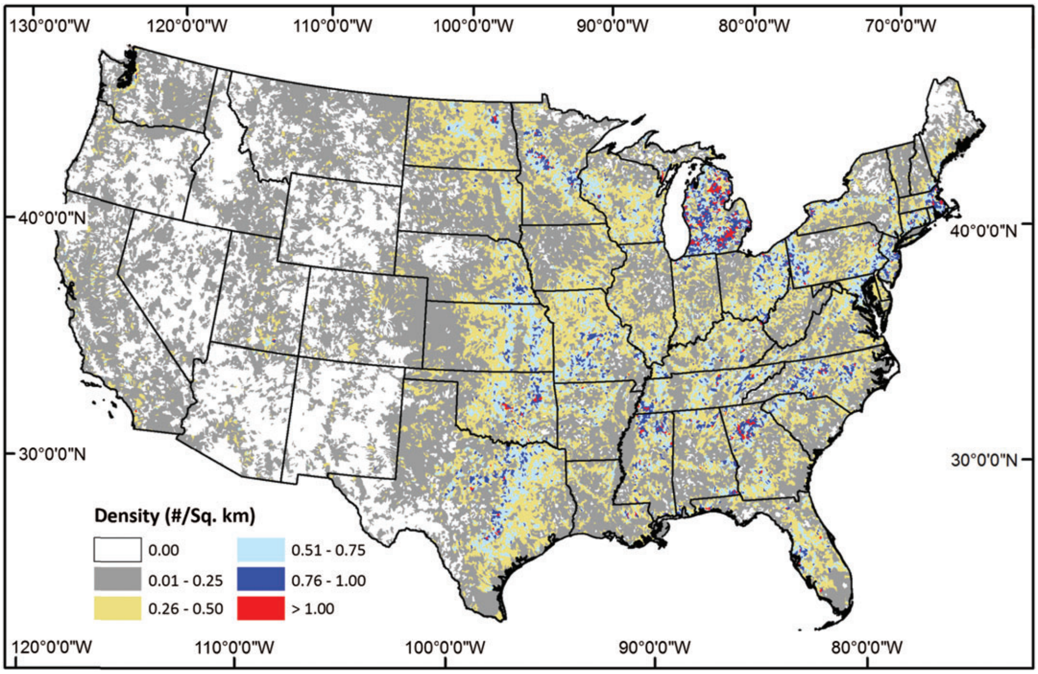

Figure 2. Density of candidate ecological restorations areas by watershed.

watersheds (approximately 20,500) had no candidate ecological restoration areas.

Candidate restoration areas were small because of the 60-m limit we imposed on the expansion of MSPA branches. Whereas the candidate site median size was approximately 15 ha (Fig. 3A), the median size of conjoined MSPA regions if restoration was completed was approximately 1,000 ha (Fig. 3B). The size of the largest MSPA vegetated region was an order of magnitude larger than the size of the second largest MSPA vegetated region (Appendix S1, Fig. S1A & S1B), and the median proportional increase in area contributed by the second largest MSPA vegetation region to the conjoined MSPA vegetated region was 8% (Appendix S1, Fig. S1C). Approximately 25% of the candidate restoration sites were roadless (Fig. 3C), and 60% of the sites with roads had only “light duty” roads (Appendix S1, Fig. S1D). Approximately 40% of the restoration areas had streams (Fig. 3D), and impaired streams were much less frequent, occurring in only 8% of the candidate ecological restoration areas (Appendix S1, Fig. S1E). The median value of average CEC across the candidate sites was 13 (meq/100 g of soil) in the upper 5 cm of soil (Fig. 3E), and decreased only slightly at a soil depth range of 5–20 cm (Appendix S1, Fig. S1F). Topographic and soil conditions that may be conducive to wetland restoration also occurred in 40% of the candidate sites (Fig. 3F). MSPA islets (small patches of unconnected remnant vegetation), barren, and water were rare occurrences in candidate restoration areas (Appendix S1, Fig. S2). Nearly 90% of the candidate restoration areas had less than 50% urban land cover (Appendix S1, Fig. S2C), indicating that agriculture was the predominant land cover across the candidate sites.

Null sites tended to be smaller and more poorly connected to the surrounding natural vegetation than candidate sites (Fig. 3A & 3B). Null sites were smaller and had a uniform size distribution because they occurred predominantly in agriculture distal to extant vegetation. For the same reason, null sites were less likely to conjoin MSPA vegetated regions and conjoined MSPA vegetated regions were smaller in size when they did occur (e.g. Midwest United States). Because of their small size, null sites tended to be roadless and without streams, whereas roads and streams were much more common in the candidate sites (Fig. 3C & 3D). It was not surprising that roads were more common in candidate sites because roads are a prominent agent of fragmentation in the continental United States (Riitters & Wickham 2003) and therefore roads are likely to split corridors into branches (see Fig. 1). Average CEC was about equivalent across both sets of sites (Fig. 3E). Areas suitable for wetland restoration occurred with about equal frequency in null and candidate sites, but occupied a greater proportion of area in null sites than in candidate sites (Fig. 3F). The tendency for potentially restorable wetlands to occupy a greater proportion of area in null sites than candidate sites is probably attributable to the small size of null sites and their tendency to occur in agriculture, which was used to define the potentially restorable wetlands attribute (Appendix S1, Methods).

There were more than 33,000 candidate ecological restoration areas in North Carolina. Approximately 650 of the candidate ecological restoration areas in North Carolina included NC forest lands rated as high or very high priority, impaired waters, and areas suitable for wetland restoration (Appendix S1, Fig. S3). To illustrate the results, we highlight one example where streamside restoration would have the potential to improve

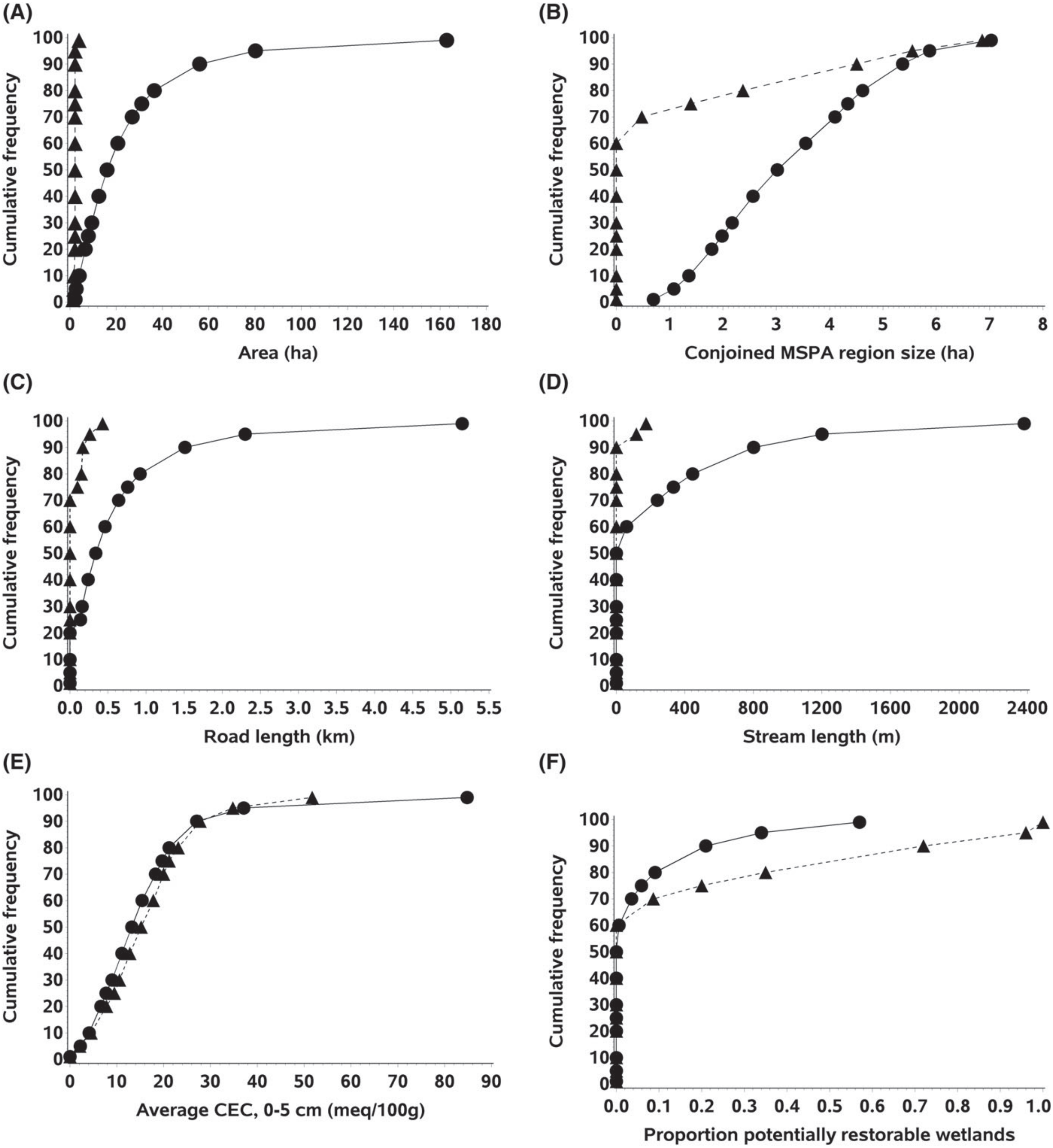

Figure 3. Cumulative frequency distributions for candidate (●) and null sites (Δ) for (A) area, (B) conjoined MSPA region size ($\log_{10}$), (C) road length, (D) stream length, (E) average cation exchange capacity (CEC) in the top 5 cm of soil, and (F) proportion of potentially restorable wetlands. The panel B x-axis is formatted as 10^x, where the displayed values equal x. Symbols represent percentiles 1, 5, 10, 20, 25, 30, 40, 50, 60, 70, 75, 80, 90, 95, and 99, but some may be obscured due to overprinting.

Figure 4. Candidate ecological restoration area (black), impaired stream (blue), and potentially restorable wetland areas (yellow) in southeastern North Carolina overlaid on an 25 October 2016 Google Earth™ image. The section of the impaired stream inside the candidate site is not shown so that the potentially restorable wetlands were not obscured. The approximate location of Prospect, NC is 34°53′00″ N, 79°13′47″ W.

water quality, restore wetland forest, and increase forest spatial extent (Fig. 4). Use of the database attributes and other geographic data reduced the number of possible sites for consideration to 2% of the total number of candidate sites in North Carolina, providing an example of how the database can be queried to prioritize sites whose characteristics are likely to facilitate specified restoration goals (Table 3).

Table 3. Frequencies of candidate ecological restoration sites by database attributes. The examples are not intended to be exhaustive.

Database attributes	*Count*	*%*
MSPA size > 250 ha	707,494	64
Minimum size of second largest MSPA region > 25 ha	473,494	43
Roadless sites and minimum size of second largest MPSA region > 25 ha	66,981	6
Roadless sites with potentially restorable wetlands, and no urban	72,337	7
Sites with streams, potentially restorable wetlands, and no urban	37,810	3
Sites with impaired streams and potentially restorable wetlands	48,669	4
Sites with no roads or only light duty roads and MSPA size > 500 ha	402,292	37
Roadless sites with cation exchange capacity in the upper 50th percentile	123,470	11
Candidate site area > 50 ha with streams and without urban	6,995	1

Discussion

Our objective was to develop a database that could encourage site prioritization based on landscape context in the science and practice of ecological restoration. This objective was based on the conceptual idea that location is an important factor for determining the likelihood of restoration success (Holl & Aide 2011; Suding 2011). The nationwide (continental United States) database includes attributes representing site content and context for each candidate site, and is designed for use in a GIS. The database attributes are relevant to prioritization for a range of different restoration objectives (e.g. water quality, reforestation, habitat improvement).

Using selected database elements and other geographic data, we demonstrated an application of the database that addressed three inter-related restoration goals: water quality, wetland restoration, and reforestation. Two objectives of the demonstration were to show the potential to attract several stakeholders through inclusion of multiple restoration objectives, and also to incorporate policy relevance by inclusion of a site that had an impaired stream. Restoration of impaired waters is mandated by the U.S. Clean Water Act. The demonstration shows how the database could be used to reduce a very large set of candidate sites to a much more manageable set (33,000 to 650) that would more easily facilitate the detailed planning (e.g. land ownership, high resolution imagery, field surveys, interviews) that would be required for site selection if such an ecological intervention was undertaken. The demonstration was supported by a simpler screening analysis using only the elements in the candidate ecological restoration database. For example, those interested in wetland restoration could extract the sites within their area of interest that had the potential for such restoration and other attributes in the database that addressed their particular objectives.

As is probably true with all databases, there are limitations to the one we have constructed for this research. The database was constructed on the assumption that revegetation would be a prominent means of restoration; it is probably less useful for restoration objectives that do not include revegetation. As noted earlier, the accuracy of the land cover classes used to identify candidate sites was approximately 90% (Wickham et al. 2017), which suggests, as a general rule-of-thumb, that approximately 10% of the candidate sites may be wrongly identified as a result of land cover misclassification. The thematic resolution of the NLCD data may also be limiting for some restoration objectives. For example, restoration of sagebrush steppe in the western United States is an important environmental issue that is supported by an active research community (http://www.sagestep.org). It would be difficult to use the database described here to support sagebrush restoration because the thematic resolution of NLCD does not distinguish sagebrush from other types of shrublands. The database can be used to inform restoration projects where generalized land cover categories (e.g. forest, agriculture, urban) are meaningful.

Young (2000) suggested that ecological restoration may be a prominent form of environmental conservation in the future due to trends in population growth, land abandonment, land degradation, and other factors (Daily 1995; Merrit & Dixon 2011). The findings by BenDor et al. (2015) that ecological restoration is a multibillion dollar (USD), job-creating industry in the United States and recent global interest in ecological restoration at very large spatial scales (Menz et al. 2013; Suding et al. 2015) are consistent with an increase in the prominence of ecological restoration. The science supporting the practice of ecological restoration has kept pace with its growth by developing guidelines, principles, and important areas of research (Shackelford et al. 2013; Perring et al. 2015), but the importance of site prioritization to successful outcomes has been largely overlooked (Holl & Aide 2011; Suding 2011). Development of a database of candidate sites suitable for site prioritization, and its dissemination through EPA's EnviroAtlas website (http://enviroatlas.epa.gov) was undertaken to further advance of the science and practice of ecological restoration.

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Supporting Information

The following information may be found in the online version of this article:

Appendix S1. Additional information on database, data sources, and GIS methods.

Table S1. NAVTEQ™ NAVSTREETS functional class descriptions (adapted from user's manual).

Figure S1. Cumulative frequency distributions for of candidate ecological restoration area attributes (A) Net 1, (B) Net 2, (C) pNet, (D) ratio of road length to "light duty" road length, (E) impaired streams, and (F) average cation exchange capacity (5–20 cm) across a site.

Figure S2. Cumulative frequency distributions for of candidate ecological restoration area attributes (A) proportion islet, (B) proportion urban, (C) proportion water, and (D) proportion barren.

Figure S3. Candidate ecological restoration areas in North Carolina that include NC forest lands identified as high and very high priorities for conservation or restoration, waters identified as impaired under the U.S. Clean Water Act, and conditions suitable for wetland restoration.

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