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A national assessment of green infrastructure and change for the conterminous United States using morphological image processing

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ABSTRACT

Green infrastructure is a popular framework for conservation planning. The main elements of green infrastructure are hubs and links. Hubs tend to be large areas of 'natural' vegetation and links tend to be linear features (e.g., streams) that connect hubs. Within the United States, green infrastructure projects can be characterized as: (1) reliant on classical geographic information system (GIS) techniques (e.g., overlay, buffering) for mapping; (2), mainly implemented by states and local jurisdictions; and (3) static assessments that do not routinely incorporate information on land-cover change. We introduce morphological spatial pattern analysis (MSPA) as a complementary way to map green infrastructure, extend the geographic scope to the conterminous United States, and incorporate land-cover change information. MSPA applies a series of image processing routines to a raster land-cover map to identify hubs, links, and related structural classes of land cover. We identified approximately 4000 large networks (>100 hubs) within the conterminous United States, of which approximately 10% crossed state boundaries. We also identified a net loss of up to 3.59 million ha of links and 1.72 million ha of hubs between 1992 and 2001. Our national assessment provides a backbone that states could use to coordinate their green infrastructure projects, and our incorporation of change illustrates the importance of land-cover dynamics for green infrastructure planning and assessment.

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1. Introduction

Green infrastructure extends the concept of built-up area needs to conservation of the natural environment (Lewis, 1964; McHarg, 1969; Noss and Harris, 1986; Benedict and McMahon, 2002, 2006; Jongman, 1995, Jongman et al., 2004; Fábos, 2004). It is a broadly encompassing concept because of its objective to harmonize communities with the natural systems on which they depend (Benedict and McMahon, 2006). Development of community parks and recreation trails, stream restoration, storm water management, and land conservation are all within the broad scope of green infrastructure. It is viewed as a conceptual advance in environmental planning (sensu Hoctor et al., 2008) because it integrates natural systems with community well being (see also Nassauer, 2006). Though broad in theme and spatial scale, green infrastructure projects all share the common goal of sustainable land management planning (Leitão and Ahern, 2002; Weber, 2004; Ahern, 2007).

A significant area of green infrastructure research is related to identification and mapping of ecological networks (Lewis, 1964; Noss and Harris, 1986; Hoctor et al., 2000; Benedict and McMahon, 2002; Carr et al., 2002; Weber, 2004; Weber et al., 2006; Hoctor et al., 2008). The two primary components of ecological networks are hubs and links (sensu Benedict and McMahon, 2002). Hubs are areas of natural vegetation, other open space, or areas of known ecological value, and links are the corridors that connect the hubs to each other. A set of hubs connected by links constitutes a network that can be used to inform conservation-related land-use decisions.

The use of green infrastructure networks represents a strategic approach (Benedict and McMahon, 2006) in that decisions about conservation, protection, and restoration can incorporate information on how potential sites fit within a network that spans a larger area (see also Opdam et al., 2006). In the United States (USA), several states and local jurisdictions have recognized the value of a green infrastructure perspective for conservation decision-making (Benedict and McMahon, 2006; Table 1). Lewis' (1964) greenways plan for Wisconsin was used by the State for land acquisition (Smith, 1993). In 1993, Florida instituted a greenways commission for protection and conservation of Florida natural areas (Benedict and McMahon, 2006), and Hoctor et al. (2000) developed a green infrastructure network for the State to meet commission needs and objectives. The network proposed by Noss and Harris (1986) was used to guide protection of the Florida

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Table 1
Green infrastructure initiatives.

The Conservation Fund	www.greeninfrastructure.net
Florida	www.greeninfrastructure.net/content/project/floridas-ecological-network
Maryland	http://www.dnr.state.md.us/greenways/gi/gi.html www.greenprint.maryland.gov/
New Jersey	www.gardenstategreenways.org
North Carolina	www.onencnaturally.org/pages/CPT_Details.html
Virgina	www.dcr.virginia.gov/natural_heritage/vclna.shtml
New England	www.umass.edu/greenway
Southeast	www.geoplan.ufl.edu/epa
Chesapeake Bay	http://www.chesapeakebay.net/resourcelandsassessment.aspx?menuitem=19096

The Conservation Fund site lists several initiatives that in total demonstrate the local to statewide perspective that characterizes green infrastructure projects. (All URLs were accessed on October 26, 2009.)

panther, and also fostered formation of the Florida Greenways Commission. Maryland mapped its green infrastructure (Weber et al., 2006) in response to state-mandated conservation initiatives (www.greenprint.maryland.gov). Many states in the USA have made use of green infrastructure for conservation planning (Table 1).

Although there are notable exceptions in the USA (e.g., Noss and Harris, 1986; Carr et al., 2002; Fábos, 2004; Weber, 2004, www.y2y.net), green infrastructure projects tend to be local or statewide endeavors (Fábos, 2004; Benedict and McMahon, 2006, Table 1). Green infrastructure plans are better able to address the connectivity they seek to achieve when political boundaries are removed (Fábos, 2004). In this paper, a nationally focused green infrastructure assessment was conducted to add the context that is lost when sub-national boundaries are imposed. We enriched the context that a national-scale focus brings by also including temporal land-cover change in green infrastructure. Incorporation of change is important because green infrastructure projects are plans that do not guarantee conservation and preservation by themselves. Hoctor et al. (2000), Carr et al. (2002), and Weber et al. (2006) all found that less than 50% of their mapped green infrastructure networks were protected. Land-cover change is probable during green infrastructure planning, and information on it has the potential to guide decisions.

We use morphological spatial pattern analysis (MSPA) (Soille and Vogt, 2009) to map green infrastructure networks for the conterminous USA. Green infrastructure mapping commonly exploits the overlay of different thematic layers (e.g., Hoctor et al., 2000; Carr et al., 2002; Weber, 2004; Weber et al., 2006) first advocated by McHarg (1969) that is characteristic of geographic information system (GIS) software used today. Hubs are commonly defined through GIS overlay of several features of interest, and links are defined primarily by river networks. MSPA, which is based on concepts from mathematical morphology (Soille, 2003), identifies hubs and links from a single land-cover map rather than GIS overlay of several maps by creating structure from the spatial relationships among land-cover features.

2. Methods

2.1. Data

Land cover is a foundation of green infrastructure network mapping (Hoctor et al., 2000; Carr et al., 2002; Weber, 2004; Weber et al., 2006). We used the NLCD land-cover change data (Fry et al., 2009) to map green infrastructure networks and to assess change in network structure for the conterminous USA. The early and late dates of the NLCD land-cover change data (Fry et al., 2009) are ca. 1992 and ca. 2001, covering an approximate 10-year period. The NLCD land-cover change data (Fry et al., 2009) were developed for temporal comparisons of the NLCD 2001 (Homer et al., 2007) and the NLCD 1992 (Vogelmann et al., 2001). The NLCD land-cover change data include an eight-class legend (water, ice, urban, bare ground, forest, shrubland, agriculture, wetland), at the native 30-meter (m) spatial resolution of Landsat Thematic Mapper (TM) data. We used the 2001 component to report and describe green infrastructure for those analyses that did not consider change (e.g., current status of green infrastructure for the conterminous USA).

We chose forest and wetland as our focal classes for green infrastructure network mapping, setting all other classes to background. We chose these classes because forests and wetlands are important resources to the USA. Assessments of forest are common because of their importance (e.g., Riitters et al., 2004), and size and connectedness are important factors of such assessments (Noss, 1999; Riitters et al., 2004). Our use of green infrastructure for forest assessment is consistent with the forest frontiers study (see Noss, 1999). We included wetlands along with forest because the NLCD land-cover change data (Fry et al., 2009) do not distinguish between woody and emergent wetlands. Change in forested wetlands would have been excluded if we had not included the wetlands class. Wetland, in addition to forest, is an important land-cover class for green infrastructure network mapping (Hoctor et al., 2000; Carr et al., 2002; Weber, 2004; Weber et al., 2006).

2.2. MSPA and green infrastructure network mapping

After reclassifying a raster land-cover map into foreground (forest and wetland) and background (all other classes), MSPA uses a series of image processing routines to identify hubs, links (corridors), and other features that are relevant to green infrastructure assessments (Vogt et al., 2007). The green infrastructure elements identified by MSPA include core, islet, bridge, loop, branch, edge, and perforation (Soille and Vogt, 2009) (Table 2). In the terminology of green infrastructure, core is equivalent to hub, and bridge is equivalent to link (corridor). MSPA processing starts by identifying core, which is based on the connectivity rule used to define neighbors and the value used to define edge width (Soille and Vogt, 2009). Connectivity can be set to either four (cardinal directions only) or eight neighbors. Edge width affects the minimum size of core and the number of pixels classified as core (Fig. 1). Increasing edge width increases the minimum size of core, thereby reducing the number of pixels classified as core. The 'loss' of core that results from increasing edge width results in gains for all other classes, not just edge (Table 3). Increasing edge width can change core to islet if the area of core is small, and core to bridge if the area of core is narrow (see Fig. 1). We used eight-neighbor connectivity and edge width values of one (1), two (2), and four (4) for this analysis. The physical distance (width) of edge translates to 30 m, 60 m, and 120 m for values one (1) two (2) and four (4), respectively, as a result of the native 30 m pixel size of the Landsat TM imagery used to produce the NLCD (Homer et al., 2007; Fry et al., 2009). Edge