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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

Table 2
Definition of MSPA classes.

Core	Foreground pixels surrounded on all sides by foreground pixels and greater than the specified edge width distance from background.
Bridge	Foreground pixels that connect two or more disjunct areas of core.
Loop:	Foreground pixels that connect an area of core to itself.
Branch	Foreground pixels that extend from an area of core, but do not connect to another area of core.
Edge	Pixels that form the transition zone between foreground and background.
Perforation	Pixels that form the transition zone between foreground and background for interior regions of foreground. Consider a group of foreground pixels in the shape of a doughnut. The pixels forming the inner edge would be classified as perforations, whereas those forming the outer edge would be classified as edge.
Islet	Foreground pixels that do not contain core. Islet is the only unconnected class. Edges and perforations surround core, and loops, bridges and branches are connected to core.

Table 3
MSPA class proportions for edge width equal to 30 m, 60 m, and 120 m.

Class	Edge width = 30 m	Edge width = 60 m	Edge width = 120 m
Branch	0.037	0.056	0.051
Edge	0.134	0.143	0.095
Islet	0.021	0.045	0.091
Core	0.731	0.579	0.361
Bridge	0.030	0.104	0.327
Loop	0.019	0.048	0.062
Perforation	0.028	0.025	0.013
Total	1.000	1.000	1.000

Proportions sum to one (1). Total is the amount of foreground (forest and wetland) in the map (see Section 2).

width can be set to any integer multiple of the pixel resolution (http://forest.jrc.ec.europa.eu/biodiversity/GUIDOS/).

Additional GIS processing was conducted to organize MSPA core and bridge classes into ecological networks of disjunct core areas connected by bridges. Connectivity among disjunct areas of core

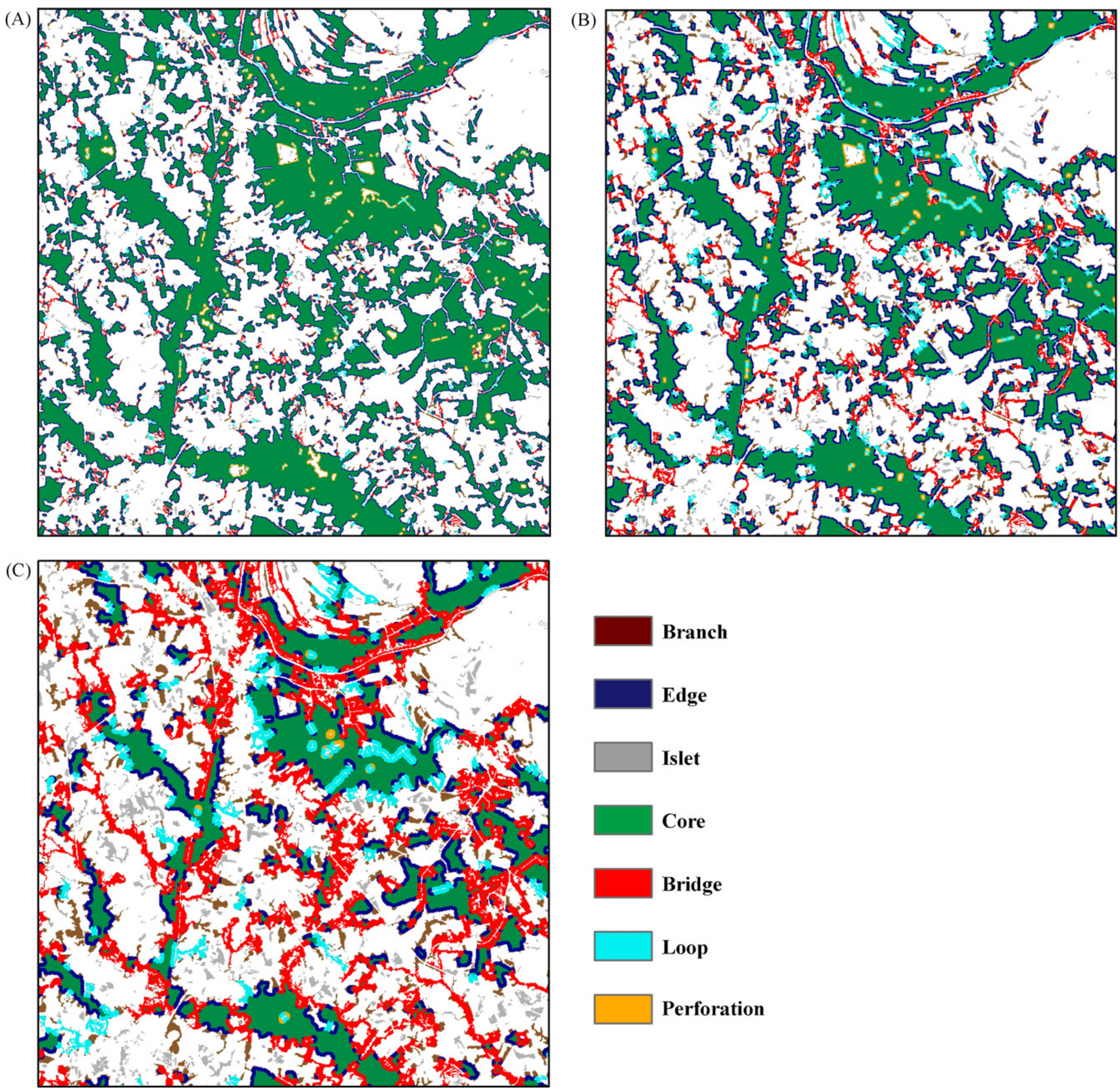

Fig. 1. Illustrations of MSPA for edge width equal to 30 m (A), 60 m (B), and 120 m (C).

Table 4
NLCD datasets.

Source	Name	Description
Vogelmann et al. (2001)	NLCD 1992	A land-cover dataset for the conterminous US derived from Landsat TM using unsupervised classification and ancillary data sources. These data were used for the Maryland and southeastern US green infrastructure networks.
Homer et al. (2007)	NLCD 2001	A land-cover dataset for the US derived from Landsat TM using regression tree modeling and ancillary data sources.
Fry et al. (2009)	NLCD land-cover change data	A land-cover dataset developed for comparison of NLCD 1992 and 2001 that overcomes differences in classification methodologies for the two NLCD eras (1992 and 2001). The NLCD 1992 component was modeled by applying NLCD 2001 classification methods to areas of spectral change. These data were used for the MSPA networks. The NLCD 2001 component of the land-cover change dataset is identical to that in NLCD 2001.

was determined by using common raster GIS routines that group adjacent and like-classified pixels, assigning each group a unique identifier. The output of the grouping routine is a raster equivalent of a vector (i.e., polygon) map where each unique occurrence of a particular class (e.g., core) has a unique identifier. Raster grouping was done for maps of core only and maps of core and bridge combined. Comparison of those two maps yields the number of core areas and the proportion of core areas that are connected to at least one other core area. Summary of the grouped bridge and core map provides the number of core areas in a network and the overall size of a network of connected core areas (excluding edges, branches and loops). We then overlaid the networks (i.e., areas of connected core) on a map of state boundaries to determine where and how many crossed state borders.

The change analysis focused on the transitions between bridge and background and core and background. We focused on bridge and core because these two classes are the main components of green infrastructure. We further restricted our focus to change from and to background because these transitions represent forest and wetland gain and loss. Most of the other changes that could be summarized in a change matrix arise from neighborhood effects. For example, conversion of forest edge to non-forest also changes neighboring core forest to edge forest. We summarized changes from background to bridge or core and vice versa using a 120 km × 120 km grid covering the conterminous USA.

2.3. *Comparison of MPSA output with other green infrastructure networks*

Our green infrastructure networks naturally differ from other published networks (e.g., Hoctor et al., 2000; Carr et al., 2002; Weber et al., 2006) because we rely solely on land cover and do not include the other layers of information that can be included when GIS overlay routines are used. To quantify the differences, we compared our network maps to the Maryland (Weber et al., 2006) and southeast US (Carr et al., 2002) networks. The comparison provides insight into the role and importance of land cover in green infrastructure network mapping. We used the 1992 component of the NLCD land-cover change data (Fry et al., 2009) for the comparisons. The Maryland (Weber et al., 2006) and southeast US networks (Carr et al., 2002) were based on NLCD 1992 (Vogelmann et al., 2001). While the NLCD 1992 (Vogelmann et al., 2001) was based on somewhat different mapping methods than the NLCD 2001 (Homer et al., 2007) and thus the NLCD land-cover change data (Fry et al., 2009), the comparisons of MSPA to Maryland and southeast US maps are based on land-cover sources that are as similar as possible. Table 4 describes the NLCD datasets used for the MSPA, Maryland, and southeastern US green infrastructure networks.

3. Results

The number of distinct core areas ranged from 1.7×10^6 (edge width = 120 m) to 7.5×10^6 (edge width = 30 m) (Table 5). A small proportion of core areas was isolated (not connected to another core), and that proportion decreased as edge width increased. The number of networks of connected core also decreased as edge width increased, from approximately 820,000 (edge width = 30 m) to approximately 93,500 (edge width = 120 m) (Table 5). Changes in edge width had a nonlinear effect on the number of networks. Doubling edge width from 30 m to 60 m resulted in a 60% reduction in the number of networks, and quadrupling edge width from 30 m to 120 m resulted in a 90% reduction in the number of networks. The nonlinear effect of edge width on the number of networks occurred because the majority of networks were small, and increases in edge width changed the classification of many of these areas to islet (Ostapowicz et al., 2008). The proportion of pixels classified as islet doubled with each increase in edge width (Table 3).

There were many places in the USA where large networks crossed state boundaries (Fig. 2). The numbers of networks with at least 100 core areas that crossed state boundaries were 313, 407, 467, for edge widths of 120 m, 60 m, and 30 m, respectively. Depending on edge width, the state-spanning networks comprised 10–15% of the total number of networks with at least 100 core areas. For example, there was a single network extending from the James River southeast of Petersburg, Virginia to the southwestern corner of the tidal portion of the Chowan River in North Carolina (Fig. 3). The network was approximately 720,000 ha of uninterrupted for-

Table 5
Core and network summary statistics for edge width equal to 30 m, 60 m and 120 m.

Core and network descriptions	Edge width = 30 m	Edge width = 60 m	Edge width = 120 m
Number of core areas	7,526,919	3,913,313	1,692,407
Number of connected core areas	6,078,757	3,457,735	1,498,338
Number of isolated core areas	1,446,558	455,758	98,754
Number of networks	820,431	333,990	93,526
Number of networks with ≥2 but <10 core areas	750,170	293,661	76,253
Number of networks with ≥10 but <100 core areas	65,657	36,804	15,291
Number of networks with ≥100 but <1000 core areas	4,236	3,162	1,819
Number of networks with ≥1000 core areas	368	273	163

Networks are defined as two or more disjunct core areas connected by bridges. Core is referred to as isolated if it is not connected to another core.

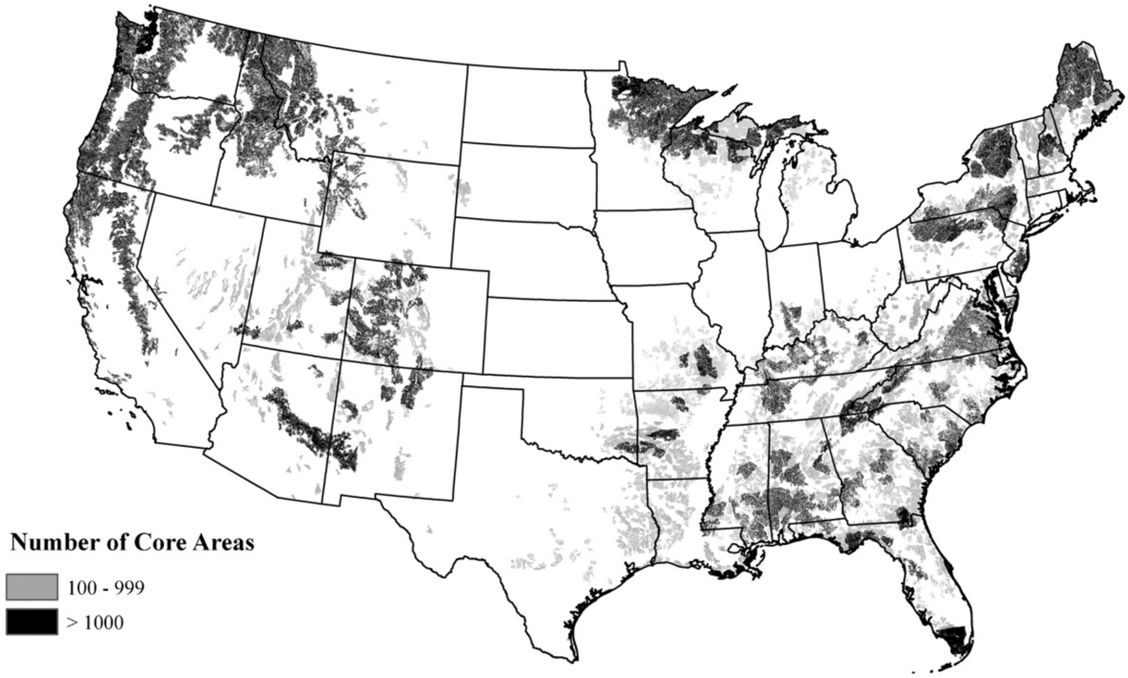

Fig. 2. National map of forest-wetland networks by number of core areas overlaid on a US State boundary map (edge width = 120 m). Only networks with at least 100 distinct areas of core are shown.

est and wetland that included approximately 10,500 distinct core areas. The network was approximately 170 km from north to south, with approximately half of the total network area in each state. Although the Virginia green infrastructure assessment (see Table 1) extended mapping approximately 32 km beyond its border (Weber, J., pers. comm., September 9, 2008), that 32 km 'buffer' around the Virginia State border would truncate an approximately 50 km portion of the network that extends to the bend in the Chowan River (Fig. 3).

Core and bridge green infrastructure elements were temporally dynamic (Fig. 4). Most areas of the conterminous USA experienced a net change in either core, bridge, or both elements for all values of edge width between ca. 1992 and ca. 2001. Net loss of core and bridge dominated nationally (Table 6), with net losses for both elements occurring in approximately 40% of the 120 km × 120 km summary units. Net loss of core and bridge characterized the eastern USA, the Pacific Northwest, and much of the southwest (Arizona, New Mexico, Utah, Colorado). For the 60 m edge width, average net losses of core were 413 ha for summary units with net losses of core, and average net losses of bridge were 378 ha for summary units with net losses of bridge. Net gains in core and bridge characterized the Great Plains, portions of the Midwest, and southern Texas. For the 60 m edge width, average net gains in core were 144 ha for summary units with net gains in core, and average net gains in bridge were 52 ha for summary units with net gains in bridge. The spatial patterns of change in core and bridge for edge widths equal to 30 m and 120 m were similar to those depicted in Fig. 4.

Although a single bridge loss does not always break connectivity within a network, the data can be used to locate where bridge losses have fragmented networks. Bridge loss in southwest Georgia, for example, disconnected a 20,000 ha portion of a 1,036,000 ha network (Fig. 5). The disruption of network connectivity illustrates how local-scale land-cover changes can have broader-scale consequences (Wickham et al., 2007a,b, 2008). A very small loss of forest and wetland occurred in a pattern that broke connections within a larger network. Such patterns suggest that the local-scale characteristics of many land-use decisions (Foster and Foster, 1999; Sampson and Decoster, 2000) are probably made without regard to their broader-scale context.

Comparison of our networks with those for the southeastern USA (Carr et al., 2002) and Maryland (Weber et al., 2006) showed the impact of models and data used for identifying green infrastructure networks (Table 7). Our models relied solely on land cover whereas the Maryland and southeastern USA models incorporated several other sources of information in addition to land cover. The proportion of Maryland and southeastern USA hubs and corridors that are labeled as background by MSPA reflect the use of the additional information in Maryland and the southeastern USA studies and differences in modeling choices (e.g., corridor width). Nevertheless, the strong agreement (e.g., 75% of both networks are also labeled as one of the six MSPA classes) shows the importance of land cover in developing green infrastructure networks.

4. Discussion

Using MSPA to map the elements of green infrastructure, we identified 1.7–7.5 million areas of core and 93,000–820,000 networks depending on the width used to define the edge around core. The sheer number of networks, and the geometric increase in the islet class with increases in edge width (Table 3), are indicators of the extensive fragmentation that is known to exist (Riitters et al., 2002; Wickham et al., 2008). If forests and wetlands were not fragmented, then the number of core areas would not decline by orders of magnitude with very small increases in edge width, there would be fewer networks, and the majority of networks would not be small (e.g., <10 core areas). For narrow edge widths (≤120 m), a significant portion of USA forests and wetlands were configured as areally small and isolated networks that do not meet the spatially extensive requirements that are typical of green infrastructure assessments (e.g., Hoctor et al., 2000; Carr et al., 2002; Weber, 2004; Weber et al., 2006).

Although fragmentation is pervasive, there were several areas throughout the US where large networks crossed state boundaries. Approximately 10–15% of the large forested-wetland networks

Fig. 3. Forest-wetland network spanning the border between Virginia and North Carolina. Edge width equals 60 m.

(≥100 core areas) crossed state boundaries. Fragmentation is a primary motivation for using green infrastructure for conservation (Noss and Harris, 1986; Hoctor et al., 2000; Carr et al., 2002; Weber, 2004; Weber et al., 2006). The state-spanning large networks are areas where multi-state efforts could be directed toward regional conservation planning using green infrastructure concepts.

Temporal analysis of land cover (i.e., change) also added useful information for green infrastructure assessment and planning. Land-cover is dynamic rather than static (Dobson et al., 1995; Fry et al., 2009), indicating that temporal change should be incorporated into green infrastructure planning where possible. Our temporal analysis indicated that losses of core and bridge green infrastructure elements were substantial over the approximate 10-year

Table 6
Net change (ha) in bridge and core classes for edge width equal to 30 m, 60 m and 120 m.

	Bridge			Core		
	Edge width = 30 m	Edge width = 60 m	Edge width = 120 m	Edge width = 30 m	Edge width = 60 m	Edge width = 120 m
Loss	−883,095	−2,356,461	−5,226,849	−3,893,266	−2,571,131	−1,137,684
Gain	199,455	594,145	1,637,227	2,169,859	1,667,573	958,434
Net	−686,640	−1,762,316	−3,589,622	−1,723,407	−903,558	−179,251

Net loss of bridge increased with edge width and net loss of core decreased with edge width because of the effect of edge width choice on the MSPA classes (see Fig. 1 and Table 3).

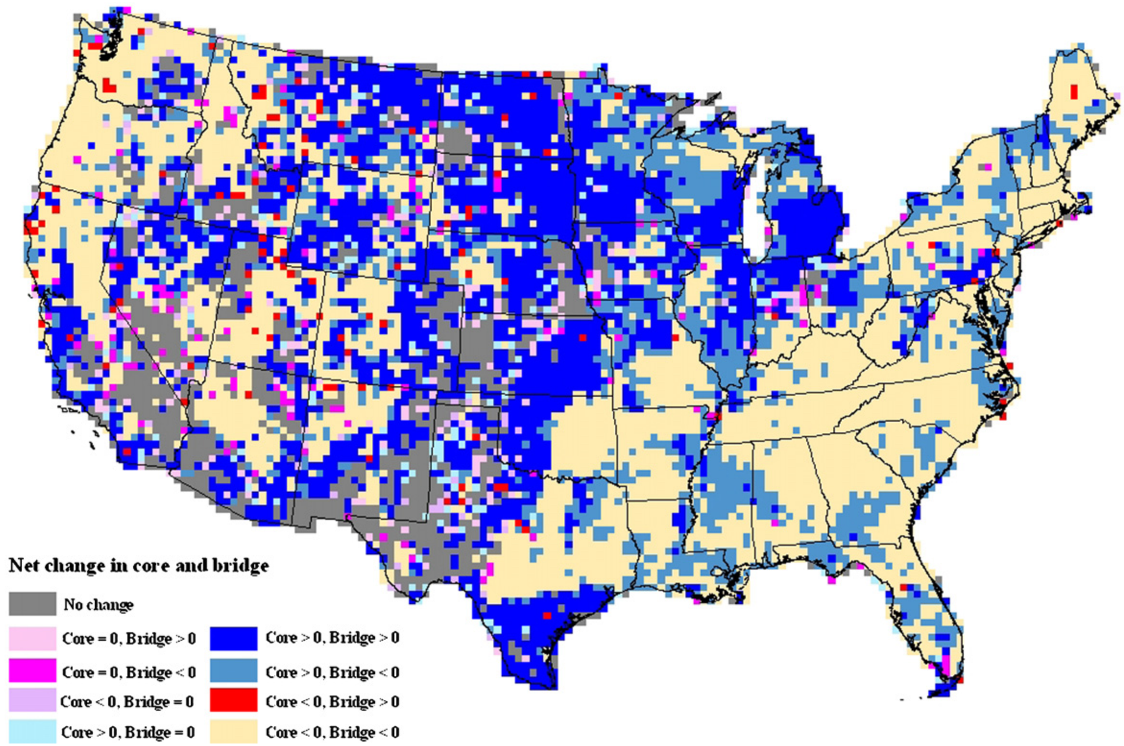

Fig. 4. Net change in bridge and core summarized using a 120 km × 120 km grid (edge width = 60 m). Each cell is color-coded according to one of the nine possible combinations of core and bridge gain and loss. The symbols "=0", ">", and "<" equal no change, gain, and loss, respectively.

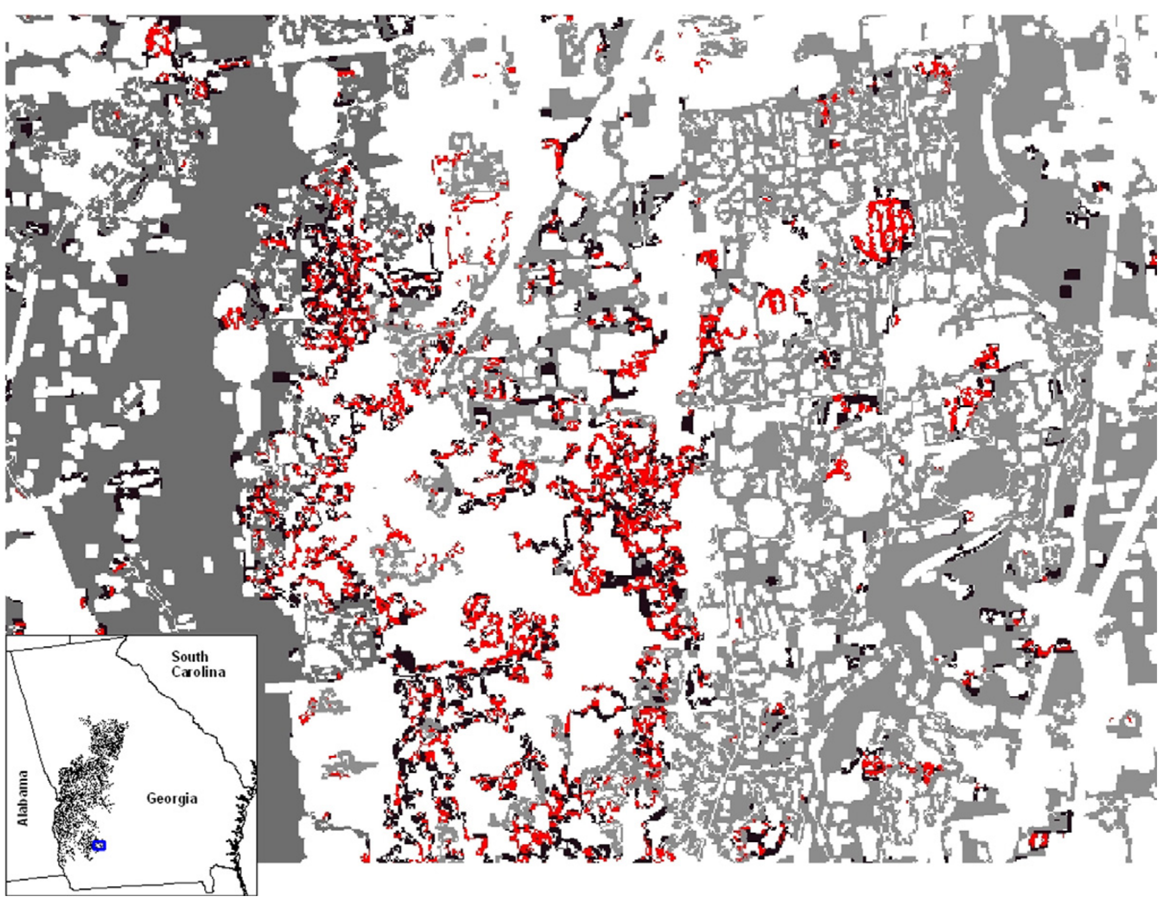

Fig. 5. Loss of bridge between ca. 1992 and 2001 for a large forest-wetland network in Georgia. The large forest-wetland network (inset) was split into smaller components as a result of loss of forest-wetland bridges (red). The loss of bridges disconnected the darker and lighter gray areas in the map, which were part of a single network in ca. 1992 (inset). The areas in black are forest-wetland losses in morphological classes other than bridge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 7
Comparison of MSPA networks (edge width = 60 m) with the Maryland and southeastern US networks.

Maryland	Background	Branch	Edge	Islet	Core	Bridge	Loop	Perforation
	MSPA							
Hub	22.6	2.3	12.2	0.4	50.4	7.6	3.2	1.3
Corridor	46.2	4.6	13.4	1.8	21.0	9.9	2.8	0.3
Hub + corridor	26.3	2.7	12.4	0.6	45.7	8.0	3.2	1.1
Southeast US								
Hub + corridor	25.0	1.9	9.0	0.5	51.0	6.9	3.8	1.9

Comparisons show the percentage of the Maryland and southeastern US networks in each MSPA class. Comparisons were based on the NLCD 1992 component in the NLCD land-cover change data (Fry et al., 2009). Background is used as the label for all non-forest and non-wetland land cover. The Maryland data are distributed as two classes (hub and corridor), and the southeastern US data are distributed as one class that combines hub and corridor. The distribution of percentages for edge widths equal to 30 m and 120 m would follow the patterns in Table 3, except for the background class. Background percentages would remain constant. The Maryland data were downloaded from http://dnrweb.dnr.state.md.us/gis/data, and the southeastern US data were downloaded from http://www.geoplan.ufl.edu/epa.

period. The dynamic character of land cover and the low proportions of green infrastructure that are actually protected (e.g., Hoctor et al., 2000; Carr et al., 2002; Weber et al., 2006) suggest that land-cover change has the potential to alter plans for conservation of unprotected green infrastructure.

Future land-cover change is sometimes modeled as part of green infrastructure planning. Carr et al. (2002) and Weber et al. (2006) used existing GIS layers to model the relative risk of urbanization. The risk analysis was then used to guide preservation decisions (e.g., unprotected hubs and links with high urbanization risk were assigned a higher priority for protection than counterparts with lower urbanization risk). Such models only consider one of many possible driving forces of land-cover change (e.g., see Claggett et al., 2004), and do not include some of the benefits that come from measuring land-cover change directly, such as forest regeneration following agricultural abandonment. Without temporal information, conservation and restoration are guided by geographic gaps in unprotected green infrastructure. Adding land-cover change to geographic gaps provides another source of information that can be used to guide conservation and restoration decisions. Loss of bridges (e.g., Fig. 5), for example, can potentially be used to prioritize restoration based on re-establishing lost connectivity. Likewise, gains in green infrastructure could be used to re-assess conservation priorities. Conservation priorities for two otherwise equal areas might change over time because of differential gains in green infrastructure.

The different perspectives on green infrastructure taken by MSPA and GIS overlay represent opportunities for integration. Green infrastructure projects typically emphasize size by applying areal thresholds to define hubs, and then rely on river networks and other linear features to determine connectedness. Hubs are typically large, edges around hubs are often set at a fixed width, and links are not necessarily comprised of 'natural' vegetation throughout their length (Hoctor et al., 2000; Carr et al., 2002; Weber et al., 2006). Rather than size, MSPA emphasizes interior and connectedness. MSPA defines hubs based on interior, which is defined by a user-specified edge width, and links cannot have gaps in 'natural' vegetation (if only 'natural' vegetation classes are used to define foreground). Comparison of output from the two approaches can be used to examine the relative roles of interior and size for defining hubs, the importance of uninterrupted 'natural' vegetation throughout a corridor's length, the value of using a range of widths for examining edge effects (Harper et al., 2005; Laurance, 2008), and for distinguishing possible differences between interior (perforation) and exterior edge effects.

The relationship between structural and functional connectivity is one example of integration that is highlighted by considering the different perspectives of MSPA and green infrastructure networks mapped using classical GIS overlay techniques. One of the striking results of the comparisons of MSPA to the other networks was the large proportion of Maryland corridors that did not contain forest or wetland (Table 7). Maryland corridors were identified with a view toward those places in the landscape that should promote functional connectivity, whereas MSPA corridors were generated from the perspective of structural connectivity. While functional connectivity is the predominant perspective of green infrastructure network mapping, there is evidence that structural connectivity promotes functional connectivity. Haddad and Tewksbury (2006) point out that corridor studies should focus on habitat specialists, suggesting that corridors should be comprised of the species' habitat to be functional. Robichaud et al. (2002), Bélisle and Desrochers (2002), Tewksbury et al. (2002), Levey et al. (2005), and Damschen et al. (2006) all found that structural corridors promoted functional connectivity in that corridor and habitat land cover were the same in each study. Dixon et al. (2006) found that dense urban land use and an interstate highway appeared to be barriers in a corridor connecting central and northern Florida black bear populations. Green infrastructure reports also commonly point out the additional environmental benefits beyond habitat and functional connectivity conservation (e.g., Weber, 2004; Hoctor et al., 2008) that are mainly a function of conservation of 'natural' lands. Water quality is often cited as one of these benefits, and the structural 'connectivity' provided by having riparian vegetation adjacent to streams is a recognized need for water quality maintenance (Peterjohn and Correll, 1984; Nakano and Murakami, 2001; Sweeney et al., 2004). Streams are an important component of MSPA, Maryland, and southeastern USA corridors, and the relationship between riparian vegetation and water quality indicates that structure and function are tightly linked for many of the additional environmental benefits of green infrastructure (Weber, 2004; Hoctor et al., 2008).

MSPA, Maryland, and the southeastern USA networks were also different in their selection of corridor width. MSPA corridors ranged in width from 30 m to 120 m, a minimum recommended corridor width of 350 m was used in Maryland (Weber et al., 2006), and southeastern USA corridor width was dependent on the inputs to their least-cost path analysis. Field studies of corridor width show similar variability. Field studies showing positive effects had corridor widths ranging from 25 m (Tewksbury et al., 2002) to 100 m wide (Robichaud et al., 2002) to 150 m wide (Mech and Hallett, 2001). Interestingly, Levey et al. (2005) found that it was the contrast (i.e., edge) between the corridor and the surrounding land cover that provided the conduit between habitat patches, suggesting that corridor presence rather than width may be a determining factor, at least for some species. Kohut et al. (2009) found that corridor width was not a significant factor for explaining abundance and richness of forest interior birds in a North Carolina, USA urban setting.

Our choices for MSPA modeling also affected our results, and hence comparisons with the Maryland (Weber et al., 2006) and southeastern USA green infrastructure networks (Carr et al., 2002). Roads are identified reliably in the NLCD 2001 (Homer et al., 2007) and the NLCD land-cover change data (Fry et al., 2009) because of the modeling used to derive NLCD 2001 land cover (Homer et al., 2004). Our use of NLCD 2001 (Homer et al., 2007) resulted in the 'fragmentation' of networks that might have been mapped as connected if land-cover data with a less well defined road network had been used. The effects of roads are an important ecological topic (Forman and Alexander, 1998; Trombulak and Frissell, 2000), and there are few places in the USA that are not within a 'road effect' zone of some type (Riitters and Wickham, 2003). Still, there is insufficient information to determine which classes of roads should be allowed to disconnect networks for which species (see Clevenger and Wierzchowski, 2006). Absent this information, we permitted all roads identified in the NLCD 2001 (Homer et al., 2007) to disconnect networks. Use of land-cover data with a less well defined road network would have resulted in fewer networks that would have been larger overall. The NLCD 1992 (Vogelmann et al., 2001), which was the primary source of land-cover data for the Maryland (Weber et al., 2006) and southeastern USA green infrastructure networks (Carr et al., 2002), has a less well defined road network. There may have been more similarity between MSPA and Maryland and southeastern USA green infrastructure networks if NLCD 2001 (Homer et al., 2007) had a less well defined road network.

Whereas our choice of land-cover data increased the number of networks because of the well-articulated road network, our choice of eight-neighbor connectivity to define MSPA classes (see Section 2) had the opposite effect. Use of the eight-neighbor rule to define connectivity increased connectivity among core areas by treating corner only adjacency as connected. Four-neighbor connectivity would treat corner only adjacency as not connected, which would have resulted in a greater number of networks.

Choice of spatial extent may have been the most important source of difference between our results using MSPA and those relying on classical GIS overlay (Riitters, 2005). Hoctor et al. (2000), Carr et al. (2002), and Weber et al. (2006) were able to incorporate more detailed information, and hence more precision, into their modeling because they were focused on smaller spatial extents. Shifting to a national extent changes the modeling perspective from precision to generality and realism (Riitters, 2005). Generality and realism were achieved by relying on a nationally consistent land-cover database (NLCD 2001) (Homer et al., 2007), which was consistent with previous green infrastructure mapping efforts that relied on a similar land-cover dataset (NLCD 1992) (Carr et al., 2002; Weber, 2004; Weber et al., 2006). Incorporation of temporal change in land cover and mapping green infrastructure networks using three different edge widths also added realism. The agreement between MSPA, Maryland, and southeastern USA networks suggests that single states or multi-state regions could combine more detailed data with MSPA-generated green infrastructure networks for conservation and environmental planning.

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