TEMPORAL TRENDS IN THE SPATIAL DISTRIBUTION OF IMPERVIOUS COVER RELATIVE TO STREAM LOCATION

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TEMPORAL TRENDS IN THE SPATIAL DISTRIBUTION OF IMPERVIOUS COVER RELATIVE TO STREAM LOCATION[1]

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ABSTRACT: Use of impervious cover is transitioning from an indicator of surface water condition to one that also guides and informs watershed planning and management, including Clean Water Act (33 U.S.C. §1251 et seq.) reporting. Whether it is for understanding surface water condition or planning and management, impervious cover is most commonly expressed as summary measurement (e.g., percentage watershed in impervious cover). We use the National Land Cover Database to estimate impervious cover in the vicinity of surface waters for three time periods (2001, 2006, 2011). We also compare impervious cover in the vicinity of surface waters to watershed summary estimates of impervious cover for classifying the spatial pattern of impervious cover. Between 2001 and 2011, surface water shorelines (streams and water bodies) in the vicinity of impervious cover increased nearly 10,000 km. Across all time periods, approximately 27% of the watersheds in the continental United States had proximally distributed impervious cover, i.e., the percentage of impervious cover in the vicinity of surface waters was higher than its watershed summary expression. We discuss how impervious cover spatial pattern can be used to inform watershed planning and management, including reporting under the Clean Water Act.

(KEY TERMS: Clean Water Act; change detection; impervious cover; National Land Cover Database; spatial pattern.)

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INTRODUCTION

It is probable that impervious cover will become a more prominent indicator for Clean Water Act (CWA) (33 U.S.C. §1251 et seq.) reporting in the coming decades (Wickham *et al.*, 2014a). The states of Connecticut (Bellucci, 2007; Arnold *et al.*, 2010) and Maine (Maine, 2012) now use impervious cover as an indicator of water quality impairment for their CWA reports. More states are likely to follow Connecticut and Maine as development of impervious cover data evolves and research on the impacts of impervious cover on aquatic condition advances (Arnold *et al.*, 2010).

Impacts of urbanization on aquatic condition have been studied for 50 years (Shuster *et al.*, 2005; Brabec, 2009), but impervious cover only emerged as a benchmark indicator of aquatic impairment over the last two decades. Its benchmark status is documented

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by the numerous papers that review the impact of impervious cover on surface water condition (Schueler, 1994; Arnold and Gibbons, 1996; Booth and Jackson, 1997; Paul and Meyer, 2001; Brabec *et al.*, 2002; King *et al.*, 2005; Meyer *et al.*, 2005; Shuster *et al.*, 2005; Walsh *et al.*, 2005; Brabec, 2009; Schueler *et al.*, 2009). The large suite of adverse impacts well documented in the aforementioned review articles includes increases in the volume of storm runoff, reduction in time of concentration between the onset of precipitation and the onset of storm runoff, increased erosion and sedimentation, increased pollutant loads (nutrients, pathogens, pesticides, and toxic substances), habitat degradation, and biotic decline. Some researchers now use the term "urban stream syndrome" to encapsulate the large suite of adverse impacts that arise from elevated amounts of impervious cover in the vicinity of surface waters (Paul and Meyer, 2001; Meyer *et al.*, 2005; Walsh *et al.*, 2005).

When used as an indicator, impervious cover is most commonly expressed as an area percentage — e.g., the percentage of a watershed that is impervious cover (Schueler *et al.*, 2009). One of the emerging research themes discussed as a potential advance in understanding impervious cover impacts on aquatic condition is spatial pattern. As an indicator, percentage impervious cover in a watershed is aspatial because it does not account for the spatial configuration of impervious cover. Specifically, indicators that distinguish the amount of impervious cover in the vicinity of streams as opposed to overall watershed percentage have been proposed as key research needed to improve understanding of impervious cover–aquatic condition relationships (Brabec *et al.*, 2002; Brabec, 2009). The call for impervious cover indicators that account for its proximity to streams is an implicit recognition of Tobler's Law — proximal features are more strongly associated than distal features (Tobler, 1970), which has been influential in the development of spatial statistics (Miller, 2004), GIS (Goodchild, 2004), landscape ecology (Meentemeyer, 1989; Wu, 2004; Wiens *et al.*, 2007), and spatial econometrics (Anselin, 1988).

There are a few site-specific studies that have shown the value of using the spatial pattern of impervious cover for understanding surface water condition. Hammer (1972) found that stream channel enlargement tended to decrease as the distance between the stream and impervious cover increased. Albertini *et al.* (2007) found that the median size of urban areas and the number of roads crossing streams provided additional explanatory power of the inverse relationship between stream benthos and urbanization that was not evident in a simple bivariate model of stream benthos *vs*. percentage impervious cover only. Schiff and Benoit (2007) found that several measures of aquatic condition were more strongly correlated with percentage impervious cover in the riparian area than percentage impervious cover across the entire watershed, and Walsh and Kunapo (2009) found benthic macroinvertebrate community composition was inversely related to distance between impervious cover and receiving waters and the degree of connection between them.

Wickham *et al.* (2014b) built on these spatially oriented studies by developing spatial pattern metrics of impervious cover for approximately 83,000 watersheds across the continental United States (U.S.). Estimates of the percentage of watershed stream length "flowing" through impervious cover were compared to watershed percentage impervious cover. Comparison of the two metrics was used to classify watersheds according to impervious cover spatial pattern as uniform, proximal, and distal, where proximal was a greater proportion of impervious cover in the vicinity of streams than across the entire watershed and distal was a greater proportion of impervious cover across the entire watershed than in the vicinity of streams. The objective of this research is to report on temporal trends in the amount of impervious cover in the vicinity of streams for the continental U.S. The research objective quantifies a common and perhaps fundamental assessment question related to impervious cover — "what is the rate of increase in streams flowing through impervious cover?" (see Meyer *et al.*, 2005) — and also represents a fundamental environmental assessment objective of many U.S. Federal environmental assessment projects (e.g., Messer *et al.*, 1991). Temporal trends in impervious cover in the vicinity of streams were assessed using nationwide data for 2001, 2006, and 2011 (Homer *et al.*, 2015).

METHODS

Data

Impervious cover data from the National Land Cover Database (NLCD), hydrography from the National Hydrography Dataset (NHD), and the watershed boundary dataset (WBD) were used to assess temporal trends in impervious cover near streams and water bodies. The NLCD, acquired from the Multi-Resolutions Land Characteristics website (http://www.mrlc.gov), provides impervious cover data at the native pixel size of Landsat TM (30 m × 30 m; 0.09 ha) for the nominal dates of 2001, 2006, and 2011 (Xian and Homer, 2010; Xian *et al.*, 2011; Homer *et al.*, 2015). Pixel-level impervious cover values range from 0 to 100% in 1% increments. The 1:100,000-scale hydrography data and the WBD data were acquired from the NHDPlus (Version 2) website (http://www.horizon-systems.com/nhdplus/NHDPlusV2_home.php). The hydrographic features for small streams, large streams, and water bodies (lakes, reservoirs) were used for the analysis. The WBD served as the analysis unit. The WBD units, commonly referred to as 12-digit watersheds, organize the country into 83,015 hierarchical watershed units whose average size is approximately 9,500 ha.

Data Processing

The impervious cover data were processed to account for adjacency. Streams and water bodies are not often coincident with impervious cover, but impervious cover is often adjacent to streams and water bodies. Adjacency was defined as a stream or water body within 30 m (1 pixel) of impervious cover. Prior to processing for adjacency, the impervious cover data were grouped into five classes: 0, 1-4, 5-14, 15-24, and ≥25%. As a result of the aggregation, each 30 m × 30 m pixel was classified as 1-4, 5-14, 15-24, or ≥25% impervious cover. The class thresholds are consistent with levels of impervious cover for which adverse impacts on surface waters are reported (Brabec *et al.*, 2002; Schueler *et al.*, 2009). Following reclassification, the individual classes were split into separate maps, and these class-specific maps (e.g., 1-4%) were expanded (“grown”) by one pixel. Expand functions in GIS software grow the target class in all directions by a specified distance (Figure 1). In the case of a single, isolated target pixel and a specified expansion distance of one pixel, the outcome would reclassify the eight nearest neighbors surrounding the target pixel into the same class as the target pixel. The individual, expanded class-specific maps (e.g., 1-4%) were then recombined into a single map. During recombination impervious cover could only “grow” into pixels that were 0% impervious cover in the original (unexpanded) map, and a maximum rule was used to assign an impervious cover class (e.g., 1-4%) when two or more impervious pixels could grow into the same 0% impervious pixel in the unexpanded map (Table 1). That is, if a pixel assigned to the 1-4% impervious cover class and a pixel assigned to the 5-14% impervious cover class could both grow into the same 0% impervious cover pixel, that pixel was assigned to the 5-14% impervious cover class in the expanded map. The alternative to the maximum rule is the minimum rule, where the class representing the lowest impervious cover percentage would be assigned to a 0% impervious cover pixel that is immediately adjacent to two or more differently classified

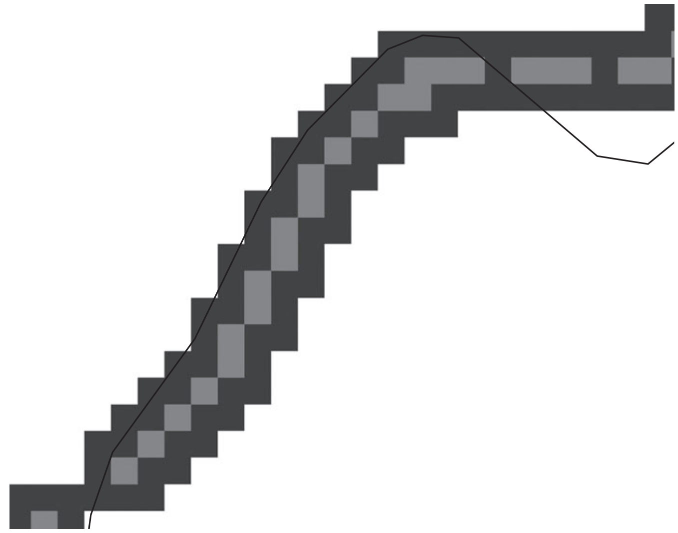

FIGURE 1. A Stream in Vicinity of Impervious Cover. Impervious cover (NLCD, 2011) is in light gray, expanded impervious cover is in dark gray, and the stream is in black.

TABLE 1. Classification of Buffered Impervious Cover Map Using Maximum Rule (based on NLCD 2011 impervious cover). An “X” denotes the impervious cover class was immediately adjacent and therefore could be grown into a 0% impervious cover pixel.

Impervious Cover Class				New Map Impervious Class (%)
1-4%	**5-14%**	**15-24%**	**≥25%**	
X				1-4
	X			5-14
X	X			5-14
	X	X		15-24
		X		15-24
X	X	X		15-24
X		X		15-24
	X	X	X	≥25
X		X	X	≥25
	X		X	≥25
X	X		X	≥25
X	X	X	X	≥25
		X	X	≥25
X			X	≥25
			X	≥25

impervious cover pixels. The difference in impervious cover class assignment between maximum and minimum rules can be used to gauge the effect of the rule on the results (Table 2).

Expansion of the impervious cover map was undertaken as a necessary alternative to the more commonly used GIS routine of buffering streams (and perhaps water bodies) to define “riparian” areas (e.g., Wang *et al.*, 2001; McBride and Booth, 2005; Schiff and Benoit, 2007). GIS buffering of streams defines an area, and overlay of impervious cover therefore

TABLE 2. Area (ha) of Expanded Impervious Cover under Maximum (see Table 1) and Minimum Rules.

Impervious Class	Maximum Rule	Minimum Rule	% Change
1-4%	21,376,034	32,941,051	54
5-14%	10,059,638	15,730,426	56
15-24%	1,505,379	4,745,716	215
≥25%	23,596,407	3,120,260	−87

results in an amount (area) of impervious cover that is some proportion of the area defined by buffering the streams. GIS buffering of streams and shorelines cannot be used to estimate the length of streams and shorelines in the vicinity of impervious cover, which was the main objective of this research.

The NHD hydrographic data include several features (e.g., canals, washes, playas, pipelines). We only used the data for streams, lakes and ponds, reservoirs, and aquaculture for the analysis. NHD maintains streams in separate linear- and area-based geographic files. Small streams are maintained in a linear geographic file, and larger streams (e.g., Ohio River) are maintained in an area geographic file. After extracting small streams from the linear hydrographic file and large streams from the polygonal (area) hydrographic file, the subset of features representing large streams from the polygonal hydrographic file were converted to linear features and merged with the small stream features to create a complete streams dataset. These processing steps were necessary so that shorelines of large rivers were accurately located, and to accommodate estimation of stream length "flowing" through impervious cover in a GIS. NHD water bodies are maintained in an area-based geographic file that is distinct from the geographic files used to maintain streams. Similar to the area-based geographic file for large streams, NHD features for lakes and ponds, reservoirs, and aquaculture were extracted and converted into linear features to facilitate estimation of shoreline length in the vicinity of streams.

Data Analysis

Following extraction and processing, tabular GIS overlays of the linear NHD features and the expanded raster impervious cover data were undertaken to estimate the stream and shoreline length in the vicinity of impervious cover. The outcome of the tabular GIS operation was the proportion of pixels in the analysis unit that contain streams or shorelines. These proportions were then related to the total stream and shoreline length in the analysis unit to estimate the length of streams and shorelines in the vicinity of impervious cover in the analysis unit by impervious cover class (0, 1-4, 5-14, 15-24, and ≥25%). The analysis was undertaken for each impervious cover dataset (2001, 2006, and 2011) so that temporal trends could be estimated. The analysis was also done separately for streams and water-body shorelines so that distinct estimates could be produced for each hydrographic feature. Estimates of the combined stream and shoreline length in the vicinity of impervious cover were produced by accounting for the relative lengths of streams and shorelines in the watershed:

$$\%\mathrm{IC} = ((((\mathrm{IC}_1/100) * L_1) + ((\mathrm{IC}_2/100) * L_2))/(L_1 + L_2) * 100) \quad (1)$$

where %IC was the percentage of IC in the vicinity of streams or water bodies in a watershed ≥ a specified threshold (i.e., 5, 15%), IC_1 and IC_2 were the percentage of stream and shoreline lengths, respectively, with IC ≥ a specified threshold, and L_1 and L_2 were the stream and shoreline lengths, respectively.

The WBD 12-digit watersheds served as the analysis unit. Prior to undertaking the tabular overlays of hydrographic features and impervious cover, the streams and water bodies were intersected in a GIS with the WBD 12-digit watersheds to attach the watershed unit code to each stream and shoreline. The GIS intersection of WBD 12-digit watersheds and hydrographic features was also used to tabulate the total length of streams and shorelines by watershed. The average WBD stream and water-body shoreline lengths were approximately 63 and 8 km, respectively.

Summary of results by watershed was focused on two thresholds. The thresholds were: (1) length of streams and shorelines in the vicinity of ≥5% impervious cover and (2) length of streams and shorelines in the vicinity of ≥15% impervious cover. The ≥5% threshold is the sum of the 5-14, 15-24, and ≥25% classes, and the ≥15% threshold is the sum of the 15-24%, and ≥25% classes. Thus, there was inherent nesting in the two class thresholds such that the ≥15% threshold is a subset of the ≥5% threshold.

Stream and shoreline length in the vicinity of impervious cover can also be compared to total impervious cover in the watershed to assess its spatial pattern (Wickham *et al.*, 2014b). We calculated impervious cover spatial pattern for 2001, 2006, and 2011 to assess temporal trends in the amount of impervious cover in the vicinity of streams and shorelines. The comparison was based on a ≥5% impervious cover threshold and a 5% difference in the two impervious cover metrics. The ≥5% impervious cover threshold, applied to both the watershed and stream and shoreline expressions of impervious cover, corresponds to the three highest impervious cover classes (5-14, 15-24, and ≥25%), and was chosen because previous research has found that adverse impacts on surface water condition can occur when impervious cover reaches this level (Ourso and Frenzel, 2003; Walsh *et al.*, 2005; Schiff and Benoit, 2007; Schueler *et al.*, 2009; Uphoff *et al.*, 2011). Specifically, the stream-based expression was the percentage of watershed stream and shoreline length within 30 m of ≥5% impervious cover, and the watershed-based expression was the percentage of watershed area that was ≥5% impervious cover. The 5% difference threshold is used to classify impervious cover in the watershed as proximal, distal, or uniform. Watersheds were considered to have a uniform distribution if the two expressions were within 5%. They were considered proximal if the stream and shoreline expression was at least 5% greater than the watershed expression, and they were considered distal if the watershed expression was at least 5% greater than the stream and shoreline expression. The 5% difference threshold is subjective. A lower difference threshold (e.g., 3%) would favor assignment to the proximal and distal classes, and a higher difference threshold (e.g., 7%) would favor assignment to the uniform class (Wickham *et al.*, 2014b).

RESULTS

For the ≥5% threshold class, impervious cover in the vicinity of streams and shorelines increased nearly 10,000 km, from approximately 474,000 km in 2001 to 484,000 km in 2011 (Table 3). The 10,000 km increase in impervious cover in the vicinity of streams is approximately a 0.15% increase relative to the 6 million km of streams and shorelines in the continental U.S. The 0.15% increase in impervious cover in the vicinity of streams and shorelines was split nearly equally across the 2001-2006 and 2006-2011 periods, with somewhat greater increases occurring during the 2001-2006 period. The majority of the impervious cover increase in the vicinity of streams and shorelines occurred in the ≥15% threshold class. Approximately 85% of the increase was in the ≥15% threshold class, and 15% of the increase was in the ≥5% threshold class. The relative amount of increase in the two threshold classes (≥5, ≥15%) would have been distributed more equitably if the minimum rule for impervious cover expansion (see Methods) had been used.

For the ≥5 and ≥15% threshold classes between 2001 and 2011, there was at least a 1% increase in the length of streams and shorelines in the vicinity of impervious cover for 3,760 and 3,388 watersheds, respectively. Since the average combined stream and shoreline length across 83,015 watersheds is approximately 71 km, a 1% increase translates to a 0.71 km increase in the length of streams and shorelines in the vicinity of impervious cover in these watersheds.

TABLE 3. Length (km) of Streams and Shorelines in the Vicinity of Impervious Cover by NLCD Date. Total stream and shoreline length = 5,891,607 (stream length = 5,226,278; shoreline length = 665,329). Summation errors are due to rounding.

	2001	2006	2011
Stream			
≥5%	416,757	421,084	424,400
≥15%	210,772	214,406	217,287
Shoreline			
≥5%	57,735	58,786	59,746
≥15%	38,683	39,686	40,591
Stream and Shoreline			
≥5%	474,492	479,870	484,147
≥15%	249,455	254,092	257,877
Differences	**2001-2006**	**2006-2011**	**2001-2011**
Stream			
≥5%	4,326	3,317	7,643
≥15%	3,634	2,881	6,514
Shoreline			
≥15%	1,052	960	2,012
≥15%	1,003	904	1,908
Stream and Shoreline			
≥5%	5,378	4,277	9,655
≥15%	4,637	3,785	8,422

The spatial pattern of watersheds with at least a 1% increase in the length of streams and shorelines in the vicinity of impervious cover is not fully consistent with the intuitive spatial pattern of urban sprawl (Figure 2). The spatial pattern highlights many of the larger (e.g., Atlanta, Georgia) and smaller (e.g., Boise, Idaho) urban areas, but also includes many watersheds that are not near urban centers, and thus appears to be more extensive than urban sprawl. Many of the watersheds where impervious cover increased by at least 1% in the vicinity of streams and shorelines follow major roads, including Interstate 70 in Colorado and Interstate 80, through Nebraska and Wyoming.

There are some differences in the spatial pattern of 1% increase in the length of streams and shorelines in the vicinity of impervious cover across the two time periods (2001-2006 and 2006-2011). Regardless of the threshold class used (≥5, ≥15%), approximately 300 more watersheds had a 1% increase in the length of streams and shorelines in the vicinity of impervious cover in the 2001-2006 period than the 2006-2011 period, resulting in a slightly denser spatial pattern of increase during the 2001-2006 per-

FIGURE 2. Watersheds in Which Impervious Cover ≥5% in the Vicinity of Surface Waters Increased by at Least 1% of Watershed Stream and Shoreline Length between 2001 and 2011 (A), 2001 and 2006 (B), and 2006 and 2011 (C). The 1% increase is based on the temporal change in amount of stream and shoreline length in the ≥5% impervious cover classes (see Methods).

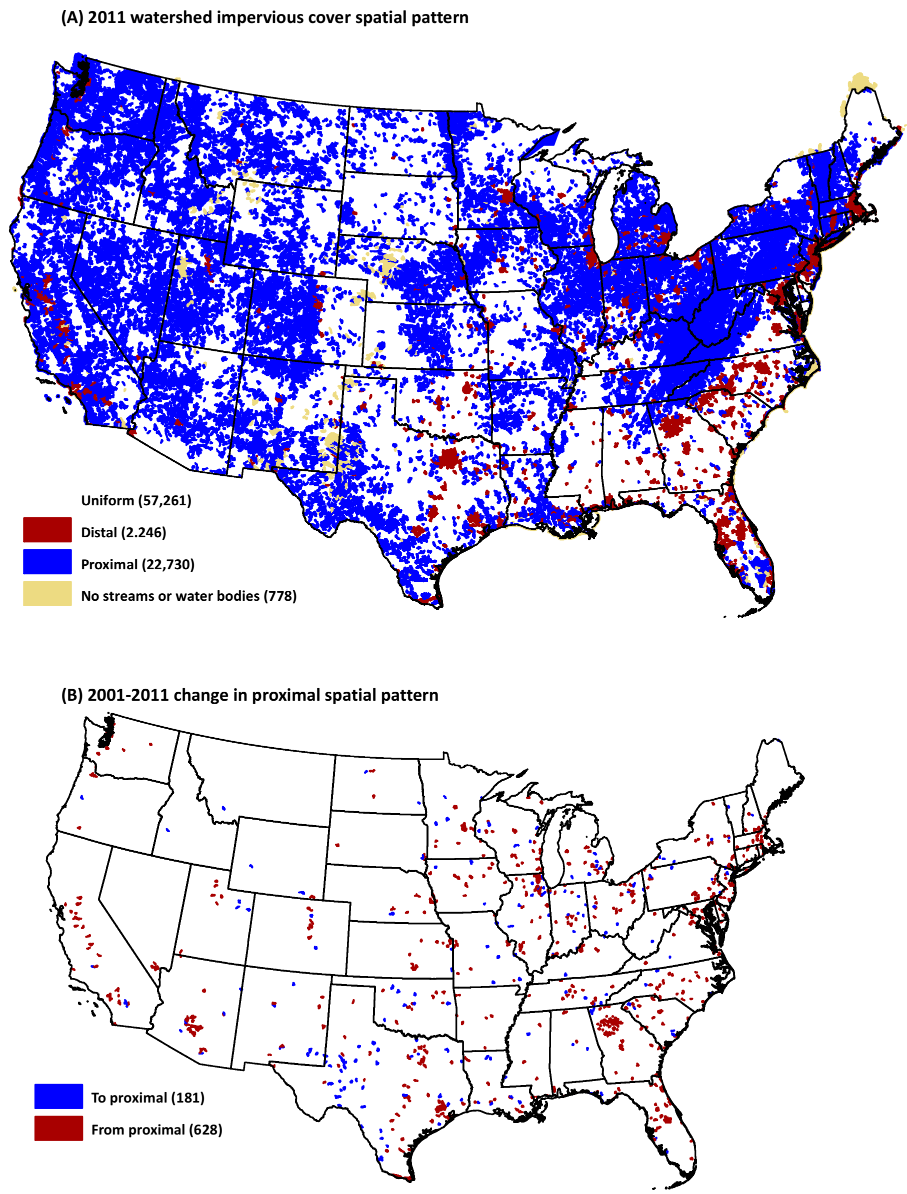

FIGURE 3. Spatial Pattern of Impervious Cover (≥5% threshold) in 2011 (A) and Change in Proximal Spatial Pattern between 2001 and 2011 (B) (see Table 4). Number of watersheds is listed in parentheses.

iod (Figure 2). A small proportion (<1,000) of the watersheds met the ≥1% increase criteria for both time periods. The mean increase in the length of streams and shorelines in the vicinity of impervious cover for these watersheds was approximately 5%, whereas for watersheds that met the ≥1% criteria in only one of the two time periods had a mean increase in the length of streams and shorelines in the vicinity of impervious cover of only 2.5%.

Approximately 27% of the 83,015 watersheds in the conterminous U.S. had a proximal distribution of impervious cover (Figure 3A). The proximal spatial pattern was widespread throughout the continental U.S. excluding the southeastern U.S. The distal spatial pattern tended to occur in urban settings, which may be attributable to decline in stream density in urban areas (relative to nonurban areas) due to hydrologic disturbance (Paul and Meyer, 2001; Elmore and Kaushal, 2008; Roy *et al.*, 2009; Lang *et al.*, 2012).

Impervious cover spatial pattern was not constant across the three time periods. Increases in impervious cover resulted in changes in its spatial pattern in some watersheds (Figure 3B; Table 4). Of the small proportion of watersheds that had a change in spatial pattern over time, most had relatively greater increases in impervious cover across the entire watershed than in the vicinity of streams and shorelines.

TABLE 4. Change in the Spatial Pattern of Impervious Cover across the Three NLCD Periods. The sum of the cell entries (per comparison) equals 82,237; 778 of the 83,015 watersheds had no streams or shorelines. Underlined cell entries (see blue in Figure 3B) represent a relatively greater increase in impervious cover in the vicinity of streams and shorelines than across the entire watershed, and italicized cell entries (see red in Figure 3B) represent a relatively greater increase in impervious cover across the entire watershed than in the vicinity of streams and shorelines.

	2011		
	Uniform	**Distal**	**Proximal**
2001			
Uniform	56,398	*332*	153
Distal	28	1,913	0
Proximal	*295*	*1*	22,577
	2011		
	Uniform	**Distal**	**Proximal**
2006			
Uniform	57,093	*113*	90
Distal	37	2,133	0
Proximal	*131*	*0*	22,640
	2006		
	Uniform	**Distal**	**Proximal**
2001			
Uniform	57,091	*246*	86
Distal	17	1,924	0
Proximal	*188*	*0*	22,685

For the 2001-2011 period, for example, 628 watersheds (cell values 332 + 295 + 1 in Table 4) had relatively greater increases in impervious cover across the entire watershed than in the vicinity of streams and shorelines, whereas 181 watersheds (cell values 153 + 28 + 0 in Table 4) had relatively greater increases in impervious cover in the vicinity of streams and shorelines than across the entire watershed. The same pattern also occurred for the 2001-2006 and 2006-2011 reporting periods.

DISCUSSION

Use of impervious cover is shifting from an indicator used for understanding aquatic condition to one that is also used for watershed management, including CWA reporting (Bellucci, 2007; Arnold *et al.*, 2010; Maine, 2012). Relatedly, impervious cover location relative to stream location is emerging as a key planning and research issue (Brabec, 2009). This research supports these emerging trends by reporting nationwide estimates of impervious cover in the vicinity of streams and shorelines, showing how the estimates have changed over time, and showing how impervious cover spatial pattern can be used to inform watershed planning and management.

The states of Connecticut and Maine recommend the use of impervious cover thresholds ranging between 5 and 16% for identification of impaired waters as part of CWA reporting (Bellucci, 2007; Maine 2012). With impervious cover proximally distributed in approximately 27% of the watersheds in the conterminous U.S., identification of CWA impaired waters using area-based thresholds would likely be different than identification of CWA impaired waters based on the occurrence of impervious cover in the vicinity of streams. For three watersheds in Maine, for example, 5% or less of their areas were ≥15% impervious cover, whereas 15% of their stream and shoreline lengths in these watersheds were in the vicinity of ≥15% impervious cover. Sixty of Pennsylvania's 1,450 watersheds had at least 15% of their stream and shoreline lengths in the vicinity of ≥15% impervious cover, but, in all cases, <10% of the watershed areas had ≥15% impervious cover. Assuming that proximal impervious cover has a greater impact on aquatic condition, managers using only watershed area summaries might not fully identify impacted streams and shorelines.

The U.S. Environmental Protection Agency (USEPA) has undertaken several efforts to make impervious cover in the vicinity of streams and shorelines available for use in watershed planning and management. USEPA developed the recovery potential screening (RPS) tool (http://www.epa.gov/recoverypotential) to help states prioritize restoration efforts for waters identified as impaired under the CWA (Norton *et al.*, 2009). USEPA's RPS tool is complemented by Watershed Index Online (http://gispub.epa.gov/wsio/), which is a data library and associated tools sets for watershed planning and management. Within the past year, USEPA has launched the EnviroAtlas (http://www.epa.gov/enviroatlas). The EnviroAtlas is an open-access, web-based suite of data and tools that can be used to understand, inform, and manage the provision of ecosystem services (Pickard *et al.*, 2015). Impervious cover in the vicinity of streams, along with many other indicators, is available for the continental U.S. through each of these web-based interfaces. Through these tools, proximal impervious cover indicators have been used in impaired waters priority setting in Connecticut and detection of stormwater runoff issues in less developed watersheds in Kentucky.

The prevalence of the proximal distribution of impervious cover across the 83,015 watersheds comprising the continental U.S. is consistent with the observation that roads are a prominent component of impervious cover (Schueler, 1994; Arnold and Gibbons, 1996). Approximately 12% of all land is within 30 m of a road, and the total lengths of roads and streams in the continental U.S. are approximately equal (Riitters and Wickham, 2003). The co-occurrence of roads and streams in valleys probably explains the prominence of the proximal distribution of impervious cover throughout most of the Appalachian Mountain region and western U.S. (Figure 3A). Roads are also a prominent contributor to the pollutant loads received by streams and water bodies (Arnold and Gibbons, 1996; Foreman and Alexander, 1998; Trombulak and Frissell, 2000). Bannerman *et al.* (1993) found that concentrations of suspended solids, fecal coliform, lead, and other metals in stormwater runoff emanating from roads were higher than from other components of impervious cover such as driveways, roofs, parking lots, and lawns. These pollutants are often conveyed directly to streams by roadside ditches (Foreman and Alexander, 1998; McBride and Booth, 2005). The prominence of roads suggests that the urban stream syndrome (Paul and Meyer, 2001; Meyer *et al.*, 2005; Walsh *et al.*, 2005) may not be restricted to streams and water bodies in urban settings.

It is possible that the prevalence of the distal spatial pattern in urban areas is attributable to reduced drainage densities. Drainage densities tend to be lower in urban areas because streams are often converted to pipes and culverts to accommodate development (Paul and Meyer, 2001; Elmore and Kaushal, 2008). If the streams were still present, a uniform spatial pattern of impervious cover in urban areas might be more likely because the abundant impervious cover would tend to fill the watershed uniformly and therefore impervious cover would be in roughly equal proportions both near and far from streams. The prevalence of the distal spatial pattern of impervious cover in urban areas tends to support the observations that urban areas have lower drainage densities (Paul and Meyer, 2001; Elmore and Kaushal, 2008) and that the remaining streams tend to occur as riparian corridors separating residential, commercial, or industrial developments.

The difference between impervious cover in the vicinity of surface waters and watershed impervious cover as reported here is conceptually related to the difference between percentages of directly connected impervious cover (Alley and Veenhuis, 1983) and total impervious cover in a watershed. Direct connection by pipes, culverts, and lined drainages "brings" impervious cover to receiving waters. Many studies have pointed out that directly connected impervious cover is a more useful indicator than total impervious cover because it does not comingle areas of impervious cover that are likely to have less impact on surface water condition (not directly connected) with areas of impervious cover that are more likely to have an impact on surface water condition (directly connected) (Alley and Veenhuis, 1983; Booth and Jackson, 1997; Lee and Heaney, 2003; Hatt *et al.*, 2004; Han and Burian, 2009; Walsh *et al.*, 2012; Vietz *et al.*, 2014). We used impervious cover in the vicinity of surface waters and watershed impervious cover to express a potential difference in the impact of impervious cover based on adjacency rather than direct connection. Our use of adjacency is not intended as a proxy for direct connection. Some areas of adjacent impervious cover may not be directly connected and some areas of impervious cover that are not adjacent may be directly connected. Adjacency is another aspect of spatial pattern in addition to direct connection.

The amount of impervious cover near streams and water bodies and throughout watersheds may be higher than estimated here with NLCD. Previous studies comparing impervious cover estimates from high resolution (e.g., 1 m $\times$ 1 m) sources found that NLCD estimates of impervious cover were less than estimates derived from the high resolution sources (Jones and Jarnagin, 2009; Nowak and Greenfield, 2010). It is intuitive that use of high resolution sources would resolve more impervious cover because it would be possible to detect fine-scale differences that go undetected at coarser resolutions, such as roads underneath forest canopies. For example, Nowak and Greenfield (2010) found a much closer agreement between NLCD and high resolution estimates of impervious cover in the western U.S. than the eastern U.S. However, use of high resolution sources typically comes at the expense of spatial extent, and thus there are no known shore-to-shore estimates of impervious cover for the continental U.S. at higher resolutions than NLCD. NLCD provides reliable estimates (Nowak and Greenfield, 2010) that can be used to examine spatial patterns of impervious cover over large spatial extents (e.g., states) to help inform planning and management related to the CWA and other regulatory constructs.

A few local-scale studies have reported that NHD underestimates stream length when compared to digital streams developed from very high resolution data, and the underestimation appears to be mostly attributable to omission of headwater and ephemeral streams (Roy *et al.*, 2009; Lang *et al.*, 2012; Elmore *et al.*, 2013; Fritz *et al.*, 2013). It is difficult to speculate on how the omission of headwater and ephemeral streams from the NHD data influenced our estimates of stream length in the vicinity of impervious cover and the spatial pattern of impervious cover because the effect of the omissions depends on two interacting spatial patterns (Wickham *et al.*, 2007): the spatial pattern of omitted streams and the spatial pattern of impervious cover. Assuming that headwater and ephemeral streams tend to occur in remote locations where there tends to be less impervious cover, our estimates of the length of streams and shorelines in the vicinity of impervious cover may be low and our estimates of the number of watersheds with a proximal spatial pattern may be high. Our estimates of stream length "flowing" through impervious cover may be low because the NHD data we used did not include some streams where impervious cover occurred. We would expect the underestimate to be small because most of the omitted streams would not be "flowing" through impervious cover. Conversely, our estimates of the proximal spatial pattern may be high because most of the missing streams did not "flow" through impervious cover thereby reducing the overall stream length "flowing" through impervious cover. Such a reduction would favor more similar estimates for stream- and watershed-based expressions of impervious cover.

Increasing by nearly 10,000 km between 2001 and 2011, the total length of streams and water-body shorelines in the continental U.S. immediately adjacent (within 30 m) to impervious cover is approaching one-half million kilometers. Assuming that impervious cover in close proximity to surface water poses a greater threat than impervious cover far from surface water, monitoring and management of watershed impervious cover that does not account for its spatial pattern may not detect impaired conditions. In this research, we assumed a fixed distance to define proximity; however, we recognize that relationships between surface water condition and distance to impervious cover requires further research (Brabec, 2009).

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