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The increase of impervious cover and decrease of tree cover within urban areas globally (2012–2017)

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ABSTRACT

Trees in cities provide numerous benefits to society by altering the local physical, biological and social environment, providing billions of dollars in annual benefits. How tree and other cover types vary and are changing globally within urban areas is currently unknown. Photo-interpretation was used to determine current urban cover (tree, impervious, grass, other cover) percentages and recent changes in cover types throughout the world. Within existing urban areas, the average global urban tree cover had a slight, but statistically significant decline from 26.7 % to 26.5 % (c. 2012–2017), or a loss of about 40,000 ha per year. All continents exhibited a loss in urban tree cover except for Europe; the greatest decrease in percent tree cover was in Africa. Concurrent with tree loss was an increase in impervious cover among all continents, which globally had a statistically significant increase from 24.3 % to 25.9 % (326,000 ha/year). Urban tree cover was significantly different among forested (30.6 %), grassland (18.5 %) and desert regions (12.6 %). Understanding global urban cover type variation and changes can improve global assessments and help guide forest management to improve environmental quality in cities.

1. Introduction

Urban areas are comprised of numerous anthropogenic (e.g., buildings, roads, parking lots) and natural (e.g., trees, grass, soil) land covers that affect the local physical and social environments, and consequently human health and well-being. However, little is known about urban tree cover globally or how it is changing. Various land cover change analyses have been conducted using classified satellite imagery (e.g., Hansen et al., 2003; Yang et al., 2003; Lunetta et al., 2006; Parlin, 2009). These classified images have limitations due to their relatively coarse image resolution and/or inaccuracies of image classifications, which can lead to false changes due to misclassification of cover types on either map. Photo-interpretation of high resolution images to detect cover changes has the ability to overcome these limitations, but lacks the ability to develop detailed comprehensive cover change maps.

Various studies have analyzed tree cover amounts within cities using photo-interpretation (e.g., Nowak et al., 1996; Pasher et al., 2014; Parmehr et al., 2016; Treeconomics, 2019) and digital cover mapping procedures (e.g., Grove et al., 2014; Parmehr et al., 2016). Tree cover varied among cities, ranging from less than one percent to greater than 50 %. The city's biome (forest, grassland, desert) has a substantial impact on overall percent tree cover (Nowak et al., 1996). Other studies have also assessed global or regional urban vegetation cover (Fuller and Gaston, 2009; Dobbs et al., 2017; Richards et al., 2017), species diversity (Kendal et al., 2014) and species composition (Yang et al., 2015). These studies reveal that the amount of green space within a city is primarily related to city area rather than city population size, and that green space, tree cover, and species diversity vary with climate and socio-economic factors.

Assessments of urban tree cover change are also limited and typically focus on individual cities or urban areas within a country (Table 1). These studies reveal varying patterns of changes, with some areas increasing tree cover and others having decreased tree cover. Change in green spaces in European cities have also been assessed and reveal that green space increased between 2000 and 2006 (Kabisch and Haase, 2013).

Tree cover is a key and simple element in understanding the magnitude of the urban forest resource and can be used to assess various ecosystem services and values derived from the forest (e.g., Nowak et al., 2014; Coville et al., 2019). The annual value produced by the world's urban forests is in the multi-billion dollar range as U.S. urban forests are conservatively estimated to produce over $18 billion annually (Nowak and Greenfield, 2018b). Impervious cover also plays an important role in the landscape as these surfaces facilitate transportation and provide shelter, but also can negatively impact the

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Table 1
Studies of urban tree cover change.

Location	Years	Tree Cover Change[a]	Methods[b]	Reference
Atlanta, GA	1951–2010	−2.1 % (53.3–51.2 %)	PI_p	Merry et al. (2014)
Baltimore, MD	1999–2004	+0.2 % (34.3–34.5%)	DI	Zhou et al. (2008)
Canada (urban areas)	1990–2012	−1.5 % (27.6–26.1 %)	PI_p	McGovern and Pasher (2016)
Detroit, MI	1951–2010	−1.5 % (32.3–30.8 %)	PI_p	Merry et al. (2014)
Los Angeles, CA (coastal area)	2009–2014	−0.3 % (14.5–14.2 %)	DI	Locke et al. (2017)
Melbourne, Australia (6 suburbs)	2010–2015	5 suburbs (+), 1 suburb (−)[c]	PI_p	Kaspar et al. (2017)
Minneapolis, MN area	1937–2009	+16 % (17–33 %)	PI	Berland (2012)
Oakland, CA	1850–1988	+16.7 % (2.3–19 %)	PI, MI	Nowak (1993)
Portland, OR	2000–2015	+3.4 % (27.3–30.7 %)	PI_p	DiSalvo et al. (2017)
Seattle, WA	2002–2007	+0.4 % (22.6–22.9 %)	DI	Parlin (2009)
Syracuse, NY	c. 1996–2009	−0.6 % (27.5–26.9 %)	PI_p	Nowak et al. (2016)
U.S. (20 cities)	c. 2004–2009	17 cities (−); 1 city (+)[d]	PI_p	Nowak and Greenfield, 2012a
U.S. (urban areas)	c. 2009–2014	−1.0 % (40.4–39.4 %)[e]	PI_p	Nowak and Greenfield, 2018a
Worcester, MA area	2008–2010	−2 % (na)	DI	Hostetler et al. (2013)

[a] Net change in tree cover. Values in parentheses indicate tree cover values in the first and second time period respectively.
[b] Methods of change detection: DI – change analyzed by comparing digital tree cover maps; MI – historical map interpretation; PI – photo-interpretation; PI_p – photo-interpretation using paired points through time.
[c] 4 suburbs had a statistically significant increase in tree cover; one had a non-significant increase, and one had a statistically significant decrease.
[d] 17 of the 20 analyzed cities had statistically significant declines in tree cover, one city had a statistically significant increase in tree cover.
[e] 23 states/districts had statistically significant declines in tree cover, 25 states had non-significant decreases or no change in tree cover, and three states showed a non-significant increase in tree cover.

environment by limiting tree regeneration, increasing air temperatures and reducing water infiltration. With 55 % of the world's population living in urban areas in 2018 (United Nations, 2018), urban trees and impervious surfaces have a substantial impact on the health and well-being of billions of people globally. Understanding the magnitude of urban tree and impervious cover globally, and how it is changing, is a first step towards a better comprehension of this global resource and an understanding of whether current city management actions need to change to sustain urban tree cover globally.

By understanding typical cover values at the continental scale, world governments can decide if these values are appropriate for sustaining human health and well-being. By understanding changes in cover classes, governments can decide if cover amounts are progressing in the desired direction. Quantifying differences in tree and impervious cover and cover change among biomes globally can also help reveal the impact of the regional environment on these cover classes. This type of global information can aid management and policies related to the appropriate amounts of cover classes and facilitate discussions regarding optimal tree and impervious cover levels and the potential means to attain these desired levels (e.g., tree planting, changing development patterns). Global urban forest information can help guide urban forest management in sustaining appropriate and desired tree cover levels for a burgeoning world urban population.

While tree cover amounts are known in select cities, the global amount of urban tree and impervious cover, and its variation through time and among different biomes and continents remains unknown. The objective of this research is to assess current amounts and changes in global urban tree, impervious, and other cover types among continents and biome types (forest, grassland, deserts). These data can improve our understanding of the magnitude and variation in global urban tree cover and tree cover change. While urban area expansion is negatively correlated with forest, cropland and grassland changes (Bagan and Yamagata, 2014), this paper focuses on cover proportions and changes within existing urban areas, not changes associated with expanding urbanization.

2. Methods

Urban areas across the globe were delimited using Moderate Resolution Imaging Spectroradiometer derived (500 m resolution) Urban Land Cover data (Natural Earth, 2018; Schneider et al., 2009). This urban area definition includes areas dominated by the built environment (> 50 %), including non-vegetated, human-constructed elements (e.g., roads, buildings, runways) for 2001–2010, with minimum mapping unit > 1 km^2.

To assess cover and cover changes, five thousand random paired-points were overlaid within these existing urban areas globally. These points were classified among global biomes (Bailey, 1995; Olson and Dinerstein, 2002; Nature Conservancy, 2018) of forest, grassland, desert, and rock/ice/tundra to assess differences in urban tree cover among these regions (Fig. 1). However, due to limited urban land in rock/ice/tundra, this classification was not analyzed. These 5,000 points were used to assess differences in cover among biomes.

The 5,000 points were then classified as to which continent (ESRI, 2018) the points were located. Given the dominance of urban land in Asia and Europe, the other continents ended up with relatively small sample sizes. To increase the precision of estimates for these continents, if a continent did not have at least 1,000 points, additional random points were laid so that each continent had 1,000 points. With 1,000 points, the standard error of the estimates will be less than 1.6 %. Occasionally points could not be assessed due to cloud cover or poor imagery, so some continents ended up with less than 1,000 interpreted points.

Each point was overlaid on Google Earth imagery and the most recent date of the image pair was determined by finding the most recent image that had high-resolution, interpretable imagery (mostly leaf-on, sub-meter resolution). The second older image paired-point was determined by finding high-resolution, interpretable images as close to five-years prior to the recent date image. The average date of the earliest photo was 2012 in all continents except for Europe (average start date = 2011); average second date for all continents was 2017. The average time difference between images was 5.1 years. Overall, 70 % of the points were 5 years apart, 22 % were either 4 or 6 years apart, and 5 % were either 3 or 7 years apart. The remaining 3 % had differences that varied between 1 year (0.1 % of points; 10 points) and 14 years (0.03 % of points; 2 points).

Each point was overlaid in the same geographic position on both sets of temporal images and paired-image interpretation was conducted (i.e., interpreter classified each point pair by contrasting and classifying the image points side-by-side). In cases of mis-registration of the image or point (i.e., the point had a slight change in location between images), the interpreter corrected the point location to ensure the exact same location was interpreted. In addition, interpreters could correct apparent false changes due to image parallax and seasonal changes

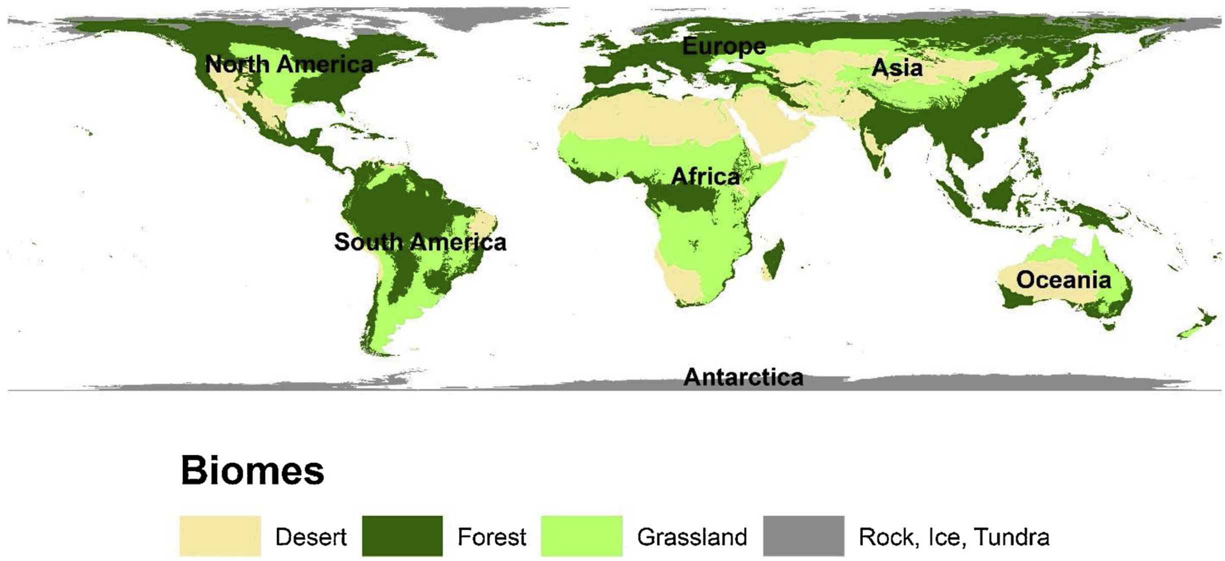

Fig. 1. Biome classifications among continents (Bailey, 1995; Olson and Dinerstein, 2002; Nature Conservancy, 2018).

between images and record them as without change as appropriate.

A trained photo-interpreter classified each point as to whether it fell on: trees/shrubs ("trees"), grass or herbaceous cover ("grass"), impervious cover (i.e., buildings, roads, other impervious), agricultural areas (i.e., soil or herbaceous cover in crop areas) or other (i.e., bare soil, water). A five-percent random sample of points was reinterpreted by another trained photo-interpreter to check for classification accuracy. Overall, the interpreters were in 100 % agreement on the change estimates and 96 % agreement on cover class designations. This 4 % disagreement on classes does not mean that there is an absolute 4 % error as the misclassifications could and often compensate (e.g., some tree points may be classified as grass, but also grass points are classified as trees), which would reduce overall misclassification error. Differences in interpretation could occur due to image quality (atmospheric haze, image darkness) affecting interpretation, mis-registration of points between original and second interpretation, and/or interpreter error in classification or recording from the original interpreter or quality check interpreter.

2.1. Cover estimates

Within each biome or continent, the percentage of each cover class (p) was calculated as the number of sample points (x) hitting the cover attribute divided by the total number of interpretable sample points (n) within the area of analysis ($p = x/n$) × 100. The standard error of the estimate (SE) in cover class j was calculated as $SE_j = [p_j(1\text{-}p_j)/n]^{0.5} \times 100$ (Lindgren and McElrath, 1969). This method has been used to assess canopy cover in many cities (Nowak and Greenfield, 2012a, Nowak and Greenfield, 2012b, Nowak and Greenfield, 2018a).

2.2. Changes in tree and other cover

As changes were observed, it is known that cover classes are changing. However, as a cover class can both gain and lose cover through time and space, the McNemar test (Sokal and Rohlf, 2003) was used to determine if the proportion of positive and negative changes are significantly different from each other (alpha level = 0.05), thereby indicating a statistically significant net change. This process of change detection for urban tree cover was originally developed in Nowak and Greenfield, 2012a, but has been used in subsequent analyses (e.g., Kaspar et al., 2017; Roman et al., 2017; Nowak and Greenfield, 2018a). As the overall time frame of change in cover varied among locations, change in percent cover was annualized for comparative purposes among areas.

To determine overall global urban tree cover and tree cover change, the tree cover estimates for each continent were weighted by the urban area in each continent. To determine if the net change was statistically significant among all urban areas globally, the 95 % confidence interval around the global change estimate was calculated. If the 95 % confidence interval (SE * 1.96) around the change variable did not contain zero, the change estimate was statistically significant at alpha 0.05. The 95 % confidence interval was calculated by weighting the variance of each continent change estimate by the square of the urban area in each continent. For contrasting differences in cover classes among continents, a 95 % confidence interval comparison was used.

2.3. Urban population change

The human population within the delimited urban area was estimated using 30 arc (approximately 1 km at the equator) resolution population data for 2012 and 2017 (WorldPop and CIESIN, 2018). Total population density and change in density was calculated for urban areas in each continent. Spearman correlation (alpha = 0.05) was used to test for associations between population density change and tree / impervious cover changes among continents and for associations between population density and tree / impervious cover.

3. Results

3.1. Tree and impervious cover

Among the continents, tree cover (c. 2017) in urban areas (c. 2010) varied from 19.9 % in Africa to 31.1 % in North America; impervious cover varied from 19.6 % in Europe to 35.8 % in South America. Europe and North America had statistically greater urban tree cover than Africa, Asia, and South America (Fig. 2, Table 2). Urban tree cover in forest biomes averaged 30.4 %, which was significantly greater than in grassland biomes (18.2 %), which was significantly greater than in deserts (12.0 %) (Table 3). Average global urban tree cover was 26.5 %, while urban impervious cover averaged 25.9 % (Fig. 2, Table 2). Urban tree cover had a non-significant negative correlation with population density (r = −0.77), while urban impervious cover had a non-significant positive correlation with population density (r = 0.49).

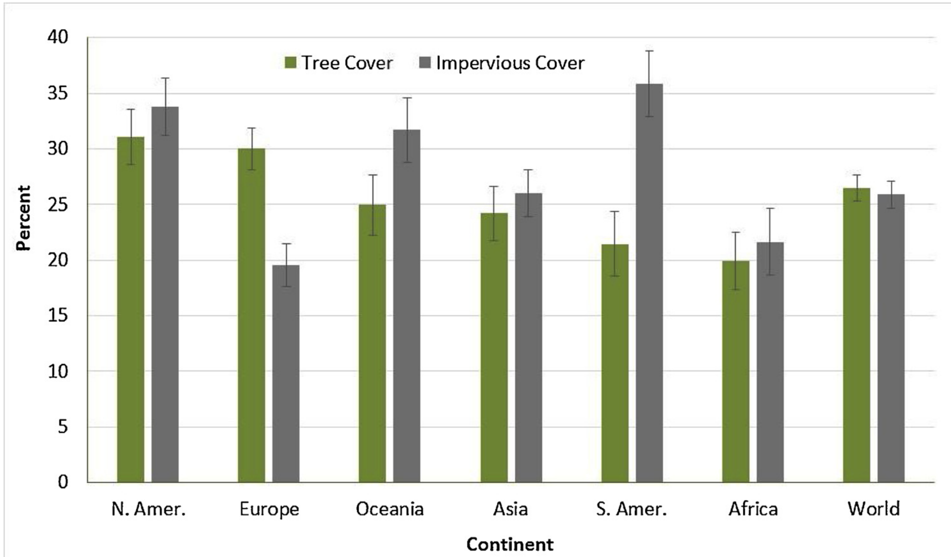

Fig. 2. Tree and impervious cover (c. 2017) in urban areas (c. 2010), with 95 % confidence intervals, by continent.

3.2. Urban land and population

Urban land area was greatest in Asia, followed by Europe, North America, Africa, South America, and Oceania. Total urban land amounts to 106 million ha or 0.72 % of the land area in these continents. Europe had the highest percent urban land, followed by Asia, North America, South America, Africa, and Oceania (Table 4).

Forest biomes had the highest percent urban land (1.3 %), followed by grassland (0.43 %), deserts (0.39 %), and rock/ice/tundra (0.002 %). Most urban land (75 %) is found in forested biomes, followed by grasslands (14 %), deserts (11 %), and rock/ice/tundra (0.003 %). Europe had the highest proportion of its urban land in forested biomes, followed by Oceania, North America, Asia, South America, and Africa (Table 4).

3.3. Urban tree and impervious cover change

The world's urban tree cover had a slight but statistically significant decline (−0.2 %) between c. 2012 and 2017. All continents exhibited a decline in tree cover, except for Europe, which exhibited 0.3 % increase. Only Africa had a statistically significant decline in tree cover. Globally, urban impervious cover increased significantly from 24.3 % to 25.9 % between c. 2012 and 2017. All continents exhibited statistically significant increases in impervious cover except for Europe and North America, which exhibited a non-significant increase. Grass, agriculture and other land cover types exhibited statistically significant declines globally (Table 2; Supplemental Table 1). All biomes exhibited a non-statistically significant decline in tree cover (range: −0.6 % to −0.2 %) and statistically significant increases in impervious cover (range: 1.4 %–2.8 %) (Table 3).

Urban tree cover change had a non-significant negative correlation with population density change ($r = -0.37$), while urban impervious cover change had a non-significant positive correlation with population density change ($r = 0.66$). The greatest urban population density increases occurred in Africa, South America and Asia (Table 5). Urban population density increases were greatest in desert biomes (265 people/km^2; 11.3 %), followed by grasslands (225 people/km^2; 11.3 %), and forests (180 people/km^2; 7.3 %).

4. Discussion

The global pattern of higher urban tree cover in forested regions (30.4 %) vs. grassland regions (18.2 %) vs. desert regions (12.0 %) is comparable to findings of urban tree cover across the United States: forest = 31 %; grassland = 19 %; desert = 10 % (Nowak et al., 1996). Along with biome effects, tree cover is also affected by population density. Studies have shown that percent green space in Europe (Fuller and Gaston, 2009) and Asia (Richards et al., 2017) declines with increasing human population density. Percent tree cover in the United States also declines within increasing population density (Nowak et al., 1996; Nowak and Greenfield, 2012b).

A dominant factor affecting the amount of local tree cover is the local environment as forested regions typically have ample precipitation and seed sources to sustain forest cover. While tree planting plays a role in the amount of local urban tree cover, natural regeneration is likely a strong force in establishing new trees, particularly in forested regions worldwide. In the U.S. and Canada, natural regeneration accounts for about 2/3 of the urban forest population (Nowak, 2012). In forested regions, vacant or unmanaged lands will tend to regenerate with trees and increase tree cover. In drier grasslands and deserts, these unmanaged lands will often not readily regenerate with trees, and will tend to have lower tree cover unless tree planting and watering programs are established to enhance tree cover (e.g., Nowak, 2012; Nowak and Greenfield, 2012b). The percentage of the tree population planted was greater in cities developed in grassland areas as compared to cities developed in forests and tended to increase with increased population density and percent impervious cover in cities. The proportion of trees planted also tended to increase on more human-dominated land uses (e.g., residential and commercial/industrial).

Various actions tend to restrict tree establishment (e.g., impervious surfaces, mowing, agriculture). Increases in impervious cover, which increases with population density (Nowak and Greenfield, 2012b), tend to lower tree cover in heavily populated areas. These actions, in conjunction with the local environment, lead to varying amounts and patterns of tree cover. Thus the mix of land uses (managed and unmanaged), population density and interactions with the local environment all affect local tree cover amounts. In addition, financial resources dedicated to management can affect local tree cover amounts. Land managers can work with local natural regeneration tendencies and tree planting efforts to establish tree cover levels appropriate to their local conditions and desires.

As most urban land globally is within forested regions, most cities will have the opportunity to use natural regeneration to help sustain tree cover. However, urban tree cover is constantly changing as a consequence of many natural (e.g., regeneration, growth, storms) and anthropogenic (e.g., development, planting, tree removal) forces. These

Table 2
Change in cover classes in urban areas between c. 2012-2017 by continent and worldwide.

			2012		2017		Diff.[c]	p-value	Ann.	n
Area[a]	Area Diff[b]	Cover	%	SE	%	SE			Diff.[d]	
AF	EU,NA	Tree	21.5	1.3	19.9	1.3	−1.5*	0.0039	−0.31	993
	NA,OC,SA	Impervious	19.5	1.3	21.7	1.3	2.1*	< 0.0001	0.43	
	AS,EU,NA,OC,SA	Grass	41.2	1.6	40.9	1.6	−0.3	0.5900	−0.06	
	AS,EU,NA,OC,SA	Agriculture	13.0	1.1	13.1	1.1	0.1	0.7815	0.02	
		Other	4.8	0.7	4.4	0.7	−0.4*	0.0455	−0.08	
AS	EU,NA	Tree	24.3	1.0	24.2	1.0	−0.1	0.8927	−0.01	2,016
	EU,NA,OC,SA	Impervious	23.6	0.9	26.0	1.0	2.4*	< 0.0001	0.48	
	AF, OC	Grass	27.4	1.0	26.4	1.0	−1.0*	0.0272	−0.20	
	AF,NA,OC,SA	Agriculture	18.9	0.9	18.1	0.9	−0.8*	0.0052	−0.17	
		Other	5.8	0.5	5.3	0.5	−0.5	0.1048	−0.10	
EU[e]	AF,AS,SA	Tree	29.7	1.2	30.0	1.2	0.3	0.4795	0.05	1,373
	AS,NA,OC,SA	Impervious	19.3	1.1	19.6	1.1	0.3	0.2850	0.05	
	AF,OC	Grass	26.8	1.2	26.7	1.2	−0.1	0.8788	−0.01	
	AF,NA,OC,SA	Agriculture	20.2	1.1	19.6	1.1	−0.6*	0.0209	−0.11	
		Other	4.0	0.5	4.1	0.5	0.1	0.7389	0.01	
NA	AF,AS,OC,SA	Tree	31.7	1.5	31.1	1.5	−0.6	0.2207	−0.12	995
	AF,AS,EU	Impervious	33.1	1.5	33.8	1.5	0.7	0.0707	0.14	
	AF,OC	Grass	26.7	1.4	26.5	1.4	−0.2	0.7055	−0.04	
	AF,AS,EU,SA	Agriculture	2.3	0.5	2.3	0.5	0.0	1.0000	0.00	
		Other	6.2	0.8	6.3	0.8	0.1	0.7055	0.02	
OC	NA	Tree	25.5	1.4	24.9	1.4	−0.5	0.2253	−0.10	990
	AF,AS,EU	Impervious	29.7	1.5	31.7	1.5	2.0*	< 0.0001	0.40	
	AF,AS,EU,NA	Grass	34.6	1.5	32.9	1.5	−1.7*	0.0016	−0.34	
	AF,AS,EU,SA	Agriculture	4.1	0.6	4.2	0.6	0.1	0.3173	0.02	
		Other	6.1	0.8	6.2	0.8	0.1	0.6547	0.02	
SA	EU,NA	Tree	21.9	1.3	21.5	1.3	−0.4	0.4652	−0.08	974
	AF,AS,EU	Impervious	32.4	1.5	35.8	1.5	3.4*	< 0.0001	0.68	
	AF	Grass	29.4	1.5	27.7	1.4	−1.6*	0.0237	−0.33	
	AS,EU,NA,OC,SA	Agriculture	10.1	1.0	9.0	0.9	−1.0*	0.0016	−0.21	
		Other	6.3	0.8	6.0	0.8	−0.3	0.3657	−0.06	
World		Tree	26.7	0.6	26.5	0.6	−0.2*	na	−0.04	7,341
		Impervious	24.3	0.6	25.9	0.6	1.6*	na	0.31	
		Grass	28.3	0.6	27.7	0.6	−0.6*	na	−0.12	
		Agriculture	15.4	0.5	14.8	0.5	−0.6*	na	−0.10	
		Other	5.3	0.3	5.1	0.3	−0.2*	na	−0.04	

n = sample size.
na – not analyzed as McNemar test was not performed due to weighting of continental urban areas (confidence internal analysis was performed to determine statistical significance).
Tree – tree/shrub, Impervious – buildings, roads and other impervious cover, Grass – grass/herbaceous, Agriculture: grass or soil areas used for agriculture, Other – bare soil and water.
[a] Area of analysis: world or continents: AF = Africa, AS = Asia, EU = Europe, NA = North America, OC = Oceania, SA = South America.
[b] Letters indicate which continent that the 2017 cover class is statistically different from based 95 % confidence interval comparisons.
[c] Net difference between c. 2012 and 2017.
[d] Annualized difference between c. 2012 and 2017.
[e] Average starting year in Europe was c. 2011.
* Statistically significant change in cover class at $\alpha = 0.05$.

forces change through time, but it is evident that within already established urban areas that development is increasing impervious cover. This new impervious cover may not necessarily reduce tree cover (e.g., new impervious cover on previously grass area), but it will limit the potential for future natural regeneration.

Globally, impervious surfaces are increasing at a rate of 326,000 ha per year (0.3 % per year) while tree cover is decreasing at about 40,000 ha per year (0.04 % per year). Global urban tree cover loss is relatively small, with changes varying at the local scale and some areas showing net urban tree cover increases. A previous study with a similar time period found that tree cover losses in the United States to be 0.2 % annually, a rate 5 times higher than the global average (Nowak and Greenfield, 2018a). Tree cover change in U.S. cities has also been shown to vary from −2.5 % per year (New Orleans, LA; impact of hurricane Katrina) to +0.2 % per year (Syracuse, NY), with 17 of the 20 analyzed cities exhibiting statistically significant declines in tree cover (Nowak and Greenfield, 2012a). The gain in tree cover in Syracuse was mainly due to natural regeneration (Nowak, 2012; Nowak and Greenfield, 2012a; Nowak et al., 2016).

While this study focused on net changes, it is important to note that cover classes are constantly swapping. Most of the urban tree cover losses converted to either grass (51 % of loss) or impervious cover (32 %), while most of the tree cover gains came from grass covered areas (65 %). Most of the impervious cover gains came from previously grass (47 %) or treed (23 %) areas. In most continents, urban impervious cover is greater than tree cover. However, at the global scale, urban impervious cover (25.9 %) is slightly less than urban tree cover (26.5 %). As tree cover is declining and impervious increasing, urban impervious cover will likely be a more dominant cover type than trees globally by 2020. As trees can cover impervious surfaces, the impervious cover estimates are conservative.

This paper only addressed cover changes within existing urban areas. However, urban areas will expand through time and likely increase overall tree cover in urban areas as urbanization expands and includes former rural trees. Globally, urban land is projected to nearly triple in area between 2000 and 2030 (Seto et al., 2012). As urban areas and populations expand in the coming years, management of urban forests will become increasingly more essential to sustaining the health

Table 3
Change in cover classes in urban areas between c. 2012-2017 by biome type.

			2012		2017		Diff.[b]	p-value	Ann.	n
Biome	Area Diff[a]	Cover	%	SE	%	SE			Diff.[c]	
Desert	For, Grs	Tree	12.6	1.5	12.0	1.4	−0.6	0.2568	−0.11	509
		Impervious	20.8	1.8	23.6	1.9	2.8*	0.0010	0.54	
	For	Grass	40.3	2.2	38.7	2.2	−1.6*	0.0455	−0.31	
	For, Grs	Agriculture	19.4	1.8	19.1	1.7	−0.4	0.4142	−0.08	
		Other	6.9	1.1	6.7	1.1	−0.2	0.7055	−0.04	
Forest	Des, Grs	Tree	30.6	0.8	30.4	0.8	−0.2	0.4904	−0.04	3,732
		Impervious	25.1	0.7	26.5	0.7	1.4*	< 0.0001	0.27	
	Des, Grs	Grass	24.0	0.7	23.6	0.7	−0.4	0.1669	−0.08	
	Des	Agriculture	14.9	0.6	14.3	0.6	−0.6*	0.0014	−0.11	
		Other	5.4	0.4	5.2	0.4	−0.2	0.2059	−0.04	
Grassland	Des, For	Tree	18.5	1.5	18.2	1.5	−0.3	0.5930	−0.06	672
		Impervious	21.6	1.6	23.7	1.6	2.1*	0.0010	0.41	
	For	Grass	40.8	1.9	40.0	1.9	−0.7	0.3173	−0.15	
	Des	Agriculture	12.9	1.3	12.4	1.3	−0.6	0.1025	−0.12	
		Other	6.3	0.9	5.8	0.9	−0.4	0.3657	−0.09	

n = sample size.
Tree – tree/shrub, Impervious – buildings, roads and other impervious cover, Grass – grass/herbaceous, Agriculture: grass or soil areas used for agriculture, Other – bare soil and water.
[a] Letters indicate which biome that the 2017 cover class is statistically different from based 95 % confidence interval comparisons (Des - desert, For – forest, Grs - grassland).
[b] Net difference between c. 2012 and 2017.
[c] Annualized difference between c. 2012 and 2017.
* Statistically significant change in cover class at $\alpha = 0.05$.

Table 4
Summary of urban land and population by continent.

	Urban Land				Urban Population	
Continent	%[a]	(ha x10^6)	%GlobUrb[b]	%For[c]	Total (x10^6)[d]	Density[e]
Europe	2.87	29.7	28	91	333	1,171
Asia	0.98	43.7	41	72	1,484	3,376
North America	0.74	18.0	17	78	309	1,717
South America	0.35	6.2	6	48	265	4,354
Africa	0.24	7.3	7	44	301	4,196
Oceania	0.18	1.4	1	81	18	1,302
World	0.72	106.3	100	75	2,711	2,580

[a] Percent of continent classified as urban.
[b] Percent of global urban land within continent.
[c] Percent of urban land in forest biome.
[d] Total population in 2017.
[e] People/km^2 (2017).

Table 5
Cover and population density changes (2012–2017) by continent.

	Tree		Impervious		Population	
Continent	%[a]	Chg[b]	%[a]	Chg[b]	DenChg[c]	DenChg%[d]
North America	31.1	−0.6	33.8	0.7	91	5.6
Europe	30.0	0.3	19.6	0.3	26	2.2
Oceania	24.9	−0.5	31.7	2.0*	7	0.6
Asia	24.2	−0.1	26.0	2.4*	274	8.8
South America	21.5	−0.4	35.8	3.4*	324	8.0
Africa	19.9	−1.5*	21.7	2.1*	573	15.8
World	26.5	−0.2*	25.9	1.6*	195	8.2

[a] Percent cover in 2017.
[b] Change in percent cover.
[c] Change in population density (#/km^2).
[d] Percent change in population density.

and well-being of urban residents and local environments.

While overall urban tree cover (i.e., hectares of cover) will likely increase as urban areas expand, more research is needed as to how percent tree cover will change within urban areas due to urban expansion. Monitoring of urban forests globally is also needed to better understand not only how tree cover is changing, but also tree composition and health. More consistent classifications of urban land globally would also help with classifying and monitoring urban forests. Global estimates of urban land vary from 276,000 km^2 to 3.5 million km^2 based on assessment methods (Schneider et al., 2009).

It is clear from this assessment that impervious cover is increasing globally within urban areas, but changes in tree cover are varied, trending downward overall. These changes will alter environmental conditions within cities. Impervious surfaces provide essential services related to sustaining urban functions (e.g., transportation, housing) and higher population densities in cities. However, the loss of leaf area and expansion of impervious surfaces can lead to increased air temperatures (Oke, 1989; Akbari et al., 2001) and storm water runoff (National Research Council, 2008). The pattern of decreasing tree cover and increasing impervious surfaces indicate a synergistic pattern of loss of environmental benefits (e.g., air temperature cooling and air pollution removal by trees) and increased environmental issues (e.g., increased air temperatures, air and water pollution, thermal stress, energy use, and runoff). These changes can affect human health and well-being, as well as infrastructure management costs.

5. Conclusion

Urban trees provide numerous benefits to society, but the amount of tree cover in cities varies globally based on local environmental conditions, development patterns and management / policies related to sustaining tree cover. In Europe, urban tree cover is trending upward, while tree cover is trending downward in the rest of the world. Overall tree cover change globally has exhibited a slight, statistically significant decline. In contrast, impervious surfaces are on the rise in urban areas across the world with an average increase in impervious surfaces about eight times greater than the average loss in tree cover.

As human populations increase, so will urban development pressures. These pressures can alter tree and impervious cover within urban and urbanizing areas, and their associated environmental benefits and costs. Local policies related to urban development, conservation of the natural environments and enhancing tree planting and/or regeneration can guide future landscapes to desirable societal outcomes. Continued and expanded monitoring of global changes within cities, particularly ground-based monitoring that can capture details on changes in tree species, health and densities, will be important for setting policies and actions to sustain human health and well-being in these areas where an increasing majority of the world's population lives.

Declaration of Competing Interest

There is no known conflict of interest with the paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2020.126638.

References

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol. Energy 70 (3), 295–310.
Bagan, K., Yamagata, Y., 2014. Land-cover change analysis in 50 global cities by using a combination of Landsat data and analysis of grid cells. Environ. Res. Lett. 9, 064015.
Bailey, R.G., 1995. Description of the Ecoregions of the United States, 2nd ed. USDA Forest Service, pp. 108 Misc. Pub. No. 1391, Map scale 1:7,500,000.
Berland, A., 2012. Long-term urbanization effects on tree canopy cover along an urban-rural gradient. Urban Ecosyst. 15, 721–738.
Coville, R., Endreny, T., Nowak, D.J., 2019. Chapter 19: Modeling the impact of urban trees on hydrology. In: Levia, D.F., Carlyle-Moses, D.E., Iida, S., Michalzik, B., Nanko, K., Tischer, A. (Eds.), Forest-Water Interactions. Ecological Studies Series, No. 240. Springer-Verlag, Switzerland AG, pp. 459–487.
DiSalvo, A., Darling, J., Crouch, R., Scott, I., Williams, R., 2017. Tree Canopy Monitoring: Protocol and Monitoring From 2000–2015. Portland Parks & Recreation, Portland, OR. pp. 18.
Dobbs, C., Nitschke, C., Kendal, D., 2017. Assessing the drivers shaping global patterns of urban vegetation landscape structure. Sci. Total Environ. 592, 171–177.
ESRI Arc Maps, 2018. World Continents. Retrieved July 2018 from. https://www.arcgis.com/home/item.html?id=a3cb207855b348a297ab85261743351d.
Fuller, R.A., Gaston, K.J., 2009. The scaling of green space coverage in European cities. Biol. Lett. 5, 352–355.
Grove, J.M., Locke, D.H., O'Neil-Dunne, J.P.M., 2014. An ecology of prestige in New York City: examining the relationships among population density, socio-economic status, group identity, and residential canopy cover. Environ. Manage. 54, 402–419.
Hansen, M.C., DeFries, R.S., Townshend, J.R.G., Carroll, M., Dimiceli, C., Sohlberg, R.A., 2003. Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continuous field algorithm. Earth Interact. 7 (10), 1–15.
Hostetler, A.E., Rogan, J., Martin, D., DeLauer, V., O'Neil-Dunne, J., 2013. Characterizing tree canopy loss using multi-source GIS data in Central Massachusetts, USA. Remote Sens. Lett. 4, 1137–1146.
Kabisch, N., Haase, D., 2013. Green spaces of European cities revisited for 1990-2006. Landsc. Urban Plan. 110, 113–122.
Kaspar, J., Kendal, D., Sore, R., Livesley, S.J., 2017. Random point sampling to detect gain and loss in tree canopy cover in response to urban densification. Urban Forest. Urban Green. 24, 26–34.
Kendal, D., Dobbs, C., Lohr, V.I., 2014. Global patterns of diversity in the urban forest: is there evidence to support the 10/20/30 rule? Urban For. Urban Green. 13, 411–417.
Lindgren, B.W., McElrath, G.W., 1969. Introduction to Probability and Statistics. MacMillan, London.
Locke, D.H., Romolini, M., Galvin, M., O'Neil-Dunne, J.P.M., Strauss, E.G., 2017. Tree canopy change in Coastal Los Angeles, 2009–2014. Cities Environ. (CATE) 10 (2) Article 3.
Lunetta, R.L., Knight, F.K., Ediriwickrema, J., Lyon, J.G., Worthy, L.D., 2006. Land-cover change detection using multi-temporal MODIS NDVI data. Remote Sens. Environ. 105, 142–154.
McGovern, M., Pasher, J., 2016. Canadian urban tree canopy cover and carbon sequestration status and change 1990–2012. Urban For. Urban Green. 20, 227–232.
Merry, K., Siry, J., Bettinger, P., Bowker, J.M., 2014. Urban tree cover change in Detroit and Atlanta, USA, 1951–2010. Cities 41 (Part A), 123–131.
National Research Council, Committee on Hydrologic Impacts of Forest Management, 2008. Hydrologic Effects of a Changing Forest Landscape. The National Academies Press, Washington, DC.
Natural Earth, 2018. Populated Places. Retrieved July 2018 from. http://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-populated-places/.
Nature Conservancy, 2018. tnc_terr_ecoregions. Retrieved July 2018 from. http://maps.tnc.org/files/metadata/TerrEcos.xml.
Nowak, D.J., 1993. Historical vegetation change in Oakland and its implications for urban forest management. J. Arboric. 19 (5), 313–319.
Nowak, D.J., 2012. Contrasting natural regeneration and tree planting in 14 North American cities. Urban For. Urban Green. 11, 374–382.
Nowak, D.J., Greenfield, E.J., 2012a. Tree and impervious cover change in U.S. cities. Urban For. Urban Green. 11, 21–30.
Nowak, D.J., Greenfield, E.J., 2012b. Tree and impervious cover in the United States. Landsc. Urban Plan. 107, 21–30.
Nowak, D.J., Greenfield, E.J., 2018a. Declining urban and community tree cover in the United States. Urban For. Urban Green. 32, 32–55.
Nowak, D.J., Greenfield, E.J., 2018b. U.S. urban forest statistics, values and projections. J. For. 116, 164–177.
Nowak, D.J., Rowntree, R.A., McPherson, E.G., Sisinni, S.M., Kerkmann, E., Stevens, J.C., 1996. Measuring and analyzing urban tree cover. Landsc. Urban Plan. 36, 49–57.
Nowak, D.J., Hirabayashi, S., Ellis, A., Greenfield, E.J., 2014. Tree and forest effects on air quality and human health in the United States. Environ. Pollut. 193, 119–129.
Nowak, D.J., Hoehn, R.E., Bodine, A.R., Greenfield, E.J., O'Neil-Dunne, J., 2016. Urban forest structure, ecosystem services and change in Syracuse, NY. Urban Ecosyst. 19, 1455–1477.
Oke, T.R., 1989. The micrometeorology of the urban forest. Philos. Trans. R. Soc. Lond., B, Biol. Sci. 324, 335–349.
Olson, D.M., Dinerstein, E., 2002. The global 200: priority ecoregions for global conservation. Ann. Mo. Bot. Gard. 89, 125–126.
Parlin, M., 2009. Seattle, Washington Urban Tree Canopy Analysis. NCDC Imaging. pp. 17.
Parmehr, E.G., Amati, M., Taylor, E.J., Livesley, S.J., 2016. Estimation of urban tree canopy cover using random point sampling and remote sensing methods. Urban For. Urban Green. 20, 160–171.
Pasher, J., McGovern, M., Khoury, M., Duffe, J., 2014. Assessing carbon storage and sequestration by Canada's urban forests using high resolution earth observation data. Urban For. Urban Green. 13, 484–494.
Richards, D.R., Passy, P., Oh, R.R.Y., 2017. Impacts of population density and wealth on the quantity and structure of urban green space in tropical Southeast Asia. Landsc. Urban Plan. 157, 553–560.
Roman, L.A., Fristensky, J.P., Eisenman, T.S., Greenfield, E.J., Lundgren, R.E., Cerwinka, C.E., Hewitt, D.A., Welsh, C.C., 2017. Growing canopy on a college campus: Understanding urban forest change through archival records and aerial photography. Environ. Manage. 60, 1042–1061.
Schneider, A., Friedl, M.A., Potere, D., 2009. A new map of global urban extent from MODIS satellite data. Environ. Res. Lett. 4. https://doi.org/10.1088/1748-9326/4/4/044003.
Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. PNAS 109, 16083–16088.
Sokal, R.R., Rohlf, F.J., 2003. Biometry: the Principles and Practices of Statistics in Biological Research. W.H. Freeman and Company, New York, New York.
Treeconomics, 2019. Urban Tree Cover. Retrieved February 2019 from:. http://www.urbantreecover.org/.
United Nations, 2018. World Urbanization Prospects: The 2018 Revision. Retrieved August 2018 from. https://esa.un.org/unpd/wup/publications/Files/WUP2018-KeyFacts.pdf.
WorldPop and Center for International Earth Science Information Network (CIESIN), Columbia University, 2018. Global High Resolution Population Denominators Project - Funded by the Bill and Melinda Gates Foundation (OPP1134076). https://doi.org/10.5258/SOTON/WP00647.
Yang, L., Xian, G., Klaver, J.M., Deal, B., 2003. Urban land-cover change detection through sub-pixel imperviousness mapping using remotely sensed data. Photogramm. Eng. Remote Sens. 69 (9), 1003–1010.
Yang, J., La Sorte, F.A., Pyšek, P., Yan, P., Nowak, D., McBride, J., 2015. The compositional similarity of urban forests among the world's cities is scale dependent. Glob. Ecol. Biogeogr. 11. https://doi.org/10.1111/geb.12376.
Zhou, W., Troy, A., Grove, M., 2008. Object-based land cover classification and change analysis in the Baltimore metropolitan area using multitemporal high resolution remote sensing data. Sensors 8, 1613–1636.