FOREST FRAGMENTATION AND CONNECTIVITY IN VIRGINIA BETWEEN 2001 AND 2011

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ABSTRACT

With an annual population growth rate currently estimated at about 5 %, Virginia presents an ideal case study for anthropogenic environmental disturbances. Urbanization as a result of increasing human activities has led to fragmentation of many crucial habitats, especially forests. Analysis of the extent to which forest fragmentation and connectivity have occurred in Virginia and corresponding changes associated with these processes, is relevant for conserving forest habitats and the biodiversity that they support. This study applies FRAGSTATS, a software system developed to assess forest fragmentation and connectivity, in combination with ArcGIS, to identify changes in forest patch metrics for Virginia over a ten-year interval (2001, 2006 and 2011) using National Land Cover Datasets (NLCD) maps as data source. Results show that, over ten years, forest patches have significantly declined in size, while the number of forest patches and total length of edge areas have increased over time. Results of this study show that road density in Virginia has no significant effect on forest fragmentation between 2001 and 2011. Analysis using ArcGIS revealed that sizes of core forest areas in Virginia are declining, and that these reductions match local topographic slope. This is because the steepness of the slope of an area dictates the degree of human activities in that area. These results suggest that urban sprawl associated with areas with gentler slopes, may have significant, long-term consequences for natural forest ecosystems and ultimately, biodiversity conservation.

Keywords: Forest Fragmentation, FRAGSTATS, Core, Connected, Fragmented, Forest patches, Patch metrics, Edge.

INTRODUCTION

Natural landscapes are essential for maintaining habitat quality and ecosystem services. Recent research shows that natural landscapes, such as intact forests, are significant for mitigating climate change, maintaining water supplies, conserving biodiversity, and protecting human health (Watson *et al.*, 2018). It is therefore important to know the degree to which expansion of the terrestrial human footprint affects natural forests and corresponding changes in environmental values.

Forest ecosystems contribute significantly to biodiversity conservation and over time, have evolved their resilience and adaptation capabilities to both anthropogenic and natural disturbances such as drought, fire and residential construction (Noce *et al*., 2017). Conservation of forest ecosystems will be more effective if impacts of changes to forest distribution due to environmental disturbances, are taken into consideration (Leroux &

Rayfield, 2014; Socha *et al*., 2016). Thus, in planning of conservation strategies, changes in species habitats and the factors affecting the composition of forest ecosystems over time, are critical (Serra-Diaz *et al*., 2015). Studies have shown that changes to forest ecosystems may occur over either a short period of time or may span hundreds of years, accompanied by species migration and evolutionary adaptations (Noce *et al*., 2017; Trumbore *et al*., 2015). Current research has also demonstrated that the changes in forest ecosystems are significantly correlated with human activities, climate and environmental conditions and topographic factors (Williams *et al*., 2012; Bellingham & Tanner, 2000; Noce *et al*., 2017).

Over the last hundred years, research conducted by the U.S. Department of Agriculture (USDA) Forest Service shows that the amount of forest land in the United States, has remained nearly constant (USDA Forest Service, 2012). A worrying trend, however, is the change in distributions of forests between different regions across the country as a direct result of human activities (USDA Forest Service, 2012). Forest fragmentation describes the process by which forested areas are reduced to smaller patches interspersed with non-forest land cover. Forest fragmentation in a particular area across a time gradient is affected by patterns of forest gain and forest loss, which invariably means that forest fragmentation can occur even if the absolute area of the forest land in a given region does not change.

Forest fragmentation forms a significant aspect of the distribution of forest systems as forest species, especially specialists, are adapted to forest habitat conditions, most particularly to either edge or interior forest habitats. As a result, changes in the patterns and extent of forest fragmentation, affect population sizes of forest species such as birds and other mammals (Fahrig, 2003). For example, increasing forest fragmentation leads to more pronounced edge effects, and to decreasing numbers of interior-adapted forest species such as the ovenbird (*Seiurus aurocapilla*) and wood thrush (*Hylocichla mustelina*) (Donovan & Flather, 2002).

Changes in landscape characteristics, and for that matter, changes in forest fragmentation, occur over an indefinite amount of time, with some changes occurring abruptly and the effects of other changes becoming more visible after several years (Bennett & Sanders, 2010). Landscape changes as a result of forest fragmentation include: (a) declining areas of total forest land in a given region, (b) reductions in sizes of forest patches, (c) increased isolation of forest patches, and (d) changes in shapes of resulting forest patches from more curvilinear boundaries to straight edges (Bennett & Sanders, 2010). Increases in lengths of edge areas are another common consequence of forest fragmentation with detrimental influences on population sizes of specialist species, as a result of increased residential and other anthropogenic developments.

Rapid residential and urban development in Virginia raises concerns about effects of human activity on environmental quality, forest fragmentation and loss of biological diversity. For example, Virginia's Loudoun County, the third most rapidly growing county in the United States, experienced a population growth rate of 55 % between 1990 and 1997 (GWU, 1999). Formerly primarily agrarian, forest lands have gradually been altered in the county, making way for extensive impervious construction (Fuller, 2001). Such effects are not limited to Loudoun County, as similar trends have been identified across the state of Virginia. These effects have been of particular concern to conservationists as division of previously contiguous natural landscapes into smaller, more fragmented, patches of forest, lead to changes in climatic conditions, hydrology, soil and topographic characteristics of the area, which consequently have significant impact on biodiversity.

These concerns have increased interests in monitoring of environmental indicators such as forest cover changes, so that decision-makers in the state of Virginia can take action to mitigate impacts of urban development. Ricketts *et al*. (1999) suggest that areas with higher levels of human threat need to be identified and conservation efforts concentrated in those areas. Understanding relationships between forest fragmentation, human activities, and species population dynamics, is important for biodiversity conservation (Boulinier *at el.*, 1998; Martin, 1998; Hanski, 1999). This study therefore aims to 1) assess the extent to which anthropogenic activities impact the state of Virginia and 2) quantify changes that have occurred in Virginia due to forest fragmentation between 2001 and 2011.

To quantify spatial patterns, measure the extent of forest fragmentation, and assess changes in a given area, McGarigal & Marks (1994) have developed a variety of indices that take into account the above listed changes. These indices measure the extent of forest fragmentation by tracking numbers of forest patches over a time gradient, aggregating resulting patches across that time gradient and assessing the complexity of the shapes of the resulting patches (Bennett & Sanders, 2010). These indices also measure connectivity between forest patches in a region, taking into consideration distances between the forest patches.

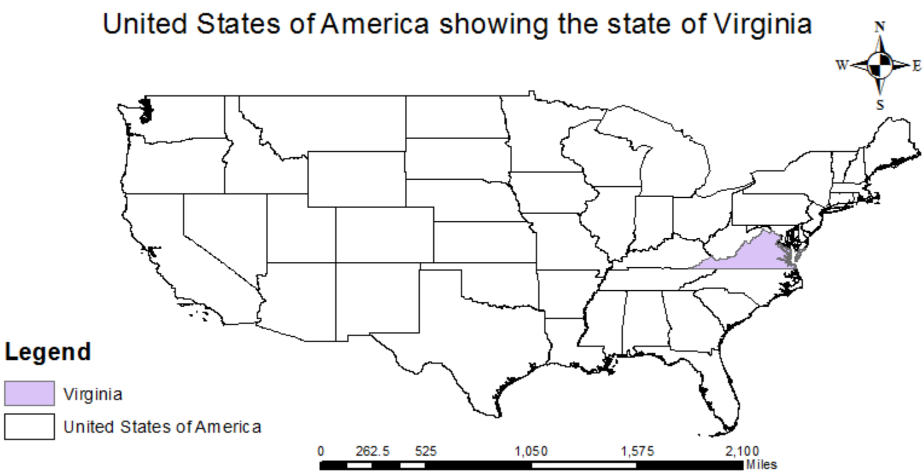
In this paper, we consider the extent of forest fragmentation in Virginia over a ten-year period between 2001 and 2011. For an in-depth analysis, we also examine changes in specific forest types in Virginia to identify which types of forests are undergoing the most changes over the study period. We also look at changes in sizes and shapes of forest habitat patches across the state, the degree of change in aggregation of patches over the ten-year period, as well as factors that might be contributing to forest fragmentation across Virginia.

METHODS

Study area

The state of Virginia forms a part of both the Southern and Mid-Atlantic United States (Fig. 1). Many of Virginia's rivers, including the Potomac, Rappahannock, York, and James, flow into the Chesapeake Bay, which separates the mainland from the Eastern Shore of Virginia, consisting of Accomack and Northampton counties.

Fig. 1: Map of the United States of America with Virginia highlighted. Virginia is one of 50 states in America.



Forest cover of the state of Virginia is currently estimated at about 15 million acres (approximately 6 million hectares), making up two-thirds of Virginia's total land cover (Barrett *et al*., 2012). In managing these forests, logging operations form a critical component, as timber provides important income to forest landowners (Bolding *et al*., 2010). Virginia presents an ideal case study for forest fragmentation, as a result of its high population growth rate, currently estimated at about 5 % annually (Decennial Census and 2016 State Population Estimates). The remarkably high rate at which the state of Virginia is changing, from forest lands to agricultural lands, and then, more recently, to residential lands, calls for examination of impacts that these changes might have on biological diversity.

Following the era of broad-scale agricultural expansion in the early 1900s and consequent high deforestation rates in Virginia, reforestation trends, as a means of meeting high timber demands, began (Gao & Yu, 2014). Agriculture was abandoned and people migrated from rural areas to urban centers as a result of this economic shift (Grimm *et al*., 2008). Urban expansion led to rapid suburban development which drove environmental changes at local, regional, and global scales and impacted biodiversity. Chambers *et al*. (2007) found that the extension of urban sprawl to distant suburbs in tropical forests caused landscape fragmentation due to altered precipitation regimes and land-use patterns. In the United States, Xie *et al*. (2015) were able to show how the forest structure in New England is significantly influenced by rainfall patterns and temperature. As a result of high urbanization rates in Virginia which may prompt fragmentation, it is important to assess the extent of forest fragmentation and its impacts on biodiversity, in Virginia.

Data

2001, 2006, and 2011 National Land Cover Database (NLCD), constructed from 30×30 m resolution satellite imagery (Jin *et al*., 2013), were used. The 2001, 2006 and 2011 NLCD maps were used because they were created using the same classification techniques (unlike the 1992 NLCD map), and are therefore comparable (Graham & Congalton, 2009). The NLCD has four main forest cover classes (deciduous, evergreen, mixed, and woody wetland forest), which were analyzed individually and also, combined into a single forest class for further analysis. The remaining NLCD classes were also combined into a single non-forest class. The raster forms of the NLCD dataset were used since raster data is the only form of data that can be analyzed in FRAGSTATS.

A Digital Elevation Model (DEM) of the state of Virginia with a 30 m resolution, obtained from the US Geological Survey, was used to derive elevation and slope maps of the state. Data on primary and secondary roads in Virginia, last modified in 2015, was obtained from the United States Development Agency (USDA). This information was used to create a road density map for the state to identify the impacts of roads on forest fragmentation and connectivity.

Methodology

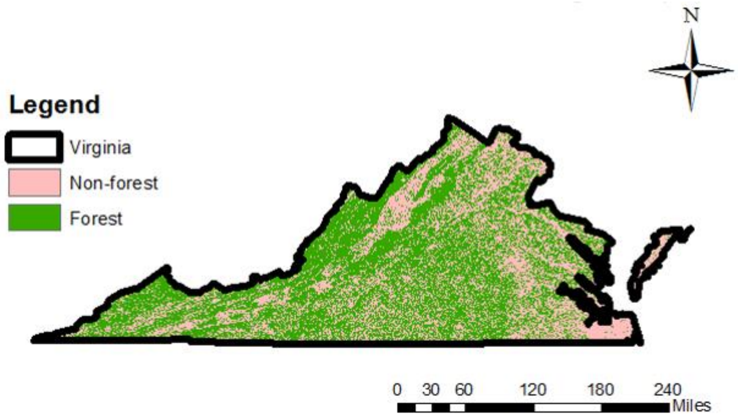
FRAGSTATS, a software system that provides detailed statistical information was chosen as one of the programs used to quantify forest fragmentation in this analysis (McGarigal & Marks, 1995). FRAGSTATS has the capacity to provide metrics such as area, density, total edge, and radius of gyration, at the individual patch level (Table 1). Similar metrics could be computed at the landscape and also, class levels. While landscape level metrics involves different land cover types such as forest, urban land and water, class level metrics emphasize specific land cover types, aggregating the patches as a single unit within the landscape instead of individual units that patch metrics is useful for. However, for this analysis, patch metrics within the forest class in Virginia, were the most important metric to determine how forest patches were changing over the ten-year time period.

Table 1: Patch metrics calculated in FRAGSTATS (McGarigal & Marks, 1995).
These patch metrics are important indicators of forest fragmentation and connectivity.

Patch Metric	Description
Patch Density	The number of patches divided by total landscape area.
Largest Patch Index	The area of the largest patch divided by the total landscape area, multiplied by 100 (to convert to a percentage)
Edge Density	The sum of the lengths (m) of all edge segments, divided by the total landscape area (m^2)
Landscape Shape Index	The sum of the landscape boundary and all edge segments (m) within the landscape boundary, divided by the square root of the total landscape area (m^2)
Radius of gyration	The mean distance (m) between each cell in the patch and the patch centroid
Cohesion	Measures the physical connectedness of the patches
Number of Disjunct Core Areas	The sum of the number of disconnected core areas contained within each patch

For each NLCD map, two main classes were created: forest and non-forest classes (Fig. 2). The forest class was comprised of the deciduous, mixed, evergreen and woody wetland NLCD classes and the non-forest class comprised of all the other NLCD classes such as developed and barren land, quarries and open water areas. With this analysis focused on forest fragmentation, the non-forest patches were treated as background values and our analysis devoted to the forest patches. A fixed edge depth, a prerequisite in the FRAGSTATS software, was defined at 30m to match the resolution of the NLCD maps.

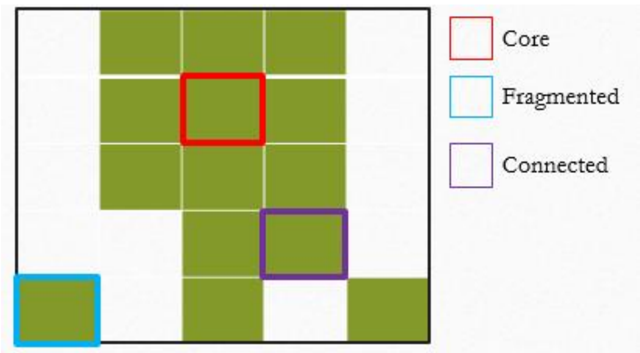
Fig. 2: Map of Virginia showing forest and non-forest areas.
Virginia is made up of about 60 % forest areas but the degree of human activity surrounding forest areas determine species diversity and the climatic conditions within.



With the NLCD dataset comprising 4 main different forest types namely Deciduous Forest, Evergreen Forest, Mixed Forest and Woody Wetlands, it was important to examine which forest types were more prone to fragmentation. The NLCD Shrub class was also examined because it comprises young successional trees and forest trees less than 5 meters tall. Areas in Virginia with each of these five NLCD classes were clipped individually so that there were five raster datasets representing Deciduous, Evergreen, Mixed, and Woody Wetland forests and the Shrub class, for every time period under investigation. Consequently, these fifteen raster datasets served as inputs for FRAGSTATS to identify the difference in patch characteristics between 2001 and 2011.

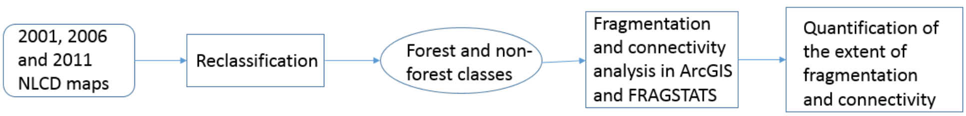
For the reclassified NLCD maps showing either forest or non-forest classes, at each date (2001, 2006 and 2011), each forest patch was described by the proportion of the pixels in a surrounding neighborhood that were classified as forest pixels. Using ArcGIS, each forest pixel was then labeled as forest 'Core' if it was completely surrounded by other forest pixels. A forest pixel surrounded by less than a 100 % but more than 60 % forest pixels was labelled as 'Connected' and 'Fragmented' if the forest pixels surrounding it was less than 60 % forest pixels (Fig. 3).

Fig. 3: Forest categorization for analysis.
A forest pixel is categorized as 'Core' if it is completely surrounded by other forest pixels such as the box with the red outline. The purple outline is categorized as 'Connected' because it is surrounded by both forest and non-forest pixels but could be categorized as 'Fragmented' like the box with the blue outline if it the surrounding forest pixels were less than 60 %.



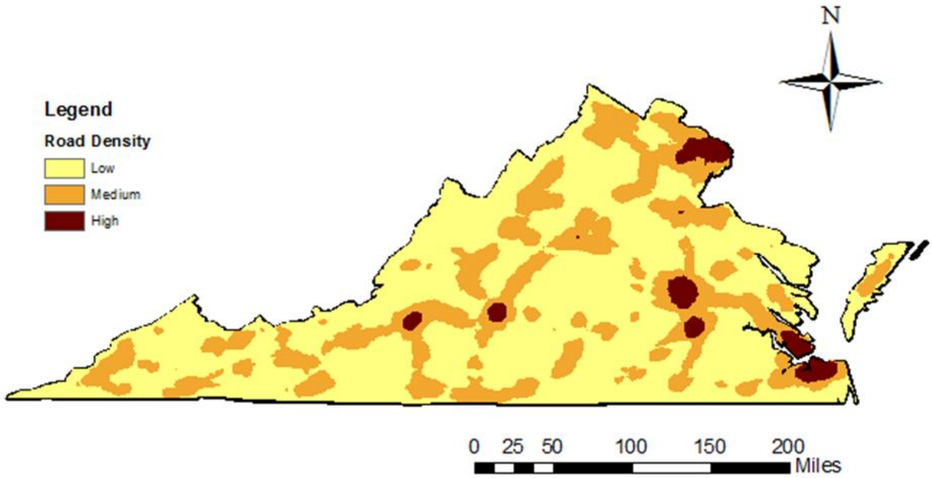
To identify contributing factors for forest fragmentation trends in Virginia, a slope map of Virginia based upon its Digital Elevation Model (DEM), was used. The slope of Virginia was then classified into 8 groups with reference to a slope report by Canada (CDA, 1974), and the amount of 'core', 'connected' and 'fragmented' forest areas in each slope class, calculated (Fig. 4). Changes in forest types across this slope gradient were then noted.

Fig. 4: Research Methodology.
The three NLCD maps were reclassified into either forest or non-forest classes before further analysis was carried out in ArcGIS and FRAGSTATS to measure forest patch characteristics.



Suspecting that the density of roads in different areas might contribute to conversion of forest areas to non-forest areas, a density map of Virginia was created based on the number of primary and secondary roads in the state. The road density map was created in ArcGIS using the Density tool and classified into three main classes based on natural breaks: High, Low and Medium Density (Fig. 5). The relationship between road density and forest fragmentation was examined by comparing the changes in the amount of 'core', 'connected' and 'fragmented' forest areas across time, in each of the three road density classes.

Fig. 5: Road density map of Virginia.
The three classes depict the number of primary and secondary roads in the area.



RESULTS

Over 60 % of Virginia is covered by forests. The *number of forest patches* differs considerably between 2001 and 2011, with an approximately 10 % increase in forest patches in 2011 compared to 2001 (Table 2). Patch density in 2001 increased from 1.7 patches per unit area to 1.88 patches in 2011.

Table 2: Patch metrics showing forest fragmentation between 2001 and 2011.
While the number of patches, total edge, LSI and NDCA have an increasing trend, the opposite is true for the patch areas.

Patch Metrics					
Year	No of Patches	Patch Area	Total Edge	LSI	NDCA
2001	175395	58.7994	594379006.7	465.6032	386029
2006	183314	56.2593	613397442.7	480.408	407312
2011	192350	53.6164	632684039.8	495.4215	426976

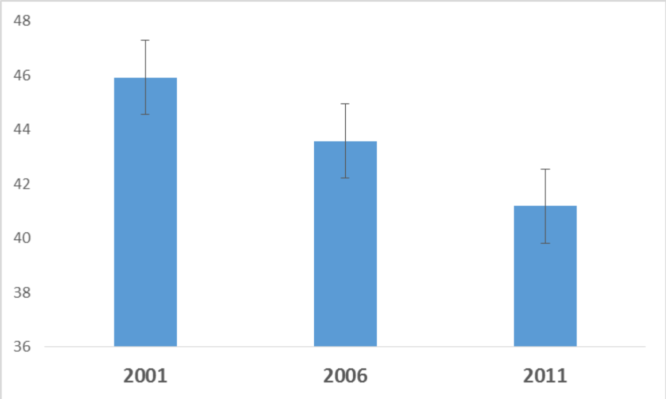
The *Number of Disjunct Core Areas* (NDCA) equals the sum of the number of disconnected core areas contained within the region. The number of disjunct core areas is an alternative to the number of patches when it makes sense to treat core areas as functionally distinct patches, instead of as part of a previously larger patch. Both NDCA and number of patches as shown in Table 2, show that, while fragmentation is increasing in Virginia with time, connectivity among forest patches is decreasing.

In FRAGSTATS, the area of a patch referred to as *mean patch size* (AREA_MN) is a measure of central tendency in the corresponding patch characteristic across the entire region, and thus equals the sum of all forest and non-forest patches. As a measure of central tendency, the mean patch size metric examines the areas of all patches within the landscape and calculates the average to represent the entire landscape. Patch size does not describe conditions within each patch but offers a primarily patch-based perspective of the landscape structure. Results in Table 2 indicate a reduction in patch area across Virginia between 2001 and 2011, pointing to the fact that Virginia's forest fragmentation continues to expand.

Total edge (TE) is an absolute measure of total edge length of a particular patch, and in this study, defines the area along the border between forest patches and the surrounding non-forest areas. Total edge is a particularly important metric for this study because forest edge areas suffer from effects from the surrounding non-forest areas and is therefore, an indication of forest fragmentation. 'Core' forest areas are those areas not affected by edge effects because they are mostly surrounded by other forest pixels. The increasing total edge length from 2001 to 2011, as shown by the results in Table 2, is a further indication of forest fragmentation. Edge density (ED), which standardizes edge to per unit area facilitates comparisons between 2001 and 2011. FRAGSTATS results show that ED increased from 57 to 61, emphasizing further, the occurrence of forest fragmentation in Virginia.

FRAGSTATS also offers the ability to specifically measure 'core' forest areas. *CORE* is a FRAGSTATS metric that represents the area in the patch greater than the specified depth-of-edge distance from the perimeter. *Mean core area per patch* (CORE_MN) therefore is the average of the core areas of the patches in an area. The results show that the core forest areas where specialist species thrive, is declining over time (Fig. 6).

Fig. 6: Core forest area percentages in 2001 decreasing over time.
This is due to increase in human activities, leading to the clearance of more and more forest areas. This has a negative impact of forest interior species that cannot thrive in forest edges.



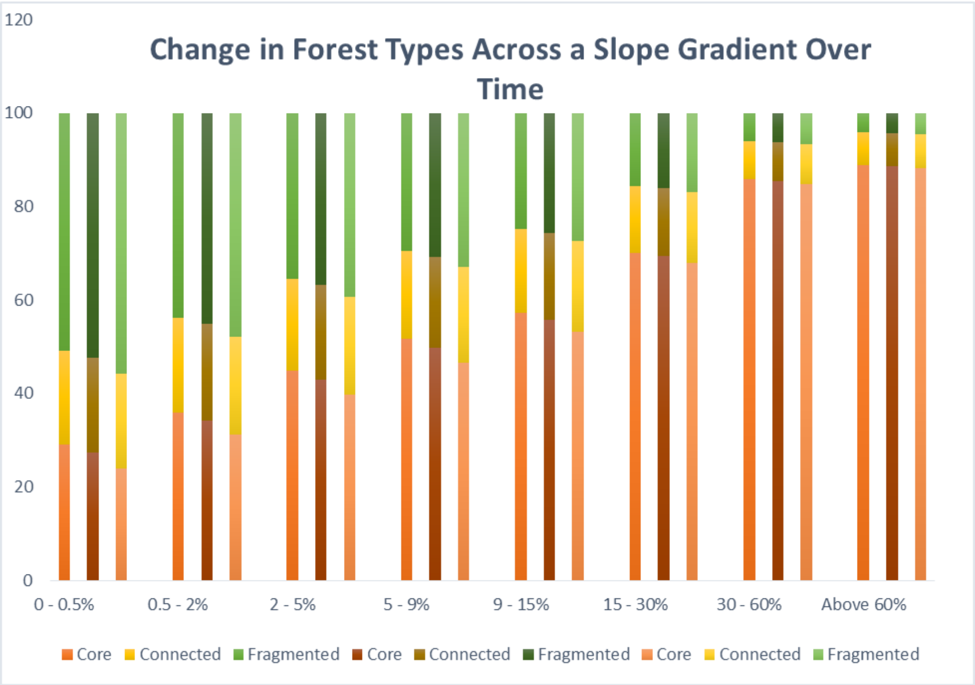
Landscape Shape Index (LSI) is a measure of the perimeter-to area ratio for the landscape as a whole. LSI can be interpreted as a measure of the overall geometric complexity of the landscape. However, it can also be interpreted as a measure of landscape disaggregation, or fragmentation. As the value of LSI increases, the more disaggregated or fragmented the landscape is. Our results in Table 2 show that fragmentation between 2001 and 2011 has been consistently increasing, while connectivity is decreasing.

Results of ArcGIS analysis indicate that, while percentages of 'core' forest areas in Virginia are decreasing significantly over time, percentages of 'connected' and 'fragmented' forest areas are increasing (Table 3). The ArcGIS results confirm the results from FRAGSTATS, which indicate that between 2001 and 2011, forest fragmentation and connectivity in Virginia have been increasing consistently.

Table 3: Percentages of forest types between 2001 and 2011.
As the percentages of core forest areas reduced from 2001 to 2011, the percentages of Connected and Fragmented forest areas increased. This is an indication of increasing human activities.

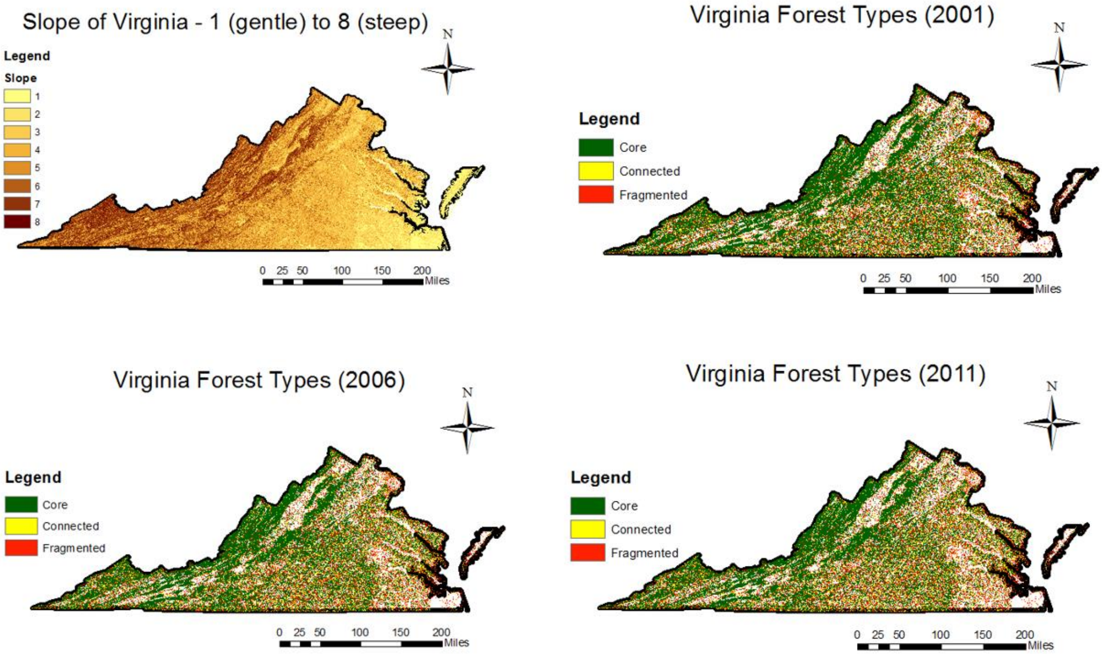
	2001	2006	2011
Core (%)	60.04	58.82	56.87
Connected (%)	15.97	16.44	16.95
Fragmented (%)	23.99	24.74	26.18

Fig. 7: Slope and forest type across time (columns in each group of three are 2001, 2006 and 2011 respectively).
Areas with steep slopes have more core forest areas, compared with areas with gentler slopes. Areas with gentle slopes have a lot more fragmented forest areas which increase over time, indicating more human activities relative to areas with steep slopes.



Our results from Figures 7 and 8 show that slope is the single most important factor contributing to this trend and that areas with relatively steeper slopes are less likely to experience changes in their 'core' forest area percentages over time. In Figure 8, inclination of core forests to steep slopes is evident as connected and fragmented forests are more pronounced in areas with gentler slopes.

Fig. 8: Map of Virginia's Topographic Slope and Forest Types.
Core forest areas are mostly in areas with steep slopes relative to areas with gentle slopes.



A closer look at the Valley and Ridge section of Virginia, where slopes are steeper, shows that core forest areas generally remained intact with only subtle changes (Fig. 9). In the Coastal Plain region where slopes are gentler, there are significant changes in the forest types of the area between 2001 and 2011 (Fig. 10). Most of the losses seen in Figure 10 occurred within core forest areas with the fragmented and connected forest areas, experiencing more gains.

The results of this study showed that areas with high road density in Virginia showed no significant change in the rates of forest fragmentation between 2001 and 2011. Our results indicate no strong correlation between forest fragmentation in Virginia between 2001 and 2011 and road density (Table 4). The percent changes in core, connected and fragmented forest areas in Virginia between 2001 and 2011, also indicated that there was no significant relationship between forest fragmentation and road density in Virginia.

Fig. 9: Valley and Ridge constitutes more core forest areas with no changes over time. Most of the changes in forest types occur within the Piedmont and Coastal Plain areas.

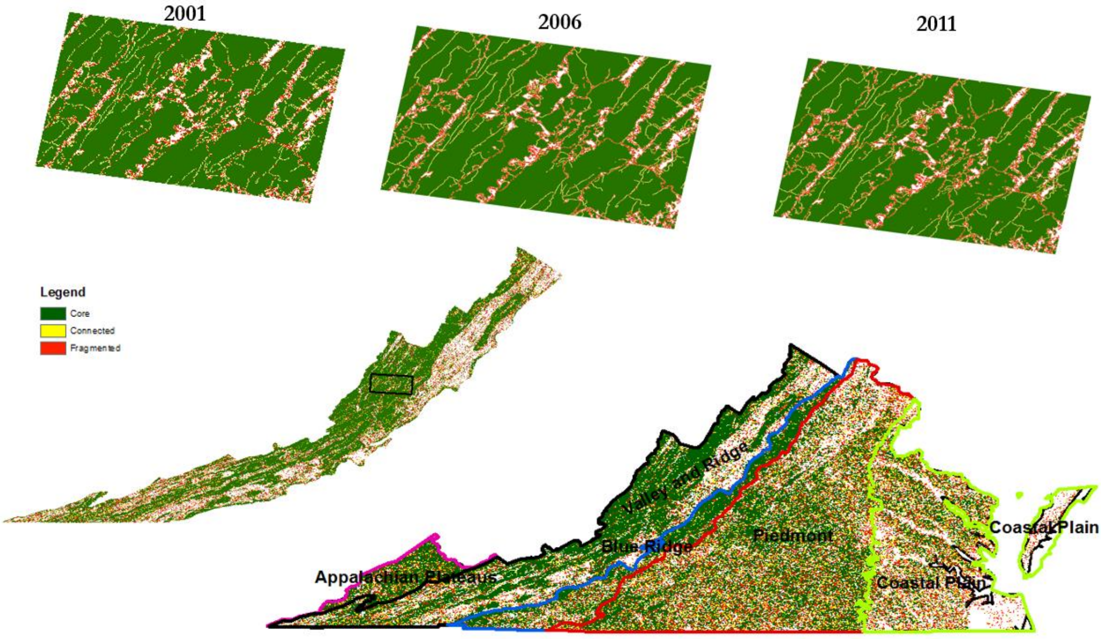


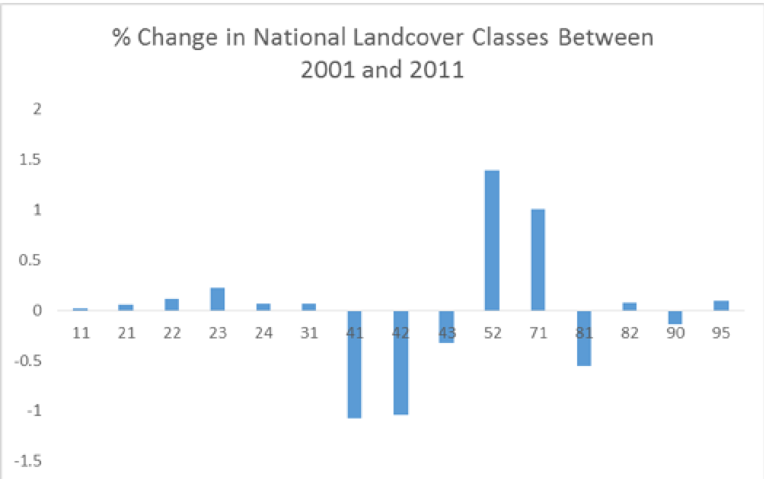
Fig. 10: Coastal Plain has gentler slopes and has more changes in forest areas over time.
This trend can be attributed to the ease and relatively low effort with which human activities such as residential construction and roads can be done in areas with gentler slopes compared to areas with steep slopes.

Table 4: Relationship between road density and forest fragmentation in Virginia.
The results show a weak relationship between forest fragmentation in Virginia between 2001 and 2011 and road density.

Road Density	% Change in Core forest area	% Change in Connected forest area	% Change in Fragmented forest area
LOW	-0.072199319	-0.07737	-0.13127
MEDIUM	0.058670343	0.009547	-0.09217
HIGH	0.085897301	0.056067	-0.04927

Between 2001 and 2011, there were changes in all the NLCD classes (Fig. 11). Remarkably, these changes were all positive except for the four forest classes and the pasture and hay class. The Shrub class which is partly forest because of its tree composition, had the most change, recording a positive 1.4 % change (Fig. 11). Negative changes in Mixed, Deciduous, Evergreen and Woody Wetland forests areas between 2001 and 2011, show that forested areas in Virginia are becoming smaller in recent years, losing to other non-forest areas such as developed lands and especially, shrub and grasslands.

Fig. 11: Changes in NLCD classes between 2001 and 2011.
All of the classes had positive changes between 2001 and 2011, except for the four forest classes and the pasture/hay class. The Shrub class had the most significant change between 2001 and 2011.



NLCD Legend
11 = Open Water
21 = Ice/Snow
22 = Developed; Low Intensity
23 = Developed; Medium Intensity
24 = Developed; High Intensity
31 = Barren land
41 = Deciduous Forest
42 = Evergreen forest
43 = Mixed Forest
52 = Shrub
71 = Grassland
81 = Pasture/Hay
82 = Cultivated Crops
90 = Woody wetlands
95 = Emergent Herbaceous Wetlands

The numbers of patches in all five NLCD forest classes in Virginia, except for the Shrub class, increased between 2001 and 2011. Within these four NLCD forest classes, the resulting patches had smaller patch sizes in 2011 compared to 2001, demonstrating a fragmentation process. The Shrub class, on the other hand, had a smaller number of patches in 2011 compared to 2001, indicating that the Virginia Department of Forestry (VDOF)'s conservation plan propelling landowners to grow more trees, is a significant factor in the increase of shrub areas in the state. With increasing patch sizes of the shrub class (Table 5), young trees in the early successional stage, are becoming more abundant, emphasizing the role of the VDOF conservation plans.

Table 5: Patch metrics showing forest fragmentation between 2001 and 2011 in the different forest type areas in Virginia.
Overall, all four forest areas experience forest fragmentation except for the Shrub forest type.

		Patch Metrics			
Forest type	Year	Patch Density	Patch Area	LSI	NDCA
DECIDUOUS FOREST	2001	4.1069	24.3494	855.2994	313415
	2006	4.124	24.248	861.7736	317519
	2011	4.302	23.2448	868.1741	322116
EVERGREEN FOREST	2001	25.2785	3.9559	814.5776	235430
	2006	26.4012	3.7877	830.1473	236755
	2011	28.6037	3.496	849.3857	234257
MIXED FOREST	2001	76.3368	1.31	1004.1583	127397
	2006	77.0369	1.2981	986.6209	122728
	2011	77.672	1.2875	962.4233	117043
SHRUB	2001	44.0112	2.2722	543.8879	56688
	2006	42.8946	2.3313	566.5366	64882
	2011	32.9072	3.0388	618.6549	92823
WOODY WETLANDS	2001	11.3871	8.7818	427.9522	72604
	2006	11.5459	8.6611	427.5921	72142
	2011	11.9591	8.3618	434.7146	73086

The Landscape Shape Index (LSI) and the Number of Disjunct Core Areas (NDCA), which indicate forest fragmentation and connectivity respectively, showed no clear direction. Increasing LSI values indicate increasing complexity due to fragmentation within the areas. LSI values increased between 2001 and 2011 for the Deciduous, Evergreen and Shrub forest types, decreased for Mixed forests and showed no clear pattern for the Woody Wetlands (Table 5). NDCA values generally increased for all forest types except for Mixed forests. The most significant change in NDCA values occurred between 2006 and 2011 within the Shrub class indicating that, although the number of patches decreased between 2001 and 2011, the patches became more disconnected within the same time period.

DISCUSSION

The number of patches in an NLCD layer is a measure of the extent of fragmentation of forest patches. Increases in the numbers of forest patches in Virginia over time indicates the occurrence of forest fragmentation (Magrach *et al*., 2011). As more and more patches are formed, there is increasing need to examine distances between those patches. There are many forest species that are incapable of migrating to other forest patches if those patches are separated by non-forest areas (Laurance *et al*., 1997b).

The trend of increasing number of disjunct core areas (NDCA) has significant implications for forest connectivity and for interior dwelling forest species. In light of the increasingly disturbing global climate change, many wildlife species will be forced to migrate to other areas, an activity significantly dependent on availability of migratory routes. As forest patterns determine levels of carbon sequestration, ultimately contributing to global climate change, this study is important to support policy makers as they formulate plans that examine migration patterns for wildlife species. According to a geospatial study on migratory routes between warm and cool zones, only 2 % of the eastern United States contains the connected green space needed for animals to find new homes (Coombs, 2016).

Increasing connectivity among Virginia's forested areas, is important for climate change considerations. As temperatures become warmer as a result of global climate change, connectivity among forest patches enables movement of animals, and the plant seeds they carry, to move to more habitable areas. With increasing number of disjunct core areas and number of patches in Virginia, as indicated by the results of this study, there should be concern about whether numbers of habitable areas will be sufficient to accommodate numbers of migrating species and if not, the population threshold for these species. This study therefore, informs policy makers about the nature of forest fragmentation and connectivity in Virginia and effects of increasing patchiness of forests, for wildlife movement and their population sizes.

Wegner & Merriam (1979) and Fahrig & Merriam (1985) noted that corridors between forest patches served an important function in determining population size and persistence of animals. Our results showing increases in the number of disjunct core areas means that, although numbers of forest patches in Virginia are increasing over time, forest corridors critical to link fragmented patches in order to support persistence of animal populations, are absent. Therefore, forest species in fragmented patches are often unable to interact in an effective way that ensures that their populations are viable over time.

Forest patch size determines species richness within an area, as numerous studies have proven that species richness, especially, that of birds, increases with increasing forest patch size (Fahrig, 2003; Wethered & Lawes, 2003; Dami *et al*., 2012). This effect is because, external factors such as wind intensity and light penetration have greater influence on smaller forest patches (Honnay *et al.,* 1997). As forest patches in Virginia decrease in size over time, it is reasonable to expect a consequent decrease in forest species persistence, especially bird species (Magrach *et al*., 2011). Decreases in area of the forest patches force a decrease in the number of species in each forest patch. This poses a problem for a lot of forest species since Magrach *et al*. (2011) showed small populations to be more susceptible to stochastic extinctions and/or allee effects (a phenomenon describing correlations between population size and mean individual fitness). Hence, results from this study showing decreasing forest patch sizes, need to be corroborated with Virginia's population sizes of certain species, such as ovenbird (*Seiurus aurocapilla*) and wood thrush (*Hylocichla mustelina*), to either confirm earlier research or provide alternative findings.

Increases in forest edge areas in Virginia, as seen from results of this study, has several implications because microclimatic conditions in forest edge areas can be significantly different from those in core forest areas, and can therefore, create either favorable or adverse conditions for plant growth and consequently, animal populations (Smith *et al*., 2018). Light, temperature, moisture content and wind intensity are some of the environmental differences between core forest and forest edge areas (Ritter *et al*., 2005). Increasing forest edge areas makes the region more vulnerable to fires through desiccation of fuels and greater exposure to potential human ignition sources (Laurance & Curran 2008).

Matlack (1993) noted that increased incident solar radiation is the singular most important factor differentiating the microenvironment of forest edges and core forest areas. With the results of this research showing a reduction in core forest areas, forest species that thrive best in darker areas are more prone to extinction, giving way to those species that are more suitable for brighter areas. Thus, forest areas in Virginia are likely to experience changes in both plant and animal populations over the coming years if steps are not taken to curb forest fragmentation.

Kautz *et al*. (2013) also noted that forest edge areas are more predisposed to species invasion and pest infestations. For example, the Ebola disease outbreak in Africa between 2013 and 2015 is purported to be a result of deforestation and fragmentation (Wallace *et al*., 2014; Bausch & Schwarz, 2014). Rulli *et al*. (2017) showed that centers for first infection of the Ebola disease were in areas with high degrees of forest fragmentation. As a result, more humans come into contact with disease reservoirs as forests are cleared for industrial and residential constructions, exposing humans to zoonotic infections (Rulli *et al.,* 2017). In the United States, spread of Lyme disease in the mid-70s, can be directly traced to anthropogenic deforestation that occurred during the expansion of the American suburb (McGrath, 2014). Proximity of humans to deer populations infected with the *Borellia burgdorferi* bacteria passed on by the bite of a deer tick, resulted in approximately half a million cases of Lyme disease infections in 2013 (McGrath, 2014). Because one of the most consequential effects of forest conversion is increased forest edge area (Smail & Lewis, 2009), it is important for policy stakeholders to investigate effects of increasing forest edge areas and decreasing core areas in Virginia, on the prevention of disease outbreaks that affect human population and health. Hence, information on forested areas that have been converted to non-forest areas, the basis of our study, is crucial for identifying hotspots for potential disease outbreaks.

The complexity of a landscape determines population sizes of many forest species. Rosch *et al*. (2013) noticed that populations of generalist insect species such as the leafhopper (Cicadellidae), decreased with increasing forest patch isolation but increased within complex landscapes. This effect is because, in simple landscapes, species such as the leafhopper may find it difficult to reach the next suitable site, unable to find suitable alternative resources or habitats with a similar vegetation type or structure during dispersal (Rosch *et al.,* 2013). More complex landscape structures provide more suitable habitats for these generalist species. With our results showing an increase in landscape complexity in more recent years, it is important to understand what this means for both generalist and specialist forest species in Virginia.

Reduction in core forest areas in Virginia is likely to pose a problem for forest interior species because their population sizes will be significantly affected. On the other hand, increased connectivity and increased edge areas as a result of more 'fragmented' forest areas, will increase the population sizes of species that thrive at forest edge areas. This means that changes in core, connected and fragmented forest areas over time, can lead to changes in forest composition (Smail & Lewis, 2009). Changes in forest composition have direct impacts on the complexity (as noticed in this study) and stability of forest ecosystems (Bodin & Wiman, 2007; Pentilla *et al*. 2006; Quetier *et al*. 2007). Holway (2005) showed that changes in forest compositions, and more specifically, decrease in core areas, led to the introduction of nonnative and invasive species which may have unknown deleterious consequences. For instance, the spread of the emerald ash borer (*Agrilus planipennis Fairmaire*) in the Great Lakes region of the United States led to the destruction and near-extinction of some ash tree species (Smail & Lewis, 2009).

The extent of forest fragmentation and connectivity in an area has different consequences for species living in that area. Hence, an analysis of forest fragmentation that takes into consideration use of multiple scales of resolution is more likely to identify suitable habitats for primary species in the area and provide insight on how corridors will be useful for all species present. With growing demands for strategies that allow for forest fragmentation estimates across multiple scales, it is important for future studies to consider the risk of biased results from fragmentation metric comparisons across different scales.

Losses in core forest area and simultaneous gains in fragmented and connected forest areas highlight the fact that slope has a strong control on urban development and forest fragmentation. Urban development is typically limited by high costs, low commercial value, and risk of landslides; all these are pronounced in areas with steep slopes (Gao & Yu, 2014). Because steep slopes cannot be used to build large urban patches, variation of slope within an area, further fragments forest areas.

Our result showing correlations of slope and forest fragmentation, is consistent with studies that have shown that land areas with steeper slopes have higher production and transportation costs and are therefore less likely to be converted from natural to anthropogenic land cover (Berry *et al*., 1990; Sheppard & Barnes, 1990; Wickham *et al*., 2000). This result is consistent with findings from Echeverria *et al*. (2008) who showed that, between 1976 and 1999 in southern Chile, forest fragmentation occurred mainly at edges of small fragments situated on gentle slopes (less than 10°). With forested areas that have steeper slopes with more core forest land areas and fewer changes between 'core', 'fragmented' and 'connected' forest types over the ten year time period, it is important for policy makers in Virginia to concentrate their efforts in areas with gentler slopes because these areas are subject to forest fragmentation.

van Kooten & Folmer's (2004) theories on land rent suggesting that land use is allocated to maximize revenue from a land of a specified quality, provides insight to why this is so. With forest fragmentation being a result of human activities and a direct consequence of human land use decisions, costs of developing a unit of land plays a significant role. Land areas with gentler slopes are more easily developed as material transportation costs are cheaper and are generally, more suitable for agricultural purposes (Alig *et al*., 2005).

Given the knowledge that increasing human activities correlate with increasing forest fragmentation and that human activities are noticeably higher in areas with high road density, there should be an increasing rate of forest fragmentation in areas with higher road density. Roads have been found to promote forest fragmentation by dividing large forest patches into smaller areas and in so doing, creating more forest edge areas at the expense of core forest areas. For instance, Reed *et al*. (1996) showed that roads contributed significantly to forest fragmentation in the Rocky Mountains. However, Miller (1994) indicated that road density in an area could be very high or increasing without increasing the number of forest patches or forest edge areas. Our results showing no correlation between road density and forest fragmentation suggest that our study period between 2001 and 2011 might not be enough time to fully capture the effect of road on forest fragmentation and therefore, subsequent studies should examine a longer time period to fully understand the impact of roads. The insignificant correlation between road density and forest fragmentation patterns in Virginia also point to the fact that other factors have more substantial impact on the forest fragmentation process in Virginia.

This led to the exploration of the different forest types in Virginia to identify how more susceptible some forest types are to forest fragmentation, compared with others. The diminishing trend of core forest areas and the increasing trend of connected and fragmented forest areas in Virginia between 2001 and 2011, raises questions on the specific types of forests undergoing conversions. For instance, pine trees that occupy approximately 20 % of Virginia's forest (VDOF, 2014), are undergoing significant harvesting followed by replacement with other species. As a result of this, pine trees in Virginia are currently considered as diminished species, triggering the Virginia Department of Forestry to initiate a pine tree restoration program with cost-share plans to enable interested landowners to re-establish them (Gagnon, 2016). It is therefore important to know the specific types of forests undergoing fragmentation in Virginia.

Shrub lands, as defined by the NLCD, are areas with trees that are less than 5 meters tall and dominated by more than 20 % shrub canopy. This NLCD class comprises true shrubs, young trees in an early successional stage or trees stunted from environmental conditions. Going by this definition, this class will comprise all the areas that undergo afforestation and reforestation annually. Given the Virginia Department of Forestry's Conservation Incentive Programs that were rolled out in the late 1990s, allowing Virginia land owners to receive financial benefits for helping in conservation efforts, it is not surprising that the NLCD Shrub class had the most significant change within the study time period (Fig. 10).

A closer look at the five NLCD forest classes to examine the extent of forest fragmentation between 2001 and 2011, concentrates on metrics that serve as the most significant indicators of forest fragmentation. The process of forest fragmentation has three main indicators namely, a) increase in forest patches, b) decrease in forest patch areas and c) increasing isolation between the resulting forest patches. The four patch metrics in Table 5 were examined to identify the extent of forest fragmentation in specific forest types in Virginia between 2001 and 2011.

Table 5 confirms the report of Heilman *et al.* (2002) that, use of the number of forest patches as an indicator of forest fragmentation should always be corroborated with the connectivity between the patches before conclusions are made. The process of division of large forest patches into many smaller patches is not always an ecological negative (Heilman *et al.*, 2002). In some forests with natural patchiness that allows for connectivity between those patches, forest fragmentation becomes a sign of higher ecological integrity (Heilman *et al.*, 2002). For the Mixed forest class where the number of forest patches is increasing over time but the disconnectivity (LSI) is decreasing over the same period of time, the disturbance could be said to be more natural, such as fires or localized windthrow (Heilman *et al.*, 2002), rather than anthropogenic disturbances. The reverse is also true, an example being the Shrub class, which is becoming disconnected over time although the number of patches is decreasing over the same period of time. This follows that the Shrub class is manipulated by anthropogenic activities rather than more natural procedures. This result highlights the role of the VDOF in forest conservation and the implications of management decisions. The results of this study provide resource managers and policy makers the information required to guide forest management decisions.

CONCLUSION

Results from FRAGSTATS present a clear description and hence, are useful for quantifying forest fragmentation. Results from the analysis show significant differences in forest fragmentation in Virginia from 2001 to 2011 with trends indicating increasing forest fragmentation and connectivity. This information is useful in developing appropriate forest management strategies that aim to mitigate adverse impacts of land use changes, especially, those due to human activities.

The reshaping of forest boundaries, changes in forest patch sizes, reduction in core forest areas and the consequent increase in total forest edge areas, increase the risk of zoonotic infections with important impacts on human health worldwide. The trend and extent of forest fragmentation and connectivity in Virginia have crucial externalities associated with human health, all of which should be accounted for while evaluating the costs, risks, and benefits of changes made to forests in Virginia.

Results also show that the slope of an area significantly contributes to the degree of forest fragmentation in that area as human activities in steeper sloped areas, reduce. Our study therefore presents an important framework for development in Virginia as policy makers can use this as a tool for making decisions. With the observed strong relationship between land use and slope in Virginia, subsequent research on what these changes mean to the populations of biodiversity present in Virginia will provide policy makers with relevant information required for conservation and development purposes. Careful consideration of slope categorization in future studies will help identify the underlying contributions of slope to landscape uses and avoid arbitrary boundaries.

Given the decreasing number of patches but increasing connectivity within the Shrub class which comprises young trees in the early succession stage, it is important for future studies to more fully consider the role of management decisions on forest conservation in Virginia. Anthropogenic interferences might have positive implications depending on the scale of measurement being used. In determining the efficiency of management decisions, it is important that every factor be fully assessed and the collective impact, recognized.

Lastly, some studies have shown better fits for regressions when soil properties are used as explanatory variables for forest fragmentation studies. Results from these studies show that significant variation in soil properties within a specific area will result in heavier forest fragmentation. Since Virginia is not a spatially homogenous unit, it is important for future studies to consider the role of soil properties on forest fragmentation and connectivity.

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