Ecosystem Service Analysis of Duke Forest

by

Author: Shouta Hayashi

Author: Eamon Horrigan

MP Advisor: Nicki Cagle

MP Client: Duke Forest Teaching & Research Laboratory

MP Client Advisor: Sara Childs

Masters project proposal submitted in partial fulfillment of the
requirements for the Master of Environmental Management degree in The Nicholas
School of the Environment of
Duke University

April 22, 2022

Executive Summary

Our team was tasked with evaluating the quantitative and monetary value of ecosystem services offered by the Duke Forest. Our client, the Duke Forest, manages and actively harvests 7,100 acres of timberlands used for research, education, and recreation by Duke University and the broader community. The overall purpose of assessing these services is to communicate the importance of the Duke Forest and offer implications for resource management. The term "ecosystem service" refers to benefits humans obtain from nature, and it is categorized into four different services; provisioning service; regulating service; supporting service; cultural service. Based on the client's requests, we analyzed a subset of ecosystem services provided by the Duke Forest – carbon storage and sequestration, which have an important implication for climate change mitigation, and nutrient and sediment retention, which contribute to downstream water quality improvement.

For spatial analysis of the focal ecosystem services, we used the InVEST suite of models, developed by the Natural Capital Project at Stanford University. We used the InVEST Carbon Storage & Sequestration model to spatially assess carbon storage and sequestration in the Duke Forest. For the land cover/ land use data input, we used spatial forest class and age data provided by the client. We referred to a USDA study to estimate carbon storage for the different forest types and age classes in the spatial data input and to populate the carbon pool table, another input of the InVEST carbon model. The monetary values of carbon storage and sequestration were estimated with the average carbon credit value for forestry projects from the World Bank, as well as with two domestic markets: the California Cap and Trade (CaT) and Regional Greenhouse Gas Initiative (RGGI), a regional northeastern US market. For assessment of water quality improvement, we ran the InVEST Nutrient Delivery Ratio (NDR) and Sediment Delivery Ratio (SDR) models to estimate phosphorus, nitrogen, and sediment export across four 10-digit HUC watersheds which Duke Forest occupies. Model calculations are determined by hydrological modelling, as well as biophysical statistics on a variety of land use/land cover classes. SDR results were used to produce a monetary estimation of Duke Forest's contribution to sediment retention using estimates of Neuse River water treatment facility cost savings from reductions in turbidity.

InVEST Carbon modelling estimated a total of 543,000 tons of carbon being stored across all Duke Forest divisions at an average of 80 tons per acre. The highest storage rates were observed in the Oosting Natural Area at 94 tons per acre and the lowest storage rates were seen in the Hillsboro division at 71 tons per acre. Using the value of carbon offset projects from terrestrial forests globally, this total storage is estimated to be worth over $15 million in value. In terms of domestic carbon offset markets across all projects, this value is estimated to be even greater: ranging from $17.3 to 35.8 million. Our future projections of carbon for the next 50 years revealed an estimate of 2,000 tons being stored yearly, equaling about $56,000 in monetary value using the global estimate for forestry offset projects.

Results from NDR and SDR indicated Duke Forest's contribution to downstream water quality protection and improvement. NDR estimated nutrient export rate in the Duke Forest is significantly lower than the watershed average. Average nitrogen export values in the Duke Forest in each of the four watersheds were lower than the average value in the watersheds by

25.7% - 44.7%. Mean phosphorus export values in the Duke Forest were lower than the watersheds by 67.3% - 83.1%. Similarly, SDR estimated sediment export rate in the Duke Forest significantly lower than the watersheds, by 78.8% ~ 98.4%. The monetary value of sediment retention based on turbidity reduction was estimated to be worth $43,000 and $113,000 annually in two different alternative land use scenarios. The greatest annual value was found in the B Everett Jordan Lake – New Hope River basin, where Duke Forest's sediment buffering was valued at $26,000 and $50,000 in the two scenarios.

For communication of significance and key results of this project to a broader audience, we developed a StoryMap on ArcGIS Oline. This StoryMap includes a brief description of the Duke Forest, an introductory explanation of ecosystem services, and key results from our analysis. It uses plain language and visual materials so audiences without a strong background can become interested in and grasp the benefits the Duke Forest provides the larger region.

Future work on ecosystem service analysis in Duke Forest should focus on collecting accurate field data to refine the biophysical statistics which drive all the models we ran, rather than using values found in the literature. In addition, assessment of other ecosystem services offered by the Duke Forest would complement the results of this analysis. Final recommendations for the client include conservatively managing older stands with high carbon stocks, tracking opportunities to become involved in carbon offsets, and mitigating erosion during timber harvests.

Table of Contents

Introduction

Ecosystem services are benefits we obtain that are derived from natural resources and are increasingly promoted to document values we place on ecosystems and evaluate those benefits (Wallace 2007). There are several types of ecosystem services, from providing materials, to contributing to our well-being, and forests are known to provide essential ecosystem services that are estimated to have large economic values, including climate regulation, carbon sequestration, water quality control, soil stabilization, erosion control, providing habitat to wildlife, and maintaining biodiversity (Krieger 2001).

The overall goal of this study is to evaluate the environmental importance of Duke Forest to the region by quantifying a subset of ecosystem services and justify the need for ongoing conservation and investment in this natural resource. We conducted this evaluation by utilizing a series of existing geostatistical models to quantitatively and monetarily approximate the benefits of several ecosystem services. These estimates can be used to educate the public on the importance of the ecosystem services provided by Duke Forest.

The two ecosystem services that we prioritized in our analysis are carbon sequestration and water quality improvement. These services were emphasized as being of great importance to the client. Quantification of these benefits was accomplished through running three InVEST geospatial statistics models: Carbon Storage and Sequestration (CSS), Nutrient Delivery Ratio (NDR), and Sediment Delivery Ratio (SDR).

Carbon Storage & Sequestration

Carbon storage and sequestration are one of the major functions that forests provide. Trees sequester carbon dioxide as they grow and store it in their root structures. Forests are known to be the largest terrestrial carbon sink and are considered as critically important resource to mitigate greenhouse gas emission and therefore global warming and climate change by reducing the concentration of atmospheric carbon dioxide (Domke et al. 2020). Forest can also be a source of carbon when trees are taken out both naturally and by humans. For example, wildfire or logging and burning by humans would lead to a release of carbon stored in the trees burnt, harvested or cleared (Mitchard 2018). For managed forests like the Duke Forest, forest management has an important implication for carbon storage and sequestration as proper managements. Appropriate management of forests, such as avoidance of landcover conversion from forests, maintaining hydrology, maintaining the ability of forests to resist pests and pathogens, and maintaining fire in fire-adapted ecosystems would protect the overall health and function of forests, which includes sequestration and storage of carbon (Ontl et al. 2020). Thus, to maintain healthy forests and services to sequester and store carbon dioxide, it is essential for the Duke Forest to understand forests' performance in carbon storage and plan forest management effectively to optimize these functions in the future.

Nitrogen and Phosphorus: Impacts on Water Quality

Despite being essential macronutrients for plant growth, nitrogen and phosphorus pose major risks to water quality. Large-scale shifts in land use, particularly anthropogenic development and agricultural operations have increased the vulnerability of our waterways by removing natural barriers to water pollution (Figure 1). Unsustainable agricultural practices continue to exacerbate this vulnerability.

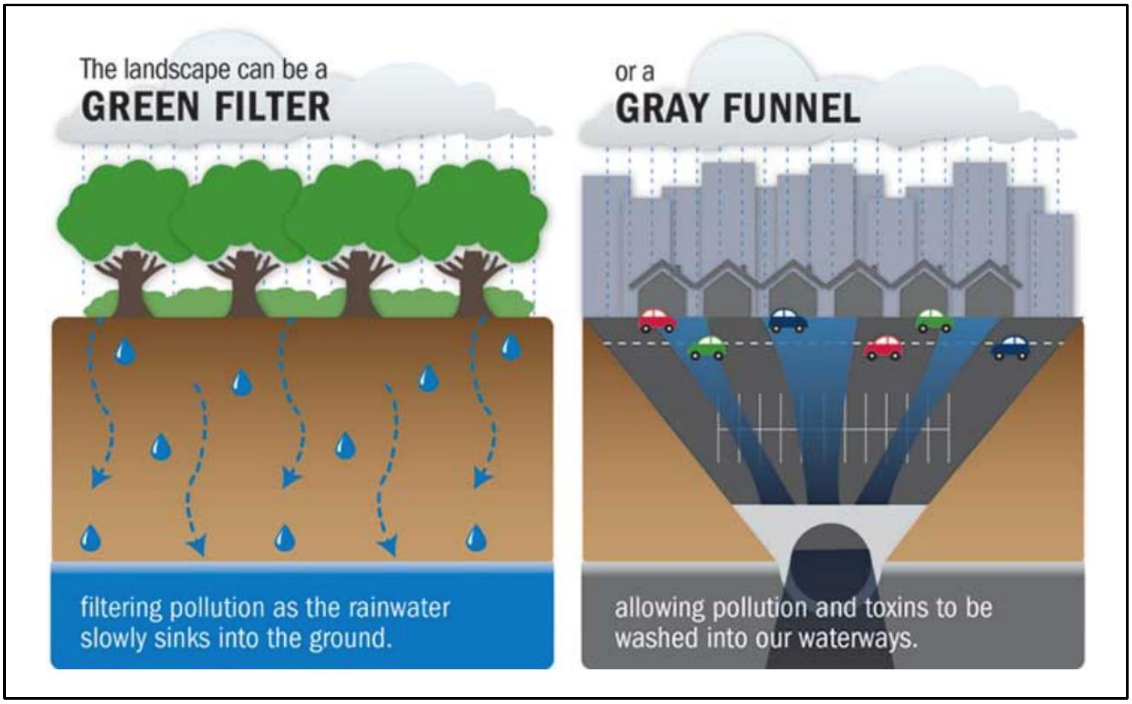


Figure 1: Graphic representation of importance of land cover to water quality. Source: Chesapeake Bay Foundation

This land use trend has resulted in uninhibited inputs of nitrogen and phosphorus causing considerable ecological damage by increasing the susceptibility of waterways to algal blooms. Algae begin to grow out of control at high nitrogen and phosphorus levels, which leads to a dearth of oxygen when the algae decompose (Chesapeake Bay Foundation, 2022). Algal blooms can result in large events of fish mortality or illness, which can pose a health risk to humans if tainted fish are consumed (EPA, 2021). Additionally, water sources contaminated with high levels of nitrates are particularly dangerous to young children. Infants under the age of 4 months who ingest nitrate-contaminated water can develop an illness known as “blue baby syndrome” because they lack an enzyme for breaking down excess nitrate (USGS Water Science School, 2018). These public health risks serve as examples of why natural lands, such as the Duke

Forest, are vital for filtering nitrogen and phosphorus runoff for community, as well as ecological resilience.

Sediment Delivery: Impacts on Habitat and Water Quality

The modification of sediment export regimes across the landscape can have dramatic effects on local terrestrial and aquatic habitats. Terrestrial ecosystems represent the source for sediment movement, while aquatic ecosystems represent the sink for sediment loads. Land cover influences the speed of movement of sediment across the terrain, and in turn, affects the size of sediment loads which reach waterways. This movement of terrain is to some degree controlled by natural precipitation patterns which affect the rate of erosion,

Sediment export is known to have a negative effect on soil fertility, which in turn reduces vegetative productivity, and therefore carbon sequestration as well. This is a great example of how ecosystem services are interwoven and how efforts to improve one service can have positive cascading effects on others. Additionally, this loss of soil fertility reduces agricultural productivity, therefore imperiling our population's food demands. In fact, a recent study in Zambia found a 15% decline in maize fields due to soil loss when comparing the soil of old agricultural fields to woodland soil (de Blécourt et al., 2019). In the US, croplands average 10 t/ha/yr of soil loss, which is unsustainable considering soil formation occurs at between 0.5-1 t/ha/yr (Pimentel, 2006). Forested land, such as Duke Forest, performs a necessary role in the retention of soil to counteract these negative effects of modern agriculture on the landscape.

From the hydrologic perspective, high rates of sediment export can lead to suspended sediments in local water bodies. These inputs result in expenditures on water treatment, reduction in fishery productivity, and ecological damage (Grove et al., 2015). High concentrations of suspended sediments in aquatic ecosystems can result in positive feedbacks, which significantly alter ecosystem characteristics. This pattern has been observed in seagrass populations where increased sediment loads block out sunlight and result in sudden seagrass mortality events. The water turbidity makes it difficult for vegetation to recover and results in ocean bed desertification. This results in cascading effects including the absence of seagrass removing a source of refuge for local organisms. These dramatic ecosystem shifts are known as alternative stable states and require a large commitment of resources to reverse (Adams et al., 2018).

Project Objectives

Our objectives are to assess carbon and water quality protection ecosystem services that the Duke Forest provides and to communicate the results to the client. For carbon storage and sequestration, we quantified these functions within the Duke Forest and summarized the results by forest division. For water quality ecosystem services, we analyzed nutrient and sediment retention and compared the results within the Duke Forest in each watershed to the results in the watershed as a whole. This comparison will clarify the relative importance and role in water quality protection in watersheds that Duke Forest overlaps. These analyses will allow the Duke Forest to further understand the current status of benefits which the Duke Forest produces and help incorporate protection of ecosystems services into their forest management and planning.

Our analysis aims to address the following research questions.

- What are the ecosystem services that Duke Forest provides?

- What value do these services provide to the larger region?

- What Duke Forest divisions are of highest importance in ecosystem service provision?

Methods

Study Area

The Duke Forest has been a resource for education and research at Duke University since its establishment in 1931. Duke Forest stretches across 7,050 acres and occupies parts of Durham, Orange, and Alamance counties of North Carolina (Figure 2). This natural resource is divided into six different management divisions: Blackwood, Dailey, Durham, Edeburn, Hillsboro, and Korstian divisions, as well as the Oosting natural area. The Duke Forest's recent Strategic Plan outlines three goals for future management: stewardship for long-term sustainability, research and stewardship, and community engagement (Childs, 2016). Assessing a subset of ecosystem services will aid in the achievement of these goals by quantifying Duke Forest's value. These valuations can then be used to reinforce the understanding of Duke Forest's importance to Duke University and the broader region.

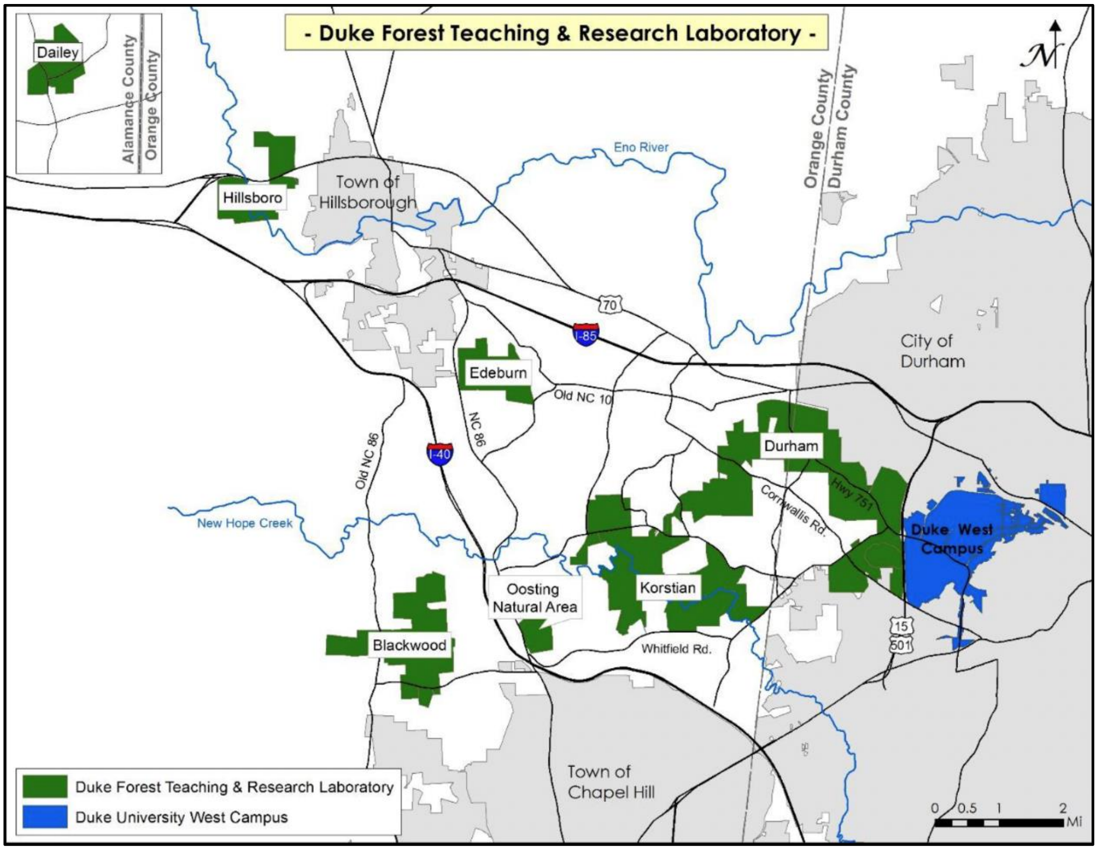


Figure 2: Focal study area of Duke Forest. Source: Office of the Duke Forest, 2022

Carbon Storage & Sequestration (CSS)

The InVEST carbon model (The Natural Capital Project, 2021) was used to quantify the spatial distribution of carbon storage and sequestration in the Duke Forest. This model estimates carbon storage by calculating per pixel the aggregate amount of carbon stored in four carbon pools: above ground biomass, belowground biomass, soil, and dead organic matter for each land use types in the land use raster provided by the model user.

The Carbon InVEST model requires LULC as a geospatial input. For this input, we used a map of forest cover types provided by the Duke Forest. This dataset specifies forest cover types and age classes across the Duke Forest.

CSS also requires a carbon pool table that contains carbon storage for the corresponding landcover types in the geospatial data input. To fill in the carbon pool for carbon storage values for each forest cover type, we referred to a study conducted by the USDA (Smith et al, 2006). This study estimated carbon pools as a function of stand age for 51 different forest types across 10 regions in the United States. We used carbon pool data from the “southeast” region and applied carbon values that are closest to the Duke Forest cover types with an appropriate age class. As the oldest age class in this USDA study is 90 years old, we applied the values from this age class to forest cover types that are 90 years old and above. For the estimation of aboveground and belowground carbons for InVEST carbon pool, we used a function produced by Dr. Ram Oren at Duke University to partition Live Tree Carbon in the study into above and belowground carbon. Based on this function, belowground carbon was defined as 0.164 x Live Tree Carbon, and aboveground carbon as 0.836 x Live Tree Carbon, respectively. Soil carbon from the USDA study was directly used for soil carbon in the InVEST input, and the sum of standing dead, down dead wood, and forest floor carbon in the same USDA study was used for the dead carbon pool in the InVEST input table. The InVEST carbon model calculates carbon sequestration by taking the difference between current and future carbon storage values. We estimated carbon sequestration at 10-year intervals for the next 50 years.

Water Quality

To quantify water quality regulation, we ran two InVEST models: Nutrient Delivery

Ratio (NDR) and Sediment Delivery Ratio (SDR). Like the carbon sequestration InVEST model, these models require land cover data, in addition to several sediment/nutrient runoff parameters (Sharp et al, 2016). These spatial estimates of nutrient and sediment export were set to the extent of four 10-digit HUC watersheds: Back Creek-Haw River (0303000204), B Everett Jordan Lake-New Hope River (0303000206), Eno River (0302020103), and Upper Falls Lake (0302020104). These four watersheds occupy the larger Cape Fear and Neuse River basins. Nutrient and sediment export statistics by land cover type within the four watersheds: Back Creek-Haw River, Everett Jordan Lake New Hope River, Eno River, and Upper Falls Lake, were then compared to nutrient and sediment export within the boundaries of Duke Forest. This comparison between estimated input of water quality contaminants at the local and regional scales was intended to highlight the contrast in nutrient export between Duke Forest and other possible land uses.

Nutrient Delivery Ratio (NDR)

To estimate the nutrient buffering capacity of Duke Forest and its importance to the broader landscape, we ran the InVEST NDR model. For data inputs (Table 1), NDR requires four geospatial inputs: land use/land cover types (raster), annual precipitation (raster), a Digital Elevation Model (DEM, raster), and watershed boundaries (vector). All raster inputs were projected to NAD 1983 UTM Zone 17N. Projected rasters were then input into NDR in their original resolution. The output raster of nutrient retention per pixel is set to the resolution of the input watershed, which in our case, was ~37.16 m^2.

Data Input	**Data Format**	**Value Range**	**Source**
Land Use/Land Cover	Raster (30m)	11-95 (land use code)	Multi-Resolution Land Characteristics, 2019
Nutrient Runoff Proxy (Annual Precipitation)	Raster (1 km)	1071-1210 (mm)	WorldClim (Fick & Hijmans, 2020)
DEM	Raster (20 ft)	0-997 (ft)	NC State University Libraries, 2013
Watersheds	Shapefile	NA	North Carolina Department of Environmental Quality (Williams, 2022)
Threshold Flow Accumulation	Integer	300	
Borselli k parameter	Integer	2	Sharp et al., 2016
Subsurface Critical Length	Integer	30	Sharp et al., 2016
Subsurface Retention Efficiency (N)	Integer	0	Sharp et al., 2016

Table 1: NDR Data Inputs

NDR also requires a biophysical table of all land use/land cover types and their corresponding nutrient load, retention efficiency, critical length, and proportion of subsurface nitrogen dissolved (Table 2). We chose to run the model to calculate estimates for both nitrogen and phosphorus retention. Threshold flow accumulation can be summarized as the number of pixels that have to flow to a pixel before it is determined to be a waterbody and not a land cover type. Waterbodies are reasonably excluded from analysis because the purpose of the model is to compare the effect of land cover on the travel of nutrients and waterbodies represent the end destination. Without local data on subsurface nitrogen retention efficiency, this parameter was set to a recommended default value of 0. The Borselli k calibration parameter was set to a recommended default value of 2 (Sharp et al., 2016). This parameter characterizes the relationship of nutrient export and the hydrologic connectivity between pixels, thereby dictating the speed of export.

		Phosphorus		**Nitrogen**	
Land Use Class Name	**Land Use Code**	**Nutrient Load**	**Retention Efficiency**	**Nutrient Load**	**Retention Efficiency**
Open Water	11	0	0	0	0
Developed Open Space	21	4	0.02	23.9	0
Developed Low Intensity	22	4	0.02	23.9	0
Developed Medium Intensity	23	4	0.01	30.5	0
Developed High Intensity	24	4	0.01	30.5	0
Barren Land	31	0.1	0.02	12.4	0
Deciduous Forest	41	0.21	0.05	11.4	0.6
Evergreen Forest	42	0.21	0.05	11.4	0.6
Mixed Forest	43	0.21	0.05	11.4	0.6
Shrub/Scrub	52	0.255	0.05	8.6	0.3
Grassland/Herbaceous	71	0.255	0.02	8.6	0.3
Pasture/Hay	81	0.75	0.02	8.6	0.3
Cultivated Crops	82	2.7	0.02	53.5	0.1
Woody Wetlands	90	0.21	0.05	3.8	0.6
Emergent Herbaceous Wetlands	95	0.21	0.05	3.8	0.6

Table 2: Biophysical table of variables for NDR calculation by land cover types of the National Land Cover Dataset (MRLC). Estimates used from Hillman, 2019.

Biophysical data is highly important to model outputs for NDR because it assigns estimates of nutrient retention and production for each land cover type. For this reason, the model is highly sensitive to statistics provided. The elevation and runoff proxy datasets are important to the model for mapping the hydrological network across the study area to properly assess where runoff will deliver nutrients. Nutrient exports in the final output raster are calculated on a per pixel basis (Figure 3)

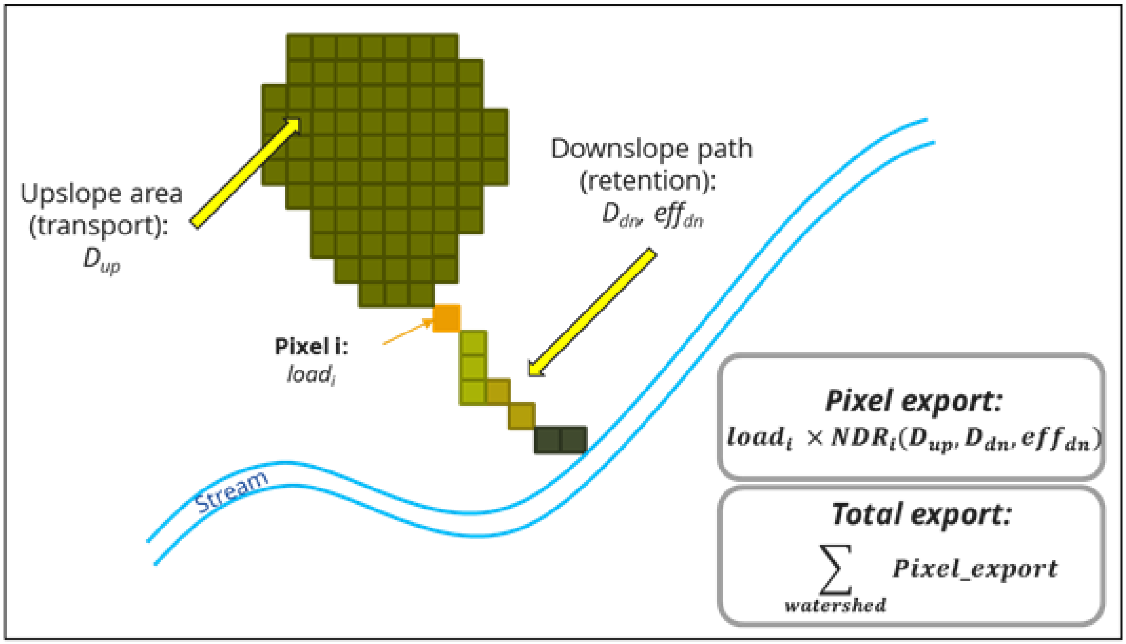
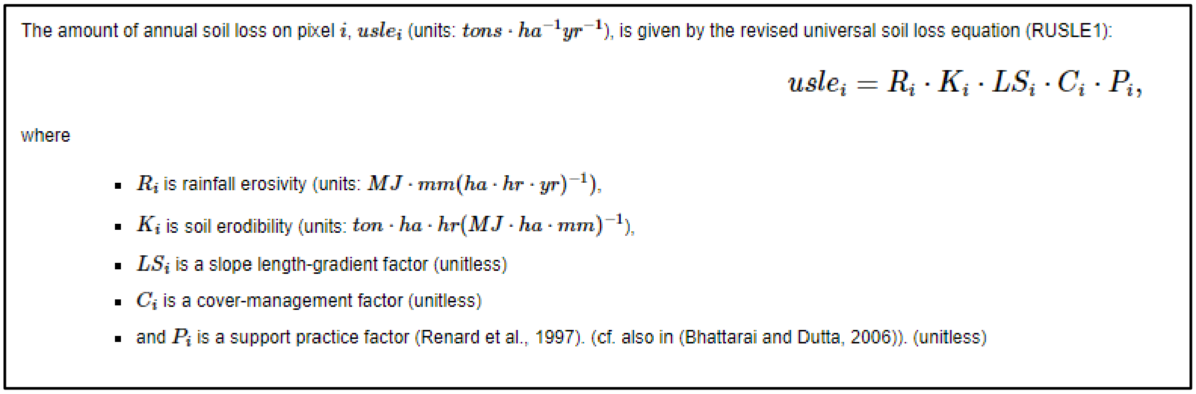


Figure 3: Graphical representation of how statistical data are applied to geospatial data in NDR. Source: Sharp et al., 2016

Sediment Delivery Ratio (SDR)

To assess Duke Forest's role in erosion control within these four watersheds, the SDR model was run to estimate its sediment buffering capacity. The model outputs a raster dataset of estimated tons of soil lost from each pixel in the input extent. These output export values are highly linked to the land cover dataset and their corresponding statistics which capture the ability of a pixel to retain soil. Typically, forest cover types have higher retention capacity values relative to barren, agriculture, and urban land cover types due to having expansive root systems, which hold sediment in place, therefore reducing export values.

The InVest SDR model is based on the Revised Universal Soil Loss Equation (RUSLE) below. This equation is run through the input of rasters pixel-by pixel at the extent of the watershed vector dataset.



The amount of annual soil loss on pixel i, $usle_i$ (units: $tons \cdot ha^{-1} yr^{-1}$), is given by the revised universal soil loss equation (RUSLE1):

$$usle_i = R_i \cdot K_i \cdot LS_i \cdot C_i \cdot P_i,$$

where

- R_i is rainfall erosivity (units: $MJ \cdot mm(ha \cdot hr \cdot yr)^{-1}$),
- K_i is soil erodibility (units: $ton \cdot ha \cdot hr(MJ \cdot ha \cdot mm)^{-1}$),
- LS_i is a slope length-gradient factor (unitless)
- C_i is a cover-management factor (unitless)
- and P_i is a support practice factor (Renard et al., 1997). (cf. also in (Bhattarai and Dutta, 2006)). (unitless)

Figure 4: RUSLE used by SDR in calculation of sediment export per pixel. Source: Sharp et al, 2016.

For assessment of sediment production and retention across the region, SDR was ran with an assortment of geospatial and statistical data inputs (Table 3). Many of the data inputs were the same as NDR, but also included erosivity and erodibility raster datasets. The erosivity raster (Panagos et al, 2017) captures the variation in rainfall intensity across the scope of analysis. Erosivity values are input into the R-factor variable of the RUSLE. Areas of higher rainfall intensity result in greater sediment loads reaching our waterways. The erodibility raster (Schwarz & Alexander, 1995) is based on soil qualities and how susceptible a soil type is to erosion. Erodibility values are input into the K-factor variable of the RUSLE. A value of 0 for the K factor would represent something like bare rock, which is unlikely to erode, whereas high K values represent soils which are highly susceptible to erosion. As with NDR, all data inputs were projected to NAD 1983 UTM Zone 17N and the final raster output was set to the spatial resolution of the elevation dataset (~37.16 m^2).

Data Input	**Data Format**	**Value Range**	**Source**
Land Use/Land Cover	Raster (30m)	11-95	Multi-Resolution Land Characteristics, 2019
DEM	Raster (20 ft)	0-997 (ft)	NC State University Libraries, 2013
Watersheds	Shapefile	NA	North Carolina Department of Environmental Quality (Williams, 2022)
Erosivity	Raster (1 km)	4191-5086 (MJ*mm/(ha*hr*yr)	European Soil Data Centre (ESDAC) (Panagos et al, 2017)
Erodibility	Raster (30 m)	0-0.0369 (ton*ha *hr/(ha*MJ*mm)	USGS (Schwarz & Alexander, 1995)
Threshold Flow Accumulation	Integer	300	
Borselli k parameter	Integer	2	Sharp et al., 2016
Borselli ICO parameter	Decimal	0.5	Sharp et al., 2016
Max SDR Value	Decimal	0.8	Sharp et al., 2016

Table 3: SDR Data Inputs

Biophysical data inputs into SDR include the C and P factors of the RUSLE. The C factor stands for cover management factor, which is intended to capture the variation in the management of fallow on agricultural lands. The P-factor stands for support practice factor, which captures the variation in agricultural approaches on sloped terrain, for example, terracing or contour plowing (Sharp et al, 2016). Ancillary data on the region’s agricultural methods would be required to have finer statistics on the C and P factors but would be outside the focus of this study.

Land Use Class Name	Land Use Code	USLE C Factor	USLE P Factor
Open Water	11	0.001	1
Developed Open Space	21	0.1	0.5
Developed Low Intensity	22	0.1	0.5
Developed Medium Intensity	23	0.1	0.5
Developed High Intensity	24	0.1	0.5
Barren Land	31	0.45	1
Deciduous Forest	41	0.001	1
Evergreen Forest	42	0.001	1
Mixed Forest	43	0.001	1
Shrub/Scrub	52	0.01	1
Grassland/Herbaceous	71	0.01	1
Pasture/Hay	81	0.01	1
Cultivated Crops	82	0.2	1
Woody Wetlands	90	0.001	1
Emergent Herbaceous Wetlands	95	0.001	1

Table 4: Biophysical table of Universal Soil Loss Equation variables by land cover types from the National Land Cover Dataset (MRLC). Variable statistics estimates from Hamel et al, 2015.

Results

Carbon Storage: Quantitative Analysis

Within the Duke Forest, InVEST estimated a total of ~543,000 tons (493,000 Mg) of carbon stored in Duke Forest at present. This amounts to an average of 80 tons of carbon stored per acre (Table 5). The Oosting Natural Area stood out as having the highest rate of carbon storage amongst the seven divisions at 94.3 tons/acre. Meanwhile, the Oosting Natural Area showed the lowest rate of storage at 71.1 tons/acre. The largest Duke Forest division, Durham, had the highest estimate of total storage of all forest divisions at ~177,000 tons.

DIVISION	Total Storage (tons)	Total area (acres)	Average Storage (tons/acre)
Blackwood	91798	1145	80.2
Dailey	33876	417	81.3
Durham	176715	2441	72.4
Edeburn	38441	487	79.0
Hillsboro	41431	583	71.1
Korstian	145609	1828	79.6
Oosting	15438	164	94.3
TOTALS	543308	7064	79.7

Table 5: Total carbon storage (tons) and average storage per acre by Duke Forest management division

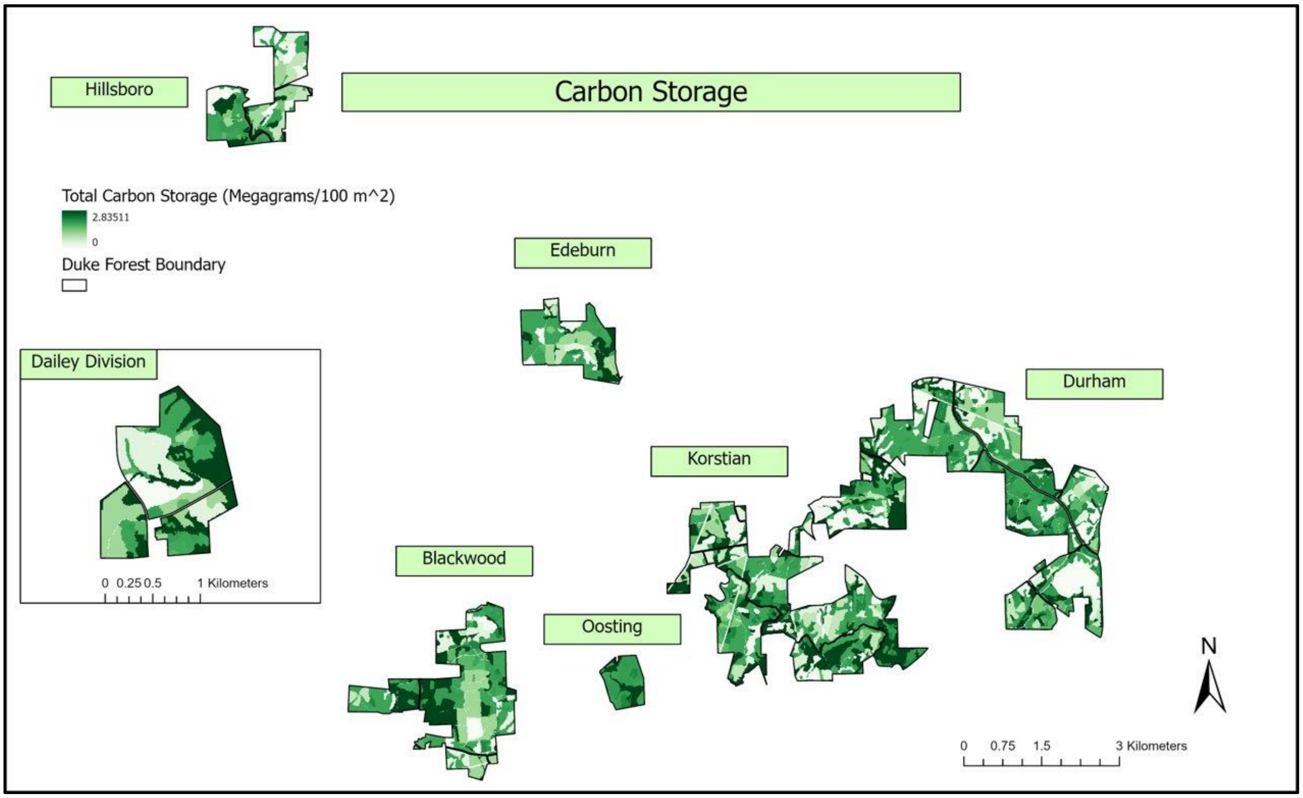


Figure 4: Map of Carbon Storage across all Duke Forest divisions. Units are in Mg/100 m^2

pixel.

In comparison to the total carbon storage across Duke Forest's three broader counties, as reported by the Duke University Nicholas Institute, the Duke Forest contributes a positively disproportionate amount of carbon to the county relative to its area in Durham county (Table 6). However, this was not found to be the case for Duke Forest stands within Orange and Alamance counties.

County	%Area	%Storage	%Diff
Durham	0.80	1.20	+0.40
Orange	2.00	1.82	-0.18
Alamance	0.15	0.10	-0.05

Table 6: Comparison of proportions of total area and total storage of Duke Forest relative to countywide totals, using estimates from the Nicholas Institute.

Carbon Storage: Monetary Analysis

Determining the monetary value of carbon at any given time is a challenge due to the fluctuations in market prices and the dramatic range in evaluated cost across different markets (The World Bank, 2021). The global average carbon credit value for deforestation/afforestation projects reported by World Bank is $7.69 (The World Bank, 2021). However, carbon credits are assessed in terms of tons of CO2 equivalents, so this value would correspond to roughly $28.22 for tons of pure carbon stored. This resulted in a total valuation of over $15 million in value across all Duke Forest divisions (Table 7).

DIVISION	Total Storage (tons)	Total area (acres)	Average Storage (tons/acre)	Valuation

Blackwood	91798	1145	80.2	$2,590,552
Dailey	33876	417	81.3	$955,978
Durham	176715	2441	72.4	$4,986,904
Edeburn	38441	487	79.0	$1,084,795
Hillsboro	41431	583	71.1	$1,169,188
Korstian	145609	1828	79.6	$4,109,088
Oosting	15438	164	94.3	$435,656
TOTALS	543308	7064	79.7	$15,332,162

Table 7: Monetary estimates of carbon storage across Duke Forest divisions using global average for forestry projects.

	Storage (tons)	**Total Seq.(tons)**	**Annual Seq.**	**Valuation**
Current	543308	NA	NA	NA
10 YR	581215	37907	3790.7	$106,974
20 YR	608294	27078	2707.8	$76,415
30 YR	623146	14852	1485.2	$41,912
40 YR	635592	12446	1244.6	$35,123
50 YR	646562	10971	1097.1	$30,959

Table 8: Projections for annual sequestered carbon for all Duke Forest divisions for next 50 years at 10-year intervals without active management using global average for forestry projects.

Carbon Sequestration

Our carbon sequestration estimates (Table 8) showed a broad range across each 10-year interval with an average annual value of over $58,000 for the next 50 years. These estimates showed a continual diminishing return in carbon stocks at each ascending interval; however, these results are somewhat misleading. These declining returns are primarily a result of not having carbon sequestration estimates beyond the stand age of 90. This resulted in our InVEST model outputs becoming saturated with forest stands with carbon storage estimates based on age class 90, which showed no increase in carbon storage because of our lack of estimates for higher age classes. In reality, carbon sequestration continues beyond age 90 even if growth rates begin to plateau and higher sequestration estimates are generally seen in younger stands. However, the active timber management of Duke Forest likely means that estimates in the first 10-20 years beyond present may be overestimated due to carbon deficits. When a stand is harvested, aboveground carbon stocks, the largest area of stored carbon in the forest is removed, and therefore results in the removal of carbon and resetting carbon sequestration rates to the slower sequestration rates seen at early age classes. Despite these decreasing estimates in future projections, our spatial representation of carbon storage across these 10-year intervals showed a visible increase in the expansion of stands with high storage rates (Figure 5).

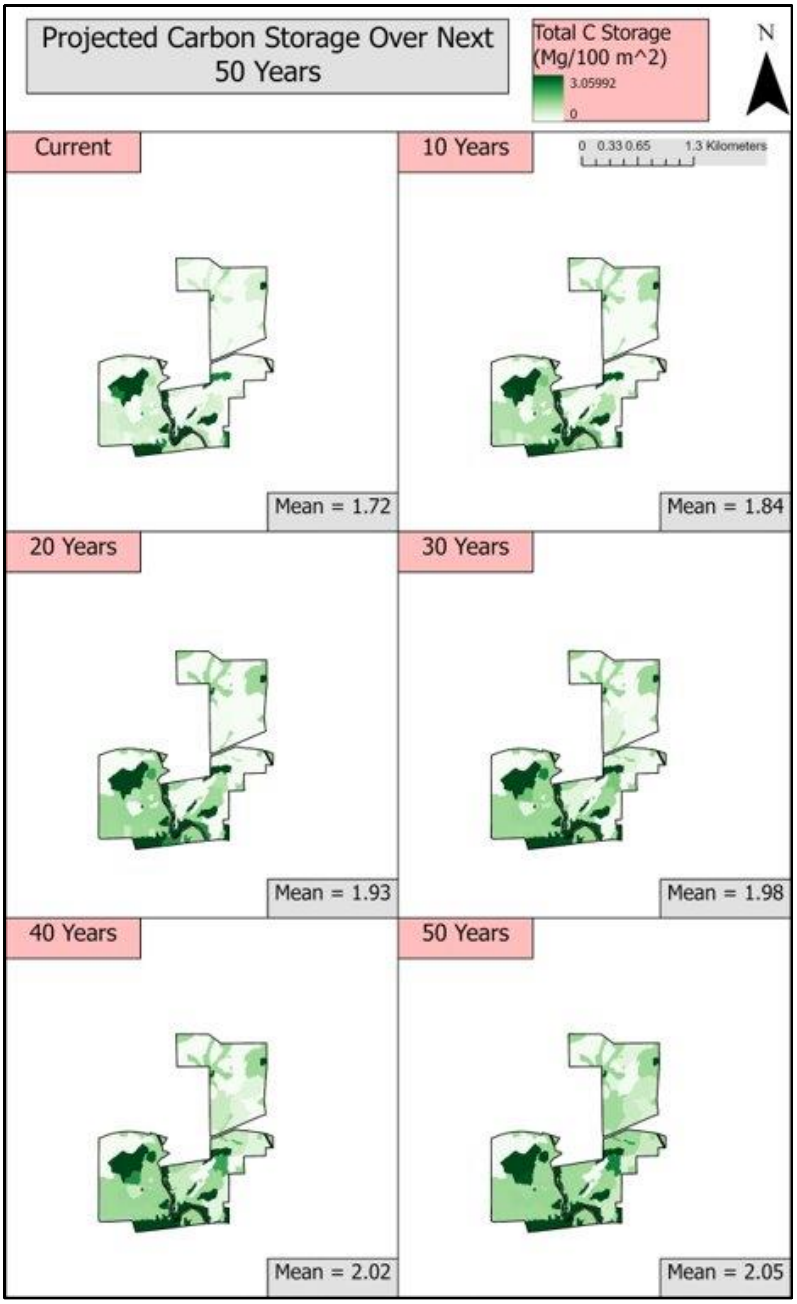


Figure 5: Visualization of projected increase in carbon storage across 50 years in 10-year intervals. For visibility, map frames are restricted to the Hillsboro division. Mean storage estimates for each 10-year increment are in Megagrams/100 m^2.

To look at a national scale, we compared carbon stock valuations (Table 6) between two domestic carbon markets across all carbon project types (Valuation 1: CaT & Valuation 2:

RGGI), carbon was valued much higher by CaT at $65.84 per ton than RGGI, a northeastern US market, which only values a ton of carbon at $31.89 (Table 9). Due to this wide range in stock value dependent on what market is used for carbon trading, the monetary value of all stored carbon in Duke Forest ranges from $17.3 (RGGI) to $35.8 million (CaT). This means the average valuation of total stored carbon in Duke Forest across these two markets is about $26.6 million.

Valuations (As of 4/21)	Market Value of 1 ton of CO2	Market Value of 1 ton of C
Valuation 1		
CaT (California)	$17.94	$65.84
Valuation 2		
RGGI (Regional Greenhouse Gas Initiative, Northeast US)	$8.69	$31.89

Table 9: Market values by ton of carbon dioxide and ton of carbon across three major carbon stock markets. Values are current as of April 2021. Source: The World Bank Group.

Water Quality: Nitrogen Retention

Nitrogen export is much lower in the Duke Forest, compared to the mean values in the watersheds (Table 10, Figure 8). As the nitrogen export value shows how much nitrogen reaches stream by surface flow, a higher value in nitrogen exports means higher susceptibility to erosion and greater nitrogen run off. Thus, lower export values in the Duke Forest indicates that forest cover has a higher capability in prevention of nutrient runoff compared to the other landcover types in each watershed. Developed urban areas shown in red in Figure 7 roughly correspond to areas with higher export values shown in red and orange in Figure 6, indicating these areas have more nitrogen runoff, probably due to less vegetation cover (Figure 6, 7.). On the other hand, forested areas, including the Duke Forest, which is shown in the inset map, have lower export values indicating that forests provide services to mitigate nitrogen runoff (Figure 6). Within the Duke Forest, the Blackwood division has the lowest nitrogen export (0.013 kg/pixel), indicating it has the highest nitrogen runoff prevention on average (Table 11). As for total sediment export, the Durham division has the largest export (~4,770 kg), and the Oosting division had the smallest export (~300 kg).

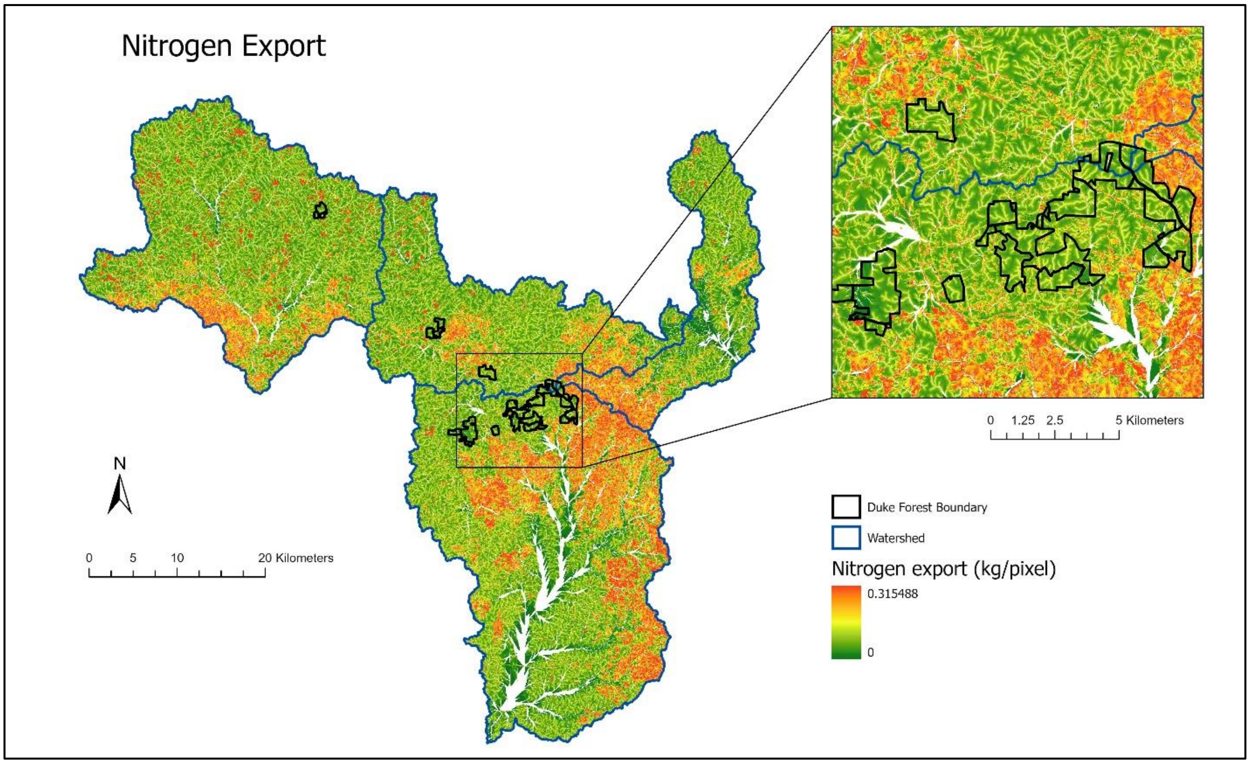


Figure 6: Map of nitrogen export. Unit is kilogram per 37.16 m^2 pixel.

.

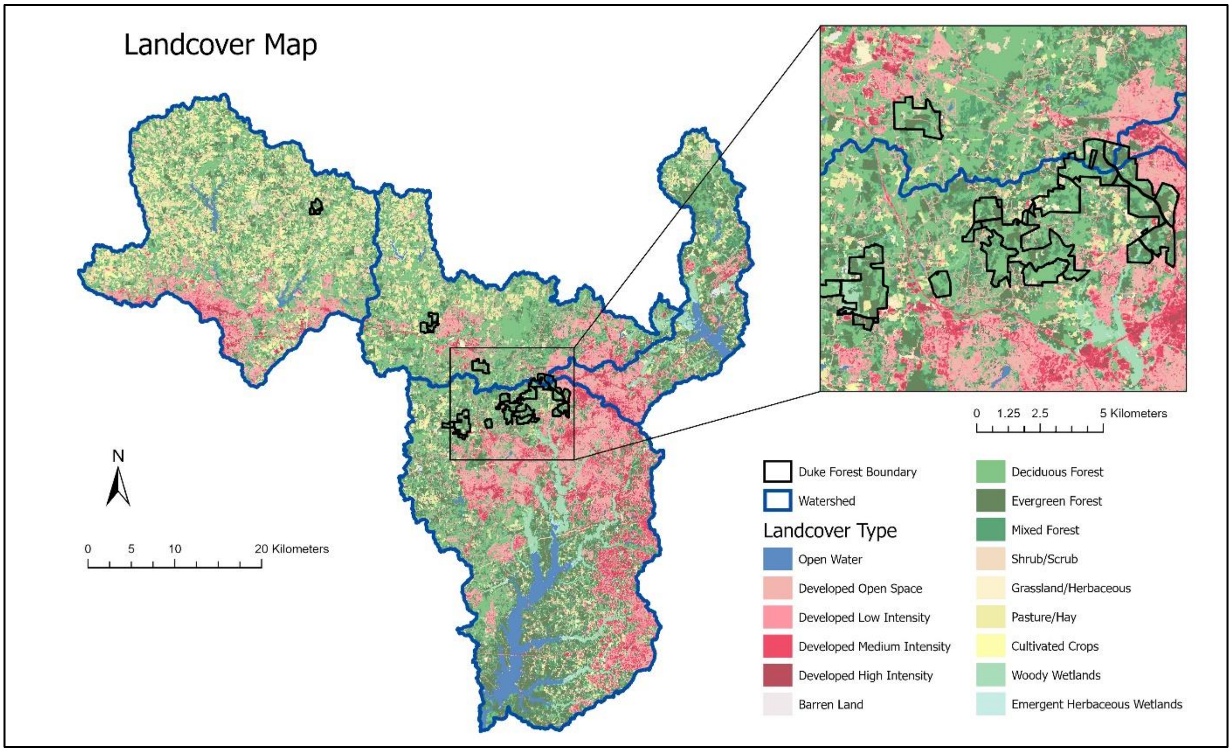


Figure 7: Land cover map. The land cover categories are based on the National Land Cover Database (NLCD).

Watershed Name	Watershed Mean (kg/acre)	Duke Forest Mean (kg/acre)	Watershed Area (acre)	Total export in watershed (ton)
Back Creek-Haw River	2.6	1.8	160394.5	417.8
B Everett Jordan Lake-New Hope River	3.0	1.7	219557.0	661.8
Eno River	2.5	1.9	99111.3	247.4
Upper Falls Lake	2.5	1.4	63714.2	162.3
Totals	-	-	542777.0	1489.2

Table 10: Nitrogen export value for the watersheds and the Duke Forest within each of these watersheds. Mean nitrogen export values show average export within the watersheds or the Duke Forest in these watersheds in kg per acre.

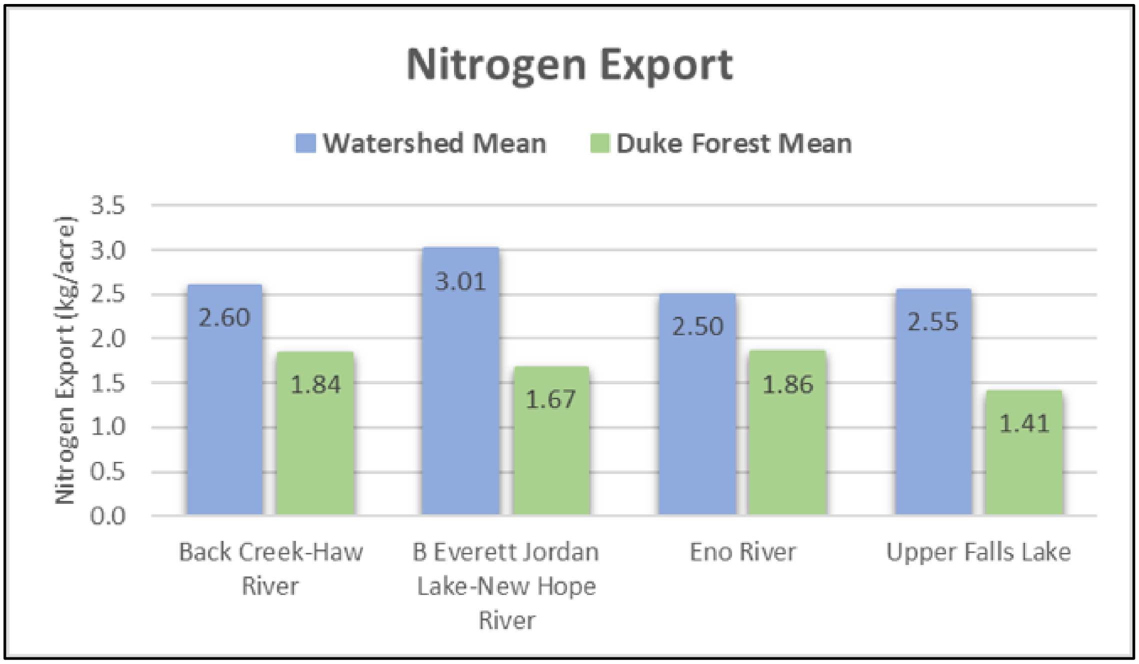


Figure 8: Nitrogen export value for the watersheds and the Duke Forest within each of these watersheds.

Division	Mean (kg/acre)	Area (acre)	Total (kg)
Blackwood	1.4	1145.4	1628.7
Dailey	1.7	417.8	698.1
Durham	2.0	2440.6	4773.5
Edeburn	2.0	486.7	973.5
Hillsboro	1.8	583.3	1079.1
Korstian	1.9	1828.5	3457.9
Oosting	1.8	163.8	299.6
Totals	-	7066.1	12910.5

Table 11: Nitrogen export value for the Duke Forest divisions. Mean nitrogen export values show average export within the forest divisions in kg per acre.

Water Quality: Phosphorus Retention

Phosphorus exports are much lower in the Duke Forests, compared to the mean values in the watersheds, as with nitrogen export (Table 12, Figure 10). As the phosphorus export value shows how much phosphorus reaches stream by surface flow, a higher value in exports means a higher susceptibility to erosion and more run off. Thus, lower export values in the Duke Forest indicate that forest cover has higher capability in prevention of phosphorus runoff compared to the rest of the landcover types in the watersheds. Developed urban areas shown in red in Figure 7 roughly correspond to areas that have higher export values shown in red and orange in Figure 8, indicating these areas have more runoff probably due to less vegetation covers (Figure 7, 9.). On the other hand, forest areas, including the Duke Forest that is shown in the inset map, have lower export values indicating that forest covers provide services to mitigate nitrogen runoff (Figure 9). Within the Duke Forest, the Hillsboro division has the lowest mean phosphorus export (0.061 kg/acre), indicating it has the highest nitrogen runoff prevention on average (Table 13). As for the total phosphorous export, the Durham division has the largest export (238.654 kg), and the Oosting division has the smallest export (10.424 kg).

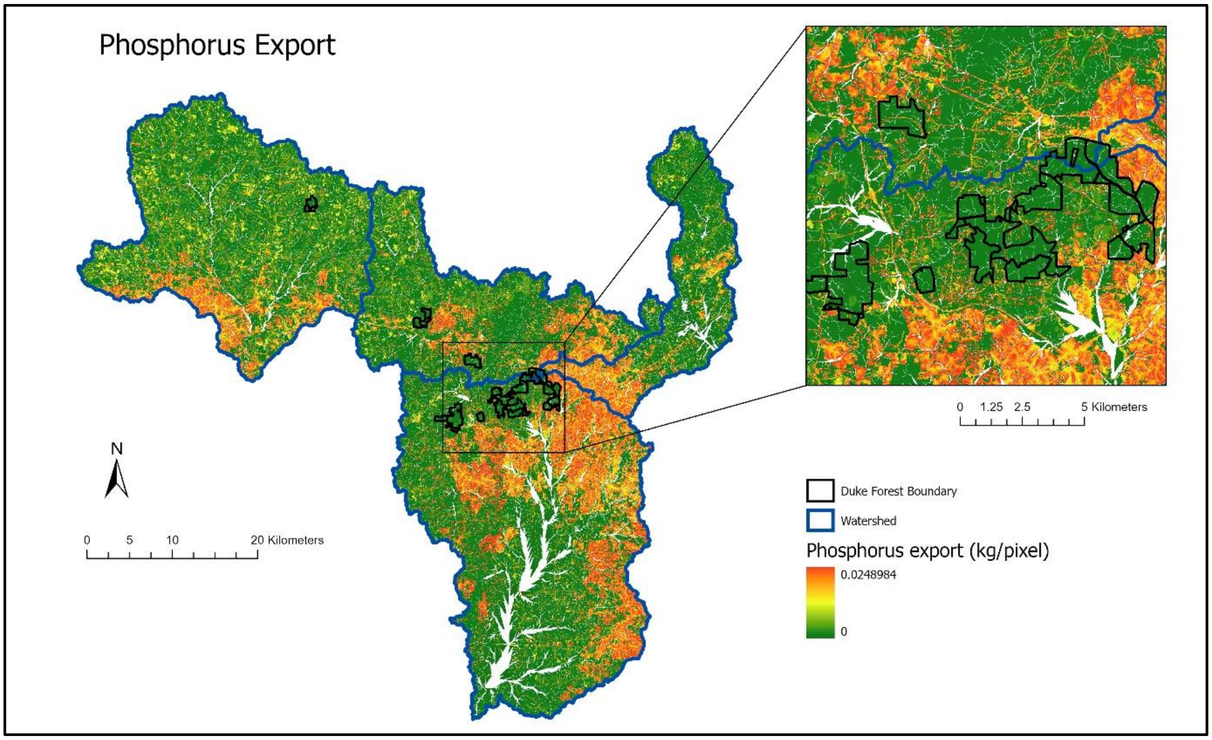


Figure 9: Map of phosphorus export. Unit is kilogram per pixel (37.16 m^2).

Watershed Name	Watershed Mean (kg/acre)	Duke Forest Mean (kg/acre)	Watershed Area (acre)	Total export in watershed (ton)
Back Creek-Haw River	0.26	0.08	160394.5	417.8
B Everett Jordan Lake-New Hope River	0.37	0.07	219557.0	661.8
Eno River	0.26	0.08	99111.3	247.4
Upper Falls Lake	0.28	0.05	63714.2	162.3
Totals	-	-	542777.0	1489.2

Table 12: Phosphorus export value for the watersheds and the Duke Forest within these watersheds. Mean nitrogen export values show average export within the watersheds or the Duke Forest in these watersheds in kg per acre.

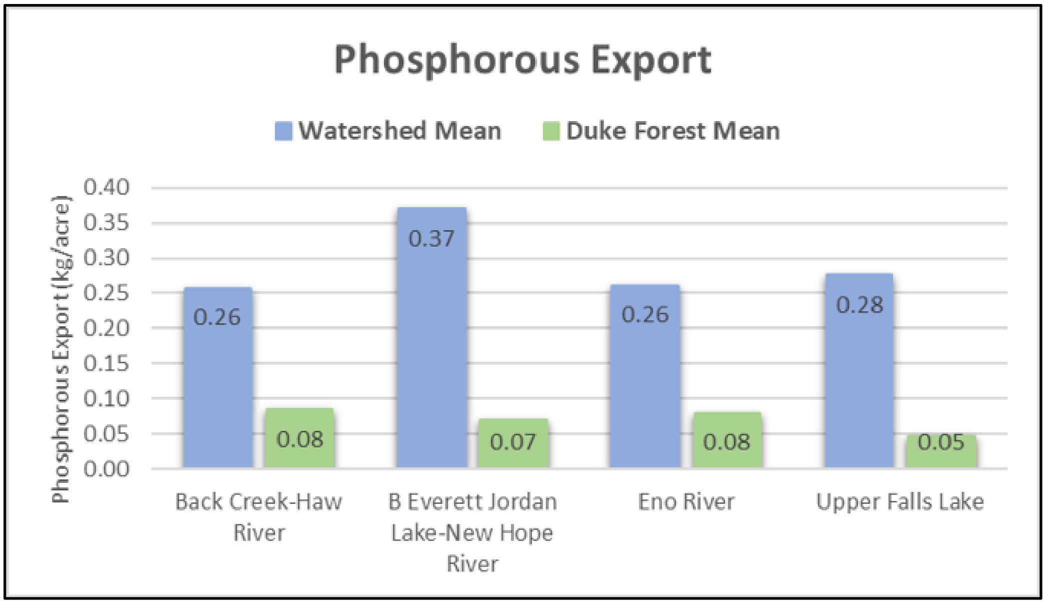


Figure 10 Phosphorus export value for the watersheds and the Duke Forest within these watersheds.

Division	Mean (kg/acre)	Area (acre)	Total (kg)
Blackwood	0.064	1145.4	73.2
Dailey	0.070	417.8	29.4
Durham	0.098	2440.6	238.7
Edeburn	0.105	486.7	50.9
Hillsboro	0.061	583.3	35.7
Korstian	0.076	1828.5	138.6
Oosting	0.064	163.8	10.4
Totals	-	7066.1	577.0

Table 13: Phosphorus export value for the Duke Forest divisions. Mean nitrogen export values show average export within the forest divisions in kg per acre.

Water Quality: Sediment Retention

Sediment exports are much lower in the Duke Forest, compared to the mean values in the watersheds, as with nitrogen export (Table 14, Figure 12). As the phosphorus export value shows how much sediment reaches stream by surface flow, a higher value in exports means a higher susceptibility to erosion and more run off. Thus, lower export values in the Duke Forest indicate that forest cover has higher capability in prevention of sediment runoff compared to the rest of the landcover types in the watersheds. Most areas with high sediment export values shown in red and orange in Figure 11 seem to fall within the developed urban areas shown in red in Figure 7, indicating these areas have more runoff probably due to less vegetation covers (Figure 7, 11.). On the other hand, forest areas, including the Duke Forest that is shown in the inset map, have lower export values indicating that forest covers provide services to mitigate sediment runoff (Figure 11). Within the Duke Forest, the Blackwood division has the lowest mean sediment export (22.1 kg/acre), indicating it has the highest sediment runoff prevention on average (Table 15). As for the total sediment export, the Durham division has the largest export (~321,000 kg), and the Oosting division has the smallest export (7,736 kg).

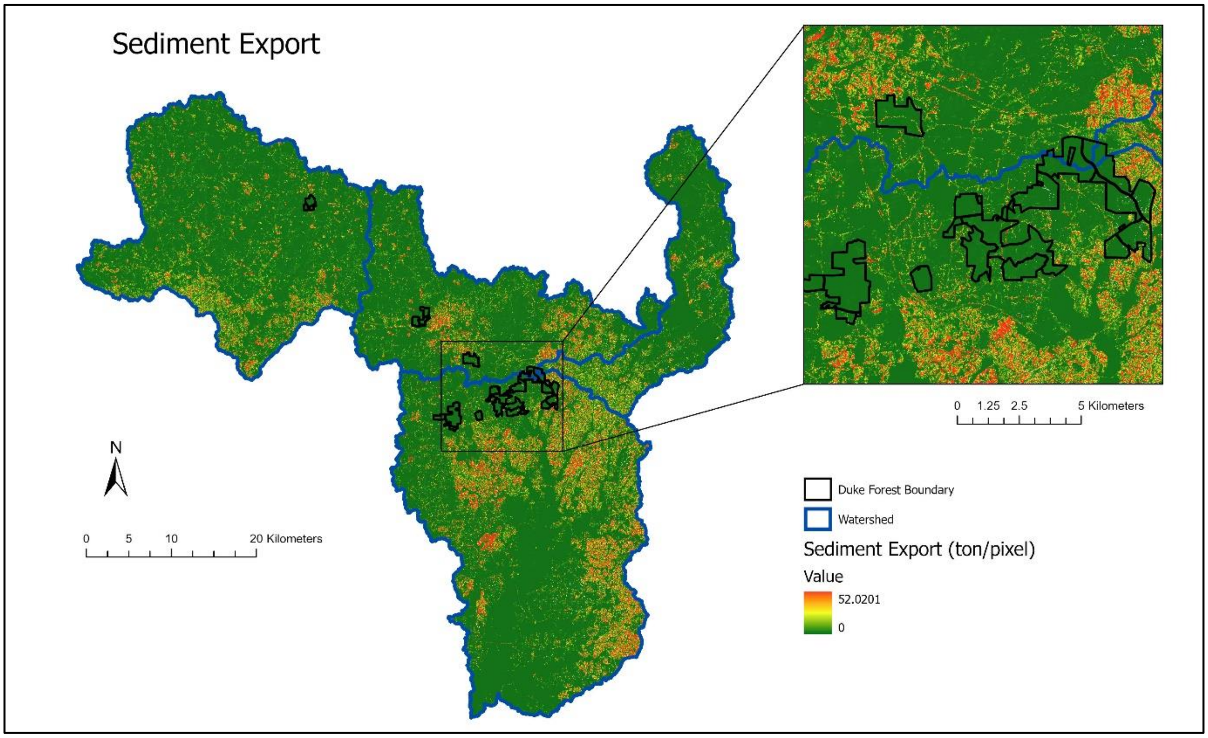


Figure 11: Map of sediment export. Units are in ton per pixel (37.16m^2).

Watershed Name	Watershed Mean (kg/acre)	Duke Forest Mean (kg/acre)	Watershed Area (acre)	Total export (ton)
Back Creek-Haw River	436.4	92.2	160394.5	69998.3
B Everett Jordan Lake-New Hope River	988.6	23.4	219557.0	217063.0
Eno River	603.3	90.5	99111.3	59797.0
Upper Falls Lake	469.5	7.3	63714.2	29916.8
Totals	-	-	542777.0	376775.1

Table 14: Sediment export value for the watersheds and the Duke Forest within these watersheds. Mean nitrogen export values show average export within the watersheds or the Duke Forest in these watersheds in kg per acre.

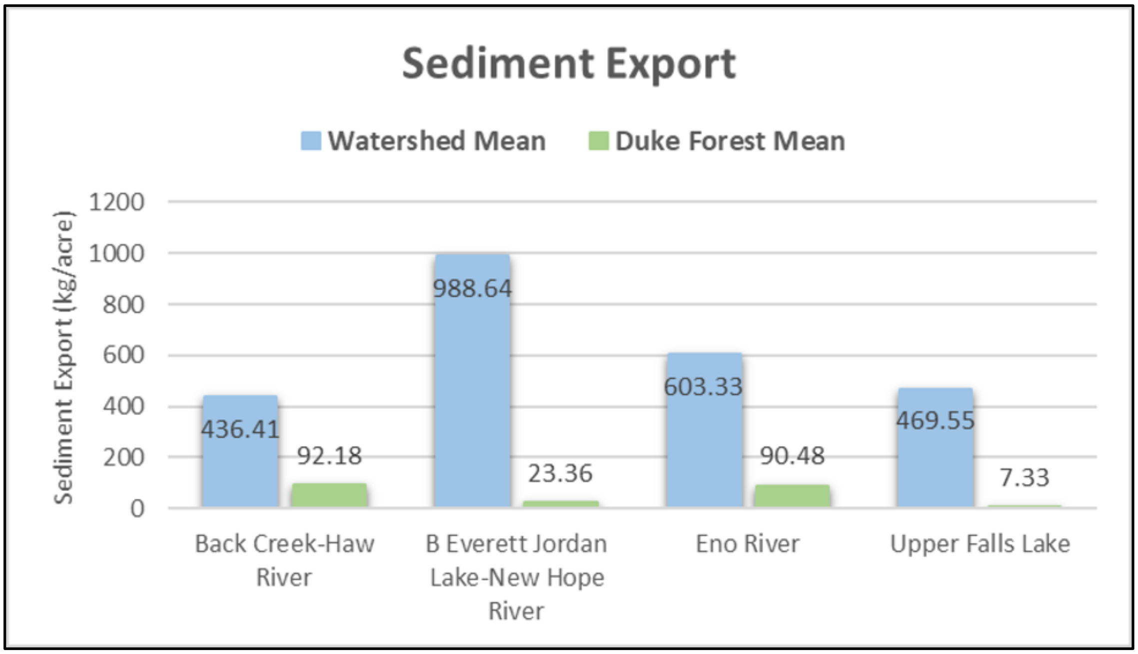


Figure 12: Sediment export value for the watersheds and the Duke Forest within these watersheds.

Division	Mean (kg/acre)	Area (acre)	Total (kg)
Blackwood	22.1	1145.4	25354.1
Dailey	23.4	417.8	9758.1
Durham	131.6	2440.6	321067.7
Edeburn	149.1	486.7	72560.3
Hillsboro	72.5	583.3	42282.8
Korstian	73.1	1828.5	133673.8
Oosting	47.2	163.8	7736.2
Totals	-	7066.1	612433.0

Table 15: Sediment export value for the Duke Forest divisions. Mean nitrogen export values show average export within the forest divisions in kg per acre.

Sediment Retention: Monetary Evaluation

To evaluate the monetary value of sediment retention by the Duke Forest, we assessed total sediment export reduction at the watershed outlet to alternate land cover scenarios. The two scenarios used for comparison were: a.) if Duke Forest contributed the average sediment export for each 10-digit HUC b.) if Duke Forest contributed the average sediment export of developed areas across the four-watershed area of analysis. These total estimates of reduced sediment input into the watershed were then compared to estimates of Neuse River water treatment facility cost savings attributable to turbidity reduction from a recent study (Elsin et al., 2009). This study used two benefit transfer approaches to cost-saving evaluation: value and function transfer. The results of these two approaches were averaged for the purpose of our analysis.

In scenario A, this cost-saving evaluation method estimated a total of roughly $43,000 in annual savings across the four 10-digit HUC region due to Duke Forest turbidity reduction (Figure 13). The effect of Duke Forest was particularly evident in the B Everett Jordan Lake – New Hope River watershed where Duke Forest was attributable to about $26,000 in total water treatment facility cost reduction. At the watershed outlet, Duke Forest was responsible for roughly a 2.4% reduction in total sediment export in this scenario.

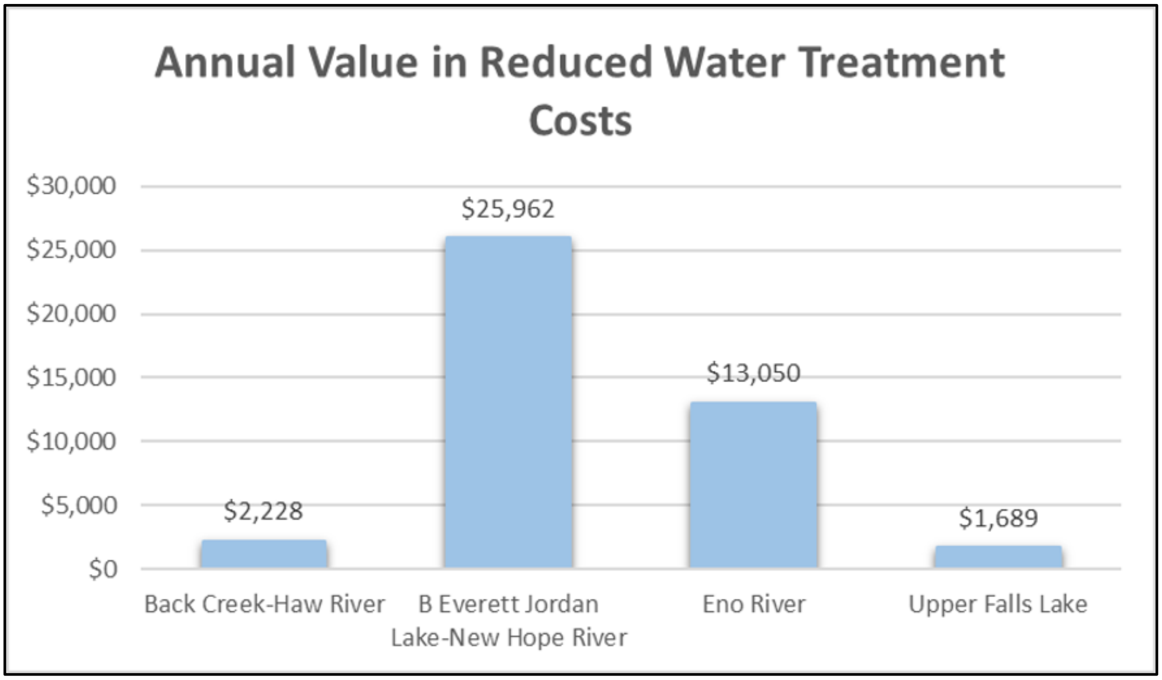


Figure 13: Histogram of estimated water treatment facility savings by watershed for alternative land scenario A.

The scenario B evaluation, in which Duke Forest becomes developed land, exhibited a much higher monetary valuation at about $113,000 annually (Figure 14). Like scenario A, B Everett Jordan Lake-New Hope River had the highest monetary benefit annually amongst the four watersheds at about $50,000 annually, closely followed by Eno River at $45,000. In comparison to this alternative land use, Duke Forest is responsible for 4.6% and 4.2% turbidity reductions at the watershed outlet of B Everett Jordan Lake-New Hope River and Eno River, respectively.

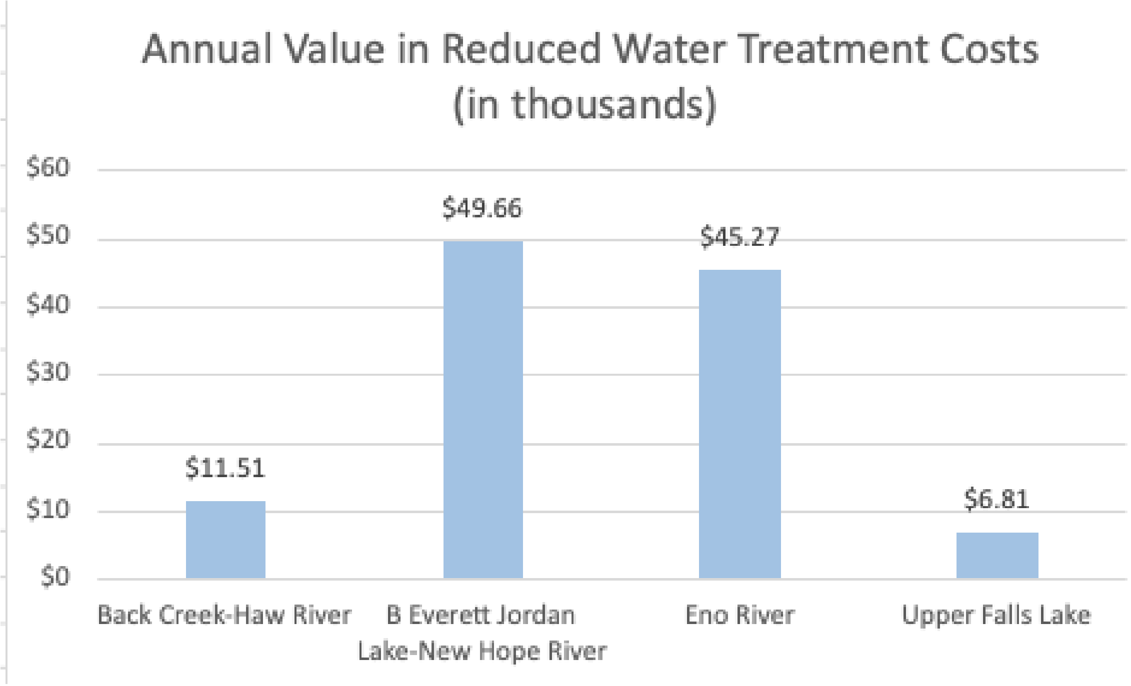


Figure 14: Histogram of estimated water treatment facility savings by watershed for alternative land scenario B.

Discussion

Carbon Storage and Sequestration

Carbon InVEST estimated a total of 543,000 tons of carbon stored in Duke Forest with an average of 80 tons of carbon stored per hectare. Analysis of Natural and Working Land in North Carolina conducted by Nicholas Institute for Environmental Policy Solutions estimated carbon storage in forests in North Carolina is 4928.9 million metric tons of CO2e (Nicholas Institute, 2022). Carbon stored in the Duke Forest accounts for about 0.04% of the carbon stored in all the forests in North Carolina. In Alamance, Durham and Orange counties where the Duke Forest is located, the total carbon storage in forested land was estimated to be 111.9 million metric tons of CO2e. Carbon stored in the Duke Forest accounts for 1.8% of the total storage across these three counties. In examination of our by-county storage analysis, Duke Forest is of particularly great value to Durham County, as evident by its high carbon storage relative to its area. Surprisingly, this considerable contribution to carbon storage was not the case in Orange and Alamance counties. This is likely due to these counties having a larger extent of natural forests relative to Durham county, in which roughly 38% of county land is classified as NLCD developed land cover types. In contrast, Orange and Alamance counties are only characterized by about 16 and 21% developed land cover types, respectively.

Based on research by the Nicholas Institute, forests in North Carolina have a carbon storage of 211.5 tons of carbon per hectare on average. Another study estimated carbon density in Southern United Sates, including North Carolina at approximately 220 ton/ha (McKinley et al. 2011). The average carbon storage in the Duke Forest of 80 tons/acre, which equals roughly 198 tons/ha. Although this estimation is somewhat lower than these published statewide averages, this is likely a product of the active management of Duke Forest. Younger stands do not have the accumulated carbon stocks which older stands possess and roughly 3,000 acres of Duke Forest's 7,100 acres are at or below 60 years of age. These larger statewide estimates also include natural forests, which are likely to have greater carbon stocks due to a lack of active management.

Among the seven divisions, Oosting had the highest mean carbon storage per acre (94.3 tons). This is likely due to the lack of management in this division, resulting in a higher average stand age. As for the total carbon storage, Durham division had the greatest estimated storage due to being the largest amongst the divisions at about 2,440 acres.

In considering monetary valuation results, the value of stored carbon varies significantly depending on the method of valuation. Due to there being no global standard for the value of stored carbon, there is a wide range in the value attributable to this ecosystem service. Using the average value of carbon credits across all global forestry projects, stored carbon in the Duke Forest can be estimated as $15.3 million in value. This value is likely the best form of valuation available by comparing the Duke Forest's to other projects responsible for carbon storage through terrestrial forests. However, it is important to note that this global average covers projects across a variety of different carbon credit markets and climates. Climate has a large effect on the actual rate of sequestration and carbon credit prices are volatile across different markets. In comparing domestic market valuations, RGGI, the lower of the two valuations and the nearest to Duke Forest geographically, has an average carbon credit value worth about half of a carbon credit on California's CaT scheme. The much higher value of carbon credits in the CaT market can be attributed to the lower cap on CO2 emissions RGGI, thereby creating a higher demand for credits among companies seeking emission allowance (Center for Climate and Air Solutions, 2021 & RGGI). Global oscillation in carbon value across markets is to be expected given these markets are still young and have a wide range in current investment. However, these domestic averages for carbon credit values include a wide variety of carbon offset projects which interferes with the accuracy of these estimates for any specific project type.

For carbon sequestration, InVEST estimated the highest sequestration for the next ten years (~3,790 tons of carbon for the next ten years, 379 tons per year). A typical passenger vehicle emits 4.6 metric tons CO2 per year (EPA, 2018), thus, the annual sequestration by the Duke Forest is equivalent to annual emission of just over 300 cars.

However, these annual sequestration estimates consistently decrease at 20, 30, 40, and 50 years into the future. This decline in sequestration is due to data limitations thresholding our storage estimates. Carbon InVEST calculated sequestration by looking at the difference between carbon storage at two separate times. As described in the method section, we provided future landcover and carbon pool data based on the current dataset, by adding 10-year intervals to stand ages for the next 50 years. However, 90 years was the oldest age class for our estimates, so all stands beyond age 90 were given estimates for stands of age 90. This decline in sequestration is mainly from not having sequestration estimates beyond the stand age of 90.

Water Quality: Nutrient Retention and Sediment Retention

We ran NDR InVEST for nitrogen and phosphorus, and SDR InVEST to quantify the services the Duke Forest provides for water quality. For NDR, the InVEST model estimated that the Duke Forest exported about 12,900 kg of nitrogen and 577 kg of phosphorus.

For both nitrogen and phosphorous, overall, the nutrient export was lower in the Duke Forest compared to the watersheds that the Duke Forest lies in. For nitrogen, mean values (export per pixel) in the Duke Forest were lower than mean values in the watersheds by 25.7% ~ 44.7%, while for phosphorus, mean values in the Duke Forest were lower than the values in the watersheds by 67.3% ~ 83.1%. This indicates that nutrient exports in the Duke Forests are much lower than exports in the watersheds in general, and that the Duke Forest contributes to water quality protection downstream by having much less runoff. There are not significant differences between divisions, it seems, for Nitrogen, Blackwood and Dailey offer more water quality protection services with lower mean expert values. For phosphorus, variance among the divisions is larger, and Blackwood, Hillsboro, Oosting, and Dailey provide higher water quality protection function with smaller mean export values.

For SDR, the Duke Forest was estimated to export about 612,000 kg of sediment. The average sediment export values are also significantly smaller than the average values in the watersheds, by 78.8% ~ 98.4%. This indicates higher soil retention capacity by forests and demonstrates an important contribution to the water quality protection in the downstream watersheds by holding sediments than the other parts of the watersheds. Sediment retention capacity differs relatively large among the forest divisions compared to NDR. Blackwood and Dailey have the highest sediment retention services, whereas Durham and Edeburn have the lowest among the divisions.

Limitations

Data: Carbon Storage and Sequestration

Limitations in our carbon storage modelling include our reliance on stand age for carbon estimates. Although this is a strong predictor for carbon storage, it may not be a one-to-one relationship due to the impact of other variables, such as tree diversity, forest structure, and topographic heterogeneity (Li et al., 2019). In addition, the USDA carbon by age class estimates we used are estimates that cover a five-state region of the southeastern US, not just North Carolina. North Carolina is the northernmost state in this range, which may cause storage rates to be overestimated due to a global trend in higher productivity at higher temperatures (Lenton & Huntingford, 2003). These estimates also may be somewhat out-of-date since they were collected and compiled in 2005. Impacts of climate change may already be shifting baseline carbon storage, which is difficult to assess given the array of possible climate scenarios and the unpredictability of human acceleration/deceleration of the issue (Wang et al., 2022).

Another issue in our age class determination is that Duke Forest breaks its parcels into age classes at 10-year increments, whereas the USDA estimates are broken into 5-year increments. To deal with this uncertainty of the optimal USDA class for each stand, we assigned the middle age class. For example, a Duke Forest stand of age 50-60 was assigned USDA carbon estimates for a stand aged at 55 years. Lastly, Duke Forest stands with uneven age classes were assigned a catch-all age of 75. This was a recommended estimate through consultation with the client but is unlikely to be an exact average age. Even if this were to be determined as an exact mean age, a stand known to be homogenously 75 years in age is likely to have different storage rates than one which unevenly averages to 75 years in age due to differences in forest structure.

The most apparent limitation in forest class determination is that the recorded Duke Forest cover classes are much more comprehensive than the three broad forest classes used from the USDA estimates: loblolly-shortleaf pine, oak-gum-cypress, and oak-hickory. In dividing Duke Forest classes between these three classes, all pine forest types were classified as “loblolly-shortleaf”, while cover types which could be described as bottomland hardwood were assigned “oak-gum cypress” estimates and upland hardwood cover types were assigned “oak-hickory “estimates. This oversimplification of our forest cover data likely does not capture the variation within each USDA class. Ideally, with more time and resources, more accurate storage estimates could be gathered by taking samples for each carbon pool of each cover type and age class.

Data: NDR & SDR

Due to the reliance of these models on the input land cover dataset and their accompanying biophysical table, there are limitations in the land cover resolution and the source of biophysical statistics. Despite the previous 2016 National Land Cover Dataset (NLCD) exhibiting roughly 72% accuracy at the level II classification of 15 classes we used (Wickham et al., 2021), NLCD is still at a somewhat coarse resolution of 30 m. and uses fifteen relatively broad classes. Unfortunately, the 2019 NLCD still does not have any available data on its accuracy because of its recent release. Regardless, certainty on the land use and land cover data could potentially be improved by conducting a local land cover classification with higher resolution satellite data and more comprehensive classes.

Moreover, biophysical statistics for each model would be most accurate if supplementary data was collected or if there was existing data gathered from previous studies within our study area. The studies referenced for biophysical data (Hamel et al., 2015 & Hillman, 2019) were also drawing estimates from other regions of North Carolina, but there may be considerable regional variability in the accuracy of these values beyond having a similar climate. Having accurate inputs for the P and C factors across our defined four-watershed frame of analysis would require a detailed dataset on farming methods and field data for other land cover types.

Lastly, for SDR monetary evaluation, there is a limitation in that Neuse River watershed is only one of the two larger watersheds which Duke Forest occupies: Cape Fear being the other. Additionally, our analysis was conducted on a smaller scale, 10-digit HUC watersheds, rather than at the major river basin scale used for these cost saving estimates, which could result in variation in reduction costs. It is important to note this is not a comprehensive analysis of the economic benefits of water quality improvement. Water quality degradation has been documented to have negative repercussions on local economies through effects on fisheries and public health (Clark, 2004). To fully encapsulate the effects of sediment export buffering, monetary analysis would need to capture the full range of collateral economic effects from reduced water quality.

Models: NDR

There are a couple limitations regarding the NDR model specifically and its sensitivity to data inputs. For the Borselli k parameter, we simply used InVEST's recommended default value of 2 because this parameter requires field data and is locally dependent. However, the model is highly sensitive to its input, and it could be further calibrated. The creators of InVEST also note how that due to having a small number of data inputs, the model is sensitive to retention load values provided by the user for each land class. As discussed above in data limitations, these values could be optimized for our specific study with field samples to determine a more accurate proxy for each cover type. Lastly, the model calculates nutrient export values at the watershed outlet. This means that it does not analyze how contributing streams and rivers are specifically affected by nutrient export (Sharp et al., 2016).

Models: SDR

One limitation of SDR is the RUSLE formula which drives its calculations due to its focus on specifically rill/inter-rill erosion processes. Rill and inter-rill erosion encapsulates the movement of sediment downhill overland during precipitation events (Gilley, 2005). However, there are other sources of erosion which SDR does not account for, such as streambank erosion, landslides, or gully erosion, which is typically caused by land use activity dislodging sediment particles (Wilkinson et al., 2014). As with NDR, the Borselli k parameter and the Borselli ICO parameter were given the default values of 2 and 0.5 respectively because of a lack of field data for these parameters. In theory, these values could be refined to our specific study area with field data collection and consultation with hydrologic experts (Sharp et al., 2016). Additionally, both models require a user-determined threshold flow accumulation to exclude water bodies of analysis, which could likely be improved to better match the extent of water bodies in the area. In our case, we experimented with a couple values, and determined setting the parameter to 300 pixels gave us the best visual representation relative to hydrologic maps.

Recommendations

To sustain current carbon storage rates, old stands with high storage rates should be left out of active timber management plans and age class proportions should be managed close to current levels. We would also recommend that Duke Forest maintains awareness of current carbon credit markets to evaluate the future financial outlook of selling credits. Currently, there is no national carbon credit market nor is there a North Carolina market like CaT. However, these carbon markets are relatively new and could see dramatic developments in the coming years. For instance, the EU only just began their multinational market in 2005 (European Commission). In terms of maximizing water quality improvement effects of Duke Forest, the Blackwood and Dailey divisions should be prioritized in conservation due to their high rates of nutrient and sediment retention. Active management should be conservative to reduce these divisions' susceptibility to erosion processes. In terms of considering landscape position, the

Korstian division should also probably be prioritized in management decisions due to having New Hope Creek run directly through it, granting it tremendous potential for nutrient and sediment buffering capacity.

Future Work

To expand the assessment of ecosystem services, additional services could be estimated beyond the subset we analyzed. The InVEST project has also developed other models for ecosystem services including assessments of urban cooling, flood mitigation, and habitat quality (Sharp et al., 2016). In addition, habitat connectivity or air quality could be analyzed using pollution data or connectivity modelling. Supplementary models could also be run for each service to develop a portfolio that captures a wider range of estimates to compensate for limitations of individual models. To refine the InVEST model specifically, collecting field data for land cover biophysical statistics and representative forest stand carbon samples would likely be the most accurate route for improvement. Lastly, using or developing a higher resolution land cover dataset with a wider range of classes would better capture the variation in sediment and nutrient export.

References

- Adams, M. P., Ghisalberti, M., Lowe, R. J., Callaghan, D. P., Baird, M. E., Infantes, E., et al. (2018). Water residence time controls the feedback between seagrass, sediment and light: Implications for restoration. *Advances in Water Resources, 117*, 14-26. doi:https://doi.org/10.1016/j.advwatres.2018.04.004
- Center for Climate and Energy Solutions. (2021, August 24). *California cap and Trade*. Center for Climate and Energy Solutions. Retrieved from https://www.c2es.org/content/california-cap-and-trade/
- Chesapeake Bay Foundation. (2022). *Nitrogen & Phosphorus*. Chesapeake Bay Foundation. Retrieved from https://www.cbf.org/issues/agriculture/nitrogen-phosphorus.html
- Childs, S. (2016, October). *Duke Forest Five-Year Strategic Plan: 2017 - 2022*. Duke Forest. Retrieved from https://dukeforest.duke.edu/files/2018/05/Duke-Forest-Strategic-Plan-Public-11Dec17.pdf
- Clark, K. (2004). Injuries to fishery resources due to contaminants in the Albemarle Bay complex: Consumption advisories.
- de Blécourt, M., Gröngröft, A., Baumann, S., & Eschenbach, A. (2019). Losses in soil organic carbon stocks and soil fertility due to deforestation for low-input agriculture in semi-arid southern africa. *Journal of Arid Environments*, *165*, 88-96. doi:https://doi.org/10.1016/j.jaridenv.2019.02.006
- Domke, G. M., Oswalt, S. N., Walters, B. F., & Morin, R. S. (2020). Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. *Proceedings of the National Academy of Sciences*, *117*(40), 24649–24651.

https://doi.org/10.1073/pnas.2010840117

- Duke Nicholas Institute. (n.d.). *North Carolina Natural & Working Lands Carbon Dashboard*. ArcGIS dashboards. Retrieved from https://dukeuniv.maps.arcgis.com/apps/dashboards/31b8eb2640384e329378fa10496100fc
- EPA. (2018). *Greenhouse Gas Emissions from a Typical Passenger Vehicle*. Retrieved from https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle#:~:text=typical%20passenger%20vehicle%3F-,A%20typical%20passenger%20vehicle%20emits%20about%204.6%20metric%20tons%20of,8%2C887%20grams%20of%20CO2.
- EPA. (2021, April 28). *Greenhouse Gases Equivalencies Calculator - Calculations and References*. US EPA. Retrieved from https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references#:~:text=To%20convert%20to%20carbon%20dioxide,in%20the%20year%20of%20conversion.
- EPA. (2021, August 31). *Nutrient Pollution: The Issue*. US EPA. Retrieved from https://www.epa.gov/nutrientpollution/issue
- Gilley, J. E. (2005). EROSION | water-induced. In D. Hillel (Ed.), *Encyclopedia of soils in the environment* (pp. 463-469). Oxford: Elsevier. doi:https://doi.org/10.1016/B0-12-348530-4/00262-9
- Grove, M. K., Bilotta, G. S., Woockman, R. R., & Schwartz, J. S. (2015). Suspended sediment regimes in contrasting reference-condition freshwater ecosystems: Implications for water quality guidelines and management. *Science of the Total Environment, 502,*

481-492. doi:https://doi.org/10.1016/j.scitotenv.2014.09.054

- Hamel, P., Chaplin-Kramer, R., Sim, S., & Mueller, C. (2015). A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. *Science of the Total Environment*, *524*, 166-177.
- Hillman, I. (2019, April 25). *Identifying Pollution Sources for Management Prioritization in the Albemarle-Pamlico watersheds*. Identifying Pollution Sources for Management Prioritization in the Albemarle-Pamlico Watersheds. Retrieved from https://dukespace.lib.duke.edu/dspace/handle/10161/18406
- Krieger, D. J. (2001). Economic value of forest ecosystem services: a review. Retrieved September 27, 2021, from http://www.truevaluemetrics.org/DBpdfs/EcoSystem/The-Wilderness-Society-Ecosystem-Services-Value.pdf.
- Lenton, T. M., & Huntingford, C. (2003). Global terrestrial carbon storage and uncertainties in its temperature sensitivity examined with a simple model. Global Change Biology, 9(10), 1333-1352. doi:https://doi.org/10.1046/j.1365-2486.2003.00674.x
- Li, Y., Bao, W., Bongers, F., Chen, B., Chen, G., Guo, K., et al. (2019). Drivers of tree carbon storage in subtropical forests. Science of the Total Environment, 654, 684-693. doi:https://doi.org/10.1016/j.scitotenv.2018.11.024
- McKinley, D. C., Ryan, M. G., Birdsey, R. A., Giardina, C. P., Harmon, M. E., Heath, L. S., Houghton, R. A., Jackson, R. B., Morrison, J. F., Murray, B. C., Pataki, D. E., & Skog, K. E. (2011). A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications, 21*(6), 1902–1924. https://doi.org/10.1890/10-0697.1
- Mitchard, E. T. (2018). The Tropical Forest Carbon Cycle and climate change. *Nature*,

559(7715), 527–534. https://doi.org/10.1038/s41586-018-0300-2

- Nicholas Institute for Environmental Policy Solutions. (2022). *North Carolina Natural and working lands dashboards*. Nicholas Institute for Environmental Policy Solutions. Retrieved from https://nicholasinstitute.duke.edu/project/north-carolina-natural-and-working-lands/dashboards
- Office of the Duke Forest. (2022). *Maps*. Duke Forest. Retrieved from https://dukeforest.duke.edu/recreation/maps/
- Ontl, T. A., Janowiak, M. K., Swanston, C. W., Daley, J., Handler, S., Cornett, M., Hagenbuch, S., Handrick, C., Mccarthy, L., & Patch, N. (2019). Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, *118*(1), 86–101. https://doi.org/10.1093/jofore/fvz062
- Pimentel, D. (2006). Soil erosion: A food and environmental threat. *Environment, Development and Sustainability, 8*(1), 119-137.
- RGGI. (n.d.). *The Regional Greenhouse Gas Initiative: an initiative of Eastern States of the US*. RGGI, Inc. Retrieved from https://www.rggi.org/
- Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Bierbower, W. (2016). InVEST 3.6.0 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund. Retrieved from https://invest-userguide.readthedocs.io/en/latest/index.html
- Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). *Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States.* U.S. Department of Agriculture, Forest Service. Retrieved from https://www.fs.usda.gov/treesearch/pubs/22954

- The World Bank. (2021, May 25). *State and Trends of Carbon Pricing 2021*. Open Knowledge Repository. Retrieved from https://openknowledge.worldbank.org/handle/10986/35620
- The World Bank Group. (2022). *Map & Data*. Carbon Pricing Dashboard | Up-to-date overview of carbon pricing initiatives. Retrieved from https://carbonpricingdashboard.worldbank.org/map_data
- USGS Water Science School. (2018, May 21). *Nitrogen and water* . Nitrogen and Water | U.S. Geological Survey. Retrieved from https://www.usgs.gov/special-topics/water-science-school/science/nitrogen-and-water
- Vigiak, O., Borselli, L., Newham, L. T. H., McInnes, J., & Roberts, A. M. (2012). Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. *Geomorphology*, *138*(1), 7488.doi:https://doi.org/10.1016/j.geomorph.2011.08.026
- Wallace, K. J. (2007). Classification of Ecosystem Services: Problems and solutions. Biological Conservation, 139(3-4), 235–246. https://doi.org/10.1016/j.biocon.2007.07.015
- Wang, Z., Li, X., Mao, Y., Li, L., Wang, X., & Lin, Q. (2022). Dynamic simulation of land use change and assessment of carbon storage based on climate change scenarios at the city level: A case study of Bortala, China. Ecological Indicators, 134, 108499. doi:https://doi.org/10.1016/j.ecolind.2021.108499
- Wickham, J., Stehman, S. V., Sorenson, D. G., Gass, L., & Dewitz, J. A. (2021). Thematic accuracy assessment of the NLCD 2016 land cover for the conterminous united states. Remote Sensing of Environment, 257, 112357. doi:https://doi.org/10.1016/j.rse.2021.112357

- Wilkinson, S. N., Dougall, C., Kinsey-Henderson, A. E., Searle, R. D., Ellis, R. J., & Bartley, R. (2014). Development of a time-stepping sediment budget model for assessing land use impacts in large river basins. Science of the Total Environment, 468-469, 1210-1224. doi:https://doi.org/10.1016/j.scitotenv.2013.07.049

Geospatial Data Sources

- Fick, S., & Hijmans, R. (2020, January). *Historical Climate Data*. WorldClim. Retrieved from https://www.worldclim.org/data/worldclim21.html
- Multi-Resolution Land Characteristics (MRLC) Consortium. (2019). *NLCD 2019 Land Cover (CONUS)*. NLCD 2019 Land Cover (CONUS) . Retrieved from https://www.mrlc.gov/data/nlcd-2019-land-cover-conus
- NC State University Libraries. (2013, July 13). *Elevation Data Sources*. NC State University Libraries. Retrieved from https://www.lib.ncsu.edu/gis/elevation
- Panagos, P., Borrelli, P., Meusburger, K., Yu, B., Klik, A., Jae Lim, K., et al. (2017). Global rainfall erosivity assessment based on high-temporal resolution rainfall records. *Scientific Reports, 7*(1), 1-12. Retrieved from https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity
- Schwarz, G. E., & Alexander, R. B. (1995). *Soils data for the Conterminous United States Derived from the NRCS State Soil Geographic (STATSGO) Data Base.* USGS. Retrieved from https://water.usgs.gov/GIS/metadata/usgswrd/XML/ussoils.xml
- Williams, M. (2022, February 11). *DWR 10-digit HUC Watersheds*. NC Dept. of Environmental Quality Online GIS. Retrieved from https://data-ncdenr.opendata.arcgis.com/datasets/ncdenr::dwr-10-digit-huc-watersheds-1/about

Acknowledgements

Primary Advisor: Dr. Nicki Cagle, Nicholas School, Division of Environmental Science & Policy

Primary Advisor & Client Representative: Sara Childs, Office of the Duke Forest

Cooperators

Katie Warnell, Policy Associate, Nicholas Institute for Environmental Policy Solutions, Ecosystem Services Program

Sara Mason, Policy Associate, Nicholas Institute for Environmental Policy Solutions, Ecosystem Services Program

Ram Oren, Nicholas School, Division of Environmental Science & Policy