2018

ASSESSING ECOSYSTEM SERVICES FROM THE FORESTRY-BASED RECLAMATION OF SURFACE MINED AREAS IN THE NORTH FORK OF THE KENTUCKY RIVER WATERSHED

Kumari Gurung
University of Kentucky, grgkumaree@gmail.com
Digital Object Identifier: https://doi.org/10.13023/etd.2018.325

Recommended Citation

Gurung, Kumari, "ASSESSING ECOSYSTEM SERVICES FROM THE FORESTRY-BASED RECLAMATION OF SURFACE MINED AREAS IN THE NORTH FORK OF THE KENTUCKY RIVER WATERSHED" (2018). *Theses and Dissertations--Forestry and Natural Resources*. 43.
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Kumari Gurung, Student

Dr. Jian Yang, Major Professor

Dr. Steve Price, Director of Graduate Studies

ASSESSING ECOSYSTEM SERVICES FROM THE FORESTRY-BASED RECLAMATION OF SURFACE MINED AREAS IN THE NORTH FORK OF THE KENTUCKY RIVER WATERSHED

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Forest and Natural Resource Sciences in the College of Agriculture, Food and Environment at the University of Kentucky

By

Kumari Gurung

Director: Dr. Jian Yang, Professor of Landscape Ecology

Lexington, KY

2018

ABSTRACT OF THESIS

ASSESSING ECOSYSTEM SERVICES FROM THE FORESTRY-BASED RECLAMATION OF SURFACE MINED AREAS IN THE NORTH FORK OF THE KENTUCKY RIVER WATERSHED

Land Use Land Cover (LULC) changes can take place at the expense of degrading environmental conditions and undermining ecosystem's capacity to deliver benefits to people. In the Appalachian region, surface mining for coal is a major driver of LULC change. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires mine site reclamation but typical reclamation practices often result in land cover dominated by grass and shrubs. The Forestry Reclamation Approach (FRA) is a promising reclamation strategy but not in widespread use by industry. Assessing ecosystem services that can be obtained from a forest landscape may help policy-makers and other stakeholders fully understand the benefits of forestry based reclamation. The objectives of this study are to 1) identify how surface mining and reclamation changed the LULC of a watershed encompassing the north fork of the Kentucky River 2) assess the biophysical value of four major ecosystem services under the contemporary LULC condition and 3) assess the benefits of the FRA scenario in the provision of ecosystem services. Geographic Information System (GIS) was used to study the LULC change and InVEST software models for ecosystem services assessment. The results indicate that watershed's forest area has decreased by 7,751 hectares from 2001 to 2011 and mining activity may have contributed 75% of the change in LULC. Barren and grassland land covers provide less carbon storage, yield more water, and export more sediments and nutrients than forests. At the watershed level, the FRA modeled scenario increased carbon storage (13%) and reduced water yield (5%), sediment export (40%) and nutrient export (7%). This study provides critical information regarding the ecological benefits of Forestry Reclamation Approach to assist policy and decision making in this region even considering the modeling and data limitations.

KEYWORDS: Surface mining, ecosystem services, InVEST, Land use land cover, reclamation, Central Appalachia

Kumari Gurung
May 16, 2018

ASSESSING ECOSYSTEM SERVICES FROM THE FORESTRY-BASED RECLAMATION OF SURFACE MINED AREAS IN THE NORTH FORK OF THE KENTUCKY RIVER WATERSHED

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Kumari Gurung

Dr. Jian Yang

Director of Thesis

Dr. Steve Price

Director of Graduate Studies

May 16, 2018

DEDICATION

I dedicate this thesis to my parents, Rel Bahadur Gurung and Jun Kumari Gurung.

ACKNOWLEDGEMENTS

I would like to thank my parents for always encouraging me to pursue education and not asking me to marry early so that I become independent.

This journey to higher education in the USA would not have been possible if my supervisor, Dr. Jian Yang did not take me as his student in the first place. He has been the greatest mentor. I would like to thank my committee members; Dr. Mary Arthur, Dr. Marco Contreras and Dr. Brian Lee for all their suggestions throughout the research process. I would also thank Dr. Dave Wagner, our previous Director of Graduate Studies for instantly solving the hurdles of an international student. I thank Dr. Steve Price and all the members of the Department of Forestry and Natural Resources for their kindness. You never let me feel like an outsider.

I would like to appreciate the help of Chase Clark for always being next door to help me with all my incompetence problems and being my English language partner in the beginning. I owe my gratefulness to Dr. Yang Bai, post-doctoral scholar and my lab mate for his inputs and validation into the research.

I would like to thank the Nepalese Community here in the University of Kentucky and outside for not letting me and my husband feel isolated. Last but not the least, I thank my husband for always being there to listen to my endless talks (and stress outcomes) even if he could not understand them all.

I owe what I am today and what I will be tomorrow to all of you.

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CHAPTER ONE: INTRODUCTION

Human land use activities such as deforestation, urbanization, and agriculture have drastically transformed terrestrial ecosystems, and the magnitude and spatial reach of these impacts are particularly prominent during the post-industrialization modern time periods (Turner et al. 1994). It is estimated as much as 50% of the earth's ice-free land surface has been transformed and much of this change is a direct consequence of land uses (Houghton 1994; Turner et al. 2008). Such pervasive changes in land cover (biophysical attributes of the earth's surface) and land use (human intent applied to these attributes) have enabled humans to extract natural resources for the immediate human needs of food, fiber, water and shelter, but often at the expense of degrading environmental conditions (Lambin et al. 2001; Foley et al. 2005). Changes in land use and land cover (LULC) is a major force of global environmental change, ranging from alteration of climate system and atmospheric composition (Vitousek et al. 1997), to land degradation (Lal, 1990; Guo and Gifford 2002), changes in hydrology (DeFries and Eshleman 2004), and loss of biodiversity (Foley et al. 2005). Understanding the extent of LULC change and its implications for human-wellbeing is a key in land change science as coupled system of human and environment (Turner et al. 2007), and it is particularly critical to study this important question at watershed, landscape and regional scales, which often consist of multiple ecosystems and represent a pivotal scale domain for the research and application of sustainability (Wu 2013).

Among all LULC change types, few are as intensive as surface mining, which extracts minerals near the Earth's surface (Hook and Aleklett 2009; Encyclopaedia

Britannica 2016). Surface coal mining generally involves a sequence of operations that involve vegetation clearing, topsoil removal, drilling and blasting the hard strata over the coal seam, and then the subsequent extracting and transporting of coals (US EPA 2011; Encyclopaedia Britannica 2016). Of the various types of surface mining (e.g., contour mining, auger mining, area strip mining), mountain top mining (MTM) is the most intensive form of coal extraction used in steep landscapes (Lindberg et al. 2011). It allows access to shallow coal seams by first removing the overlying mountain ridges with explosives and then excavating the underlying coal (US EPA 2011). These operations permanently alter topography and soil parent material and exert far-reaching environmental impacts compared to those caused by deforestation and urbanization.

Surface mining and specifically MTM has been predominantly conducted in the central Appalachian Mountains of the US that are mainly located in southern West Virginia, eastern Kentucky, southwestern Virginia, and northeastern Tennessee (Wickham et al. 2013). It is estimated that more than 500 mountaintops have already been removed and nearly 500,000 hectares of land, almost as large as the state of Delaware, have been mined in this region (Perks 2009; Appalachian Voices 2015). Various studies have documented persistent negative impacts of mining on ecological integrity in Appalachia (Bernhardt and Palmer 2011, Wickham et al. 2013, Lindberg et al. 2011). One of the most prominent environmental consequences of surface mining in this region is large-scale direct forest removal. In addition, the indirect loss of interior forest can be 1.5-5.0 times greater than such direct forest loss (Wickham et al. 2013). Such forest fragmentation would greatly affect habitat suitability for many interior species (e.g., Pileated woodpecker, American redstart, Black bear) that require large contiguous forest blocks to breed and prey. Surface mining also changes hydrology and aquatic ecosystems in Appalachia. The overburden from surface mining has permanently buried more than 2,000 km of stream channels (Bernhardt and Palmer 2011), altering drainage networks and topography (Miller et al. 2014) and posing grave threats to water quality and for flood risk in downstream communities (Lindberg et al 2011). Soil loss and subsequent substrate compaction induced by reclamation also contribute to water quality deterioration and the increased flood risk (Dickens et al. 1985). Surface mining can also convert an area that was a carbon sink into a carbon source through land clearing, excavation, and ultimately the burning of coal in electric power plants (Wickham et al. 2013; Fox and Campbell 2010).

The Surface Mining Control and Reclamation Act of 1977 (SMCRA) was initiated to regulate the environmental effects of coal mining in the United States of America. SMCRA requires reclamation of mountaintop-mined sites to a state that provides an equal or better use than the pre-mining condition. However, the law is vague on what constitutes equal or better use. Often the reclamation approach has resulted in plant communities dominated by persistent herbaceous species, grasses sown during reclamation, and early successional woody species (Zipper et al. 2011), which is not an adequate substitute for the original diverse forest (Perks 2009). To address this issue, the Appalachian Regional Reforestation Initiative (ARRI) was formed in 2004 by a coalition of citizens, government officials, and coal industry representatives dedicated to restoring forests in the abandoned coal mines (ARRI 2010; Zipper et al. 2011). ARRI advocates a technique known as the Forestry Reclamation Approach, or FRA, a series of recommendations to guide successful regeneration of native forest on surface mined sites (Sena et al. 2014). The five-step guidelines include: creating a suitable growth medium, grading the top soil to get a noncompacted growth medium, planting less competitive ground covers that are compatible with trees, planting a mix of early successional woody species for wildlife and soil stability and commercially valuable crops, and using proper tree planting techniques to accommodate the seedling's root system (ARRI 2010, Zipper et al. 2011). Experimental reclamation trials utilizing FRA techniques have been successful in West Virginia (Wilson-Kokes et al. 2013) and Kentucky (Sena et al. 2014). However, the reclamation approach is not in widespread use in the Appalachian region because its implementation is difficult and expensive for mining companies; it requires resources and human power (Angel et al. 2009). In addition, local residents and the public are nonchalant toward forestry-based reclamation practices. Such situations might have arisen because the value of ecosystem services from forests in this landscape are not correctly valued. The public, mining companies and policy makers are not fully aware of the extent of ecosystem degradation induced by surface mining and the benefits to human wellbeing brought by the FRA approach compared to comparing to traditional reclamation practices.

Appalachian forests are a globally significant ecological resource (Ritters et al. 2000). The forests host nearly 40 commercially important tree species and a rich understory of grasses and herbs to make this mountainous landscape among the most diverse non-tropical ecosystems in the world (Ricketts et al. 1999). The mountains have been providing vital ecosystem services, like carbon storage, watershed and water quality protection (Zipper et al. 2011) that aid human habitation. The forests also provide vital wildlife habitat, mitigate flooding, and recycle nutrients. However, surface coal mining has transformed much of these forested lands into other land-cover types which diminishes the ecological services provided by forests (Drummond and Loveland 2010; Westman 1977;

Costanza et al. 1997). In addition, this conversion has aggravated the on-going poverty-related socioeconomic issues (Appalachian Voices, 2015) in Appalachian communities. Finally, there are few accountings of how much surface mining has contributed to the loss of ecosystem services from a regional landscape perspective (Zipper et al. 2011).

Ecosystem services evaluation can help the decision making and the implementation of FRA techniques in reestablishing forest patches in the Appalachian Mountains. Evaluation of ecosystem services such as carbon storage, water production, sediment and nutrient retention at a local watershed or regional level can help establish sound ecological restoration policies (Daily et al. 2000) because it can help individuals and stakeholders appreciate and capture the value of ecosystem services to produce different outcomes (Berks and Folke 1998). Ecological restorations can then in return, help in the increased provision of biodiversity and ecosystem services (Benayas et al. 2009).

Ecosystem service can be evaluated either in biophysical terms or monetary terms (Nelson et al. 2009). In this study, a quantitative biophysical evaluation is used for multiple ecosystem services. The overarching study objective is to assess the value of major carbon and water-related ecosystem services in the North Fork Kentucky River (NFKR) watershed of Kentucky, which is a watershed in Central Appalachia that has been severely impacted by surface coal mining (Wickham et al. 2013; Kentucky Water Resource Research Institute 2000), and evaluate the potential ecological service benefits of FRA reclamation at the landscape level. This study objective has been divided into three specific objectives: 1) examining how LULC has changed in NFKR watershed from 2000s to 2010s and the contribution of mining and reclamation to the overall landscape change, 2) quantifying the value of major ecosystem services (carbon retention, flood control, sediment retention, nutrient retention) under current LULC conditions, and 3) assessing the changes in the provision of these major ecosystem services under a Forestry Reclamation Approach scenario.

In this study, it is hypothesized that: (H1) even during the period of declining mining industry, there are still considerable transitions from forest to barren and grasslands that may be attributed to mining and reclamation; (H2) under the contemporary LULC conditions, the barren and grassland land covers will provide the least amount of ecosystem services and the sub watersheds with the less mining/reclamation activities will have higher mean ecosystem service provision by area; (H3) FRA will produce higher ecosystem services compared to current reclamation practices, but there will be still considerable spatial variability of ecosystem service provision at the sub-watershed level driven by LULC composition, topography and climate.

CHAPTER TWO: METHODS

1. *Study Area*

The North Fork Kentucky River (NFKR) watershed is situated in the Eastern Kentucky Coal Field physiographic region, which is part of a larger physiographic region, the Cumberland Plateau (Kentucky Water Resources Research Institute 2000). The watershed occupies most of Letcher, Perry, Knott, Breathitt counties and a small portion of Lee County (Figure 1). These counties are part of the 65 counties in Central Appalachia where surface mining has been concentrated (Wickham et al. 2013). The welfare of many residents in central Appalachia have been affected by surface mining in the past (Hendryx and Ahern 2008; Appalachian Voices 2015). Although coal production from Appalachian mountaintop removal mines has declined by nearly 50% since its peak in 2008, a recent study that constructed mining activities across 30 years showed that surface mining are continuing to expand in Central Appalachia, and many rural communities in these counties continue to face the spread of surface mining and the associated risks to the environment and human livelihood (Appalachian Voices 2015). The NFKR watershed ranks among the groups with highest need for protection and restoration (Kentucky Water Resource Research Institute 2000).

The NFKR watershed occupies a total area of 3430 sq.km. There are 44 Hydrologic Unit Code (HUC) -12 sub watersheds (Appendix A1). A HUC is a unique digit to identify a hydrologic unit, with HUC-2 representing the broadest region level and higher number of HUC digits representing spatially smaller levels. The size of the HUC-12 sub watersheds ranges from 38 sq. km (Hell Creek) to nearly 143 sq. km (Frozen Creek) and the mean area is 76 sq. km (Appendix A2).

The watershed’s geology is comprised of coals, sandstones, and shales (Haag et al. 1995). Land form is characterized by mountainous terrain, rapid surface runoff, and moderate rates of groundwater discharge (Kentucky Water Resources Research Institute 2000). Elevation ranges from 193 meters to 998 meters. The North Fork Kentucky River headwaters are allocated in Letcher County. The main stem of the river is 270 km long and flows northwest through the communities of *Whitesburg*, *Hazard*, and *Jackson* to reach *Beattyville* where it joins with the South Fork to form the Kentucky River (Figure 1).

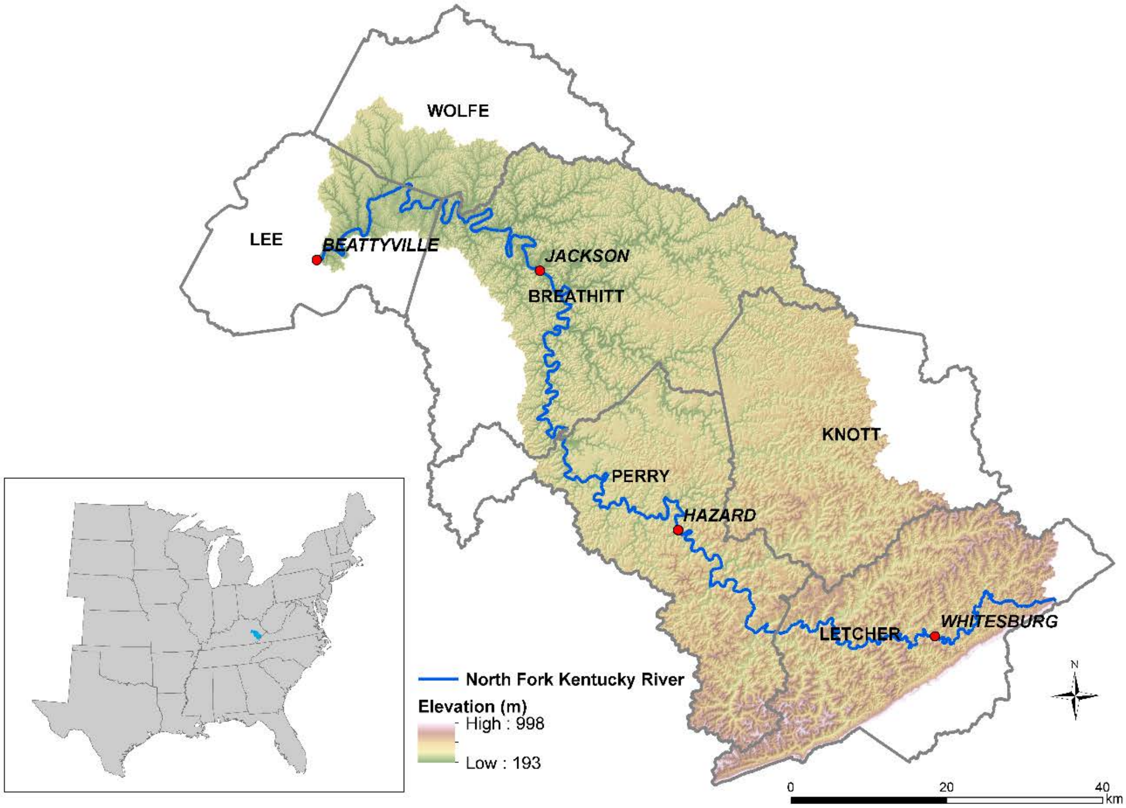


Figure 1 The North Fork Kentucky River Watershed

2. *GIS Operations and InVEST Scenario Modeling Methods Overview*

The analysis can be divided into three major components, with each addressing one of the three specific objectives (Figure 2). First, several GIS analysis operations (e.g., reclassification, tabulate area) were conducted on the revised and compatible National Land Cover Datasets (NLCD) (2001 and 2011 Edition) (Homer et al. 2012) to identify where on the landscape the land use land cover has changed and how each LULC type has transitioned to another between the two time periods from 2001 to 2011. Second, the reclassified NLCD 2011 was used as a primary input in an ecosystem service assessment software (InVEST) to quantify major regulating ecosystem services (climate regulation, flood control, sediment retention, and surface water quality) with the corresponding biophysical indicators under contemporary LULC conditions. Third, in order to assess the potential changes in the ecosystem service provision brought by FRA, a new LULC map was created to replace currently mined barren land and reclaimed grassland to forest and used in InVEST to model a future LULC scenario. The modeled results were then compared with the ones evaluated under the contemporary (2001) LULC conditions to examine the forest restoration benefits.

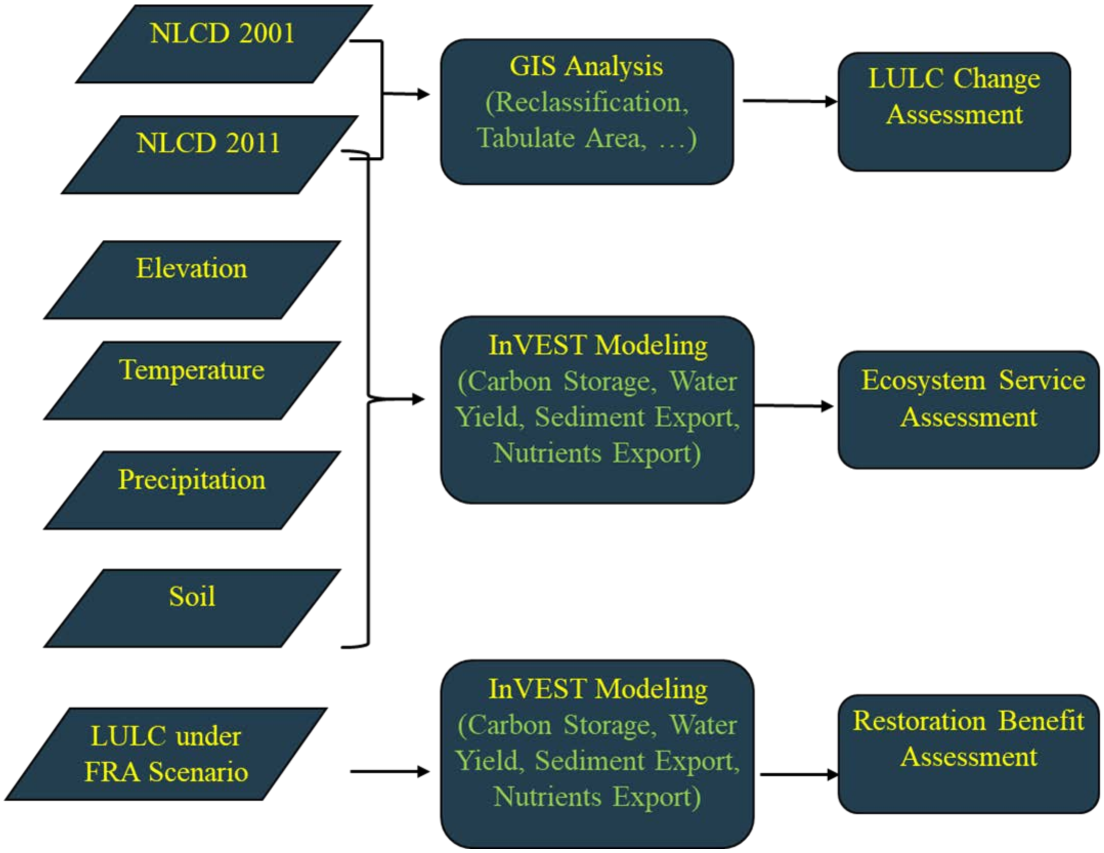


Figure 2 GIS Operations and InVEST Modeling Methods Overview

3. *Land Cover Change Analysis*

The Kentucky portion of the NLCD for 2001 and 2011 were obtained from the Kentucky Geography Network. The NLCD is a comprehensive Landsat-based, 30-meter resolution land cover product. The NLCD has 16 land cover classifications applied across the continental United States. The first NLCD dataset was published for 1992, but its classification scheme does not match with that for the subsequent years of 2001 and forward, so the land covers of 2001 and 2011 (the latest available with the 2016 data are scheduled for release on December 28, 2018) have been chosen to study the land cover change over a decade.

The NLCD classification system is based on the Anderson Land Cover Classification System Level II (Anderson 1976). There are generally a few fine-level LULC classes for each Level I LULC types. For instance, LULC type *Forest* has three sub categories: Deciduous, Mixed and Evergreen forest. *Developed Land* as a broad land cover has four sub categories with varying intensities (i.e., percentage) of impervious surfaces. These sub classes were aggregated as a single land cover type for simplicity in this research. In addition, the wetlands were aggregated with water class, and the cultivated crops were reclassified into pasture because there were negligible cultivated areas and comparison to the crop landscape dataset of CropScape (USDA National Agricultural Statistics Service Cropland Data Layer 2018) showed that crops classified in the NLCD were actually pastures in this watershed.

The GIS data of watershed boundary was obtained from the National Hydrography Dataset (NHD). This watershed boundary data was used in the GIS operation *Clip* to extract NLCD data only for the NFKR watershed (Figure 3). The *Not Equal* operation in ArcGIS - Spatial Analyst toolbox was used to determine where in the watershed land cover has changed from 2001 to 2011. The output from this operation was a new raster layer in which cell/pixels valued 1 indicated land cover has changed and 0 indicated no change. To identify the magnitude of LULC changes among the 44 HUC-12 sub watersheds, a *zonal statistics* operation was performed on the output of *Not Equal* tool to compute the total number of cells/pixels changed land cover within each sub watershed. Then *Join field* tool was used to join the contents of the zonal statistics table to the watershed shapefile for mapping the amount of area with LULC changes at the sub watershed level. Finally, the *tabulate area* operation was applied in order to calculate the amount of area that has changed from one land cover type in 2001 to another in 2011 by sub watershed. The transition matrix computed from *tabulate area* tool was then used to determine the contribution of mining and reclamation to the overall LULC change based on the percentage of forest transition to barren land and the transition from barren land to vegetated land cover types (mainly grassland), respectively.

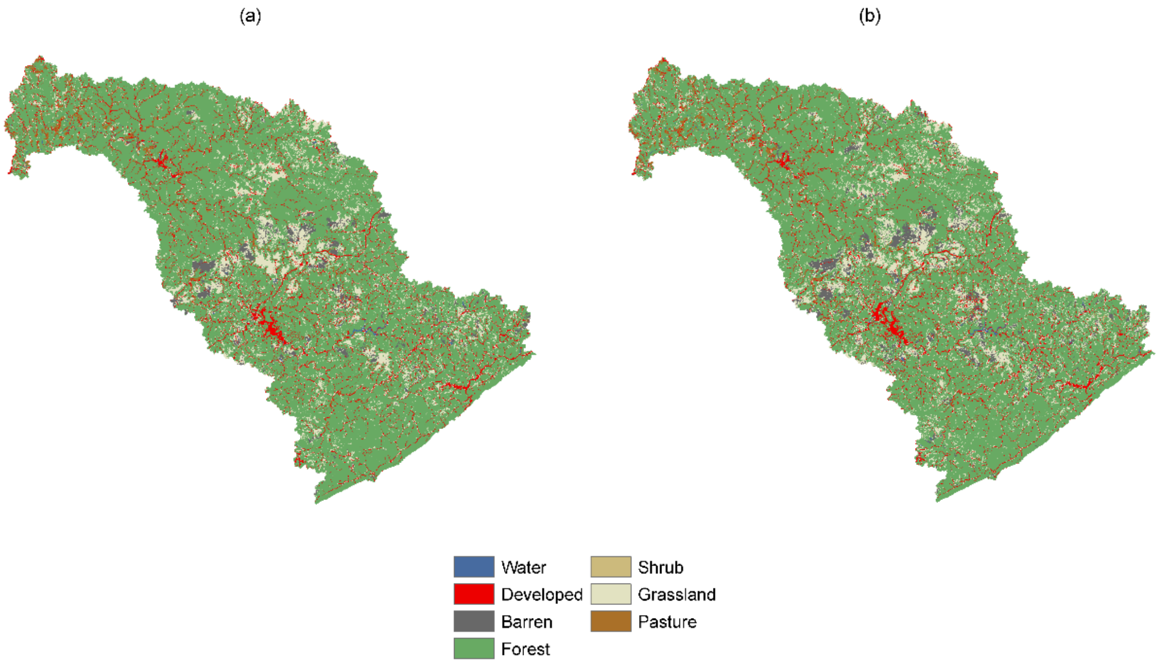


Figure 3 Land use land cover map of the NFKR watershed with an aggregated classification system for years a) 2001 and b) 2011

4. *Ecosystem Service Assessment*

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software [InVEST 3.3.3, Natural Capital Project] was used to quantify the provision of four critical ecosystem services provided by the NFKR watershed under the most recently available LULC data (2011). InVEST software was developed by the Natural Capital Project, Stanford University (Burkhard et al. 2009). It uses ecological production functions to generate spatially explicit predictions of ecosystem service supply with inputs of LULC maps, corresponding biophysical attributes, and additional GIS data representing environmental conditions such as climate and soil and topography. InVEST is an open source modular software. This means that depending on the ecosystem service being considered, a different software module is invoked requiring individual parameterization and execution. For this study, InVEST's Carbon Storage and Sequestration, Water Yield: Reservoir Hydropower Production, Sediment Delivery ratio and Nutrient Delivery ratio (nitrogen and phosphorus) modules were used to estimate and map the annual delivery of the corresponding regulating services: carbon storage, flood control, soil retention and surface water quality (Table 1).

Table 1. *Ecosystem services assessed in this study and their biophysical indicators*

Ecosystem service	Biophysical Indicator	Unit	Description
Climate regulation	Carbon storage	Mg/ha	Average annual amount of carbon stored at each pixel
Flood Control	Water yield	mm	Annual water yield: low water yield indicating high flood control capacity
Soil Retention	Sediment export	Kg/ha	The reverse of sediment export is the retention capacity
Surface Water Quality	Nutrient (N and P) export	Kg/ha	The lower the N and P export, the better is the water quality

Carbon Storage and Sequestration

The InVEST carbon model aggregates the amount of carbon stored in four carbon pools: aboveground biomass, belowground biomass, soil, and dead organic matter to produce total amount of carbon storage. Aboveground biomass pool consists of all living plant material above the soil such as branches, leaves, trunks. Belowground biomass pool is the whole living root systems of the aboveground biomass. Soil organic matter pool is the organic component of the soil and represents the largest terrestrial carbon pool. Dead organic matter pool includes litter as well as dead wood. The input for this model includes a user defined biophysical attribute table that quantitatively describes each of these four biomass pools for each land use land cover type, and a LULC map. The model generates a map of total carbon storage by summing these four carbon pools for each grid cell based on its corresponding LULC type in million grams (i.e., tons) per hectare (Mg per ha). In this study, the reclassified LULC map of NFKR watershed derived from NLCD 2011 was used as the input to the carbon storage model. The coefficient values used for the four carbon pools were from published data (Qui and Turner 2013) and the InVEST manual.

Table 2. *Carbon storage estimates for each carbon pool and each land use land cover (LULC) type to be used in the InVEST Model (unit, Mg per ha)*

LULC Type	Aboveground	Belowground	Soil OM	Dead OM
Developed	5	3	20	0
Barren	0	0	0	0
Forest	90	60	80	25
Shrubland	30	20	40	10
Grassland	10	5	30	0
Pasture	5	2	20	0

Note: Aboveground means carbon stored in aboveground biomass. Belowground stands for carbon stored in belowground biomass. Soil OM stands for the carbon stored in soil organic matter. Dead OM stands for the carbon stored in dead and litter matter.

Water Yield: Reservoir Hydropower Production

The InVEST Reservoir Hydropower Production model calculates annual water yield from a watershed (Sharp et al. 2015). The model estimates the total annual water yield (*Y*) for each pixel of the watershed as total annual precipitation (*P*) minus total annual actual evapotranspiration (*AET*) (Eq.1).

$$Y = \left(1 - \frac{AET}{P}\right) \cdot P$$

(1)

The InVEST water yield model relates *AET* to potential evapotranspiration (*PET*), which is estimated as the product of the reference evapotranspiration (ET_0) and the plant ET coefficient (K_c) associated with the LULC for each pixel (Eq. 2).

$$PET = K_c \cdot ET_o$$

(2)

The method for estimating *AET* from *PET* was developed by Budyko (1974) and adapted by Fu (1981) and Zhang et al. (2004) (Eq. 3) where ω is an empirical non-physical parameter to define the shape of the curve relating potential to actual evapotranspiration.

$$\frac{AET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{\omega}\right]^{1/\omega} \tag{3}$$

The key to this approach is the estimation of ω, which is related to the plant available water content (AWC), precipitation and the constant Z representing the local precipitation pattern and additional hydrogeological characteristics (Eq. 4) (Sharp et al. 2015).

$$\omega = Z\frac{AWC}{P} + 1.25 \tag{4}$$

The input of the water yield model includes five biophysical parameters as georeferenced raster inputs. These inputs are precipitation (mm), average annual potential evapotranspiration (mm), depth to root restricting layer (mm), plant available water content (AWC, as a proportion) and LULC (Table 3). The precipitation data were obtained from the PRISM climate group of Oregon State University (PRISM Climate Group, 2015). The precipitation data are 30 year Normal (1981-2010) dataset with a resolution of 800 m. The precipitation layer was resampled to a spatial resolution of 30 m by an interpolation method in ArcGIS. The *PET* was obtained from CGIAR-CSI website (http://www.cgiar-csi.org). The depth to root restricting layer and the AWC were extracted from the SSURGO (Soil Survey Geographic database) in the Soil Map viewer of the Web Soil Survey [(USDA Natural Resources Conservation Service (NRCS)]. The LULC 2011 was obtained from the Kentucky Geoportal Network and its coordinate system was projected to meters.

The InVEST water yield model also requires several tabular values for each LULC class (Table 4). These values include an attribute indicating whether the land cover class is vegetated or not (1 being vegetated and 0 being not vegetated), maximum rooting depth for vegetated LULC and plant evapotranspiration coefficient (K_c). Kc is used to modify the reference evapotranspiration to obtain potential evapotranspiration. The reference ET is based on a 15 cm tall surface of actively growing, well-watered alfalfa. The plant ET coefficient (K_c) is a decimal number between 0 and 1.5 based on plant physiological characteristics. These tabular values were obtained from the biophysical attribute table compiled by Sharp et al. (2015).

Sediment Delivery Ratio (SDR)

The InVEST Sediment Delivery Ratio model (SDR) quantifies average annual sediment delivery per sub watershed and produces a map representing per-pixel contribution to sub watershed-level sediment yield. For each pixel, the model first computes the amount of eroded sediment or soil loss based on precipitation pattern, soil properties, and topographic conditions. The model then estimates the sediment delivery ratio (proportion of soil loss actually reaching the sub watershed outlet) based on the pixel's hydrologic connectivity (Borselli et al. 2008). Finally the model estimates sediment export based on the product of soil loss and sediment delivery ratio.

The amount of soil loss (*SL*) is given by the universal soil loss equation (USLE) (Eq. 5), in which *R* is the rainfall erosivity (MJ·mm (ha·hr) $^{-1}$), *K* is the soil erodibility (ton·ha·hr (MJ·ha·mm) $^{-1}$), *LS* is the slope length–gradient factor, *C* is the cover-management factor and P is the support practice factor (Renard et al. 1997).

$$SL = R \cdot K \cdot LS \cdot C \cdot P \tag{5}$$

The sediment delivery ratio (SDR) is computed as a function of hydrologic connectivity of the area (Borselli et al. 2008). Connectivity for sediment flow is defined as the likelihood that a particle can reach the nearest sink. SDR value depends on the distance to the sink, the route characteristics, water available to transport from upslope, and water that is gained or lost along the downslope route. For each raster pixel, the algorithm first computes an index of connectivity IC (Eq. 6), where: D_{up} = upslope area and D_{dn} = downslope path.

$$IC = log10 \left(\frac{D_{up}}{D_{dn}}\right) \tag{6}$$

The upslope area is delineated from the D-infinity flow algorithm (Eq. 7).

$$D_{up} = \bar{C}\bar{S}\sqrt{A}$$

(7)

Where $\bar{C}$ is the average cover-management factor of the upslope contributing area, $\bar{S}$ is the average slope gradient and *A* is the upslope contributing area.

The downslope flow path is determined from the D-infinity flow routing algorithm (Eq. 8; Tarboton, 1997).

$$D_{dn} = \sum \frac{d}{CS} \tag{8}$$

Where d is the average length of the flow path in the downslope direction, from a pixel to the stream (m); *C* and *S* are the C factor and the slope gradient of the pixel, respectively.

The SDR ratio for a pixel is then derived from the connectivity index using a sigmoid function as Eq. 9:

$$SDR = \frac{SDR_{max}}{1+\exp\left(\frac{IC}{k}\right)} \tag{9}$$

Where $SDRmax$ is the maximum theoretical SDR, set to an average value of 0.8 (Vigiak et al. 2012), and k is a calibration parameter that defines the shape of the *SDR-IC* relationship.

Finally, the sediment export from a pixel (ton·ha^{-1}·yr^{-1}) is the direct product of soil loss and SDR factor (Eq. 10).

$$Sediment\ export = SL \cdot SDR \tag{10}$$

The raster inputs required for the InVEST SDR model are a Digital Elevation Model (DEM), Rainfall Erosivity Index, Soil Erodibility, and LULC. The DEM and LULC were derived from Kentucky Geoportal Network. The Rainfall Erosivity Index was obtained from European Soil Data Centre. The soil erodibility raster layer was acquired from the Soil Map Viewer program in GIS using SSURGO database. The tabular data needed for the SDR model includes biophysical parameters of cover management factor and support practice factor for the USLE. These factors are a floating point value between 0 and 1 for each land cover. These biophysical parameters are from Sharp et al. (2015).

Nutrient Delivery Ratio (NDR)

The InVEST Nutrient Delivery Ratio (NDR) model aims to quantify nutrient export across different watershed or sub-watersheds. The model maps the transport of nutrients from watershed sources to the stream network. The model uses a mass balance approach, describing the long-term, steady flow of nutrients based on nutrient sources (nitrogen and phosphorus) associated with different LULC and the retention properties of pixels belonging to the same path (Sharp et al. 2015).

Sources of nutrient across the landscape, also called nutrient loads, are determined based on the LULC map and associated loading rates. Nutrient loads are divided into sediment-bound and dissolved parts, which are transported through surface and subsurface flow, respectively. The model does not include nutrient point sources by default. The model uses topographic routing and an index, the NDR factor, to emulate the movement of nutrients across the landscape and into a water course. The NDR factor is calculated for each landscape pixel based on the properties (e.g. slope, retention coefficient) of pixels that belong to the same flow path. At the watershed/sub watershed outlet, the nutrient export is computed as the sum of the pixel-level contributions.

The input raster layers required for the InVEST NDR model are: DEM, LULC, and precipitation. The DEM and LULC used are same as the SDR model inputs, obtained from the Kentucky Geoportal Network. The precipitation raster is from the PRISM Climatic Group of Oregon State University (PRISM Climate Data, 2018). The tabular coefficient values for Nitrogen and Phosphorus loading for each land use category required are from Sharp et al. (2015) and Line et al. (2002) respectively.

Table 3. *GIS Data requirements and preparation for the InVEST models*

Required GIS Data	Description	Source	Related Models
Digital Elevation Model (DEM)	A GIS raster dataset with an elevation value for each cell	Kentucky Geographic Network, kygisserver.ky.gov/geoportal	Sediment Delivery, Nutrient Delivery
Land use/ Land cover (LULC)	Raster, 30m *30m resolution	National Land Cover Database, https://www.mrlc.gov	All
Rainfall Erosivity Index (R)	A raster dataset with an Erosivity index value for each cell. Depends on the intensity and duration of rainfall.	European Soil Data Centre, https://esdac.jrc.ec.europa.eu	Sediment Delivery
Soil Erodibility (K)	K is a measure of susceptibility of soil particles to detachment and transport by rainfall and runoff	Soil Map Viewer, https://www.mrlc.gov	Sediment Delivery
Depth to root restricting layer	A raster dataset with an average root restricting layer depth value for each cell. (mm)	NRCS, https://websoilsurvey.nrcs.usda.gov/	Water Yield

Annual average precipitation	A raster with a non- zero value for average annual precipitation. (mm)	PRISM Climate Data-Oregon State University, prism.oregonstate.edu/	Sediment Delivery, Nutrient Delivery, Water Yield
Reference evapotranspiration	The potential loss of water from the soil by both evapotranspiration from the soil and transpiration by healthy alfalfa (grass) if sufficient water is available. (mm)	Consortium for Spatial Information (CGIAR CSI), http://www.cgiar-csi.org/data/global-aridity-and-pet-database	Water Yield
Plant available water content	The fraction of water that can be stored in the soil profile for plants' use.	NRCS, https://websoilsurvey.nrcs.usda.gov/	Water Yield
Watersheds and sub watersheds (optional)	A layer of watersheds such that each watershed contributes to a point of interest where water quality will be analyzed.	National Hydrography Dataset, https://nhd.usgs.gov	Sediment Delivery, Nutrient Delivery, Water Yield

Table 4. *Biophysical attributes used for the InVEST water yield, sediment delivery and nutrient delivery models*

LULC	lucode	Kc	root_depth	usle_c	usle_p	sedret_eff	load_n	eff_n	load_p	eff_p
Water	1	1	0	0.001	0.001	0.8	0.001	0.05	0.001	0.05
Developed	2	0.1	300	0.001	0.001	0.05	7.75	0.05	1.3	0.05
Barren	3	0.2	10	0.25	0.01	0.2	4	0.05	0.001	0.05
Forest	4	1	7000	0.003	0.2	0.6	1.8	0.8	0.011	0.05
Shrub	5	0.85	4750	0.003	0.2	0.5	1.8	0.75	0.011	0.8
Grassland	7	0.65	2000	0.01	0.2	0.4	4	0.4	0.05	0.75
Pasture	8	0.85	1000	0.02	0.25	0.4	3.1	0.25	0.1	0.25

Note: lucode refers to the code used for each LULC type. Kc is the plant evapotranspiration coefficient. Root depth is the maximum root depth (mm) for vegetated land use land covers. usle_c and usle_p are the cover management factor and support practice factor for the USLE respectively. Load_n and load_p are the nutrient loading for each land use (kg per ha per yr.). eff_n and eff_p are the maximum nutrient retention capacity.

5. *Ecosystem Service Assessment: Forest Reclamation Scenario*

To assess the ecological benefits brought by a FRA reclamation scenario, a new LULC map was created and used in InVEST models, while all other GIS input data and biophysical parameters were kept the same as the ecosystem service assessment of the contemporary LULC conditions. A new LULC map was derived from NLCD 2011map using the reclassification tool in ArcGIS in which all the barren, grassland, and shrubland are reclassified into forests (Figure 6). The ecosystem services indicators assessed in this scenario are: carbon storage, water yield, sediment export and nutrient export. The output of the various InVEST models were then analyzed in ArcGIS to examine differences in the biophysical indicators between this FRA scenario and the business as usual (BAE) scenario at the watershed and the HUC-12 sub watershed levels.

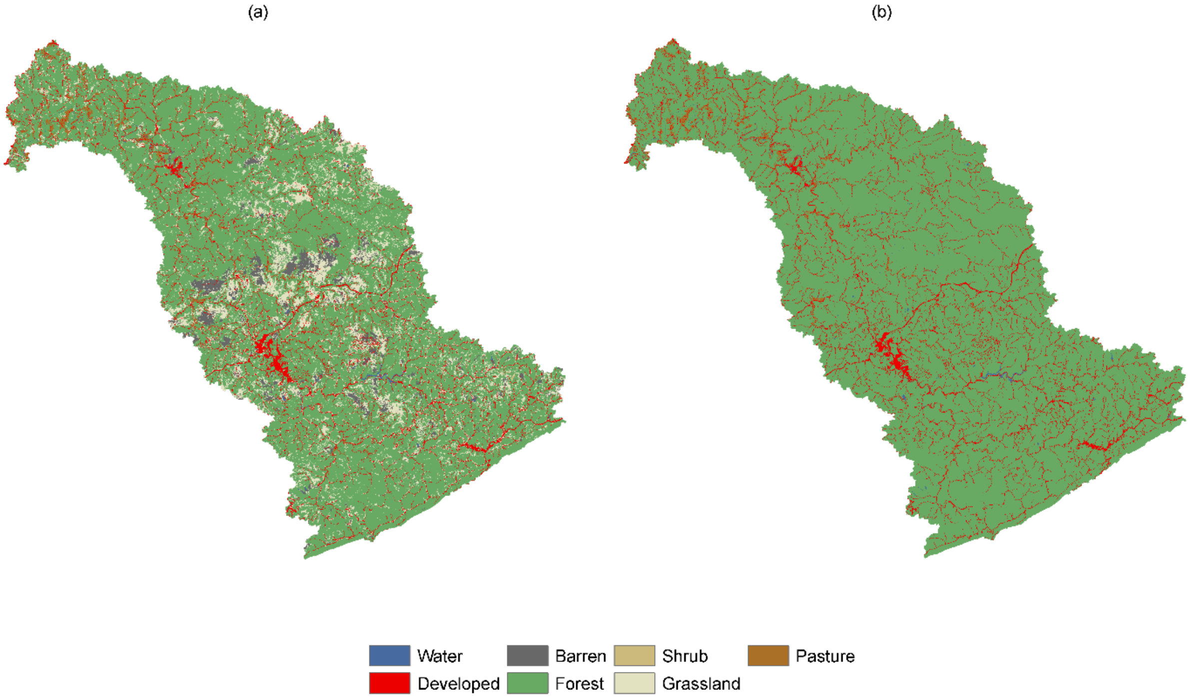


Figure 4 Land use land cover maps for the NFKR watershed a) LULC 2011 and b) LULC representing the FRA scenario; barren, shrub and grassland are reclassified as forests.

CHAPTER THREE: RESULTS

Land Cover Change

Six of the seven land use land cover categories increased their areal coverage between 2001 and 2011, only forest was reduced its area (Table 5). The forest area reduction is notable, with a decline of 7751 hectares from 2001 (266,256 ha) to 2011(258,505 ha). The loss in forests is mostly accompanied with an increase in barren lands (which is considered surface mined lands in this study): 3,844 hectares gain in 2011. Similarly, 3352 hectares of grasslands – which mostly resulted from reclamation – have been on increase. The area occupied by shrub land covers increased slightly by 53 hectares.

In terms of spatial distribution of land cover change, a distinct variability can be observed in the landscape (Figure 5). Most land cover changes are clustered at the central location of the watershed and the size of these patches are large. The Russell Branch-Troublesome Creek sub watershed (HUC No. 051002010204) has the largest changes in land cover, followed by Buckhorn Creek (HUC No. 051002010506); both of which occupy the central location of the watershed. The rest of the watershed is not free of land cover changes; however, the land cover change patches are smaller in size and they are more spread out throughout the landscape (Figure 5).

Table 5. *Area of each land use land cover (LULC) type in 2001 and 2011 (unit, hectares) and its changes*

LULC	2001	2011	Change	Percent Change (%)
Water	744	783	39	5.24
Developed	23621	23838	217	0.92
Barren	7923	11767	3844	48.52
Forest	266256	258505	-7751	-2.91
Shrub	219	272	53	24.20
Grassland	39011	42533	3522	9.03
Pasture	5120	5196	76	1.48
Total	342894	342894	0	86.48

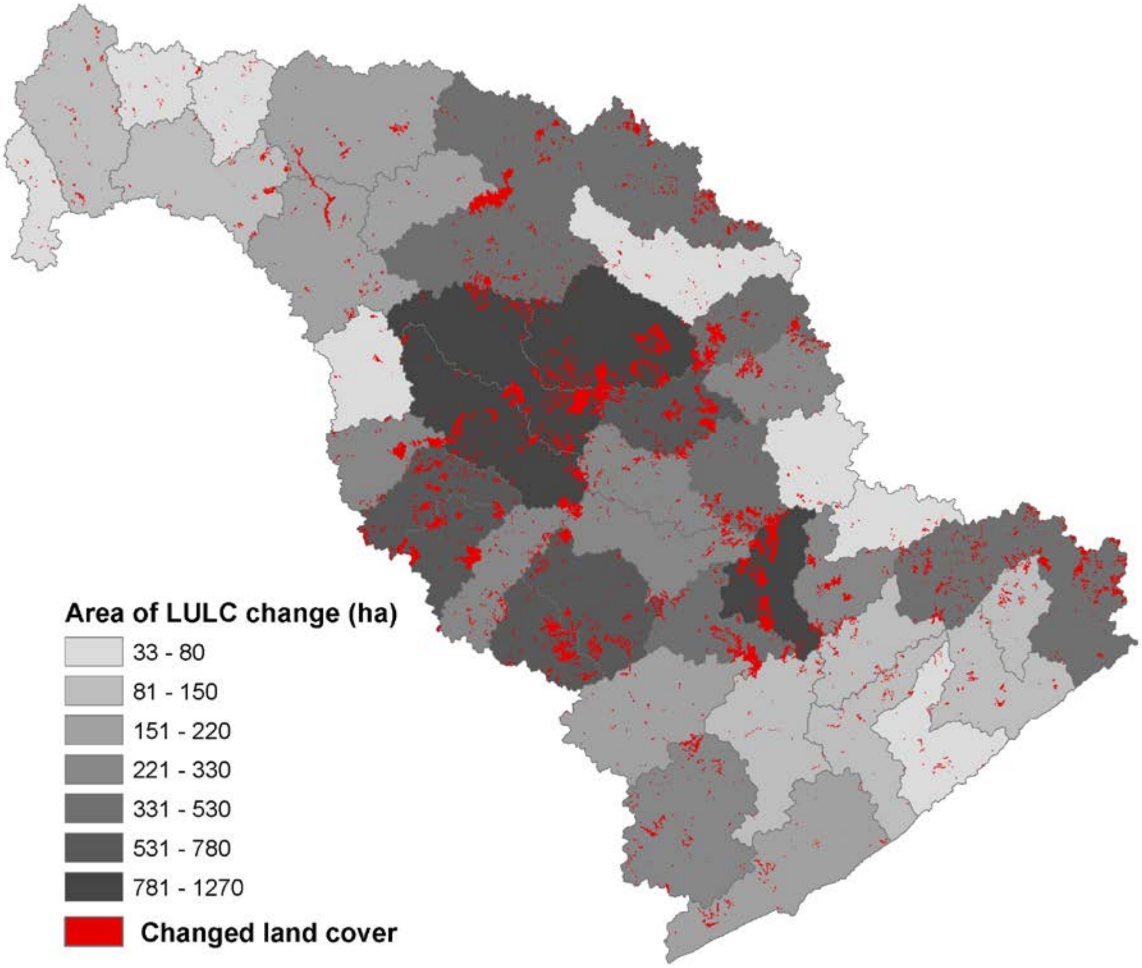


Figure 5 Land use land cover change in the NFKR watershed by HUC-12 sub watershed between 2001 and 2011.

Of the total area 342,805 hectares, 15,414 hectares of land covers converted to other land cover categories between 2001 and 2011, which accounts for 4.5% of the watershed. The greatest transition is observed from forest in 2001 to barren land covers in 2011 with 4,840 hectares of forest having changed to barren. This is followed by conversion of forest to grassland, where 4,594 hectares of forest in 2001 are changed to grassland in 2011. The change of barren land covers to grassland cover is 2,189 hectares in size (Table 6).

It is assumed in this study that the transformation of forest to barren lands, grasslands and barren to grasslands are due to mining and reclamation activities in the watershed. Such changes make up a total of 11,623 hectares out of a total change on 15,414 hectares. This contributes to a total of 75% of total land use land cover transitions in this watershed. The other noteworthy transition is the conversion of grasslands to barren (1,397 hectares). This might be due to the fact that previously reclaimed mined areas are re-mined. The results thus show mining and reclamation as a major driver of overall land use land cover change in the watershed.

Table 6. *Size of area that has experienced transition from one land cover category to another between 2001 and 2011 (unit, hectares)*

		2011							
	LULC	Water	Developed	Barren	Forest	Shrub	Grassland	Pasture	Total
2001	Water	720	1	11	4	0	9	0	735
	Developed	0	23,621	0	0	0	0	0	23,622
	Barren	27	16	5505	179	0	2,189	7	7,915
	Forest	14	97	4,840	256,611	12	4,594	88	266,222
	Shrub	0	0	9	6	198	6	1	220
	Grassland	22	96	1,397	1705	62	35,726	2	44,090
	Pasture	0	6	5	1	0	9	5098	5120
	Total	783	23,838	11,756	258,483	272	42,533	5196	342,895

Note: The transition matrix shows the area of LULC that has transformed from one category to another (off-diagonal). The diagonal of the matrix shows size of area that did not change LULC between two time periods.

Ecosystem service assessment

Ecosystem services production varied across the watershed and among the land cover types (Figure 6 and Table 7). The central locations of the landscape where LULC changes are concentrated have lower ecosystem service production than other areas. Forests generally produce greater ecosystem services than any other land cover types. They are associated with highest carbon storage, lowest water yield, sediment export, and nutrient export. In contrast, barren lands provide the least ecosystem services among all non-urban land cover types; they produce lowest carbon storage, highest water yield, sediment export, and nutrient export.

Carbon Storage

The total modeled carbon storage for the watershed is 71,343,168 Mg. Carbon storage is different in different land cover types. Carbon storage is highest in the forested lands with a mean of 250 Mg per ha. The shrub lands ranks second in storing carbon (100 Mg per ha). Pasture ranks third with a carbon storage of 71 Mg per ha. Grasslands rank fourth with a mean carbon storage of 45 Mg per ha. Barren lands produce zero carbon storage. (Table 7).

At the sub-watershed level, the highest mean carbon storage is that of Upper Line Fork (231 Mg per ha), followed by Howards Creek-North Fork Kentucky River (230 Mg per ha). The lowest ranking sub watersheds are Lower Balls Fork (136 Mg per ha) and Grapevine Creek (138 Mg per ha) (Appendix A3).

Water Yield

The InVEST water yield model applies a simplified water balance approach, in which water yield is the subtraction of evapotranspiration from precipitation. Since vegetated land covers have higher evapotranspiration, their water yield is generally low. In this study, the inverse of water yield is a biophysical indicator of flood control. Thus, vegetated land covers are efficient is conserving water and regulating flood in the landscape than barren lands, which constitute a very high water yield (931 mm).

High water yield is concentrated in the barren lands that mostly occupy the central location of the watershed (Figure 6b). Forested areas produce the least water yield, with an average of 534 mm (Table 7). Grasslands have higher average water yield (665 mm) than the forests. Sub watershed level ranking for water yield is led by Grapevine Creek (702 mm) and then by Upper Second Creek (698 mm). The two sub watersheds with lowest water yield are: Headwaters Carr Fork (522 mm) and Little Carr Fork Creek (525mm) (Appendix A3).

Sediment Export

Sediment export is an inverse biophysical indicator of soil retention, i.e. lower sediment export indicates higher soil retention. The barren areas have the highest mean sediment export (971 kg per ha) among all other land cover types (Table 7). Pasture lands rank second with a mean sediment export of 628 kg per ha. The grasslands have a mean sediment export of 404 kg per ha. Forest land covers have the least mean sediment export (110 kg per ha).

Figure 6c shows the watershed's spatial distribution of sediment export. The highest sediment export is clustered around the central locations of the watershed where there are more barren areas. The sediment export is minimum in the areas shown in blue color which are mainly forested areas. The Big Creek and Irishman Creek-Carr Fork sub watersheds have the highest mean sediment export, 313 and 291 kg per ha respectively. The Walker Creek and Howards Creek sub watersheds have the lowest mean sediment export of 112 and 101 kg per ha respectively (Appendix A3).

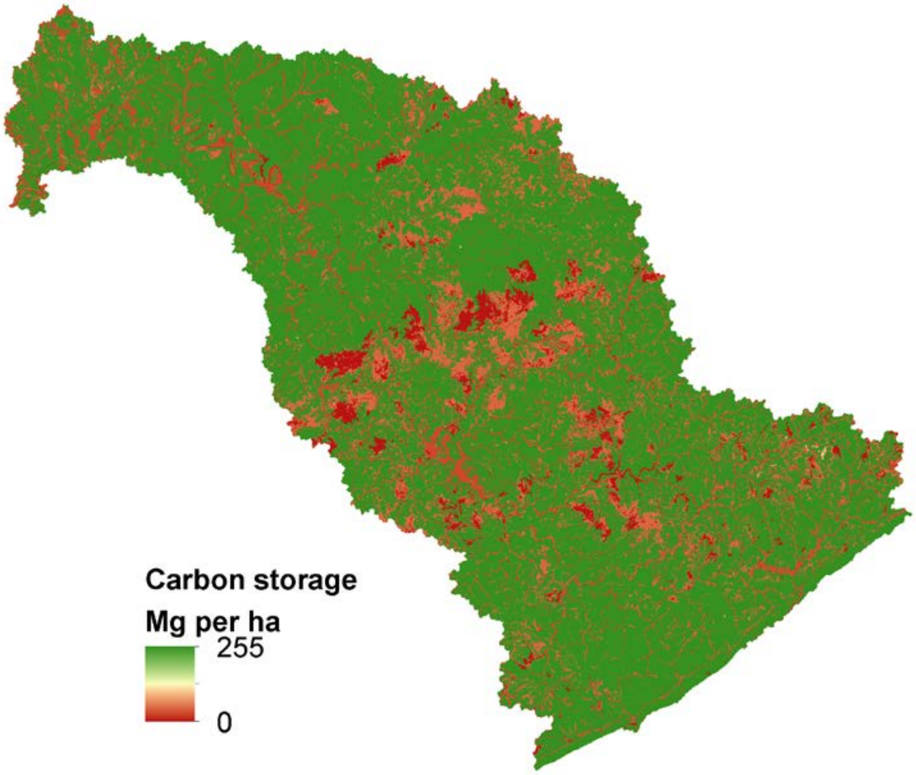
Nutrient Export

Nitrogen (N) and Phosphorus (P) export are inverse biophysical indicators for maintaining surface water quality. In general, the lower the number, indicates likely better surface water quality. Among all the five non-urban terrestrial land covers, Nitrogen export is highest in barren areas (2 kg per ha), followed by pasture (1.6 kg per ha) and grassland (1.6 kg per ha) (Table 7). The forest and shrub lands both have least nitrogen export with a mean value of 0.5 kg per ha. In case of phosphorus export, it is highest in pasture (0.051 kg per ha) and then grassland (0.02 kg per ha) (Table 7). Forest and shrub lands show a similar pattern, with a mean phosphorus export of 0.003 kg per ha. The barren lands have the least phosphorus export (0.001 kg per ha).

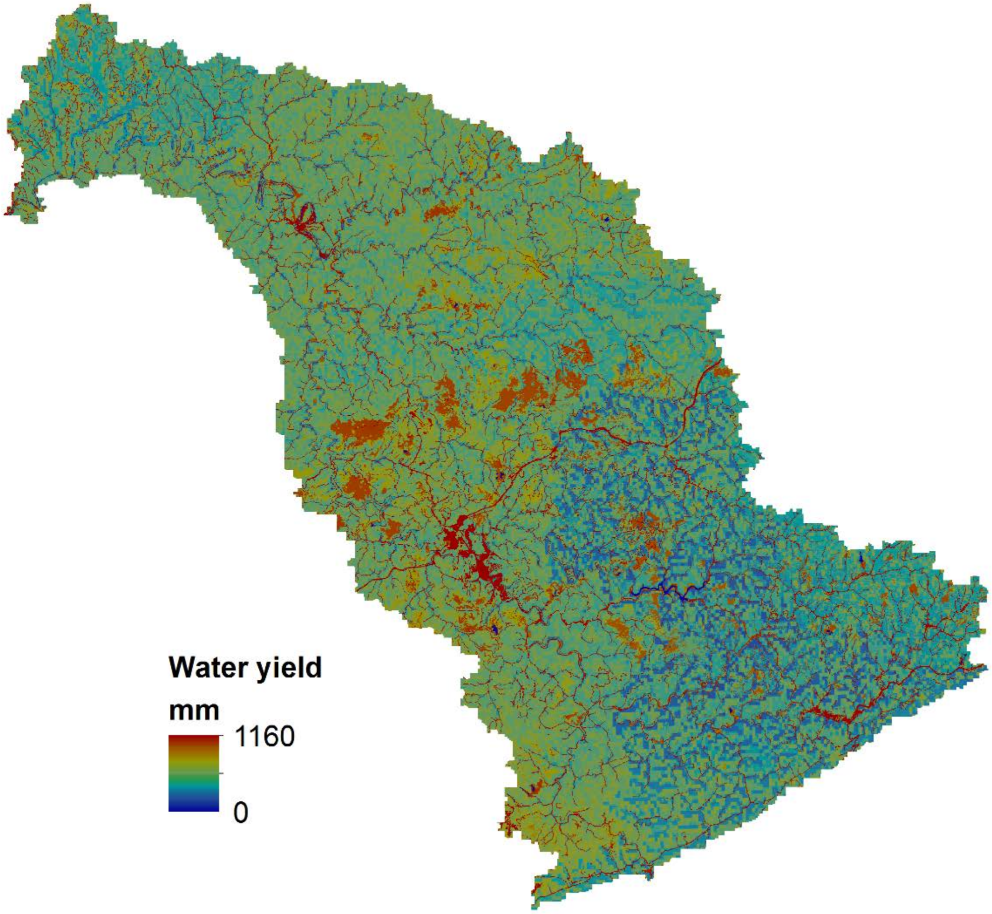
At the sub watershed level, the Upper Second Creek has the highest modeled Nitrogen export at 1.40 kg per ha. The Grapevine Creek has the second highest Nitrogen export (1.31 kg per ha). The lowest Nitrogen export is that of Lower Laurel Fork with 0.67 kg per ha. Howards Creek follows with 0.71 kg per ha of Nitrogen export. Similarly for Phosphorus export, the Upper Second Creek has the highest with a mean export of 0.14 kg per ha. Big Willard has the second highest phosphorus export at 0.09 kg per ha. Upper Laurel Fork Quicksand Creek has the lowest phosphorus export of 0.025 kg per ha.

Figures 6d and 6e show the spatial distribution of nitrogen and phosphorus export respectively in the watershed.

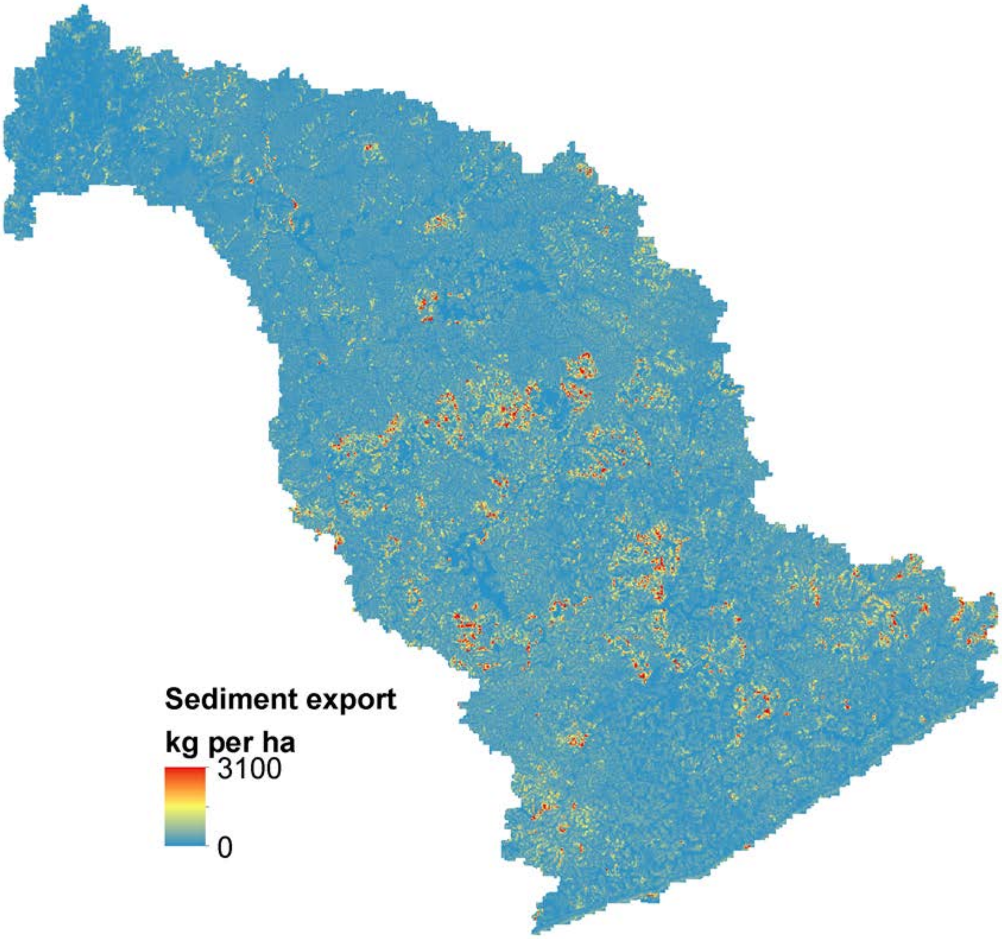
(6a)



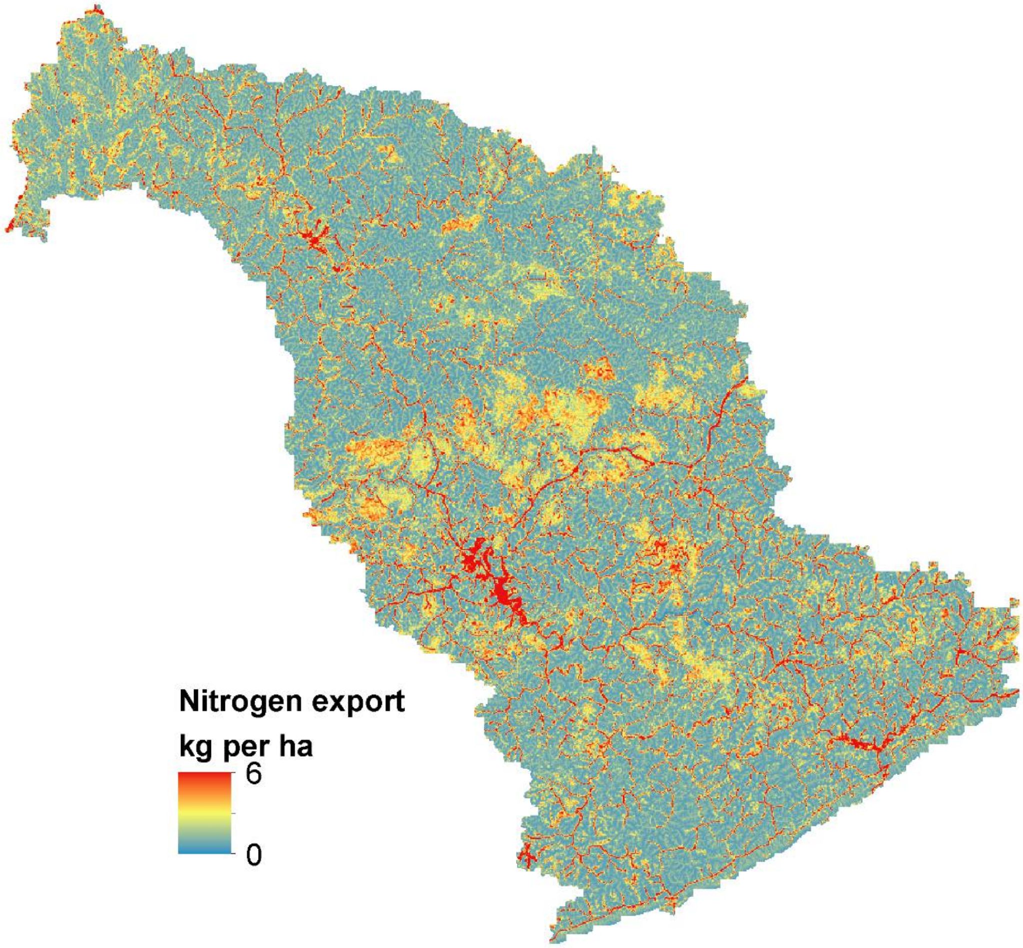
(6b)



(6c)



(6d)



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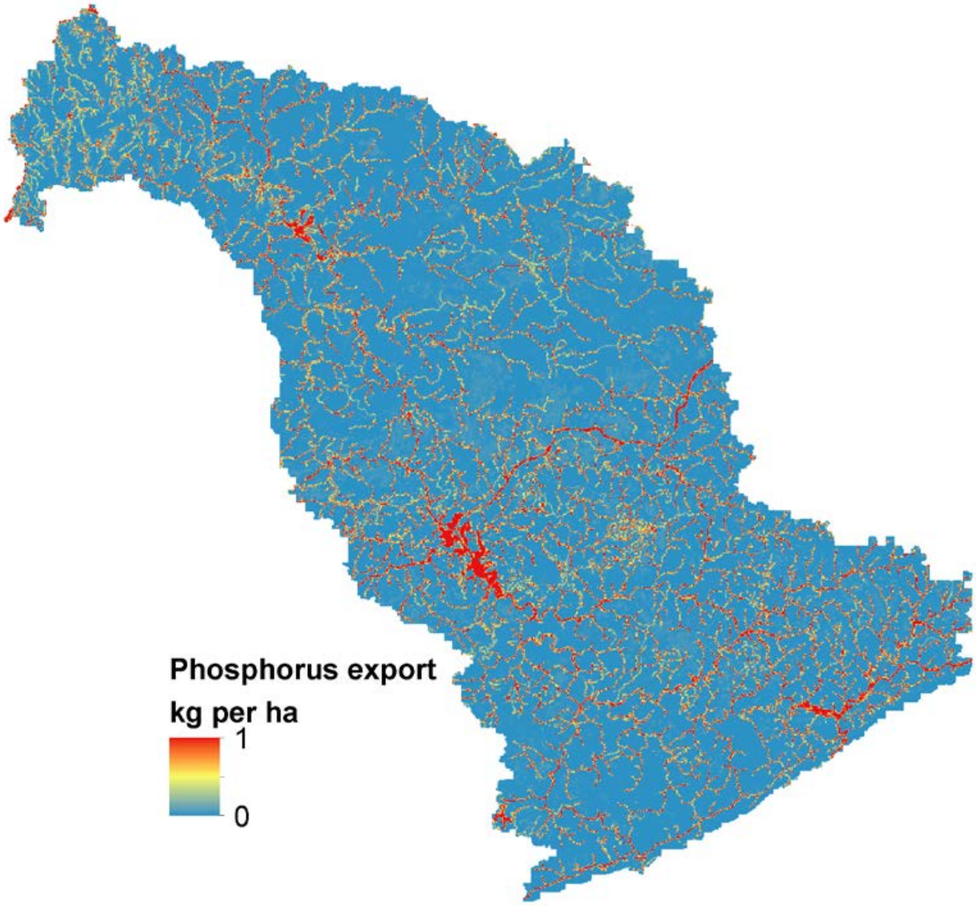


Figure 6 Spatial distribution of modeled (a) carbon storage (Mg per ha) (b) water yield (mm), (c) sediment export (kg per ha), (d) nitrogen export (kg per ha), and (e) phosphorus export (kg per ha) across the NFKR Watershed under 2011 LULC conditions.

Table 7. *Ecosystem service assessment for the 2011 LULC.*

LULC	Carbon storage (Mg per ha)	Water yield (mm)	Sediment export (kg per ha)	Nitrogen export (kg per ha)	Phosphorus export (kg per ha)
Developed	36	1055	0.02	4.34	0.727
Barren	0	931	971	2	0.001
Forest	250	534	110	0.5	0.003
Shrub	100	582	122	0.5	0.003
Grassland	45	665	404	1.6	0.02
Pasture	71	632	628	1.6	0.051

Note: The table above is the result of a zonal statistics showing the mean production of individual ecosystem services by each land cover type.

Ecosystem Service Assessment: Forest Reclamation Scenario

The benefits of forest reclamation approach (FRA) scenario are evident in the production of all the ecosystem services assessed in this study. Total water yield, sediment export and nutrient export have decreased under FRA scenario, suggesting it is capable of regulating flood, retaining soil and maintaining surface water quality. The climate regulation ecosystem service of the landscape would also be improved under FRA scenario, since there are more forested areas which are then able to store more carbon than otherwise would have been stored.

The total carbon storage of the landscape would be 80,633,377 Mg of Carbon under the FRA scenario. Compared to 71,343,168 Mg of Carbon under the 2011 LULC, the difference is 9,290,209 Mg of Carbon which makes up an increase of 13% (Table 8). The spatial distribution of carbon storage in the landscape has changed (Figure 7a) because the barren, grasslands and shrub lands have been reclassified to forests. These land covers now have higher carbon storage. Carbon storage is lowest in developed areas and all other impervious surfaces.

At the sub-watershed level, the highest mean carbon storage is that of Upper Laurel Fork Quicksand Creek (249 Mg of Carbon), followed by Buckhorn Creek (247 Mg of Carbon). The lowest ranking sub watersheds are Upper Second Creek-North Fork Kentucky River (206 Mg of Carbon) and Hell Creek-North Fork Kentucky River (207 Mg of Carbon) (Appendix A4).

The watershed’s overall predicted water yield has decreased under the FRA scenario as expected due to the increased water evapotranspiration. The water yield decreased by more than 5% (Table 8). Similar to carbon storage, the spatial distribution of water yield has changed because of the reclassification of barren, grasslands and shrub lands to forest (Figure 7b).

Sub watershed level ranking for water yield is led by Upper Second Creek-North Fork Kentucky River (667 mm) and then by Big Willard Creek-North Fork Kentucky River (642mm). The two sub watersheds with lowest water yield are: Irishman Creek-Carr Fork (476 mm) and Lower Rockhouse Creek (495mm) (Appendix A4).

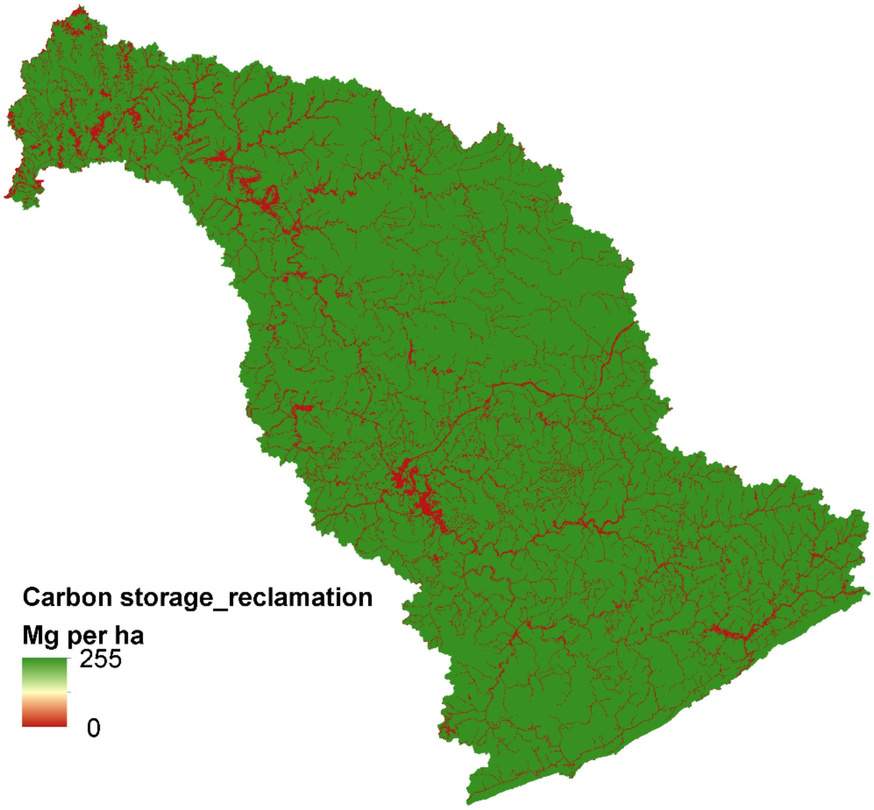
The sediment export of the entire watershed was predicted to be reduced by 40% in the FRA scenario (Table 8) suggesting the contribution of barren areas, grasslands and shrub lands in sediment export are high under 2011 LULC conditions. The FRA can significantly offset such export and hence increase ecosystem service of soil retention in the watershed. The spatial distribution of sediment export is opposite to the distribution of contemporary LULC 2011, meaning that the areas which exported more sediment in the past (LULC 2011) are now exporting zero to very low sediment (Figure 7c).

The Holly Creek and Leatherwood Creek sub watersheds have the highest mean sediment export, 42 and 41 kg per ha respectively. The Hell Creek-North Fork Kentucky River and Walker Creek-North Fork Kentucky River sub watersheds have the lowest mean sediment export of 23 and 18 kg per ha respectively (Appendix A4).

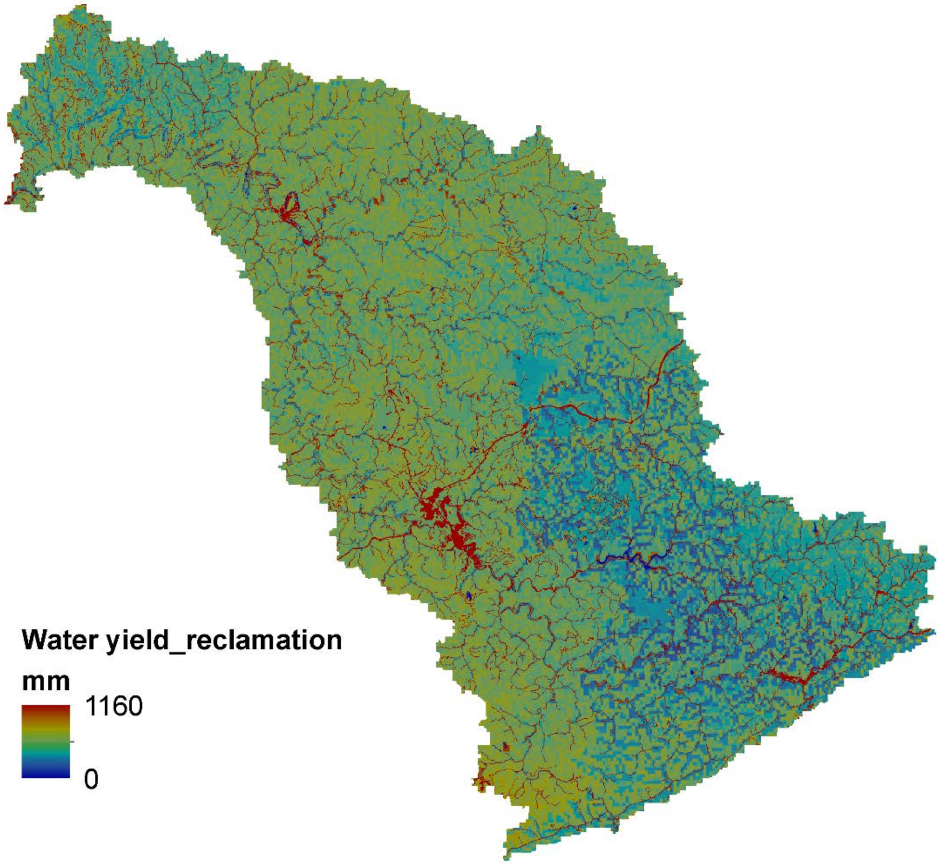
Nitrogen export has decreased by 22% in the FRA scenario in comparison to the contemporary LULC of 2011 and Phosphorus has also decreased by 7%. Less export of these nutrient sources to the river systems means improved capacity of the watershed in preserving and maintaining water quality. The spatial distribution of nutrient export is shown in Figures 7d and 7e. The pattern is similar to other ecosystem services.

The Upper Second Creek-North Fork Kentucky River and the Big Willard Creek-North Fork Kentucky River sub watersheds have the highest Nitrogen and Phosphorus export (Appendix A4). Similarly, Buckhorn Creek and Upper Laurel Fork Quicksand Creek have the lowest nutrient exports.

(7a)



(7b)



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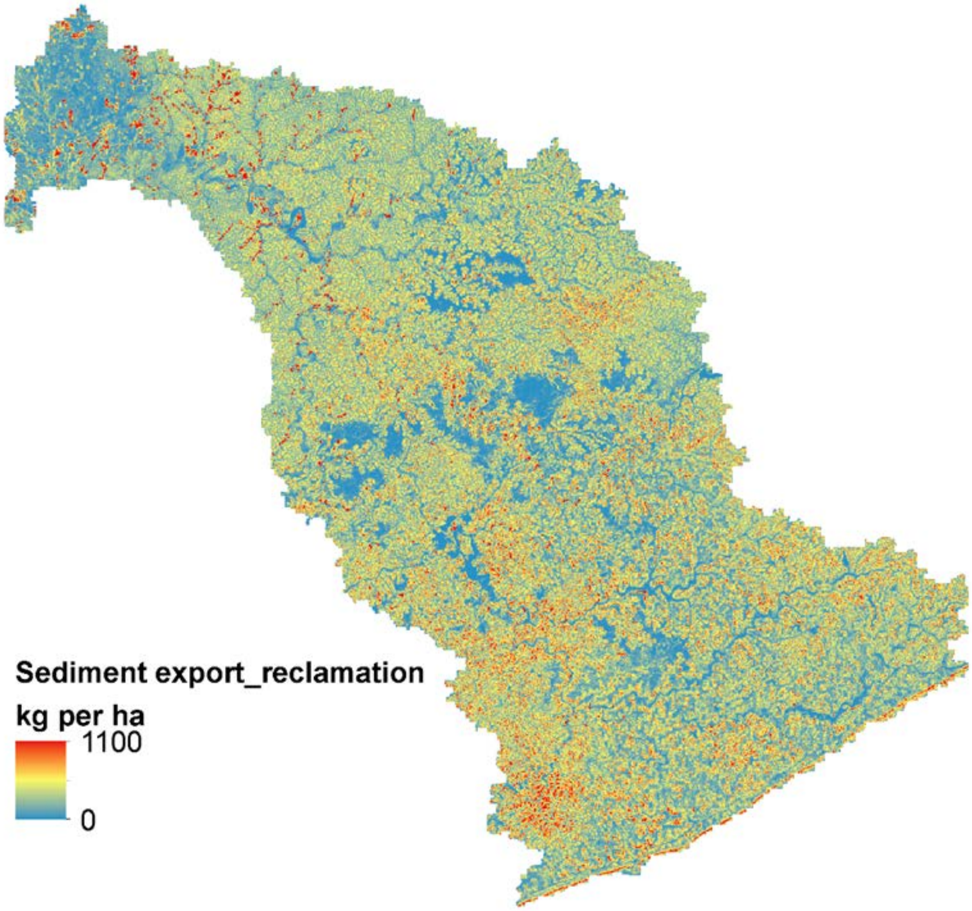
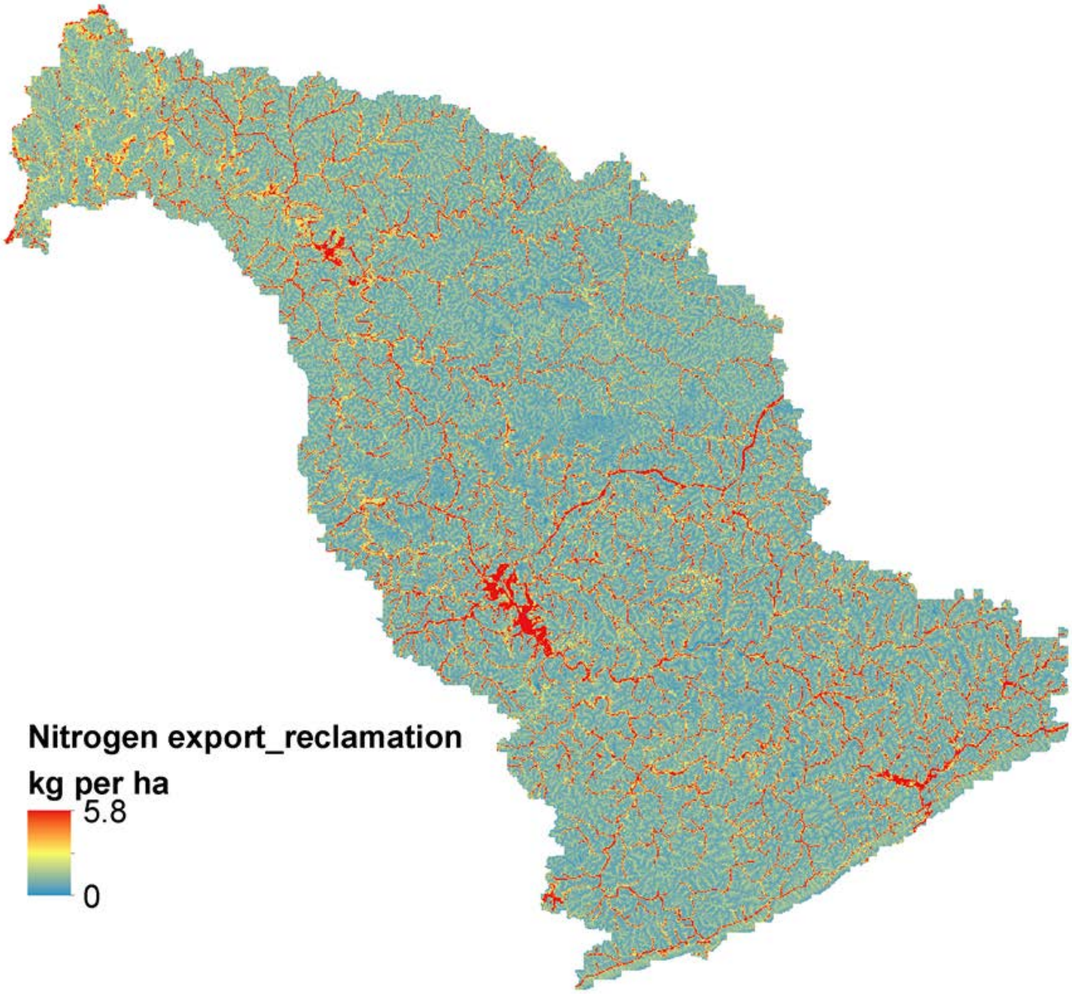


(7d)



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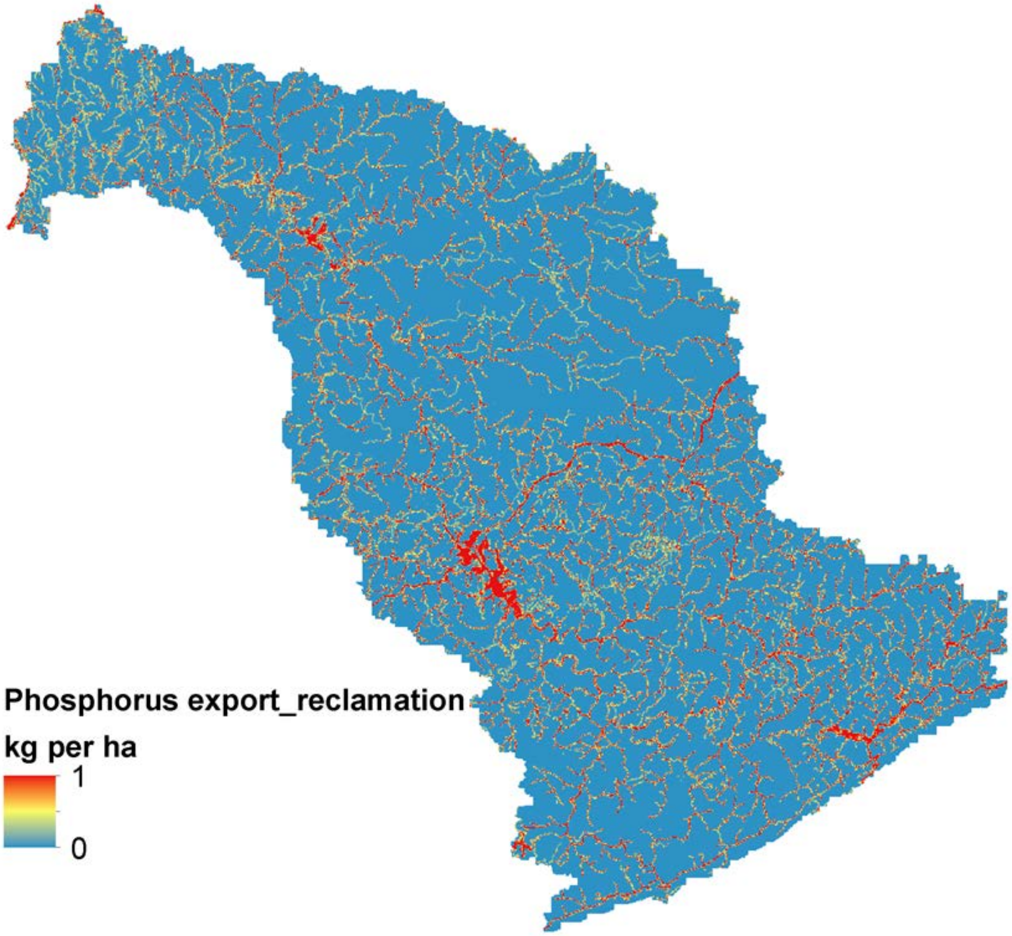


Figure 7 Spatial distribution of (a) carbon storage (Mg per ha) (b) water yield (mm), (c) sediment export (kg per ha), (d) nitrogen export (kg per ha), and (e) phosphorus export (kg per ha) across the NFKR Watershed under the FRA scenario.

Table 8. *The modeled ecosystem service benefits and changes as a result of implementing FRA scenario to the 2011 LULC.*

LULC	Carbon storage (Mg of carbon)	Water yield (mm)	Sediment Export (kg)	Nitrogen Export (kg)	Phosphorus Export (kg)
Contemporary	71,343,168	2,219,528,435	52,848,288	320,525	18,384
FRA	80,633,377	2,105,058,148	31,425,868	248,045	17,072
Difference	9,290,209	-114,470,287	-21,422,420	-72,480	-1,312
Percentage change	13%	-5.2%	-40.5%	-22.6%	-7.1%

Note: This analysis is for the entire watershed; not only for the reforested areas.

CHAPTER FOUR: DISCUSSION

This study investigated how LULC has changed in NFKR watershed and the contribution of mining and reclamation in the overall land cover land use change, followed by the valuation of major ecosystem services under contemporary LULC conditions and the assessment of the benefits of the Forestry Reclamation Approach (FRA). The results show that forest area was reduced by 7751 hectares (2.3% of the watershed) 2001 to 2011 and barren and grasslands LULCs have increased 3844 and 3352 hectares respectively. The conversion of forest to barren, and barren to grasslands make up 75% of the total LULC change in the watershed from 2001 to 2011. These findings suggest that surface mining and reclamation is a major driver of LULC change in the NFKR watershed. The modeled results for the 2011 LULC conditions identify barren or mined lands as least effective providers of several valuable ecosystem services: climate regulation, flood control, and sediment and nutrient retention. The capacity of the entire watershed was reduced because of the presence of surface mined lands. On the contrary, when the FRA scenario was applied, the provision of ecosystem services improved. When all the grasslands, barren lands and shrub lands reclassified to forests, there was more carbon storage, higher water conservation, and improved sediment and nutrient retention.

LULC Change and Ecosystem Service Assessment

The results of the LULC change analysis is similar to other studies done in the Appalachian region. The United States Environmental Protection Agency (EPA) had estimated that by 2012, surface mining would have impacted 6.8% of the largely forested 4.86 million hectare portion of the Appalachian Coalfield Region within West Virginia, Kentucky, Virginia and Tennessee. Simmons et al. (2008) and Lookingbill et al. (2009)

found that surface coal mining and subsequent reclamation represents the dominant land use change in the Central Appalachian Plateau region of the United States. A similar study done by Wickham et al. in 2007 showed that the area of reclaimed mined lands have increased from 1.35% to 4.99% from 1976 to 2006 and land cover conversions to mined and then reclaimed mines after 1976 was exclusively from forest. These studies indicated that mine reclamation leaves the landscape in a condition more similar to urban areas rather than does simple deforestation, and called into question the effectiveness of reclamation. Zipper et al. (2011) also found that surface mining in Appalachia has caused extensive replacement of forest with less productive non-forested land cover.

The LULC change analyses demonstrate the ineffectiveness of SMCRA reclamation practices. Only 179 hectares of barren lands in 2001 have converted to forest by 2011, whereas conversion of barren lands to grasslands is 2,189 hectares (Table 6). Grasslands provide less ecosystem services in comparison to forests. Grasslands have a mean carbon storage of 45 Mg per ha, which is much less than what forests can store (250 Mg per ha). Comparing to grassland, forests have less mean water yield (534 vs. 665 mm), sediment export (110 vs. 404 kg per ha), nitrogen (0.5 vs. 1.6 kg per ha) and phosphorus export (0.001 vs. 0.02 kg per ha) than grasslands (Table 7). Although SMCRA mandates restoring the post-mining land to a condition capable of supporting the uses to the level similar to or higher than that prior to any mining, the majority of reclamation has failed to meet such standards when ecosystem services are considered as the evaluation criteria.

Although ecosystem services are considered important, there is a lack of studies in Appalachia to evaluate how different land use and land cover might change the provision of various ecosystem services. However, there are studies that are consistent with our findings that LULC changes driven by mining and reclamation can significantly reduce the potential of a watershed to provide ecosystem services. Foley et al. (2007) showed that intensified agriculture and urbanization degrade ecosystem services, especially those tied to the functioning of the ecosystem. Zipper et al. (2011) reviewed a suite of valuable ecosystem services provided by Appalachian native forests. However, coal surface mining has caused forest fragmentation and net loss of a productive forestland (Wickham et al. 2007; Townsend et al. 2009; Drummond and Loveland 2010). According to Burkhard et al. (2009), the highly modified land cover types such as mine sites have very low or no relevant capacities to provide ecosystem services. They have also stressed that unique impacts brought about by mining, particularly mountain top mining such as altering landform shape and structure and burying headwater streams. All these changes adversely affect the functioning of ecosystems and results in reduced capacity of the landscape to regulate climate and flood, to retain sediments and nutrients, and to conserve and purify water.

Limitations and Future Work

An important limitation of this study is the land cover dataset. The NLCD is a broad dataset and analysis for this study is for a relatively small spatial area of the continental scale dataset, so compromises are inherent in the classification of land use land covers. The NLCD classifications were based on the information from multiple years prior to 2001 and 2011, meaning classification used in the NLCD may not truly represent ground truth in all pixels for a given year. There are also known inaccuracies that are expected because of the techniques used to collect and classify the remotely sensed data. These accuracy assessments have been documented elsewhere (Wickham et al. 2010; Wickham et al.

2013). In addition, the analysis done here is pixel based and spatial configuration of land cover change were not within the scope of this study although spatial configuration (edges, corridors, and interiors) is known to be important in landscape ecology.

The InVEST software has its own modeling limitations. For the InVEST carbon storage model, the model only estimates the temporally average carbon storage for each LULC hence assumes that none of the LULC types in the landscape are gaining or losing carbon over time. Changes in carbon storage simulated in this model can only be induced by the changes from one land cover type to another. The InVEST water yield model is based on annual averages, which neglects extremes and do not consider the temporal dimensions of water supply. It does not consider complex land use patterns or underlying geology, which may induce complex water balances. The main limitation of the InVEST sediment delivery model is its reliance on the Universal Soil Loss Equation. Even though this equation is widely used, it only represents rill erosion process, which is the removal of soil by concentrated water running through little streamlets. The InVEST nutrient delivery model is highly sensitive to inputs, so small errors in the empirical load parameter, will have a large effect on predictions of nutrient delivery. Most of all, the tabular values used are not entirely from the study area because of data limitation in the study area; they have been acquired from published sources and the master table of the InVEST manual.

Although this study focused on the forestry reclamation approach, other uses of the abandoned mined lands may be considered valuable alternatives, depending on landscape location and spatial configuration of those mined lands. A diverse landscape will yield different suites of ecosystem services (Turner et al. 2013). Hence, tradeoffs and synergy are likely to take place between the ecosystem services under different reclamation scenarios. Recognizing where tradeoffs and synergy takes place, and hotspots and cold spots can help policymakers to identify priority areas for protection and restoration in a landscape.

This study assessed ecosystem services in biophysical terms, future direction for this research can be the monetary valuation of ecosystem services. Biophysical valuation and monetary valuation have equal supporters and critics and the debate may not end. Biophysical valuation is a necessary step towards monetary valuation and the latter is able to provide a better understandable language to contribute positively to the formulation and evaluation of environmental policies (Howarth and Farber 2002). The InVEST model can provide results in economic terms if social valuation option is chosen. However, this is beyond the time frame or scope of this thesis, and future work may be done to assess the monetary value of all these services.

Policy and Management Implications

A major implication of quantitative assessment of LULC change is to understand the ecological consequences brought by such changes and to make fully informed decisions about land use (DeFries et al. 2004). When land use change takes place such as conversion of forest to reclaimed mined land, the change is not only spatial but is accompanied by major ecological changes like changes in vegetation community, wildlife habitat, and soil structure and properties (Johnson and Skousen 1995, Williams et al. 1995, Boerner et al. 1998). The changes in the hydrology, biogeochemical cycles, stream characteristics and flora and fauna will ultimately affect the benefits that flow to people. Thus LULC change analysis can enable prediction of ecosystem responses to land use activities and help understand the mechanisms behind the changes.

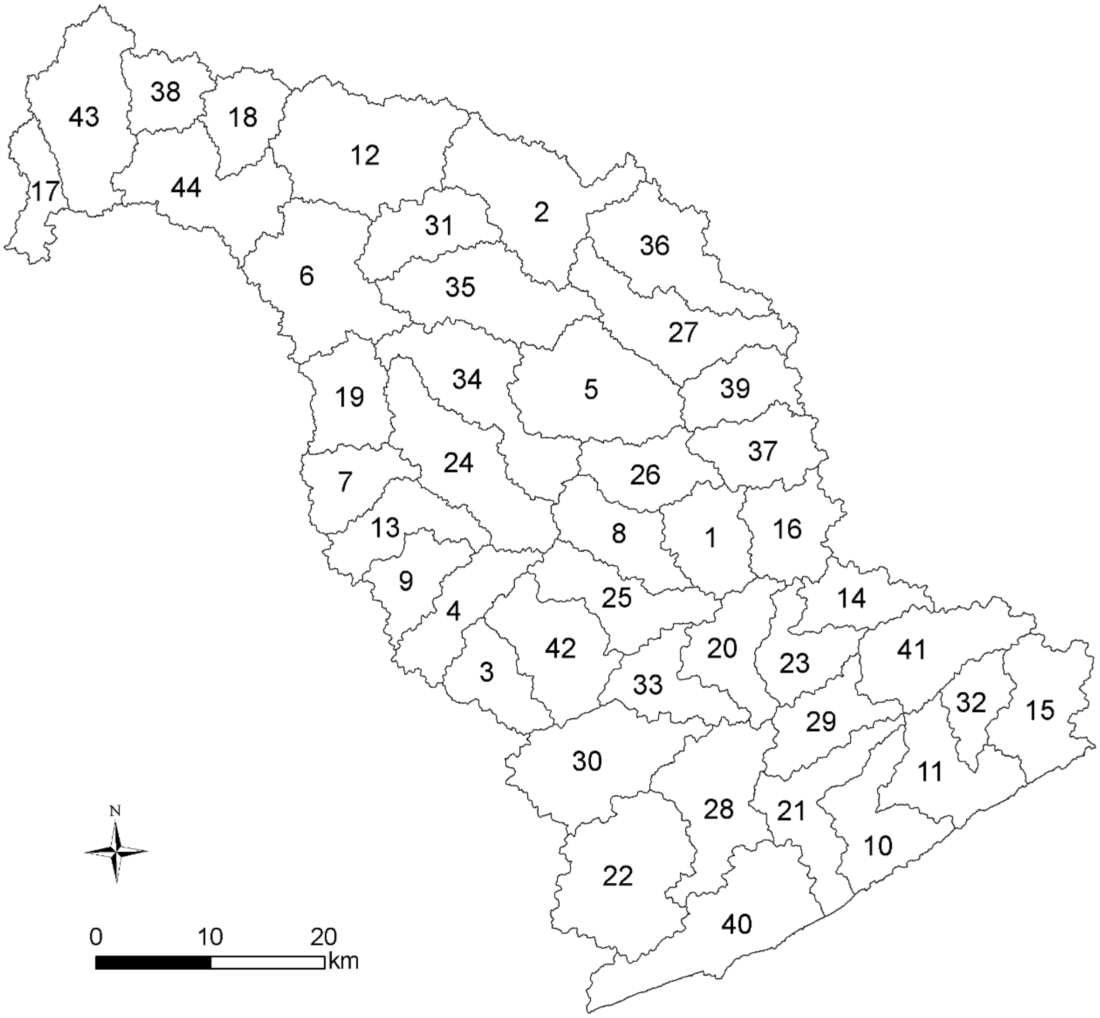
For the ecosystem service assessment conducted in this study, a major implication is for the authorities and general public to appreciate the value of ecosystem services; to gain knowledge about the loss of ecosystem services due to land conversions like mining, and the potential improvement in the delivery of ecosystem services when forest-oriented reclamation practices are applied. This study adds a block to the study of ecosystem services study of Kentucky as there is a scarcity of such studies in this Appalachian state. The outcomes presented in tables and maps illustrate the potentials of land cover types to provide ecosystem services. The maps produced in this study provide important spatially explicit information to support managers to identify areas where the ecosystems are produced in larger quantities and where not.

For the time and scope of this study, it has provided important information on biophysical valuation and spatial distribution of ecosystem services. Despite model and data limitations, this study can be helpful in enforcing and popularizing reclamation strategies like the forestry reclamation approach. As Environmental Ecologist Gretchen Daily puts, “imperfect measures of value of ecosystem services, if understood as such, are better than simply ignoring ecosystem services altogether, as is generally done in decision making today” (Daily 1997).

APPENDICES

Appendix A1

Sub- watersheds included in the study area



Appendix A2

Sub- watershed features

ID	Name	Area Sq. km	HUC code
1	Big Branch-Troublesome Creek	60	51002010502
2	Big Caney Creek-Quicksand Creek	122	51002010604
3	Big Creek	51	51002010306
4	Big Willard Creek-North Fork Kentucky River	61	51002010401
5	Buckhorn Creek	118	51002010506
6	Cane Creek-North Fork Kentucky River	119	51002010701
7	Caney Creek-North Fork Kentucky River	50	51002010404
8	Clear Creek-Troublesome Creek	63	51002010503
9	Colwell Fork-North Fork Kentucky River	48	51002010402
10	Cowan Creek-North Fork Kentucky River	73	51002010104
11	Crafts Colly Creek-North Fork Kentucky River	75	51002010103
12	Frozen Creek	142	51002010702
13	Grapevine Creek-North Fork Kentucky River	60	51002010403
14	Headwaters Carr Fork	48	51002010201
15	Headwaters North Fork Kentucky River	79	51002010101
16	Headwaters Troublesome Creek	61	51002010501
17	Hell Creek-North Fork Kentucky River	38	51002010707
18	Holly Creek	50	51002010703
19	Howards Creek-North Fork Kentucky River	61	51002010405
20	Irishman Creek-Carr Fork	64	51002010203
21	Kings Creek-North Fork Kentucky River	75	51002010105
22	Leatherwood Creek	129	51002010303
23	Little Carr Fork-Carr Fork	53	51002010202
24	Lost Creek	110	51002010507

25	Lotts Creek	73	51002010305
26	Lower Balls Fork	58	51002010505
27	Lower Laurel Fork Quicksand Creek-Quicksand Creek	95	51002010602
28	Lower Line Fork-North Fork Kentucky River	99	51002010302
29	Lower Rockhouse Creek	57	51002010107
30	Maces Creek-North Fork Kentucky River	111	51002010304
31	Meatscaffold Branch-Quicksand Creek	60	51002010606
32	Millstone Creek-North Fork Kentucky River	38	51002010102
33	Montgomery Creek-Carr Fork	56	51002010204
34	Russell Branch-Troublesome Creek	107	51002010508
35	South Fork Quicksand Creek	104	51002010605
36	Spring Fork Quicksand Creek	92	51002010603
37	Upper Balls Fork	59	51002010504
38	Upper Devil Creek	45	51002010705
39	Upper Laurel Fork Quicksand Creek	53	51002010601
40	Upper Line Fork	122	51002010301
41	Upper Rockhouse Creek	88	51002010106
42	Upper Second Creek-North Fork Kentucky River	86	51002010307
43	Walker Creek-North Fork Kentucky River	113	51002010706
44	War Creek-North Fork Kentucky River	104	51002010704

Appendix A3

Note: For appendices A3 and A4, the highest two indicator values are highlighted with a blue shaded color background and the lowest two indicator values are highlighted with a yellow shaded color background.

Ecosystem service assessment per sub-watershed under 2011 LULC conditions

		Biophysical indicators of ecosystem services				
ID	Sub-watersheds	Carbon storage (Mg per ha)	Water yield (mm)	Sediment export (kg per ha)	Nitrogen export (kg per ha)	Phosphorus export (kg per ha)
1	Big Branch-Troublesome Creek	182	582	221	1.06	0.065
2	Big Caney Creek-Quicksand Creek	210	617	129	0.79	0.038
3	Big Creek	180	680	313	1.08	0.058
4	Big Willard Creek-North Fork Kentucky River	186	672	204	1.14	0.091
5	Buckhorn Creek	191	611	235	0.88	0.027
6	Cane Creek-North Fork Kentucky River	210	620	127	0.92	0.065
7	Caney Creek-North Fork Kentucky River	198	636	176	0.88	0.036
8	Clear Creek-Troublesome Creek	181	601	202	1.07	0.069
9	Colwell Fork-North Fork Kentucky River	176	677	236	1.11	0.061
10	Cowan Creek-North Fork Kentucky River	218	536	126	0.82	0.052
11	Crafts Colly Creek-North Fork Kentucky River	206	560	132	1.04	0.087
12	Frozen Creek	228	608	115	0.75	0.036

13	Grapevine Creek-North Fork Kentucky River	138	702	263	1.32	0.066
14	Headwaters Carr Fork	217	522	150	0.82	0.049
15	Headwaters North Fork Kentucky River	198	564	201	1.02	0.072
16	Headwaters Troublesome Creek	216	554	140	0.86	0.056
17	Hell Creek-North Fork Kentucky River	187	622	117	1.01	0.069
18	Holly Creek	215	558	172	0.9	0.053
19	Howards Creek-North Fork Kentucky River	230	597	112	0.71	0.039
20	Irishman Creek-Carr Fork	169	548	291	1.02	0.047
21	Kings Creek-North Fork Kentucky River	212	532	163	0.85	0.05
22	Leatherwood Creek	209	653	214	0.86	0.047
23	Little Carr Fork-Carr Fork	208	525	151	0.85	0.055
24	Lost Creek	181	656	230	1.01	0.048
25	Lotts Creek	198	589	193	0.98	0.069
26	Lower Balls Fork	136	615	278	1.25	0.053
27	Lower Laurel Fork Quicksand Creek-Quicksand Creek	222	567	134	0.67	0.029
28	Lower Line Fork-North Fork Kentucky River	219	542	117	0.8	0.047
29	Lower Rockhouse Creek	192	529	173	1.02	0.076
30	Maces Creek-North Fork Kentucky River	218	621	176	0.83	0.051
31	Meatscaffold Branch-Quicksand Creek	220	621	134	0.81	0.048
32	Millstone Creek-North Fork Kentucky River	196	548	199	0.95	0.058

33	Montgomery Creek-Carr Fork	181	616	247	1.02	0.056
34	Russell Branch-Troublesome Creek	190	631	232	0.91	0.04
35	South Fork Quicksand Creek	201	623	128	0.8	0.031
36	Spring Fork Quicksand Creek	191	617	181	0.85	0.032
37	Upper Balls Fork	194	578	181	0.96	0.057
38	Upper Devil Creek	200	586	145	1	0.061
39	Upper Laurel Fork Quicksand Creek	196	582	179	0.86	0.026
40	Upper Line Fork	231	577	123	0.75	0.042
41	Upper Rockhouse Creek	190	558	246	0.97	0.053
42	Upper Second Creek-North Fork Kentucky River	172	698	196	1.4	0.146
43	Walker Creek-North Fork Kentucky River	199	588	101	0.94	0.052
44	War Creek-North Fork Kentucky River	210	591	124	0.89	0.049

Appendix A4

Ecosystem service assessment per sub- watershed under the Forestry Reclamation Approach scenario

		Biophysical indicators of ecosystem services				
ID	Sub-watersheds	Carbon storage (Mg per ha)	Water yield (mm)	Sediment export (kg per ha)	Nitrogen export (kg per ha)	Phosphorus export (kg per ha)
1	Big Branch-Troublesome Creek	233	528	30	0.67	0.053
2	Big Caney Creek-Quicksand Creek	241	594	28	0.57	0.031
3	Big Creek	237	633	38	0.65	0.047
4	Big Willard Creek-North Fork Kentucky River	228	642	33	0.79	0.075
5	Buckhorn Creek	247	546	30	0.5	0.021
6	Cane Creek-North Fork Kentucky River	222	611	32	0.74	0.055
7	Caney Creek-North Fork Kentucky River	240	594	30	0.56	0.03
8	Clear Creek-Troublesome Creek	232	561	30	0.68	0.055
9	Colwell Fork-North Fork Kentucky River	234	621	30	0.66	0.05
10	Cowan Creek-North Fork Kentucky River	239	519	32	0.64	0.044
11	Crafts Colly Creek-North Fork Kentucky River	229	539	28	0.78	0.072
12	Frozen Creek	238	600	30	0.62	0.031
13	Grapevine Creek-North Fork Kentucky River	230	617	27	0.67	0.052

14	Headwaters Carr Fork	240	503	35	0.62	0.042
15	Headwaters North Fork Kentucky River	234	533	32	0.72	0.061
16	Headwaters Troublesome Creek	239	534	32	0.65	0.047
17	Hell Creek-North Fork Kentucky River	207	608	24	0.78	0.057
18	Holly Creek	223	552	42	0.74	0.045
19	Howards Creek-North Fork Kentucky River	239	591	32	0.6	0.033
20	Irishman Creek-Carr Fork	234	476	30	0.56	0.036
21	Kings Creek-North Fork Kentucky River	240	507	32	0.62	0.041
22	Leatherwood Creek	240	630	42	0.61	0.039
23	Little Carr Fork-Carr Fork	235	498	29	0.64	0.047
24	Lost Creek	239	603	31	0.59	0.039
25	Lotts Creek	231	561	34	0.68	0.056
26	Lower Balls Fork	240	509	25	0.58	0.041
27	Lower Laurel Fork Quicksand Creek-Quicksand Creek	245	551	35	0.52	0.024
28	Lower Line Fork-North Fork Kentucky River	240	525	28	0.61	0.039
29	Lower Rockhouse Creek	230	495	30	0.72	0.062
30	Maces Creek-North Fork Kentucky River	239	605	39	0.63	0.042
31	Meatscaffold Branch-Quicksand Creek	233	608	31	0.65	0.041
32	Millstone Creek-North Fork Kentucky River	238	508	30	0.65	0.048
33	Montgomery Creek-Carr Fork	237	564	37	0.62	0.045
34	Russell Branch-Troublesome Creek	239	588	34	0.57	0.033

35	South Fork Quicksand Creek	244	590	27	0.51	0.023
36	Spring Fork Quicksand Creek	245	583	29	0.5	0.023
37	Upper Balls Fork	238	535	29	0.64	0.048
38	Upper Devil Creek	221	570	27	0.75	0.049
39	Upper Laurel Fork Quicksand Creek	249	534	27	0.5	0.02
40	Upper Line Fork	243	566	32	0.61	0.036
41	Upper Rockhouse Creek	239	509	35	0.61	0.042
42	Upper Second Creek-North Fork Kentucky River	206	667	33	1.05	0.124
43	Walker Creek-North Fork Kentucky River	219	574	19	0.71	0.041
44	War Creek-North Fork Kentucky River	224	581	27	0.7	0.04

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VITAE

Kumari Gurung was born in Nepal. She spent her early childhood years in a rural village and then migrated to the nearby city, Pokhara. She got her education in Pokhara starting from school to university. She graduated from Tribhuwan University in 2014 majoring in Forestry Science. She received merit scholarship for her undergraduate there. She also holds a Bachelor’s Degree in Humanities. She came to the University of Kentucky, United States in January 2016 to receive her Master’s degree in Forestry and Natural Resources Science. She is preparing a paper for publication. Ms. Gurung plans to attend a PhD program by 2019.