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Impact of land use and climate change on water-related ecosystem services in Kentucky, USA

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ABSTRACT

Policy-makers are interested in knowing the relative importance and combined effects of land use and climate change on ecosystem services. However, knowledge of how to identify these relationships is still lacking. This study aims to provide a comprehensive assessment of water-related ecosystem services and to improve understanding of how they are impacted by land use and climate change in Kentucky, USA. By using InVEST models and environmental setting scenarios, this study first quantifies water-related ecosystem services in a spatially explicit manner. The effects of land use and climate change on these ecosystem services are assessed using two indicators developed in this study. The results show that at the state scale, climate change has a greater impact than land use on water retention, but land use change has a greater impact on soil retention, nitrogen export, and phosphorus export. Climate and land use change have a significant inhibitory effect on water retention, nitrogen export, and phosphorus export. The relative importance and combined influences of land use and climate change also depend on the scale and landscape composition. Unraveling the drivers of ecosystem services in the context of global change can provide critical knowledge for developing practical policy and land management applications.

1. Introduction

Ecosystem services are the benefits that people obtain either directly or indirectly from ecological systems (MEA, 2005; La Notte et al., 2017). Quantifying, mapping, and valuing ecosystem services are emerging as important and reliable tools for natural capital management and policy making (Bai et al., 2011; Bateman et al., 2013; Kindu et al., 2016; Olander et al., 2018). Due to increasing demand of the public and changes in the global environment, the capacity of ecosystems to provide ecosystem services is being threatened at an unprecedented level (MEA, 2005; Verburg, 2006). According to the results of Millennium Ecosystem Assessment, at least 15 types of global ecosystem services are currently declining, for example, erosion regulation, water purification and natural hazard regulation, and this trend may accelerate in the future (MEA, 2005). Increasing some ecosystem services, especially provisioning services, may cause a decline in other ecosystem services, and unsustainable management may undermine the future provision of services as well. Therefore, policy-makers need straightforward information to better understand the tradeoffs among different ecosystem management practices to ensure the effective provision of desired ecosystem services (Nelson et al., 2009; Albert et al., 2015; Cabral et al., 2016).

Land use change and climate change have been identified as the two main factors driving the provision of ecosystem services and tradeoffs among different types of ecosystem services (Hoyer and Chang, 2014). Land use changes directly affect the composition and configuration of ecosystems, and ultimately impact the capacity of ecosystems to supply ecosystem services (Quintas-Soriano et al., 2016; Mononen et al., 2016). Studies have shown that land use change, especially in urban areas, significantly impacts ecosystem services through changes in the carbon balance and nutrient flows (Kreuter et al., 2001; Lorencová et al., 2016). Spatial changes in land use over time have significant impacts on the future provision and location of ecosystem services on the landscape (Lautenbach et al., 2011; Hoyer and Chang, 2014). In fact, many studies use land use change as a proxy or visual representation of ecosystem services change for conveying potential future development and assessing environmental change (Lorencová et al., 2016; Chuai et al., 2016). Climate change is another important driver affecting the distribution of ecosystems, and their capacity to provide ecosystem services (Parmesan and Yohe, 2003). Climate change may be responsible for increases in the frequency and severity of extreme events, such as high-winds, temperature waves, and changes in

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precipitation patterns. Climate change affects ecosystem services by modifying the biophysical processes of ecosystems. This is expected to increasingly threaten ecosystems and biodiversity and is projected to become a more severe threat in the next decade (EEA, 2015; Song et al., 2015).

Research on the impacts of land use and climate change on ecosystem services has provided vital insight and guidance to policy makers, yet most of this research has focused primarily on the effects of land use change or climate change, independently of one another. In addition, most of the available studies are location specific, and do not discern general principles that can be applied more widely. For instance, the effects of land use change on ecosystem services have been researched mainly in cities, other human dominated landscapes, and coastal ecoregions (Zank et al., 2016; Li et al., 2017). Research on the effects of climate change on ecosystem services has been performed mainly in mountainous landscapes (Rocca et al., 2014), rivers (Stubbington et al., 2017; Stubbington et al., 2018), and lakes (Zilio et al., 2017). Policy-makers are interested in understanding the relative importance and combined effects of land use change and climate change on both individual and aggregated ecosystem services (Fu et al., 2017). However, mechanisms to identify and calculate the relative importance of the drivers of ecosystem services change are still under development. Analyzing the combined effects of these drivers spatially is a minimally developed field as well, which makes planning and management challenging. Holistic ecosystem service assessments need to consider both land use change and climate change. This is especially true for water-related ecosystem services, which are sensitive to both land use change and climate change. Land use change may affect water quantity by changing infiltration and evapotranspiration rates, and climate change can lead to changes in the hydrologic cycle. Changes in the hydrologic cycle can lead to shifts in the amount and timing of water movement, which can impact water quantity, nutrient concentrations, and sediment load (Sample et al., 2016; Hoyer and Chang, 2014). Ultimately, such hydrological shifts impact both human and natural systems, as all systems depend on the provision of water. Changes in water availability across space and time can significantly impact the function and productivity of any ecological system.

Different water-related ecosystem services relate to different components of hydrological cycles. In mountainous areas, the hydrologic cycle is often initiated by rain. The land-cover structure of these regions often determines the flow rates and sediment loads of rivers, which provide key ecosystem services along their routes. Mountainous areas occupy 22% of the Earth's surface, and are home to 915 million people (Romeo et al., 2015), partially because they provide a wide range of essential ecosystem services (TEEB, 2012). However, land use change and climate change have altered the capacity of mountain ecosystems to regulate the hydrologic cycle and to control downstream water quantity and quality (Kim et al., 2017). There is a globally acknowledged reliance on the goods and services provided by mountainous areas. This reliance implies a critical need for assessment and monitoring to maintain the integrity of mountain ecosystems, and to allow for their continued provision of services, despite increasing levels of environmental change (Gleeson and Greenwood 2015; Singh and Thadani, 2015; Egan and Price, 2017).

The interest in technological aspects relative to water is now growing amidst the increasing concern over water shortage, water quality deterioration and a changing climate (Aldieri and Vinci, 2017). Technological innovation can help address tough water challenges and achieve a more sustainable path while supporting economic growth (Kemp and Pontoglio, 2011). Exploring the effect of drivers on ecosystem services aims to promote and support technology innovation to protect and ensure the sustainability of water resources (US EPA, 2014). However, understanding these systems and how to best regulate them is challenging and can only accurately be done at the scale at which ecological processes occur. Landscape-level case studies can allow for exploration of ecosystem function, as well as the reaction of ecosystems to different forms of perturbation. Studies done at this scale could inform the development of more universal principles and mechanisms that could be applied more broadly to understand ecosystem service provision in different regions and landscapes.

The Eastern Kentucky Mountains are an important part of the Appalachian Mountains and the source of the Kentucky, Green, Licking, and Cumberland Rivers, which supply water and other resources to a vast area of the Eastern United States. Land use and climate change could cause severe soil erosion and water quality degradation in the Eastern Kentucky Mountains through sediment transportation and excessive nutrient export to these rivers, which would likely impact water quantity and quality in the Mississippi, Ohio, and Tennessee Rivers. However, there is no existing research that examines these potential land use and climate change outcomes for the state of Kentucky. Through examination of three water-related ecosystem services (water retention, soil retention, and water purification, in terms of nitrogen export and phosphorus export), this study addresses the knowledge gap of how the combined effects of multiple drivers, including land use change and climate change, impact water-related ecosystem services in the state of Kentucky. The objectives of the study are to: (1) assess the spatial distribution of water-related ecosystem services and their historical relationship with land use and climate change; (2) determine the combined effects and relative importance of land use and climate change in determining shifts in the three ecosystem services.

2. Materials and methods

2.1. Study area

Kentucky (36°30′N–39°09′N, 81°58′W–89°34′W, Fig. 1), covering an area of 104,749 km^2, is located in the east south-central region of the United States and is bounded by the Appalachian Mountains in the east and the Ohio and Mississippi Rivers in the north and the west, respectively. The Highest point in Kentucky is 1259 m and lowest is 78 m, along the Mississippi River. Kentucky has a humid subtropical climate with an average annual precipitation ranging from 1016 to 1397 mm and monthly average temperature ranging from about −1 to 27 °C. Kentucky has an estimated population of 4,436,974 with a GDP-per-capita of 45,424 US dollars as of 2016 (BEA, 2017). Kentucky has a coal reserve of 168.5 million tons, which ranks in the top three largest coal reserves in the United States. There are 23,000 oil wells in the state that produce 4 million barrels a year, and the annual output of natural gas is about 73 billion cubic feet. The state's abundant forests contribute to Kentucky's hardwood industry, ranking third in the United States.

2.2. Framework for quantifying the impact of land use and climate change on ecosystem services

An operational framework, which contains four core steps, was developed to quantify the impact of land use and climate change on ecosystem services for optimal land management in Kentucky (Fig. 2). First, remote sensing and climate datasets were used to analyze the land use and climate spatial distributions and changes in Kentucky during the period 1992–2011. Secondly, ecosystem services assessment under alternative land use and climate scenarios using spatially explicit models was conducted. Thirdly, factor analysis to identify the relative importance and combined effect of land use and climate changes on ecosystem services was performed. And in the last step, the land use and management policy implications of the results are highlighted.

2.2.1. Land use and climate changes

Land use layers with a spatial resolution of 30 m were downloaded from the National Land Cover Database (NLCD). There are 9 land use classes used in this research, namely water, developed, barren, forest, shrubland, grassland, pasture, cultivated and wetlands (Supplementary Table 2). Climate data containing the average annual precipitation and

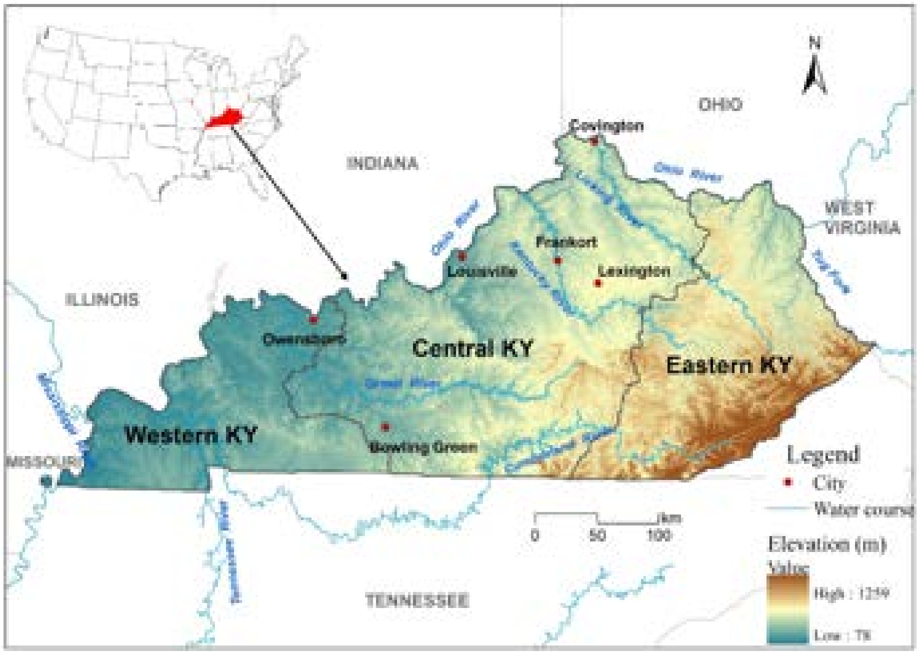

Fig. 1. Spatial location of Kentucky (KY) and its topographic features.

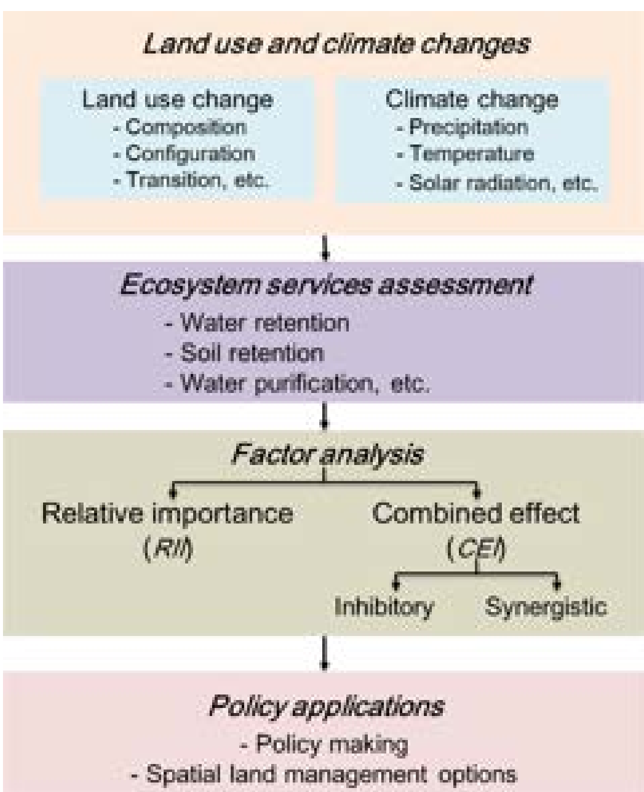

Fig. 2. Methodology framework of the research.

temperature from 1981 to 2016 were downloaded from the PRISM Climate Group.

2.2.2. Ecosystem services assessment

(1) Ecosystem services selection

Mountain areas provide a wide range of essential ecosystem services to human society, most notably through the supply of purified fresh water from upstream headwaters (Kim et al., 2017; Egan and Price, 2017). However, land use and climate change have hindered the capacity of mountain areas to regulate the hydrologic cycle and to control downstream water quantity and quality (Bhaduri et al., 2000). Water flow and erosion control are the key water-related ecosystem service types in mountain regions; water purification is another key ecosystem service that is lesser known (Egan and Price, 2017). Given the importance of water-related ecosystem services in Kentucky, three water-related ecosystem services were selected for this study: water retention, soil retention, and water purification.

(2) Ecosystem services evaluation

The InVEST (Version.3.3.3) suite of tools has been developed to enable decision makers to assess trade-offs among ecosystem services and to compare the consequences of different future change scenarios, like land use or climate change (Sharp et al., 2016). This study used the Water Yield model (for water retention), the Sediment Delivery Ratio model (for soil retention), and the Nutrient Delivery Ratio model (for nitrogen and phosphorus export) to evaluate the corresponding ecosystem services in Kentucky. A detailed version of our estimation process can be found in supplementary 1. InVEST model parameterization and validations are described in supplementary 2. Data availability and sources are summarized in Supplementary Table 3. Related input parameters can be found in Supplementary Tables 4 and 5.

Water retention: The service of water retention is defined as the ability of ecosystems to intercept or store water resources from precipitation and is calculated by subtracting runoff and evapotranspiration from precipitation (Bai et al., 2011). First, we estimated precipitation minus evapotranspiration by using the water yield model in InVEST. Then, water retention was calculated by subtracting runoff from water yield. In InVEST, the annual water yield for each pixel is estimated based on average annual precipitation and the Budyko curve (Sharp et al., 2016). The calculation further involves data on mean annual precipitation, annual reference evapotranspiration, and correction factors for vegetation type, soil depth, and plant-available water content (Sharp et al., 2016) (Supplementary Tables 3–5; Supplementary 1.1). Then, we used an extended model to evaluate water retention, which is calculated by subtracting runoff from water yield (supplementary 1.2).

Soil retention: The InVEST sediment delivery ratio model maps overland sediment generation and delivery to the stream. For each cell, the model first computes the amount of eroded sediment, then the sediment delivery ratio, which is the proportion of soil loss that reaches the catchment outlet to the total amount eroded (Sharp et al., 2016). The amount of annual soil loss in each pixel is computed using the revised universal soil loss equation (RUSLE). Outputs from the sediment model include the annual sediment load delivered to the stream, as well as the amount of sediment eroded in the catchment and retained by vegetation and topographic features. The input data for the Sediment Delivery Ratio model includes maps of land cover and land use, digital elevation models (DEM), rainfall, and soil erodibility, along with biophysical attributes related to sediment retention based on land cover (Supplementary Tables 3–5; Supplementary 1.3).

Water purification: The InVEST Nutrient Delivery Ratio model maps nutrient sources from watersheds and nutrient transport to the stream (Sharp et al., 2016). The model uses a mass balance approach, describing the movement of nutrient mass through space. Sources of nutrients across the landscape, also called nutrient loads, are determined based on the land use map and associated loading rates. Nutrient export from each pixel is represented by the product of the load and the nutrient delivery ratio. Each pixel's load is modified to account for the local runoff potential, which can be divided into surface and subsurface runoff (Sharp et al., 2016). Although there are multiple potentially significant impairments of water quality, in this study we focused on nitrogen (N) and phosphorous (P). The input data for the water purification model includes maps of land cover and land use, DEMs, and rainfall, along with biophysical attributes related to the nutrient loading and retention efficiency for each land use and land cover class (Supplementary Tables 3–5; Supplementary 1.4).

2.2.3. Factor analysis

(1) Land use and climate change settings

The combined effects of land use and climate changes and their relative importance on ecosystem services can be evaluated by developing various scenarios with different land use and climate conditions. We created four scenarios using two periods of land use and climate data to explore the combined effects of land use and climate change on Kentucky's ecosystem services. Scenario 1, the baseline, was based on real environmental conditions in 1992. Scenario 4 was based on real environmental conditions in 2011. In contrast, in scenario 2, climate was kept constant from 1992 to 2011, leaving land use change as the sole driver affecting changes in ecosystem services. In scenario 3, land cover remained constant from 1992 to 2011, leaving only the effects of climate change to relate to changes in ecosystem services (Table 1). Using this approach, we were able to disaggregate the impacts of different facets of change on ecosystem service provision.

(2) Relative importance and combined effects analysis

Two potentially relevant indicators were proposed for effects analysis, namely, a relative importance index (RII) and a combined effect index (CEI). These two metrics were calculated for each water-related ecosystem service type at the scale of the entire state of Kentucky.

Table 1
Land use and climate scenario settings.

	Land use 1992	Land use 2011
Climate 1992	Scenario 1	Scenario 2
Climate 2011	Scenario 3	Scenario 4

RII reflects the relative influence of various factors (e.g., land use and climate in this study) on ecosystem services in each pixel. A value greater than 0 indicates that land use change has a greater relative importance than climate change. A value lower than 0 indicates climate change has greater relative importance than land use change, and a value of 0 indicates that the influence of both factors is equal. RII is calculated as:

$$\mathrm{RII} = \frac{|ES_{scenario2} - ES_{scenatio1}| - |ES_{scenatio3} - ES_{scenatio1}|}{\max(ES_{scenario1})}, \begin{pmatrix} >0,\text{Landuse} \\ =0,\text{Equal} \\ <0,\text{Climate} \end{pmatrix}$$

CEI reflects the combined effects of climate and land use factors on ecosystem service provision in each pixel. A value greater than 0 indicates land use and climate factors have an inhibitory effect on ecosystem service. A value lower than 0 indicates land use and climate factors have a synergistic effect on ecosystem service. A value of 0 indicates a state independent from the effects of these variables. CEI is calculated as:

$$\mathrm{CEI} = \frac{((ES_{scenario2} - ES_{scenario1}) + (ES_{scenario3} - ES_{scenario1})) - (ES_{scenario4} - ES_{scenario1})}{\max(ES_{scenario1})}, \begin{pmatrix} >0,\text{Inhibitory} \\ =0,\text{Independant} \\ <0,\text{Synergistic} \end{pmatrix}$$

which can be simplified to:

$$\mathrm{CEI} = \frac{ES_{scenario2} + ES_{scenario3} - ES_{scenario1} - ES_{scenario4}}{\max(ES_{scenario1})}, \begin{pmatrix} >0,\text{Inhibitory} \\ =0,\text{Independant} \\ <0,\text{Synergistic} \end{pmatrix}$$

where, $ES_{scenario1}$, $ES_{scenario2}$, $ES_{scenario3}$, $ES_{scenario4}$ represents the value of sole or aggregated ecosystem services in each scenario set.

2.3. Ecoregion zoning

The United States Environmental Protection Agency (US EPA) and United States Forest Service (USFS) have different definitions and delineations of ecoregions based on similarity in ecosystems and climate, and in the type, quality, and quantity of environmental resources present (Omernik and Griffith, 2014). Kentucky has a distinct horizontal landscape distribution. To create a more accurate ecosystem services assessment and more targeted ecosystem management strategies, distinct ecoregions within the landscape should be considered. We divided the study area into three ecoregions, namely, the mountainous landscapes in the east (Eastern Kentucky, 29,472 km^2, 28% of total area), the pasture landscape in the central study area (Central Kentucky, 52,882 km^2, 50% of total area), and the cultivated landscape to the west (Western Kentucky, 22,395 km^2, 22% of total area) (Fig. 1). The zoning process was performed in 'Focal statistics' module in ArcGIS using a land use layer as input. Neighborhood settings were specified as 30*30 cells and the statistics type was 'Majority'.

2.4. Data requirement and preparation

The InVEST model requires multiple gridded data sets combined with specific biophysical data as inputs. For example, DEM data with a spatial resolution of 10 m was downloaded from the Kentucky Geoportal. Spatial data for the state of Kentucky and other relevant data collected for this study are listed in Supplementary Table 3, which includes summaries of each dataset by source, a short introduction, and the associated models. Also, Supplementary Tables 4 and 5 list key parameters used in the InVEST model. All spatial layers were resampled to a 30 m resolution and assigned the Kentucky State Plane FIPS 1600 reference system.

Table 2
Land use composition in 1992–2011 as percent and total area (km^2).

	1992		2011	
	Area	Percentage	Area	Percentage
Water	1947.48	1.86%	1944.08	1.86%
Developed	1832.64	1.75%	7823.75	7.47%
Barren	251.17	0.24%	493.72	0.47%
Forest	59721.11	57.01%	54280.73	51.82%
Shrubland	213.99	0.20%	397.92	0.38%
Grassland	3585.18	3.42%	4456.52	4.25%
Pasture	21567.34	20.59%	22610.39	21.59%
Cultivated	13796.91	13.17%	11638.70	11.11%
Wetland	1833.18	1.75%	1103.20	1.05%
Total	104,749	100%	104,749	100%

3. Results

3.1. Land use and climate change

3.1.1. Land use change

Forest is the dominant land use type in Kentucky, occupying 51.82% of the state's total area in 2011. However, forest area decreased from 59721.11 km^2 in 1992 to 54280.73 km^2 in 2011 (Table 2). From 1992 to 2011, 80.62% of forest cover was retained, 9.28% was converted into pasture, and 4.95% was converted into developed land (Table 3). In 2011, 88.70% of forest cover was forested in 1992; 4.15% of forest land in 2011 came from pasture, and 3.52% came from previously cultivated land. The area of cultivated land, wetlands, and water also decreased from 1992 to 2011, with 15.64%, 39.82%, and 0.17% reductions in area, respectively. Cultivated land was largely converted to pasture, forest, and developed land. Wetlands mainly transitioned to forest, cultivated, and pasture. The area of developed, pasture, and barren lands increased by 326.91%, 4.84% and 96.57% in area, respectively, between 1992 and 2011. The increase in developed land mainly came from the modification of forest, pasture, and cultivated lands. Pasture lands in 2011 were generally forest and cultivated land in 1992. The increase of barren land mainly came from forest and grassland.

Land use composition and transition varied among the three ecoregions (Supplementary Fig. 2). In western Kentucky, cultivated was the dominant land use type, which covered an area of 8341.98 km^2 in 2011, or 37.25% of the total western Kentucky region. Moreover, the area of cultivated land increased between 1992 and 2011 (Supplementary Tables 6 and 7). This increase in cultivated area was largely from the conversion of pasture (3065.31 km^2) and forest (530.28 km^2) (Supplementary Table 8). Meanwhile, forest area increased from 6707.33 km^2 in 1992 to 7642.40 km^2 in 2011. Developed area increased from 398.87 km^2 in 1992 to 1361.82 km^2 in 2011. Conversely, pasture area decreased from 6327.59 km^2 in 1992 to 2981.03 km^2 in 2011.

Forest occupied 46.67% of the total area of central Kentucky in 2011, however, its spatial distribution of forest cover was not contiguous. Forest cover in central Kentucky was mostly composed of shelterbelt and vegetative buffers for rivers, grassland, and cultivated land. The area of pasture increased greatly from 14410.43 km^2 in 1992 to 17682.21 km^2 in 2011. This increase mainly came from the conversion of forest (4235.34 km^2) and cultivated lands (3327.28 km^2) (Supplementary Table 9). As in western Kentucky, developed area increased from 1250.42 km^2 in 1992 to 4377.61 km^2 in 2011. In contrast, cultivated land decreased by 52.97% between 1992 and 2011 due to conversion to pasture and forest.

In eastern Kentucky, forest was the dominant land use type, which covered an area of 22090.44 km^2 in 2011, or 74.95% of the total area of eastern Kentucky. However, the area of forest cover decreased between 1992 and 2011. This decrease mainly came from conversion to developed land (1628.38 km^2) and pasture (1261.53 km^2) (Supplementary Table 10). Developed area, unsurprisingly, increased from 182.44 km^2 in 1992 to 2093.85 km^2 in 2011.

Developed area increased in all three ecoregions between 1992 and 2011, with a 243.28% increase in western Kentucky, 252% increase in central Kentucky, and 1076.2% in eastern Kentucky. Forest area only increased in western Kentucky, with a slight increase of 13.94%, and decreased in central Kentucky and eastern Kentucky, by 10.09% and 14.04%, respectively. Pasture area decreased in western Kentucky and increased in both central and eastern Kentucky. Cultivated area increased in western Kentucky and decreased in central and eastern Kentucky.

3.1.2. Climate change

The overall climate of Kentucky showed a wetting and warming trend in the 1981–2016 period. Both mean annual precipitation and mean annual temperature in Kentucky increased over the 1981–2016 period, by quantities of 6.312 $mm \cdot a^{-1}$ and 0.0108 $°C\,a^{-1}$, respectively (Fig. 3). The 5-year average value of precipitation increased from 1207 mm for the period from 1992 to 1996 to 1398 mm for 2011 to 2015; the 5-year average value of temperature increased from 12.91 °C for the period from 1992 to 1996 to 13.53 °C for 2011 to 2015.

The 5-year average values of precipitation and temperature presented different spatial change patterns between the period from 1992 to 1996, and the period from 2011 to 2015. Between 1992 and 1996, the spatial distribution of high precipitation values was relatively narrow, existing mainly in the southern regions of eastern and central Kentucky. In contrast, the range of high values significantly expanded between 2011 and 2015, which was mainly located in central Kentucky, western Kentucky, and the southern part of eastern Kentucky (Supplementary Fig. 3). Unlike precipitation, temperature showed a relatively consistent spatial pattern in both time periods, with high temperatures on the western side of the state and low temperature on the eastern side (Supplementary Fig. 4).

Table 3
Land use conversion matrix from 1992 to 2011 (km^2).

		2011								
		Water	Developed	Barren	Forest	Shrubland	Grassland	Pasture	Cultivated	Wetland
1992	Water	1612.17	13.75	23.60	129.88	1.06	13.60	31.95	38.68	77.29
	Developed	9.06	1342.90	2.93	225.40	1.47	13.79	160.33	68.17	7.53
	Barren	6.65	25.74	38.15	41.32	0.71	101.37	13.31	21.71	2.06
	Forest	194.47	2954.72	348.51	48117.26	151.73	1047.15	5541.35	1047.84	280.37
	Shrubland	0.06	1.43	0.38	33.94	171.07	1.86	4.71	0.25	0.19
	Grassland	7.32	346.27	54.63	637.61	16.25	2324.16	123.02	68.66	5.16
	Pasture	17.40	1989.61	11.73	2251.34	25.47	647.75	12328.74	4245.00	37.39
	Cultivated	50.75	1108.48	10.77	1909.57	22.62	283.74	4323.69	5952.06	126.97
	Wetland	36.14	36.18	2.69	903.23	7.32	20.58	70.67	189.71	565.45

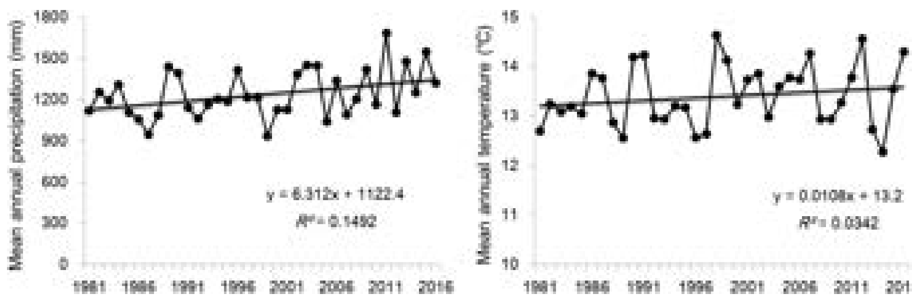

Fig. 3. The temporal variation of mean annual precipitation (left) and mean annual temperature (right), 1981–2016 in Kentucky.

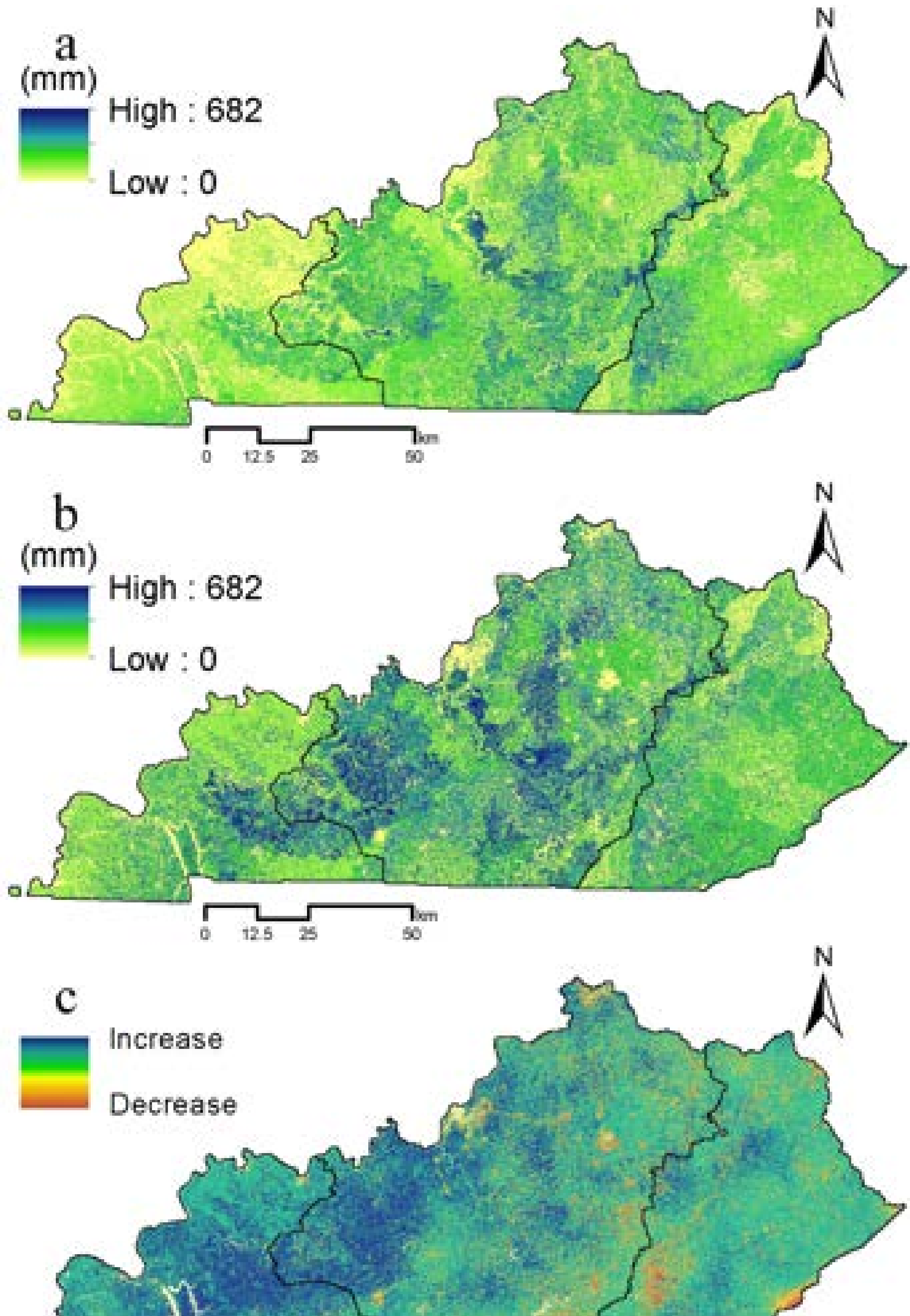

Fig. 4. Spatial distribution and changes in water retention from 1992 to 2011. (a: water retention in 1992; b: water retention in 2011; c: changes from 1992 to 2011).

3.2. Ecosystem services change

3.2.1. Water retention

Total water retention for the state of Kentucky was 12.78 billion m^3 in 1992. In 2011, after land use and climate change, water retention was 65.19% higher, at a total value of 21.11 billion m^3 (Fig. 4). Water retention increased across all three ecoregions. Although western Kentucky contributed the lowest total water retention (10.83% in 1992 and 18.23% in 2011) of the three ecoregions, it contributed the highest increase from 1.38 billion m^3 in 1992 to 3.85 billion m^3 in 2011, with an increase rate of 178.08%, due to the increase in forest area and precipitation. In spite of extensive forest loss and developed land expansion in central and eastern Kentucky, water retention still showed increases of 53.80% and 46.19%, respectively, mainly due to the increase in precipitation. Despite the overall increase in water retention, many locations in east-central Kentucky and in the southern part of eastern Kentucky experienced reductions in water retention due to the expansion of developed areas at the expense of forest and pasture (Fig. 4).

Forest land presented the highest water retention capacity, with mean values of 158 mm in 1992 and 285 mm in 2011. However, the water retention capacity of forest land varied among the three ecoregions. Driven by the spatial heterogeneity of precipitation and slope, forests in central Kentucky provided the highest water retention capacity, with mean values of 201 mm in 1992 and 331 mm in 2011. This made central Kentucky a hotspot for the provision of water retention services during the study period.

3.2.2. Soil retention

Soil retention was 29.69 million tons in 1992 and 33.32 million tons in 2011, demonstrating a 12.24% increase (Fig. 5). The three ecoregions also showed individual increasing trends in total soil retention as well. Western Kentucky contributed the lowest total soil retention (2.96% in 1992 and 3.49% in 2011) of the three ecoregions, but showed the greatest soil retention increase from 0.88 million t in 1992 to 1.16 million t in 2011 (a 32.41% increase), mainly due to the increase of forest area. In both central and eastern Kentucky, soil retention rates increased 17.10% and 9.50%, respectively. Despite the overall increase in soil retention amounts, several areas in central and eastern Kentucky experienced reductions in soil retention due to forest and pasture loss (Fig. 5).

Forest land presented the highest soil retention capacity, with a mean value of 4.80 t/ha in 1992 and 5.54 t/ha in 2011. However, the level of forest soil retention varied among the three ecoregions. Topography plays a large role in soil retention. Forests in eastern Kentucky showed the highest soil retention capacity of the three ecoregions, with a mean value of 7.88 t/ha in 1992 and 10.26 t/ha in 2011. In a mapping of soil retention capacity across the state, eastern Kentucky was a hotspot for the provision of soil retention services.

3.2.3. Nitrogen and phosphorus export

Nitrogen export and phosphorus export generally presented the same change patterns in 1992 and 2011(Figs. 6 and 7). The total amounts of nitrogen export and phosphorus export increased 7.33% and 9.98%, respectively, between 1992 and 2011. Meanwhile, all three ecoregions showed increases in total nutrient export. Conversely from water and soil retention, eastern Kentucky had the lowest contribution of nutrient export. Nitrogen export in eastern Kentucky contributed 19.54% and 22.10% of the state totals in 1992 and 2011, respectively. Phosphorus export in eastern Kentucky contributed 10.91% and 16.11% of the state totals in 1992 and 2011, respectively. Eastern Kentucky also showed the greatest increase in nutrient export, with a 21.38% increase in nitrogen export and a 62.41% increase in phosphorus export between 1992 and 2011. Spatially, most of western Kentucky and the northwestern portion of central Kentucky showed increases in nitrogen and phosphorus export while most of eastern Kentucky and the southern part of central Kentucky showed a slightly decrease trend (Figs. 6 and 7).

Forest land demonstrated the lowest nutrient export capacity, with a mean nitrogen export values of 2.36 kg/ha in 1992 and 2.33 t/ha in 2011, and mean phosphorus export values of 0.49 kg/ha in 1992 and 0.48 kg/ha in 2011. The capacity of forest nutrient export varied among the three ecoregions. Forests in eastern Kentucky showed the highest nutrient export capacity with mean nitrogen export values of 2.58 kg/ha in 1992 and 2.62 kg/ha in 2011 and mean phosphorus export values of 0.54 kg/ha in 1992 and 0.55 kg/ha in 2011. A mapping of nutrient export across the state showed the highest nutrient export areas (or hotspots) in cultivated land in western Kentucky. Areas with the lowest nutrient export values were mainly distributed in the forests of western Kentucky.

3.3. Factor analysis

3.3.1. Relative importance

When assessed at the state level with all pixels considered, climate change has a greater impact than land use change on water retention and nitrogen and phosphorus export. The RII showed that climate change was a stronger influence than land use on water retention in 57.52% of pixels, on nitrogen export in 58.43% of pixels, and on phosphorus export in 55.29% of pixels. Soil retention presented a different pattern in which land use change played a stronger role than climate change. Soil retention was more strongly influenced by land use change than climate change in 80.79% of the total pixels (Fig. 8).

When only the land use changed pixels were considered, all water-related ecosystem services indicated that land use change had a greater impact than climate change. Land use change had a significantly higher impact on soil retention in 87.80% of pixels, on nitrogen export in 88.63% of pixels, and on phosphorus export in 89.74% of pixels. Water retention still showed a lower sensitivity to land use change than soil retention and nutrient export. Land use change more strongly influenced water retention in 46.11% of pixels, and climate change more strongly influenced water retention in 45.71% of pixels. The influence of land use change on water retention and soil retention increased from west to east. Land use change more strongly influenced water retention in 23.43% pixels in western Kentucky, 53.58% of pixels in central Kentucky, and 60.15% of pixels in eastern Kentucky. The pattern was the same for soil retention; soil retention in 82.76% of pixels in western Kentucky, 89.33% of pixels in central Kentucky, and 89.42% of pixels in eastern Kentucky was more heavily influenced by land use change. However, nitrogen and phosphorus export presented a different pattern. The influence of land use change on nitrogen and phosphorus export decreased from west to east (Fig. 9a). The influence of climate change exhibited an opposite pattern, which increased from the west to east on water retention and soil retention and decreased on nitrogen and phosphorus export (Fig. 9b).

3.3.2. Combined effect

Land use and climate change presented an inhibitory effect on water retention in 50% of the total pixels in the state, on soil retention in 42.62% of pixels, on nitrogen export in 42.39% of pixels, and on phosphorus export in 43.17% of pixels. Land use and climate change presented a synergistic effect on water retention in 42.63% of pixels, on soil retention in 47.14% of pixels, on nitrogen export in 36.89% of pixels, and on phosphorus export in 37.53% of pixels (Fig. 10).

When considering only land use change pixels, inhibitory effects can be seen in water retention in 57.35% of pixels, in soil retention in 41.42% of pixels, in nitrogen export in 50.99% of pixels, and in phosphorus export in 51.15% of pixels. Additionally, synergistic effects can be seen in water retention in 35.65% of those pixels, in soil retention in 50.67% of pixels, in nitrogen export in 45.60% of pixels, and in phosphorus export in 45.78% of pixels. Water retention and soil retention were the services most inhibited by land use and climate change in

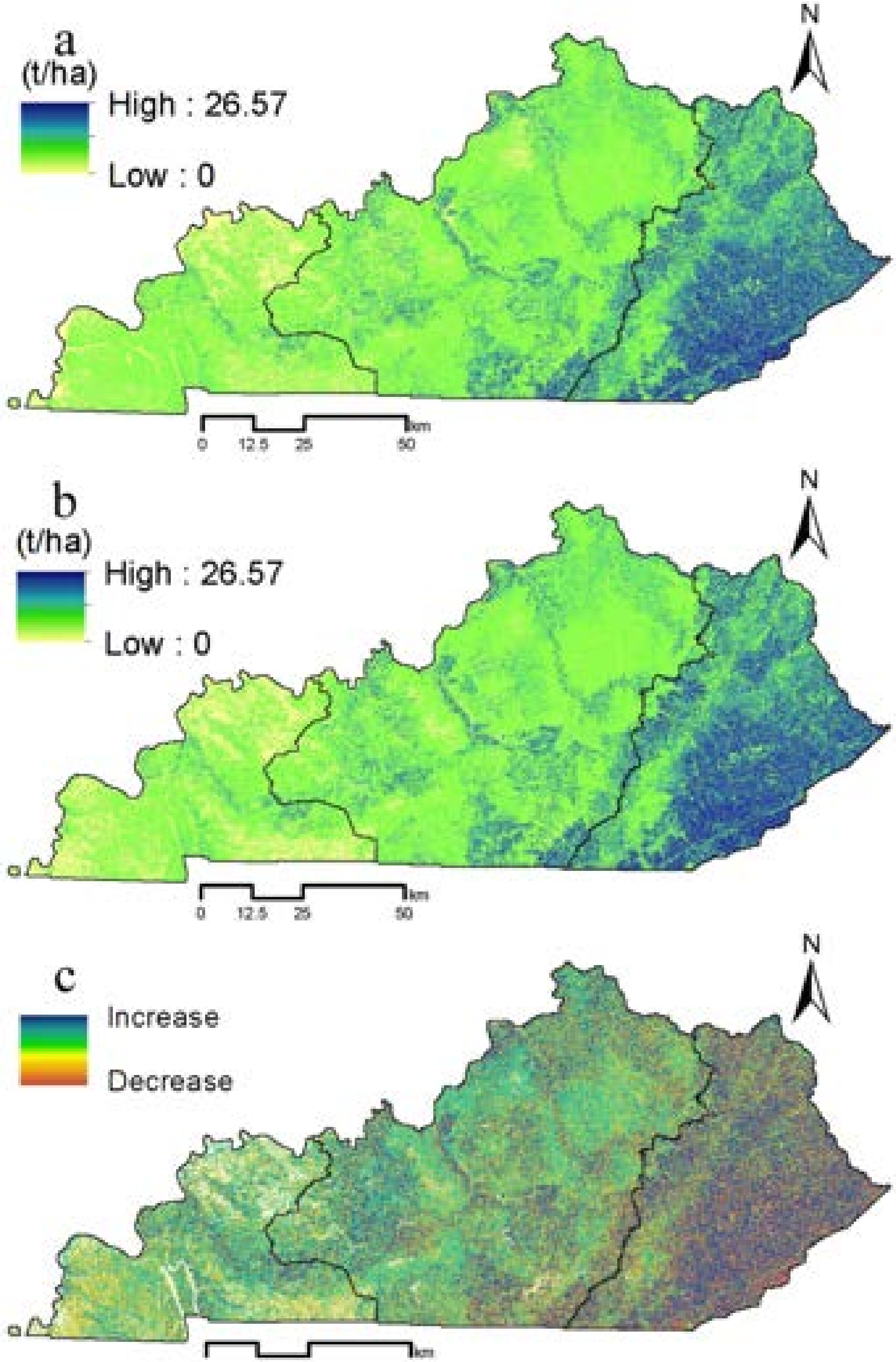

Fig. 5. Spatial distribution and changes in soil retention from 1992 to 2011 (a: soil retention in 1992; b: soil retention in 2011; c: changes from 1992 to 2011).

eastern Kentucky, where water retention in 70.33% of pixels and soil retention in 53.38% of pixels experienced inhibitory effects. Inhibitory effects on nitrogen and phosphorus export increased from west to east. Nitrogen export was inhibited in 45.40% of pixels in western Kentucky and 61.84% of pixels in eastern Kentucky. Phosphorus export experienced inhibitory effects in 46.97% of pixels in western Kentucky and 59.37% of pixels in eastern Kentucky (Fig. 11a). Conversely, synergistic effects on water retention and soil retention were highest in the central Kentucky and decreased to both the eastern and western sides. Synergistic effects on nitrogen and phosphorus export decreased from the west to east (Fig. 11b).

4. Discussion

4.1. Land use and climate effect

Integrating scenario analysis with ecosystem service evaluation provides an efficient and powerful way to evaluate the relative importance and combined effects of factors on ecosystem services (Runting et al., 2016; Martinez-Harms et al., 2017). A relative importance index and combined effect index were proposed and calculated in this study to evaluate trade-offs among different global change scenarios. RII, as stated above, was used to identify which factor has more significant impacts on ecosystem service provision. CEI was used

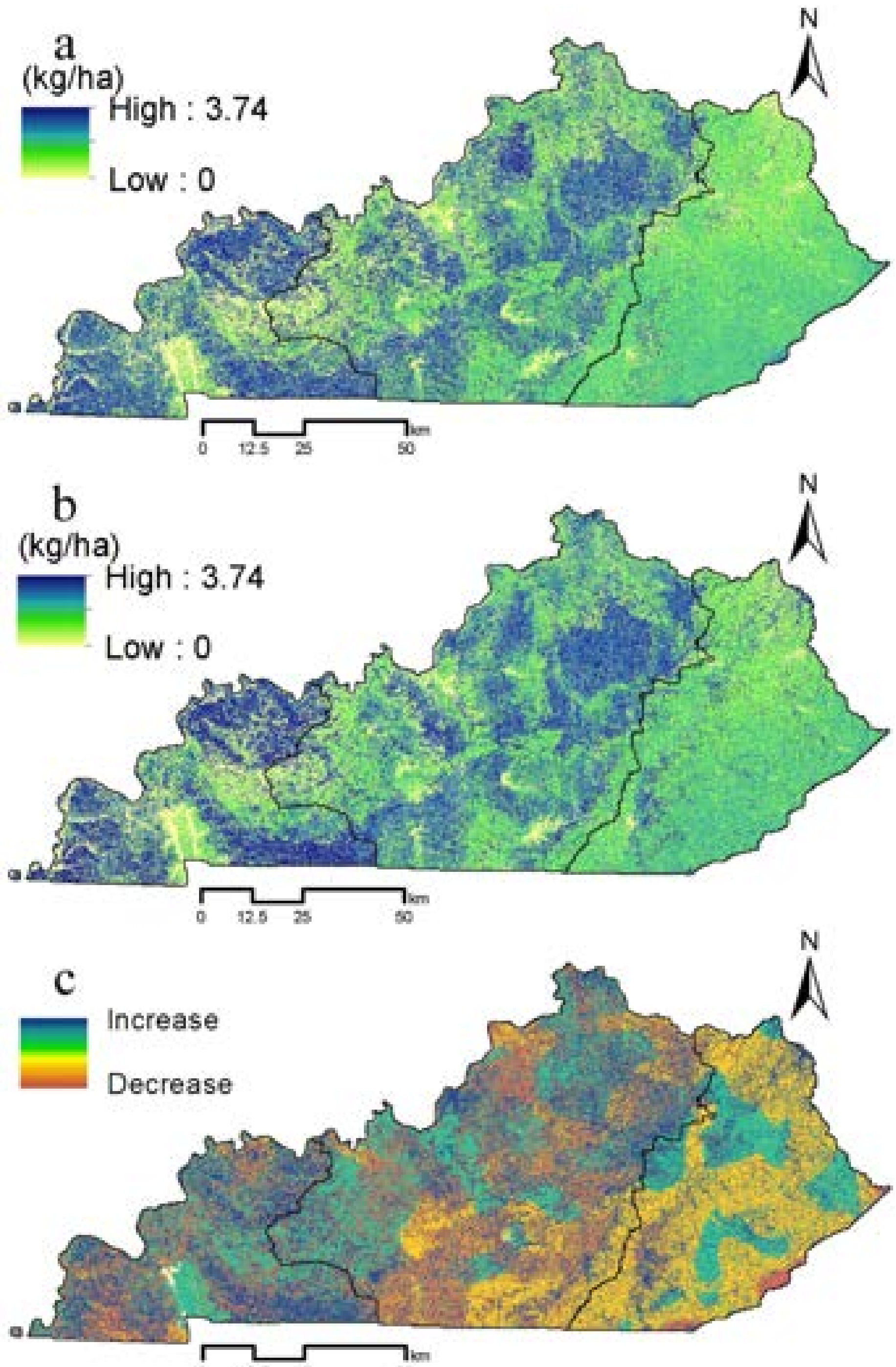

Fig. 6. Spatial distribution and changes in nitrogen export from 1992 to 2011 (a: nitrogen export in 1992; b: nitrogen export in 2011; c: changes from 1992 to 2011).

to identify the combined effects of climate factors and land use factors on ecosystem service provision. Generally, the combined effects can be categorized as synergistic or inhibitory. Using these tools, we assessed the impact of land use and climate change factors on the provision of ecosystem services in Kentucky, which had seldom been explored before. Our results demonstrate that land use change, climate change, and their interactions placed substantial pressures on the capacity of ecosystems for ecosystem service provision.

In accordance with existing studies (Hoyer and Chang, 2014; Castillo et al., 2014; Fu et al., 2017), climate change has a greater impact on water retention than land use change at a large scale. For soil export and nutrient export, land use had greater impacts than climate change. At smaller spatial scales, such as the ecoregions investigated in this study, land use presented a more important impact than climate change on soil retention and nutrient export. Nutrients were transported through surface and subsurface flow, and additional anthropogenic nutrient sources include point sources, e.g. industrial effluent or water treatment plant discharges, and non-point sources, e.g. fertilizer used in agriculture and residential areas, which contribute significantly to nutrient export (Sharp et al., 2016). But in a mountainous area like eastern Kentucky, where forested area is decreasing, land use change had a greater effect on all water-related ecosystem services. It has been demonstrated that forests have the potential to adapt to climate change but are sensitive to human activities (Egan and Price,

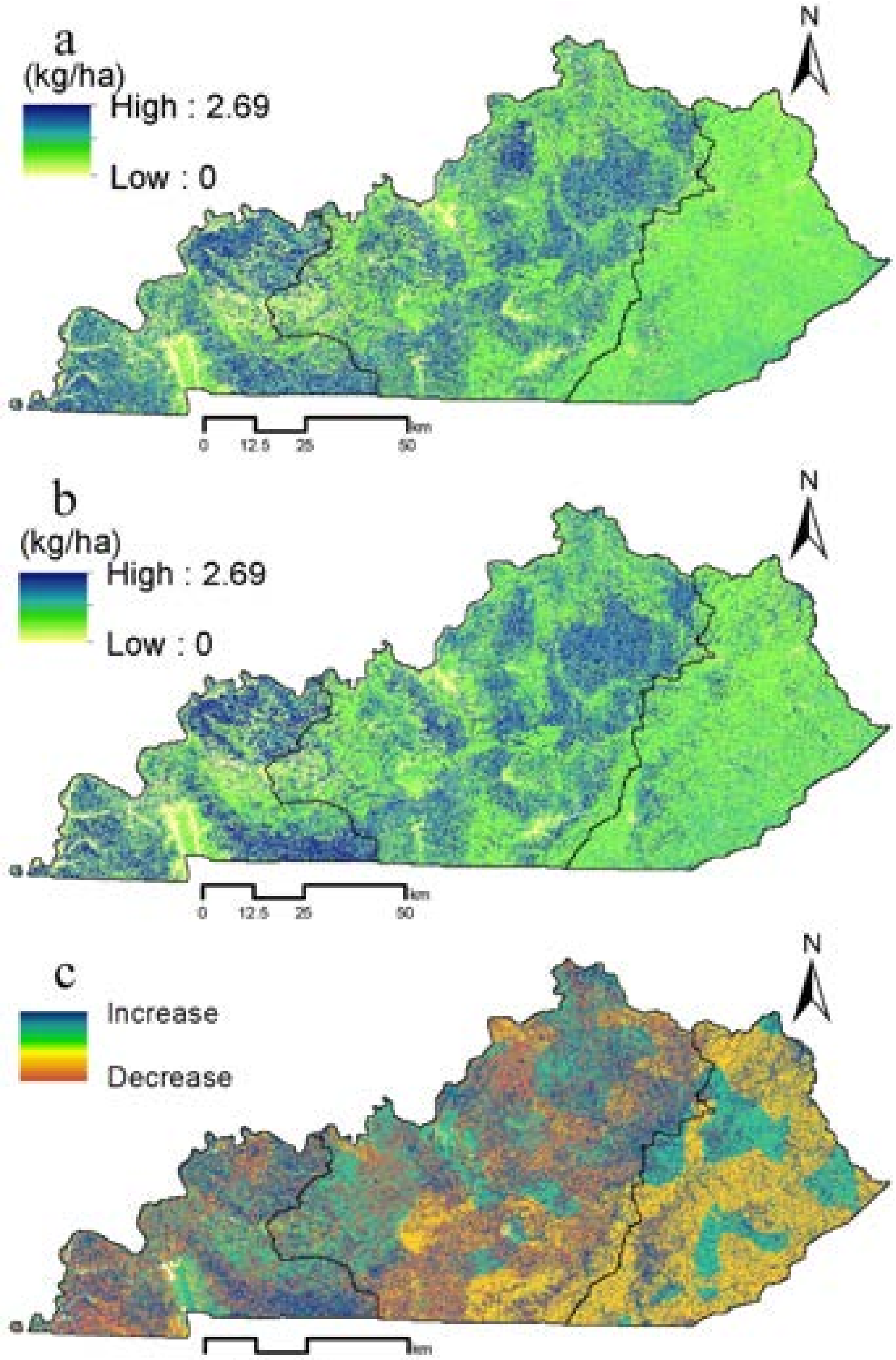

Fig. 7. Spatial distribution and changes in phosphorus export from 1992 to 2011 (a: phosphorus export in 1992; b: phosphorus export in 2011; c: changes from 1992 to 2011).

2017; Schirpke et al., 2017). Loss of forest will decrease the capacity of ecosystems to continue to maintain ecosystem service provision (Zank et al., 2016; Kim et al., 2017).

From cultivated landscapes (Western Kentucky) to pasture landscapes (Central Kentucky) to forest landscapes (Eastern Kentucky), our results showed increasing effects of land use change on water retention and soil retention, and decreasing effects of land use change on nitrogen and phosphorus export. Conversely, for water retention and soil retention, the percentage of pixels more strongly influenced by climate change decreased, and for nitrogen and phosphorus export, the percentage of pixels more strongly influenced by climate change increased during the study period. In addition, we observed that only 30.79% of pixels actually experienced land use change from 1992 to 2011. However, according to results in the relative importance index, land use change more strongly influenced water retention in 15.32% of pixels, soil retention in 57.01% of pixels, nitrogen export in 57.84% of pixels, and phosphorus export in 58.95% of pixels. Those areas were affected by spillover, which is worth investigating further in the future.

For more informed decision making, policy-makers are interested not only in the relative importance of factors, but also in the combined effects of those factors (Fu et al., 2017). In cultivated landscapes (western Kentucky), land use and climate change had a greater

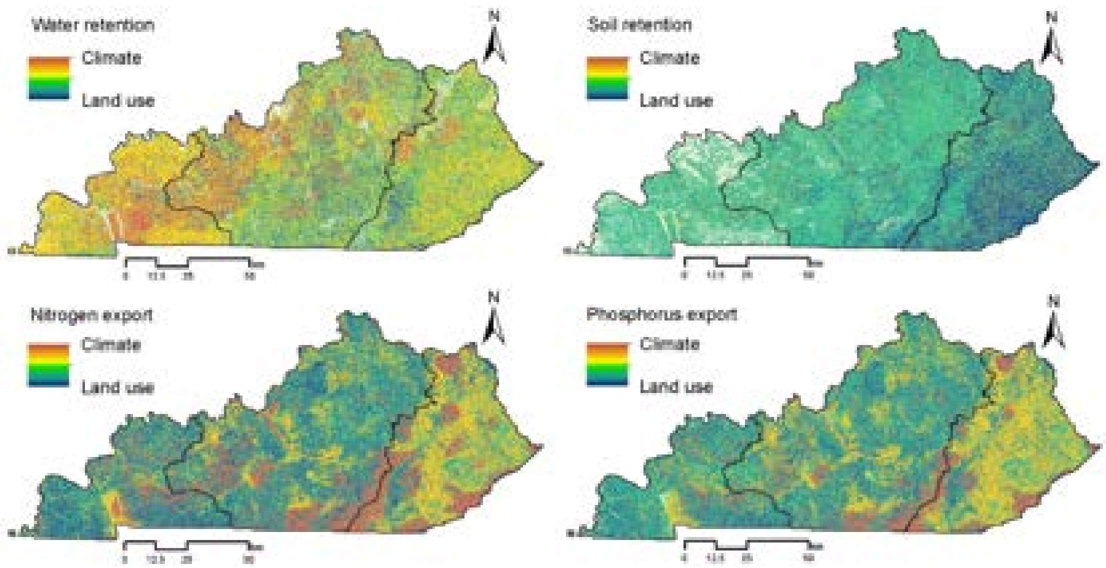

Fig. 8. Relative importance of land use and climate on ecosystem services.

synergistic effect on soil retention and nutrient export, which is useful knowledge to inform agricultural practices. Furthermore, the combined effects of land use and climate were greater than their individual effects in the cultivated areas of this study. Managers could use this information to make strategic land use changes to adapt to future climate scenarios, and thereby optimize the production of desired ecosystem services. In contrast, in the mountainous forest landscapes of our study (eastern Kentucky), most of the areas experienced inhibitory effects from land use and climate change on all selected ecosystem services. Land use change reduced water and soil retention capacities, but climate change increased them. In this case, managers would need to focus resources on offsetting the negative consequences of either climate change or land use change to enhance ecosystem services provision.

4.2. Strategies and implications

Our approaches, which facilitate identification of hotspots of ecosystem service gains and losses, can be used for more-informed environmental investments decisions. One of the Sustainable Development Goals specifically mentioned in the 2030 Agenda for Sustainable Development (United Nations, 2015) is the protection and restoration of water-related ecosystems (Egan and Price, 2017). Local policy makers are anxious to know where to protect and invest (Bai et al., 2016), in order to maintain ecosystem service provision. Our maps and comparisons provide a potential tool for identifying what areas are most sensitive to land use change and climate change, which allows for a cost-effective spatial targeting of investment needs for enhancing or restoring ecosystem services (Hoyer and Chang, 2014). In Kentucky, our ecosystem service distribution and change maps suggest that ecosystem service enhancement measures targeting forest area in central and eastern Kentucky would lead to the most gains in water and soil retention. Enhancement measures in cultivated and pasture areas (i.e. forest and forest corridor restoration) in western Kentucky would lead to the greatest reductions in nutrient export.

Second, local policy makers can benefit from results of this study by gaining an understanding of how to protect ecosystems integrity and enhance provision of ecosystem services. Our approach helps to bridge science-policy-management gaps through its techniques for assessing the relative importance and combined effects of land use and climate changes on ecosystem services with two simple indicators. Moreover, from science to policy, the spatially explicit maps of water-related ecosystem services can provide an important basis for landscape policies and management decisions (Figs. 8 and 10). These maps provide a means to quantify changes in ecosystem services driven by land use and climate factors (Kindu et al., 2016). From our relative importance analysis, we showed that land use change had a significantly higher impact on soil retention and nitrogen and phosphorus export than climate change, especially in forested areas like eastern Kentucky. Our results suggest that wise land use management could increase the capacity of ecosystems to provide water-related ecosystem services. Meanwhile, based on the synergistic or inhibitory effects across space, policy-makers can identify better tradeoffs to ensure effective provision of desired ecosystem services. Policy-makers can adopt climate-adaptive management by pinpointing synergistically influenced hotspot areas as priorities for future protection. Additionally, policy makers could choose areas impacted by inhibitory effects for forest restoration, as intensive forest loss was seen in such areas in our case study.

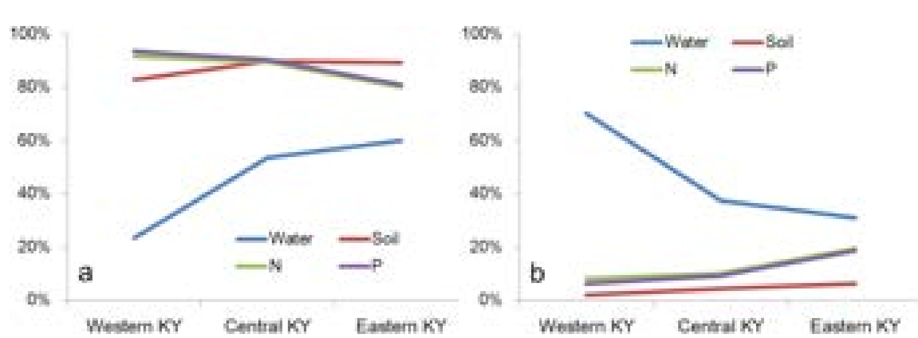

Fig. 9. Percentage of pixels mainly influenced by land use (a) and climate (b).

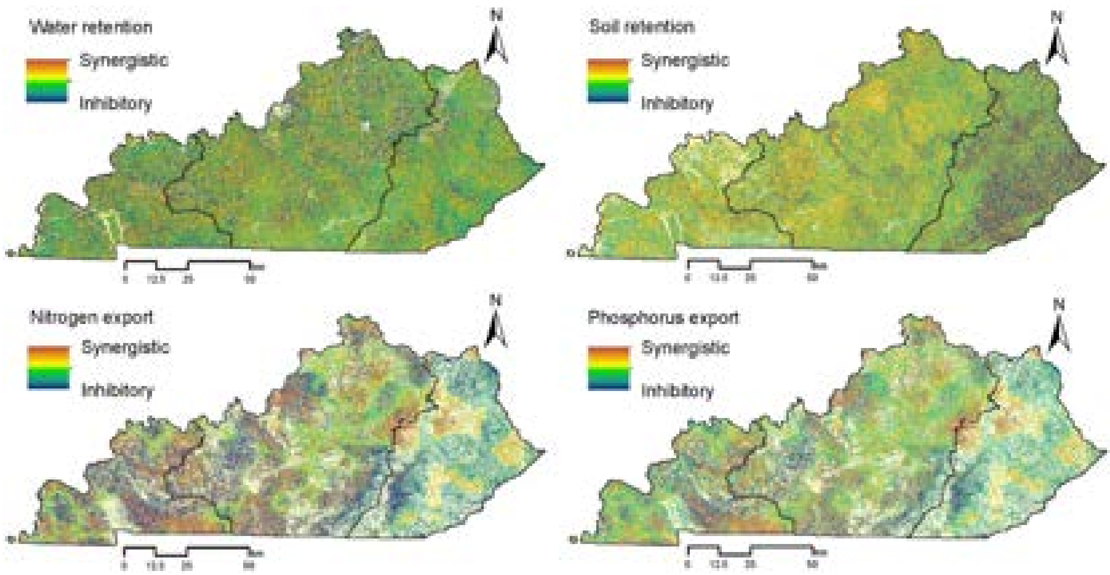

Fig. 10. Combined effects of land use and climate on ecosystem services (a: water retention; b: soil export; c: nitrogen export; d: phosphorus export).

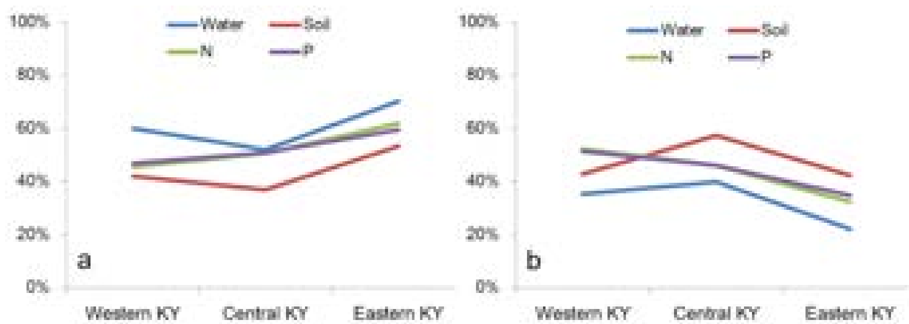

Fig. 11. Percentage of pixels undergoing inhibitory (a) and synergistic (b) effects.

Environmental policies and management strategies should always consider scale, as ecosystem service provision and analyses are scale-dependent. As shown in this and other studies (Fu et al., 2017), the characteristics of landscape composition, ecosystem service changes, and factor effects were completely different between large scale (state) and small scale (ecoregion). Policies that consider these scale-dependent changes are more likely to be effective and cost-efficient. For example, in mountainous areas (eastern Kentucky), while land use was more influential than climate change, land use and climate change had combined effects that differed from their individual effects on the selected ecosystem services. Loss of forest decreases the capacity of ecosystems to maintain ecosystem services provision (Zank et al., 2016). Increasing the forest coverage in mountainous areas would increase ecological resistance to climate change and adaptability of the inhabitants, and would still maintain and enhance the provisioning of ecosystem services (Egan and Price, 2017). However, forest area has diminished in eastern Kentucky over the past 20 years at an alarming rate due to intensive human activities, such as surface coal mining and timber harvesting (Lindberg et al., 2011).

Kentucky is internationally known as the Bluegrass State because of the iconic pasture landscapes in the central part of the state where world-famous race horses are raised. Pasture land supports both provisioning and regulating ecosystem services and helps to preserve the aesthetic, recreational, and cultural values of the landscape (Bernues et al., 2014; Schirpke et al., 2017). The area of pasture land in central Kentucky increased between 1992 and 2011, which has positive impacts to ecosystem service production and human wellbeing. However, afforestation is recommended in this ecoregion (i.e. riparian buffers or shelterbelt forests) to prevent soil loss and nutrient export. Cultivated land is as important as pasture as it provides vital ecosystem services, such as food, fiber, and recreation space (Bai et al., 2013). The construction of riparian buffers or shelterbelt forests is also recommended in western Kentucky to control agricultural non-point source pollution. However, additional tradeoffs between food provision and other desired ecosystem services must be taken into account when considering any land cover conversion measures.

To conclude, the analytical framework (Fig. 2) proposed in this study provides an effective tool not only for identifying the hotspots of ecosystem service gains and losses with spatial explicit maps, but also for making trade-off decisions to ensure the provision of desired ecosystem services based on the synergistic or inhibitory effects across landscape. Policy makers can be better-informed on cost-effective spatial targeting of investment for enhancing or restoring ecosystem services. Furthermore, it is evidenced from the results that policy implications from this approach are landscape-dependent and scale-dependent. Our analytical framework is applicable in other regions. However, special attention should be paid to the localized landscape context and planning scales for developing efficient measures to meet local conditions.

4.3. Strengths and limitations

This study has its strengths and weakness, which we summarize here. As stated in the methodological framework (Fig. 2), the main elements of our approach are factor selection, ecosystem services assessment, and factor analysis. Our methodology provides a straightforward way to explore possible implications of land use and climate change for three water-related ecosystem services. This approach is simple and replicable for other regions. Another strength is that the driving factor analysis yields a series of effective and cost-efficient policy implications at both state and ecoregion scales, which provides a basis for landscape management and decision making.

Despite these strengths, this study also has some limitations. First, although RII and CEI can be used to evaluate the effects of factors on ecosystem services, only two factors or two groups of factors can be considered at this stage of analysis. Both indicators may be modified so more factors can be included and analyzed in the future. A more nuanced analysis would allow for a more holistic understanding of ecosystem services change mechanisms and would generate more effective policy recommendations.

This study was carried out at two scales: state and ecoregion. Results differed significantly between these two scales, not only in ecosystem composition and ecosystem service provision, but also in the factors' relative importance and combined effects. Therefore, we recognize the need for future research applying more localized approaches to provide more accurate estimates as the basis for more sustainable landscape decisions (Lorencová et al., 2016). For Kentucky, analysis at the ecoregion scale can yield more detailed information on ecosystem services provision and driving factors for policy-making purposes. Temporal scales should also be considered as most of the climate factors have clearly seasonal characteristics (Hao et al., 2017). It is not unusual for some driving factors to exhibit lag effects on ecosystem services (Wu et al., 2015). Identifying the factors driving changes in water-related ecosystem services at different temporal scales is an important step in optimizing landscape management. We expect to improve our knowledge of how ecosystem services respond to their driving factors at multiple spatial and temporal scales in future studies (Hao et al., 2017).

Although InVEST models have been challenged as less accurate than process-based models such as SWAT (Soil and Water Assessment Tool), they have been widely recognized as suitable for multiple-scale ecosystem services assessments (Vigerstol and Aukema, 2011; Lorencová et al., 2016). However, it is still crucial to consider the modeling and data limitations of InVEST models (Cabral et al., 2016). All the models used here have the same limitations and assumptions described in the software documentation (Sharp et al., 2016). For example, InVEST cannot incorporate seasonal or monthly fluctuation in nutrient loads, which may lead to a potential time scale mismatch between InVEST outputs and management. A time-disaggregated modeling approach would be necessary to address the effects of time-fluctuating runoff on water quality (Hoyer and Chang, 2014).

5. Summary and conclusions

This study provides a comprehensive spatial assessment of water-related ecosystem services and contributes to understanding the historical and interactive effects of land use and climate change on water-related ecosystem services in Kentucky. The combined effects and relative importance of land use and climate change in determining shifts in ecosystem services were determined. The results showed that climate change has a greater impact than land use change on water retention at the state scale. However, land use contributed more significant impacts than climate change on soil retention, nitrogen export, and phosphorus export. In most of our study area, climate change and land use change had an inhibitory effect on water retention and nutrient export at the state scale.

Despite the limitations in this study, the results have practical, methodological, and policy applications which support the use of ecosystem service information in landscape planning for developing more effective ecosystem protection strategies. Our study also supports the hypothesis that climate-adaptive management can help managers generate plans that are more spatially comprehensive. Combined scenario analysis, InVEST models, RII, and CEI can be used as straightforward ways to evaluate effects of driving factors on ecosystem services. These tools facilitate a better understanding of the change mechanisms of ecosystem services and generate more tailored and effective policy suggestions. Finally, this research can guide activities and policies that promote sustainable ecosystem services provision in Kentucky and other similar regions by identifying where and how to protect and invest at the landscape scale.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.01.079.

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