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Quantifying and mapping multiple ecosystem services change in West Africa

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ABSTRACT

Although ecosystem services have been identified to be declining over the previous decades, there is no clear methodology of evaluating the impacts of land use change on ecosystem services. This paper presents a methodology for quantifying and assessing changes in multiple ecosystems services as a result of land use change using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. The model was used to map and quantify biodiversity and four ecosystem services for Ghana and Cote d'Ivoire for 2000, 2005 and 2009 land use conditions: water yield, carbon storage, nutrient retention, and sediment retention. The study developed a suite of indices to analyze land use change impacts on the status, change and spatial patterns of multiple ecosystem services. On a national scale, the results show a mix of increases in service (water yield, N retention and P retention in Ghana, and, N and P retention in Cote d'Ivoire), little change in services (sediment retention in Ghana and sediment retention and water yield in Cote d'Ivoire) and decreases in services (biodiversity and carbon storage in both countries) from 2000 to 2009. The assessment illustrates a methodology that can be employed by land managers in exploring multiple management scenarios and their implications for multiple ecosystem services change.

1. Introduction

Agriculture has become one of the world's largest land uses, consisting of over 40% of total global land area accounting for over 80% of the total global consumptive water use (Foley et al., 2005). Recent studies have shown that increase in agricultural land use can have direct consequences on ecosystem services or reduced productivity which may be considered as an "ecosystem disservice" (Zhang et al., 2007; Dale and Polasky, 2007). There is a critical need to manage locations that are important for maintaining ecosystem services provisioning while maintaining agricultural demand (Wade et al., 2010; van Jaarsveld et al., 2005; Chan et al., 2006; Egoh et al., 2007). This is especially true in many low-income countries in Africa where the conversion of forest to agriculture land is expanding at a rapid pace (Barbier, 2004; Gibbs et al., 2010). Managing ecosystem services requires knowledge of the dynamic patterns and the status of the services of concern and an understanding of the connection and interaction among ecosystem structures, functions, and landforms. Although a number of recent studies have quantified and mapped ecosystem services (e.g. Chan et al., 2006; Egoh et al., 2008, 2009; Nelson et al., 2009), such studies are scarce, especially in the tropics which serves as a major source of the world's biodiversity. For example, out of 153 regional ecosystem services case studies reviewed by Seppelt et al. (2011), over 50% of the studies were located in only six countries (US, China, Sweden, UK, Mexico and Canada) and no study was from West Africa. Further, very few of the studies analyzed multiple ecosystem services (Seppelt et al., 2011). There is a need to develop quantitative methods of evaluating the effects of increased agricultural production on multiple ecosystem services globally (Power, 2010). Unfortunately, many regions of Africa lack such studies primarily due to a lack of data, this is particularly so in West Africa (Seppelt et al., 2011), where rapidly expanding demand for cocoa, shea, cashews and other cash crops is driving agriculture production (Gockowski and Sonwa, 2011; Kolavalli and Vigneri, 2011).

This study performed a biophysical assessment of ecosystem services change by developing spatially explicit models of land use change. The goal of this project was to assess the regional impact of land use change on biodiversity and multiple ecosystem services for the West African countries of Ghana and Cote d'Ivoire. This assessment was achieved by exploring the spatial patterns of the provisioning of multiple ecosystem services in order to better understand linkages and consequences of land use change. Specifically, the objectives of this study were to:

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1. Identify and quantify a set of ecosystem services that are influenced by land use change at the local, subbasin and basin levels.
2. Develop quantitative indices to measure status and change in multiple ecosystem services at the basin and subbasin scale.
3. Quantify changing land use and its impacts on ecosystem services.
4. For each ecosystem service, map locations of changes in services given land use change patterns.

2. Methods

2.1. Study site

The study area encompassed Ghana and Cote d'Ivoire in West Africa. The total area of Cote d'Ivoire is 322, 460 km^2 while Ghana occupies an area of 238, 540 km^2 (FAO, 2011). Both countries are located within three major ecological regions: the Guinean forest savanna mosaic (GFSM) which lies between the Western Sudanian savanna (WSS) in the north and the Eastern Guinean forests (EGF) to the south. The WSS ecoregion is characterized by mainly flat topography and elevation rages of between 200 and 400 m (WWF, 2007) and the EGF which is highly undulating with elevation between 50 and 300 m above sea level (WWF, 2008). The climate for both countries is tropical and seasonal with temperatures between 18 °C and 34 °C in the EGFs and higher temperatures occurring in the northern Western Sudanian savanna regions. Rainfall pattern of this region is a complex mix of wet, dry and hot seasons. Both countries have three predominant soil groups: *Lixisols* which are sandy clay loam, *Acrisols* which are sandy clay loam and *Plinthosols* which are loam. Land use characteristics for both countries are similar; Cote d'Ivoire consists of 63% agricultural land and 32% forest land area whereas Ghana consists of 65% and 21% agricultural and forest land areas, respectively in 2009 (FAO, 2011).

2.2. Mapping ecosystem services

This study uses the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool (Tallis et al., 2011) to map and quantify Ecosystem services states for the study area. InVEST is a geospatial modeling framework tool that evaluates the impact of land use change on ecosystem services (Nelson et al., 2009; Polasky et al., 2011). This study selected biodiversity and five ecosystem services to model: surface water yield defined as the precipitation minus storage and evapotranspiration losses, carbon storage, sediment retention, nitrogen (N) retention and phosphorous (P) retention as relevant to the study area. Services were selected based on the availability of data to determine services. A number of public global datasets were combined to map services. A LULC map of the region for 2000 was developed from the 1 km resolution European Commission, Joint Research Centre Global Land Cover database (http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php). A Global land cover map for 2004–2006 (henceforth referred to as 2005 LULC) and 2009 were downloaded from the ESA/ESA Globcover Project database (http://postel.mediasfrance.org). The 2000 LULC was reclassified and resampled to be consistent with the 300 m resolution of the 2005 and 2009 LULCs based on the recommended Globcover reclassification scheme (Table A.1). A 30 m resolution digital elevation model (DEM) for West Africa which is a product of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation model (GDEM) was downloaded from the ASTER GDEM site (http://asterweb.jpl.nasa.gov/gdem.asp) and used to delineate hydrologic basins. A total of 40 hydrologic basins were delineated for both countries to correspond to the FAO major hydrological Basins in Africa dataset (Fig. 1). These hydrologic basins were further delineated into 122 subbasins.

2.2.1. Water yield

Water yield in InVEST is defined as the amount of water that runsoff the landscape (precipitation minus storage and evapotranspiration losses, Tallis et al., 2011). The model uses average annual precipitation (P_x), annual reference evapotranspiration, soil depth, plant available water content, plant root depth, and land use characteristics to calculate the average annual water yield (Y_{xj}) in each 300 m × 300 m grid cell as:

$$Y_{xj} = \left(1 - \frac{\mathrm{AET}_{xj}}{P_x}\right) P_x \tag{1}$$

where AET is the annual actual evapotranspiration and AET_{xj}/P_x is an approximation of the Budyko curve (Zhang et al., 2001) given as:

$$\frac{\mathrm{AWC}_x}{P_x} = \left(\frac{1 + w_x R_{xj}}{1 + w_x R_{xj} + (1/R_{xj})}\right) \tag{2}$$

and

$$w_{xj} = \left(\frac{\mathrm{AWC}_x}{P_x}\right) Z \tag{3}$$

where AWC_x is the volumetric plant available water content and Z is a seasonal rainfall factor. The Budyko dryness index (R_{xj}) is given as

$$R_{xj} = \frac{k_{xj}\mathrm{ETo}_x}{P_x} \tag{4}$$

where ETo_x is the reference evapotranspiration from pixel x and k_{xj} is the evapotranspiration coefficient for LULC j. The average annual precipitation (1950–2000) for the West Africa region was downloaded from the WorldClim database (Hijmans et al., 2005). Reference annual evapotranspiration was downloaded from the FAO GeoNetwork database (FAO, 2004). Soil characteristics data for the region was estimated from the FAO Harmonized World Soil Database (HWSD, version 1.2; FAO, 2009).

2.2.2. Nutrient retention (N and P)

The InVEST nutrient retention model employs a three-step process to evaluate the LULC change impacts on water quality (Tallis et al., 2011). The model first computes the average annual water yield presented above across each grid cell based on each LULC. Then the average annual amount of nutrients exported from each grid cell is calculated based on literature reported nitrogen (N) and phosphorus (P) exports coefficients for each LULC category (Table A.2).

$$\mathrm{ALV}_x = \left(\frac{\lambda_x}{\lambda_{\bar{w}}}\right) \times pol_x \tag{5}$$

where ALV_x is the adjusted loading value at pixel x and pol_x is the export coefficient and λ_x and $\lambda_{\bar{w}}$ are the runoff index at pixel x and mean runoff index for the watershed of interest. The nutrient load is determined by routing water along flow paths based on slope as:

$$\lambda_a = \log\left(\sum Y\right) \tag{6}$$

where Y is the sum of water yield pixels along the flow path from pixel x and above. In the final step, the amount of nutrient load retained by the landscape is calculated using the nutrient retaining capacity of each LULC class as:

$$\mathrm{Retention} = \mathrm{ALV}_x \times \mathrm{filtration} \tag{7}$$

where filtration is the nutrient retention capacity of LULC j. There is very little data on nutrient export coefficients for West African

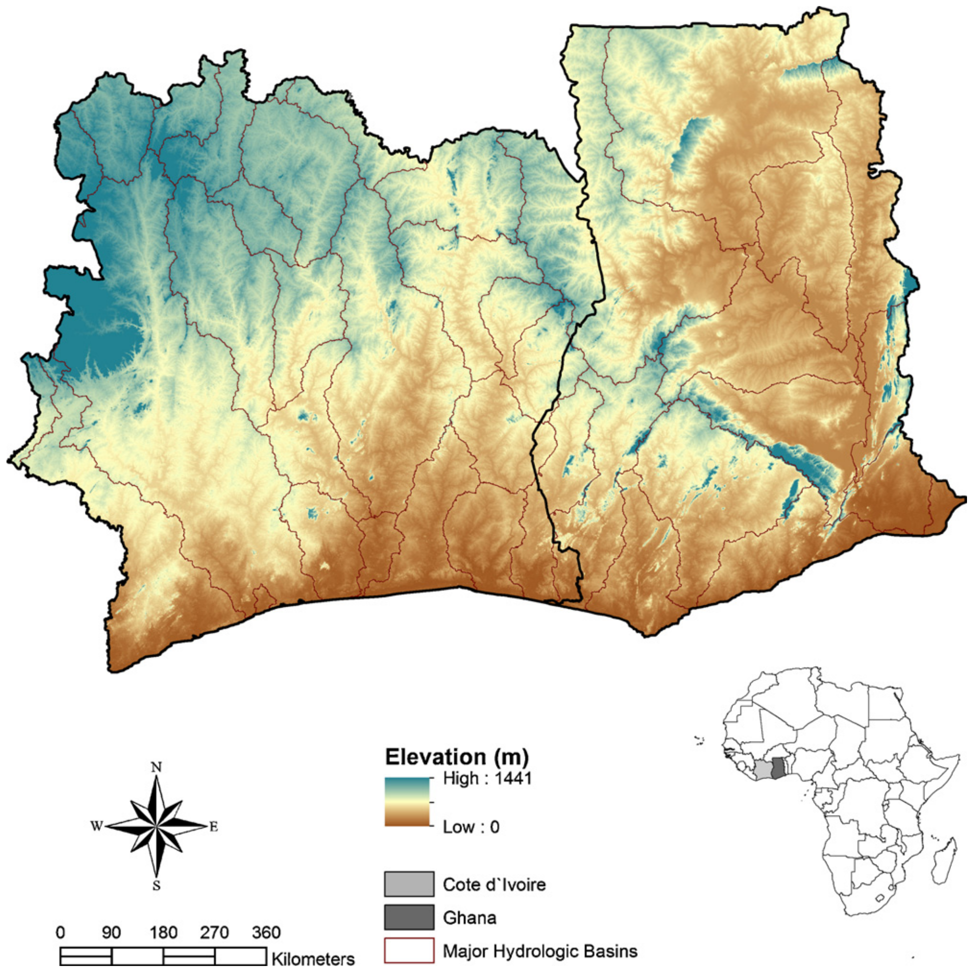

Fig. 1. Study locations Ghana and Cote d'Ivoire in West Africa showing topography and major hydrological basins.

LULC types (Amegashie et al., 2011; Mensah, 2009). We modified literature reported export coefficients (Owusu-Sekyere et al., 2006; Reckhow et al., 1980; Harding, 2008; Lin, 2004) to be representative of the region in consultation with local experts (Amegashie, personal communication; Mensah, personal communication; Table A.2).

2.2.3. Sediment retention

The ability of each basin to retain sediment was quantified by evaluating the interaction between the sediment retention capacity of each LULC, rainfall, soil characteristics and topography. Using the Universal Soil Loss Equation (USLE; Eq. (8); Wischmeier and Smith, 1978) implemented in the sedimentation module of InVEST, the potential soil loss of each land use grid was computed as:

$$\mathrm{USLE} = R \times K \times LS \times C \times P \tag{8}$$

where USLE is the potential average annual soil loss, R ($\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}}$) is the erosivity factor, K is the soil erodibility factor ($\mathrm{t\,ha\,h\,ha^{-1}\,MJ^{-1}\,mm^{-1}}$), LS is the slope length and steepness factor, C is the land cover management factor, and P is the supporting practice factor. Sediment retention is then computed by finding the difference between potential soil loss (USLE) of the landscape and the maximum potential soil loss (RKLS) which assumes the landscape is bare.

$$\text{Sediment Retained} = \mathrm{RKLS} - \mathrm{USLE} \tag{9}$$

A rainfall erosivity map was generated for West Africa following the method of Roose (1996):

$$R = 0.5 \times Precip + 0.05 \tag{10}$$

where *Precip* is the average annual precipitation obtained from the WorldClim database (Hijmans et al., 2005). Soil erodibility factor was estimated from the HWSD using the method of Torri et al. (1997). The land cover and support practice factors for each LULC class was assigned with values obtained from literature (Table A.3; Yang et al., 2003; Mati and Veihe, 2001).

2.2.4. Carbon storage

The InVEST model employs a simplified carbon cycle that maps and quantifies the amount of carbon stored and sequestered based on five carbon pools: above ground biomass, below ground biomass, soil, dead organic matter and harvested wood products. Using average literature values (Woomer et al., 2004; Gockowski and Sonwa, 2011; Adu-Bredu et al., 2011; Asase et al., 2011; Yao et al., 2010) this study developed estimates of the carbon stored in each carbon pool for each land use category (Table A.4). This study only considered three carbon pools – above ground biomass, below ground biomass and soil organic carbon. The carbon in each pool was aggregated over the basin to provide estimates of the carbon stored across the landscape.

2.2.5. Biodiversity

Although biodiversity in itself is generally not an ecosystem service it is included in this analysis since it is fundamental to

Table 1
Biodiversity input table showing land use land cover (LULC), habitat suitability scores and weights of sensitivity of each LULC class to sources of habitat degradation.

LULC class	Habitat suitability[a]	Sensitivity to urban sources of threats[b]	Sensitivity to agriculture sources of threats[b]
Post-flooding or irrigated croplands (or aquatic)	0.3	0.5	0.3
Rainfed croplands	0.2	0.5	0.3
Mosaic cropland (50–70%)/vegetation (grassland/shrubland/forest) (20–50%)	0.4	0.5	0.3
Mosaic vegetation (grassland/shrubland/forest) (50–70%)/cropland (20–50%)	0.5	0.8	0.6
Closed to open (>15%) broadleaved evergreen or semi-deciduous forest	1	1	1
Closed (>40%) broadleaved deciduous forest	1	1	1
Open (15–40%) broadleaved deciduous forest/woodland	1	0.8	0.5
Closed (>40%) needleleaved evergreen forest	1	1	1
Open (15–40%) needleleaved deciduous or evergreen forest	1	0.8	0.6
Closed to open (>15%) mixed broadleaved and needleleaved forest	1	1	1
Mosaic forest or shrubland (50–70%)/grassland (20–50%)	0.95	0.7	0.5
Mosaic grassland (50–70%)/forest or shrubland (20–50%)	0.9	0.7	0.5
Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland	0.85	1	1
Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	0.85	1	1
Sparse (<15%) vegetation	0.8	0.6	0.4
Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) – fresh or brackish water	0.7	1	1
Closed (>40%) broadleaved forest or shrubland permanently flooded – saline or brackish water	0.85	0.9	0.7
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil – fresh, brackish or saline water	0.75	1	1
Artificial surfaces and associated areas (Urban areas >50%)	0	0	0
Bare areas	0	0	0
Water bodies	0	0	0

[a] Greater values indicate higher suitability for biodiversity habitat.
[b] Greater values indicate higher sensitivity of LULC habitat type to urban and/or agricultural sources of threats.

the functional processes that provide ecosystem services (Hassan et al., 2005). The InVEST biodiversity model uses a habitat based approach, where habitat quality and rarity serve as a proxy for biodiversity. Habitat quality in InVEST is defined as the landscapes' ability to provide suitable conditions for the persistence of an organism (Tallis et al., 2011). Consequently, habitats that have a high quality are considered intact with functioning within its range of historic variability. A reduction in habitat quality or habitat degradation is assumed to increase as the intensity of land use increases (Tallis et al., 2011, citing McKinney, 2002). The habitat quality is assumed to be dependent on the relative impact of threats, sensitivity of habitat to threats, distance between habitats and sources of threats and location of protected areas. The model uses an exponential decay function to describe the impact i_{rxy} of

Table 2
Proportion of land use land cover (LULC) area and modeled ecosystem services found in major land classes in Ghana and Cote d'Ivoire, West Africa. Values represent total percentage calculated across both countries for each land use category.

Land use land cover (LULC)	% LULC area	% of ecosystem service in land use class					
		Water	N ret.	P ret.	Carbon	Sed. ret.	Biodiv.
2000							
Cropland	0.38	0.10	0.35	0.28	0.14	0.10	0.23
Agroforests	40.47	48.86	66.51	70.84	34.14	48.29	8.68
Forest	36.28	16.58	15.69	10.27	59.58	35.93	58.69
Shrubs/vegetation	18.55	21.50	15.97	16.87	2.89	10.39	28.32
Wetland	2.16	6.94	1.24	1.25	3.23	4.63	1.12
Urban areas	0.21	0.65	0.10	0.37	0.03	0.14	0.00
Bare areas	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Water bodies	1.94	5.36	0.13	0.13	0.00	0.52	2.96
2005							
Cropland	0.18	0.00	0.14	0.18	0.06	0.04	0.08
Agroforests	31.36	39.69	34.14	56.30	25.84	35.91	9.81
Forest	44.18	27.51	59.58	22.98	68.83	49.13	58.35
Shrubs/vegetation	22.13	26.98	2.89	19.89	5.10	14.06	29.16
Wetland	0.09	0.36	3.23	0.03	0.13	0.21	0.11
Urban areas	0.20	0.57	0.03	0.37	0.03	0.13	0.00
Bare areas	0.06	0.11	0.00	0.02	0.01	0.01	0.00
Water bodies	1.79	4.78	0.00	0.23	0.00	0.50	2.48
2009							
Cropland	0.18	0.00	0.20	0.17	0.06	0.04	0.09
Agroforests	38.16	46.18	59.69	62.49	35.74	43.21	11.17
Forest	34.24	19.89	19.28	16.35	57.85	40.77	49.95
Shrubs/vegetation	25.29	28.45	20.44	20.34	6.14	15.16	36.34
Wetland	0.09	0.34	0.05	0.04	0.15	0.22	0.07
Urban areas	0.20	0.56	0.10	0.36	0.03	0.14	0.00
Bare areas	0.13	0.27	0.05	0.06	0.03	0.02	0.00
Water bodies	1.71	4.31	0.18	0.19	0.00	0.45	2.39

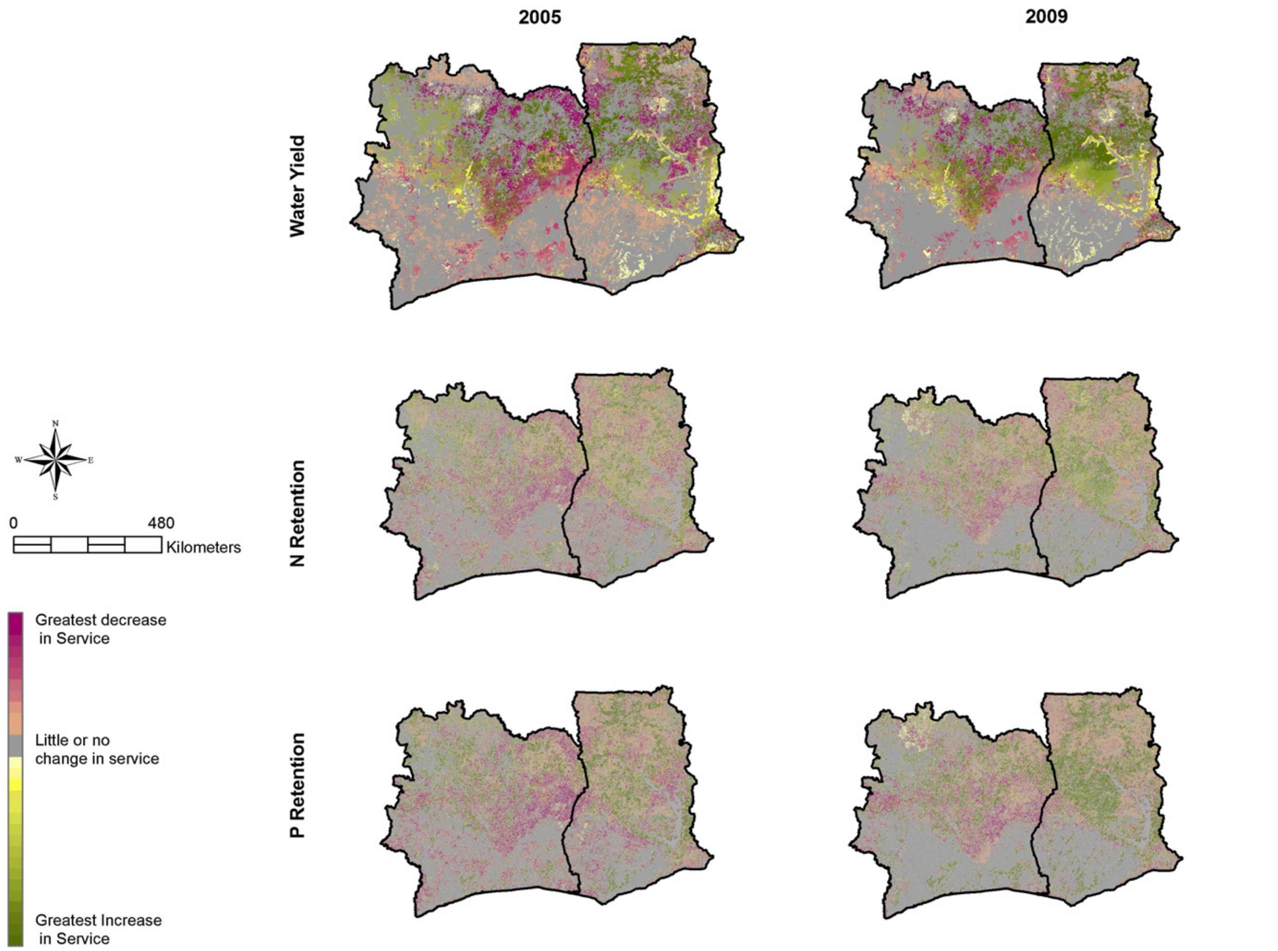

Fig. 2. Spatial distribution of changes in Ecosystem Services Change Index (ESCI) for Water Yield, N retention and P retention in Ghana and Cote d'Ivoire for years 2005 and 2009 relative to 2000.

threat r from grid cell y on habitat in grid cell x, distance between habitat and the source of threats:

$$i_{rxy} = \exp\left[-\left(\frac{2.99}{d_{rmax}}\right)d_{xy}\right] \quad (11)$$

where d_{xy} is the linear distance between grid cells x and y d_{rmax} is the maximum effective distance of the threat. The total threat level D_{xj} in a grid cell x with LULC j is then calculated as

$$D_{xj} = \sum_{1}^{R}\sum_{1}^{Y}\left(\frac{W_r}{\sum_R^1 W_r}\right) r_y i_{rxy} \beta_x S_{jr} \quad (12)$$

The habitat quality Q_{xj} of LULC j is finally calculated based on the habitat suitability of LULC j as

$$Q_{xj} = H_j[1 - D_{xj}] \quad (13)$$

Due to the lack of specific biodiversity data, this study modeled general terrestrial biodiversity as habitat quality by considering disturbed and undisturbed LULC category as non-habitat and habitat areas respectively. Habitat suitability or quality score that ranged from 0 to 1 where non-habitat LULC classes were given a score of 0 and perfect habitat LULC classes were scored 1 was used as input to the InVEST biodiversity model (Table 1). The primary sources of habitat degradation were weighted and combined with a maximum distance of degradation influence to map the extent of habitat quality for each LULC layer.

3. Analysis and land use change impacts

The study analyzed ecosystem services status and change by combining modeled services to generate a suite of indices. GIS analysis was done using ArcGIS version 10 (ESRI, 2012). Land use change impacts was measured by modeling ecosystem services state dues to each LULC layer (2000, 2005 and 2009) and developing measures of ecosystem change due to changing land use.

3.1. Assessing ecosystem services states

In order to assess the temporal change of ecosystem services, the study mapped and determined ecosystem services states (ES_i) which were time and location-dependent variables that quantify a particular ecosystem service at particular time i. A change in each individual ecosystem service relative to its historic state can be calculated as:

$$ESCI_X = \left[\frac{ES_{CURxj} - ES_{HISxi}}{ES_{HISxi}}\right] \quad (14)$$

where $ESCI_X$ is the Ecosystems Services Change Index of service X, ES_{CURx} and ES_{HISx} are the current and historic ecosystem service state values of service X at times j and i, respectively. Combining the ESCI of each of the ecosystem services with respect to the number of services being considered represents the Ecosystem

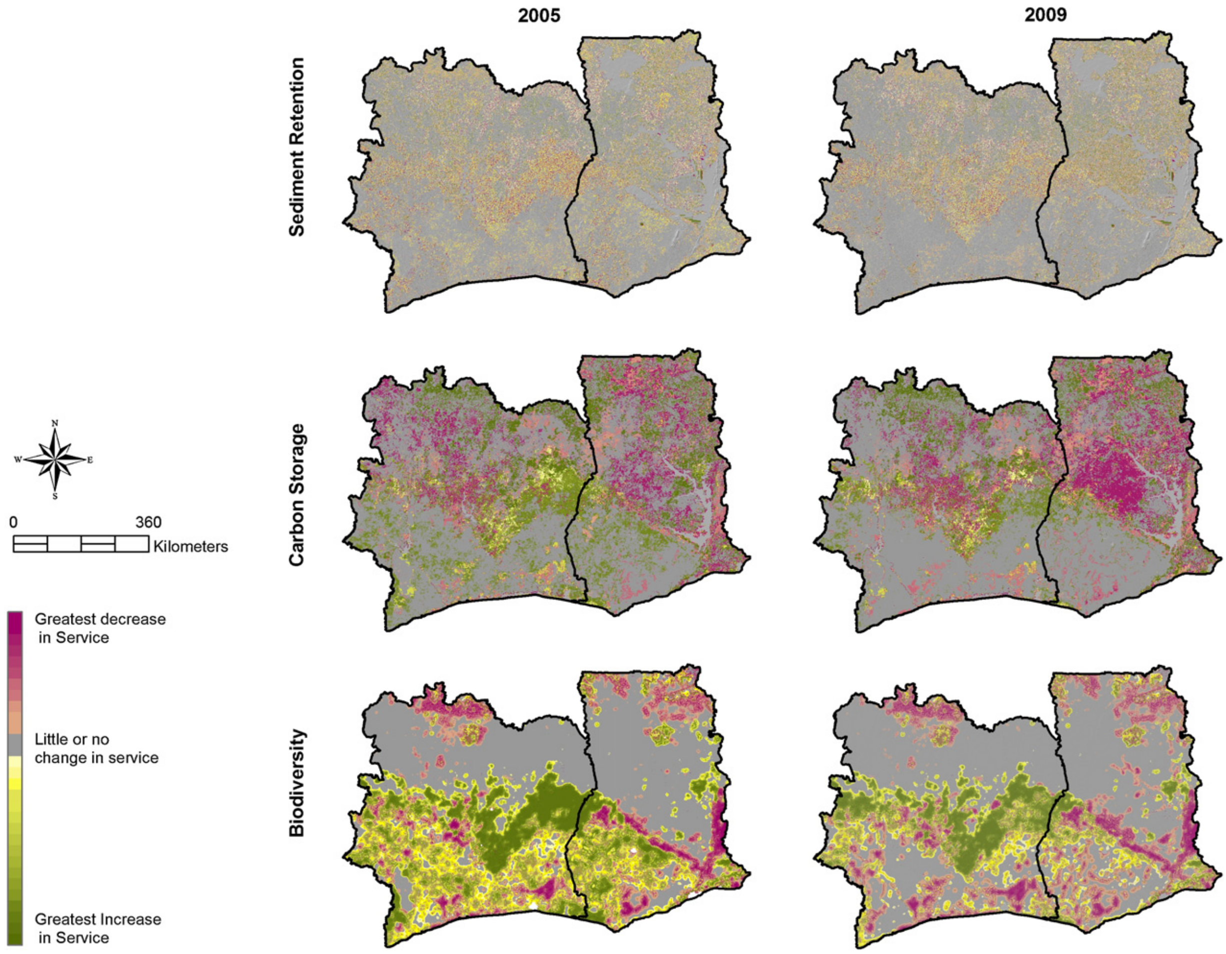

Fig. 3. Spatial distribution of changes in Ecosystem Services Change Index (ESCI) for Sediment retention, Carbon storage and Biodiversity in Ghana and Cote d'Ivoire for years 2005 and 2009 relative to 2000.

Services Status Index (ESSI) of a location (modified from Matlock and Morgan, 2011):

$$\text{ESSI} = \frac{\sum \text{ESCI}_X}{n} \tag{15}$$

The ESCI represents the relative gain or loss of each of the individual ecosystem services while ESSI is a unitless measure of the cumulative status of all considered ecosystem services for a site. Both range from negative 1 to positive 1, with an ESCI of 0 indicating no change in ES and an ESSI of 0 indicating an overall assessment of neither gain or loss in all the ES considered. A negative 1 ESCI indicates a loss of all the ES relative to baseline while negative 1 ESSI indicates a cumulative loss of all services over the reference period. Each ES index informs management differently, while the ESCI provides insight on the temporal change of a particular service, ESSI provides an assessment of the cumulative status of all the services. It must be noted that whereas ESCI measures directionality of ES change and identifies which particular service is changing, ESSI does not. The purpose of ESSI is to provide an integrated assessment of the status of all the ecosystem services being considered. The ecosystem services indices were evaluated at the pixel, subbasin and basin scales by setting the 2000 LULC as the historic and the 2005 and 2009 LULC as the current land use conditions. This allowed for comparison of changes across ecosystem services both temporally and spatially.

4. Results

Based on the land use assessment, LULC change has been variable since 2000 in both Cote d'Ivoire and Ghana (Table 2). In general, agroforests decreased in the 2000–2005 period but increased in the 2005–2009 period whereas cropland areas decreased from 2000 to 2005 and there was no change in 2009. Conversely, forests area increased 2000–2005 but decreased from 2005 to 2009, while shrubland and vegetation areas increased steadily throughout (Table 2).

The increase in agroforest land use is mainly due to the increased cultivation of cocoa and other agroforestry products over the last decade (Asare, 2005). The decrease in cropland area was surprising as croplands were expected to increase with an increase in population growth. The decrease was therefore attributed to the spatial limitations of the LULC dataset and caution should be taken in drawing conclusions based on this result due to limitations in the dataset. Although the 2000 LULC was resampled to the 2005/2009 resolution (300 m), its original 1 km resolution posed a challenge, in that areas less than 1 km may not accurately reflect their actual land use category. Further discussion on this limitation is provided later.

Ecosystem services followed a similar pattern of distribution by land use, over 80% of each of the services were located in the forests, shrubland and agroforest land uses which occupied over 90% of the study area, suggesting these land use areas are critical for sustained ecosystem service provisioning. Very little quantities of the services were located in the urban and bare land use areas

(Table 2). A number of studies have identified the forests, shrubland and agroforest land uses as important sources of ecosystem services provisioning. Martínez et al. (2009) identified forests areas of the La Antigua basin in Mexico as highest providers of ecosystem services value. Similarly, Reyers et al. (2009) reported higher percentage of five ecosystem services hotspots in the pristine vegetation and moderate degraded (grazing land) land use categories. Unsurprisingly, services in the urban, bare and cropland areas were low. There was a large amount of variability in the distribution of biodiversity and ecosystem services change between services and across the years of study (Figs. 2 and 3). Relative to 2000 conditions, the forest regions experienced the greatest change in ecosystem services; the northern regions of both countries experienced a mix of relatively high increases and high decreases in water yield while southern regions experienced moderate decreases in water yield in 2005. Water yield in Ghana improved somewhat with low increases in service in the south in 2009 but remained relatively the same in Cote d'Ivoire. The spatial distribution of nutrient (N/P) retention was similar, increases in service occurred in the north and decreases occurred in the central to south with improved services in 2009 for both countries. The decline in water quality provisioning (N/P and sediment retention) due to land use change in the cropland and agroforest areas is consistent with other water quality studies that have documented decline in water quality as a result of increased agricultural activities. Martínez et al. (2009) reported high rates of degradation of nitrates, suspended solids, chlorides and cations in coffee plantation basins of Mexico. Carbon storage was very dynamic with great decreases in the central to northern regions and medium decreases in the south which expanded from 2005 to 2009 mainly in the forest areas. Ghana experienced a greater loss in services compared to Cote d'Ivoire.

4.1. Ecosystem services change analysis

Ecosystem services change was analyzed at the regional, basin, and subbasin scales. Regionally, there was a mix of increase and decrease of ecosystem services across both countries (Fig. 4). Water yield experienced a greater increase in service in Ghana (ESCI = 0.08 in 2005 and 0.23 in 2009) compared to Cote d'Ivoire (ESCI = 0.02 in 2005 and 0.03 in 2009). Although carbon storage and biodiversity decreased from 2005 to 2009 in both countries, both services experienced a decrease relative to 2000 conditions in Ghana but an increase relative to 2000 condition in Cote d'Ivoire. N retention and P retention decreased in 2005 for both countries, but increased in 2009 for Ghana (Fig. 4). At the Basin scale, ecosystem services varied between the two extremes of change (ESCI values ranged −1 and 1; Figs. 5–7) across all the ecosystem services for both years. For both years, P retention experienced the greatest change in services (ESCI values ranged −1 and 1 for both years; Fig. 6) whereas water yield, carbon storage and biodiversity experienced the greatest increase in service (maximum ESCI = 1 in 2005 for biodiversity and ESCI = 1 for all three in 2009; Figs. 5 and 7). The overall status of all the ecosystem services ESSI at the basin level ranged −0.30 to 0.21 for 2005 and −0.38 to 0.33 for 2009 (Fig. 8). Relative to the ecosystem services status in 2000, there was an increase in services by 2005 but substantial decrease by 2009 in the southern basins (Fig. 8). The subbasin ESCI ranged from −0.64 to 1 in 2005 and from −0.84 to 1 in 2009, across all the ecosystem services. For the subbasin scenario, all the services except sediment retention experienced the greatest increase in services (maximum ESCI = 1 for 2005 and 2009). On the other hand, P retention also experienced the greatest decline in service in (ESCI = −0.64 in 2005 and −0.843 in 2009). Analysis of the land use distribution at the basin scale indicated that 41% of the basins were located mainly in agroforestry dominated basins, 28% in forest and 26% in shrubland dominated basins. Most of the decrease in services occurred in the basins dominated by

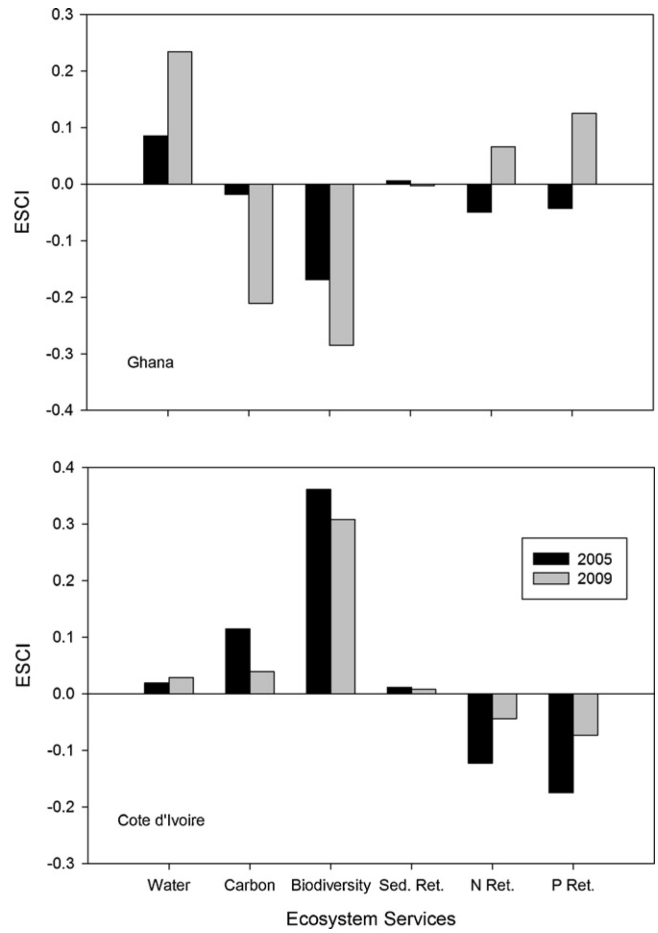

Fig. 4. Ecosystem Services Change index (ESCI) over time for Ghana and Cote d'Ivoire.

agroforestry, suggesting that the increased agroforestry production has direct effects on biodiversity and ecosystems services. Overall Ecosystem Status decline at the subbasin level occurred in 31% of the study area in 2005 but expanded to 33% of the study area in 2009, relative to 2000 service status. There was a shift in ESSI from relative increases in the south in 2005 to decreases in 2009. Ecosystem services status was dynamic, resulting in a mix of subbasins that showed improvements in services (e.g. subbasins 71, 98, 34, 43 and 99), decreases in service (e.g. subbasins 103, 106, 117, 113 and 85) and others that experienced little to no change in service status (subbasins 101, 109, 82, 29 and 27) from 2005 to 2009 (Fig. 9).

5. Discussion

5.1. Land use impacts on ecosystem services

This study is one of the first of its kind in the West African region on mapping multiple ecosystem services and understanding the status of ecosystem services and the effects of land use. Previous work has mainly been local studies that have often analyzed single ecosystem services or biodiversity under land management scenarios (Wade et al., 2010; Yeo et al., 2011). This study contributes to the evolving study of ecosystem services science by providing a general overview of ecosystem services status at the local and watershed scale from a data scarce region. The land use change analysis provided mixed results. The increase in agroforest land use is mainly due to the increased cultivation of cocoa and other agroforestry products over the last decade (Asare, 2005). On the other hand, the decrease in cropland area was surprising since croplands were

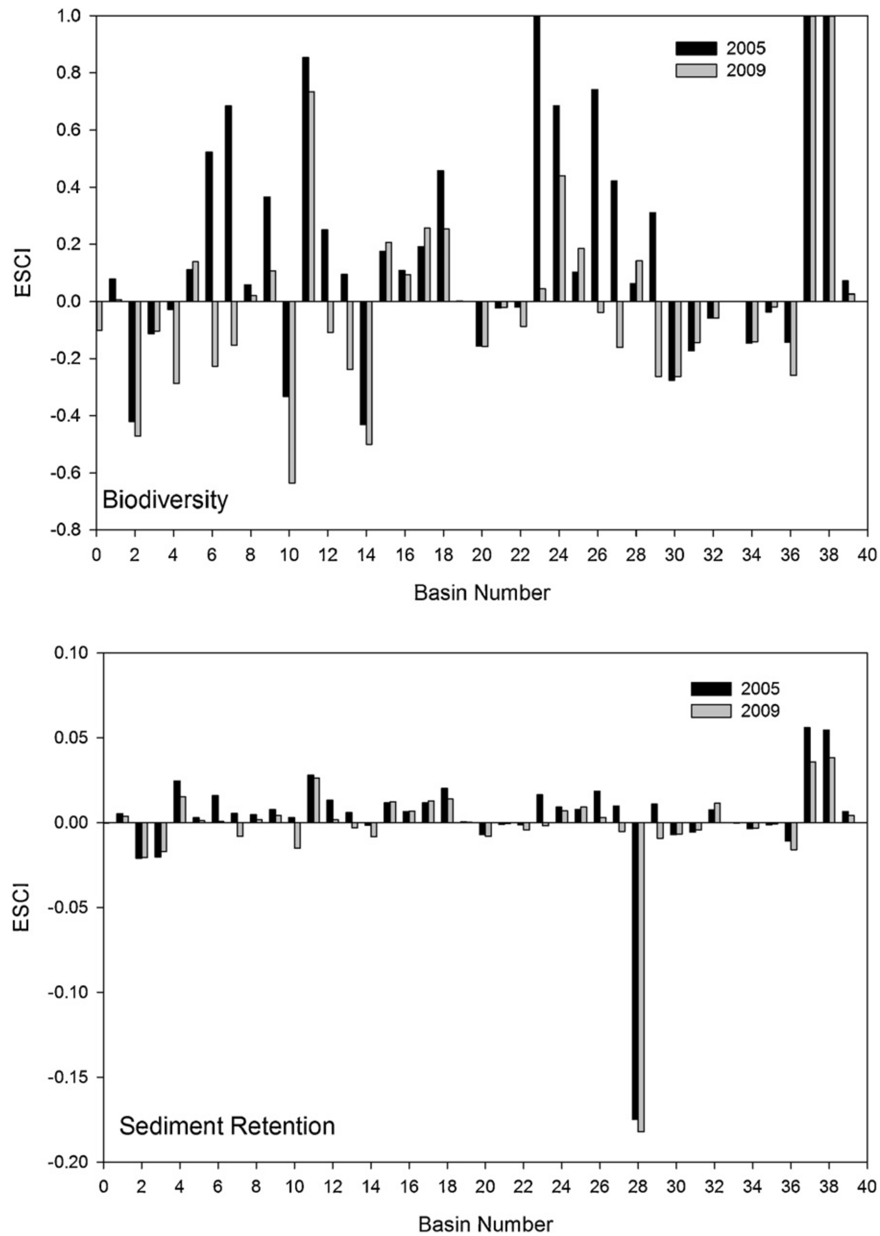

Fig. 5. Basin scale Ecosystem Services Change index (ESCI) over time for biodiversity and sediment retention.

expected to increase with an increase in population growth. The decrease was therefore attributed to the spatial limitations of the LULC dataset and caution should be taken in drawing conclusions based on this result due to limitations in the dataset. Although the 2000 LULC was resampled to the 2005/2009 resolution (300 m), its original 1 km resolution posed a challenge; in that areas less than 1 km^2 may not accurately reflect their actual land use category. Nonetheless in the absence of higher resolution data, our results could provide some useful information of the relative impacts of land use change. Further discussion on this limitation is provided later.

The identification of forests, shrubland and agroforest land uses as important sources of ecosystem services provisioning follows previous studies in other regions (Bai et al., 2011; Koch and Hobbs, 2007). For example, agroforests can improve biodiversity and ecosystem services while providing rural livelihoods (Rey Benayas and Bullock, 2012). In another study, Martínez et al. (2009) identified forests areas of the La Antigua basin in Mexico as highest providers of ecosystem services value. Similarly, Reyers et al. (2009) reported higher percentage of five ecosystem services hotspots in the pristine vegetation and moderate degraded (grazing land) land use categories in the Little Karoo watershed, South Africa. However, our results are highly dependent on the set of ecosystem services analyzed. It is quite possible that a different set of ecosystem services would identify other land use classes as important for ecosystem service provisioning. This illustrates the context-specific nature of ecosystems metrics, and the need for standardized indices for comparison and assessment. The decline in water quality provisioning (N/P and sediment retention) due to land use change in the cropland and agroforested areas is consistent with other water quality studies that have documented decline in water quality as a result of increased agricultural activities. Martínez et al. (2009) reported high rates of degradation of nitrates, suspended solids, chlorides and cations in coffee plantation basins of Mexico.

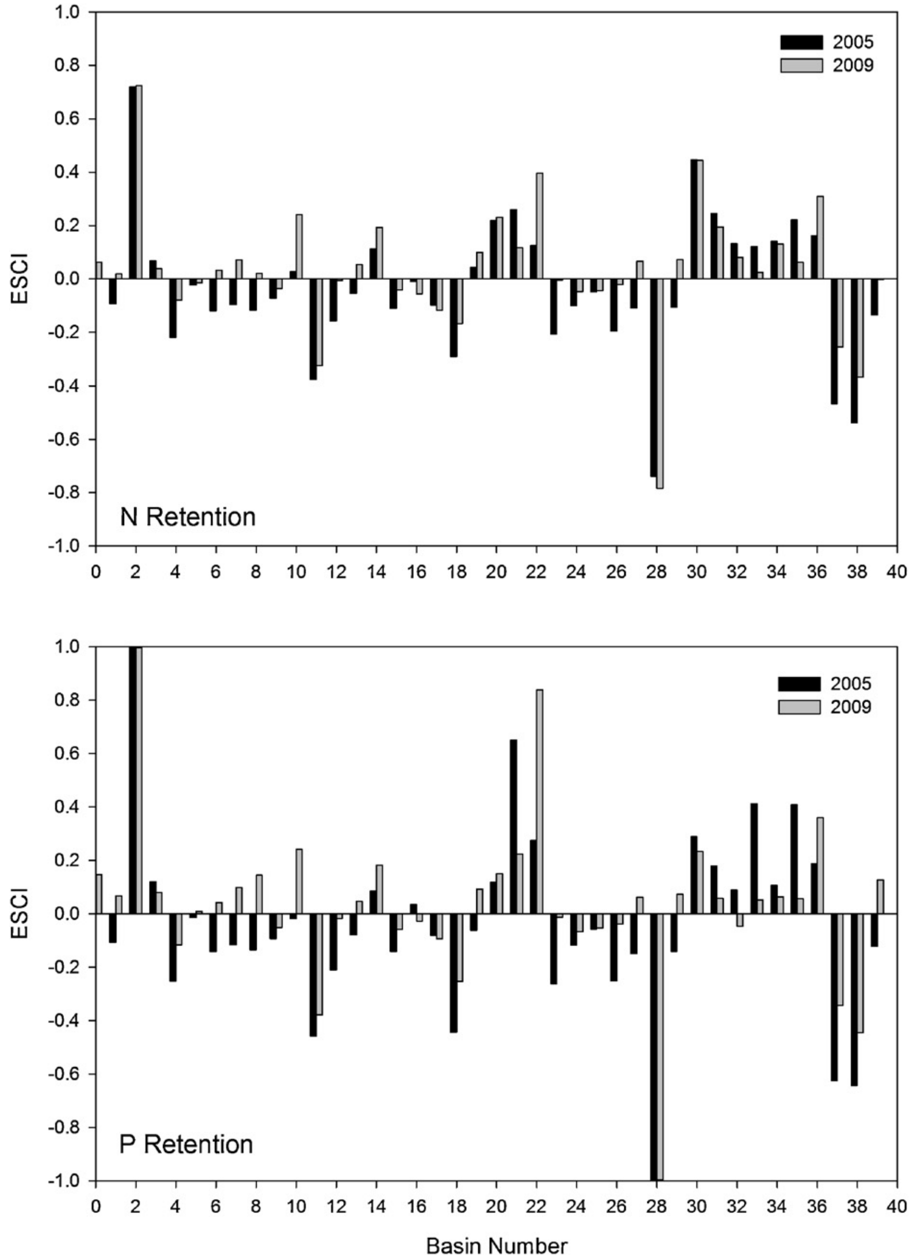

Fig. 6. Basin scale Ecosystem Services Change index (ESCI) over time for nutrient (N and P) retention.

5.2. Assessing ecosystem services states using an ecosystem index

Ecosystems are complex, non-linear systems affected by multiple anthropogenic and natural processes. The goal of ecosystem services management therefore is to manage the system for the cumulative impacts of all activities on ecosystem health. Assessing the cumulative status of multiple ecosystem services produces a picture quite different from individual ecosystem service assessments (Figs. 2–9). This can only be achieved by (1) knowing spatial and temporal variability of the flow of ecosystems services across a given landscape, (2) identifying and quantifying the interactions between services, and (3) assessing the cumulative impacts of different management practices on these services. Our approach enabled us to quantify change of individual ecosystem services (ESCI) and then integrate each of these changes to provide an overall assessment of ecosystem services status (ESSI) for a location. The ESCI allows us to prioritize individual services while the ESSI allows us to prioritize the location of these services. For example, at the basin scale, an ESSI of −0.09 in basin 10 (Fig. 8) for 2009 indicates that the basin has lost on average, 9% of the total number of ecosystem services analyzed from 2000 conditions. On the other hand, an ESSI of 0.28 in basin 22 (Fig. 8) for 2009 suggests that the basin had an average total ecosystem services increase of 28% from 2000 conditions. We use the ESCI to identify which services to target for conservation and mitigation. For example an examination of the ESCI values for basin 10 reveals that biodiversity, water yield and carbon storage should be targeted since they lose 63%, 19% and 10% of their services relative to 2000 conditions respectively. This provides the critical information needed in the design of management strategies for the ecosystem services.

5.3. Applications to other study locations

The modeling procedures outlined in this study could be extended to other study locations. One major challenge in ecosystem service assessments is the availability of spatially explicit

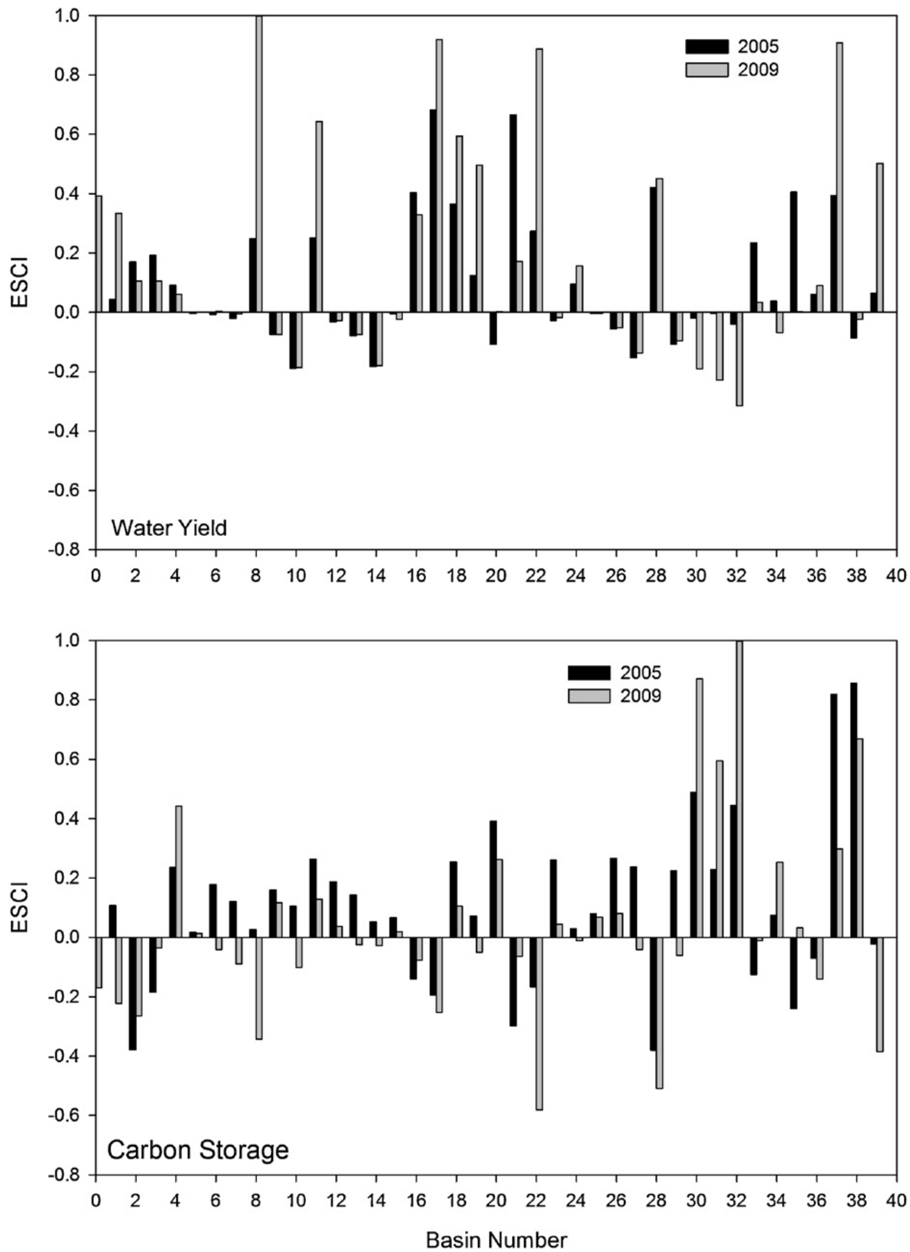

Fig. 7. Basin scale Ecosystem Services Change index (ESCI) over time for water yield and carbon storage.

models for predicting the temporal and spatial distribution of service delivery (Nelson et al., 2009). However, with the use of relatively simple ecosystem services models like InVEST or other comprehensive hydrological models such as the Soil Water Assessment Tool (SWAT; Arnold et al., 1998), maps of the delivery and temporal distribution of ecosystem services across the landscape can be developed. Vigerstol and Aukema (2011) recommended the use of ecosystems services specific models when assessing multiple ecosystem services with limited data and the more comprehensive process models if specific services were of interest and the relevant data available. Once services are mapped, GIS analysis can be performed at the pixel, subbasin and basin levels to inform the spatial and temporal variability of individual services change (ESCI) and then integrated to assess the cumulative status (ESSI). The application of this modeling procedure to other basins will vary according to the biophysical data available, however readily available global spatially referenced data such as elevation data (GDEM), land cover (Globcover) and soil data (HWSD) could be used to supplement field measurements for data scarce regions.

5.4. Limitations and uncertainties

A major challenge in this study was the lack of a spatially representative database of high spatial resolution biophysical data for both Ghana and Cote d'Ivoire. We use global datasets in a regional setting. This limitation could potentially lead to inaccuracies and biases in ecosystem services and land use change detection. For example, the coarse resolution (1 km for 2000, 300 m for 2005 and 2009) of the LULC data limited detailed LULC change detection and therefore most likely influenced the ecosystem services prediction. In particular, LULC areas of less than 100 ha in the case of 2000 and 10 ha in the case of 2005/2009 would have a lower likelihood of being categorized properly. A number of researchers have documented the high cost of acquiring fine resolution remote sensing

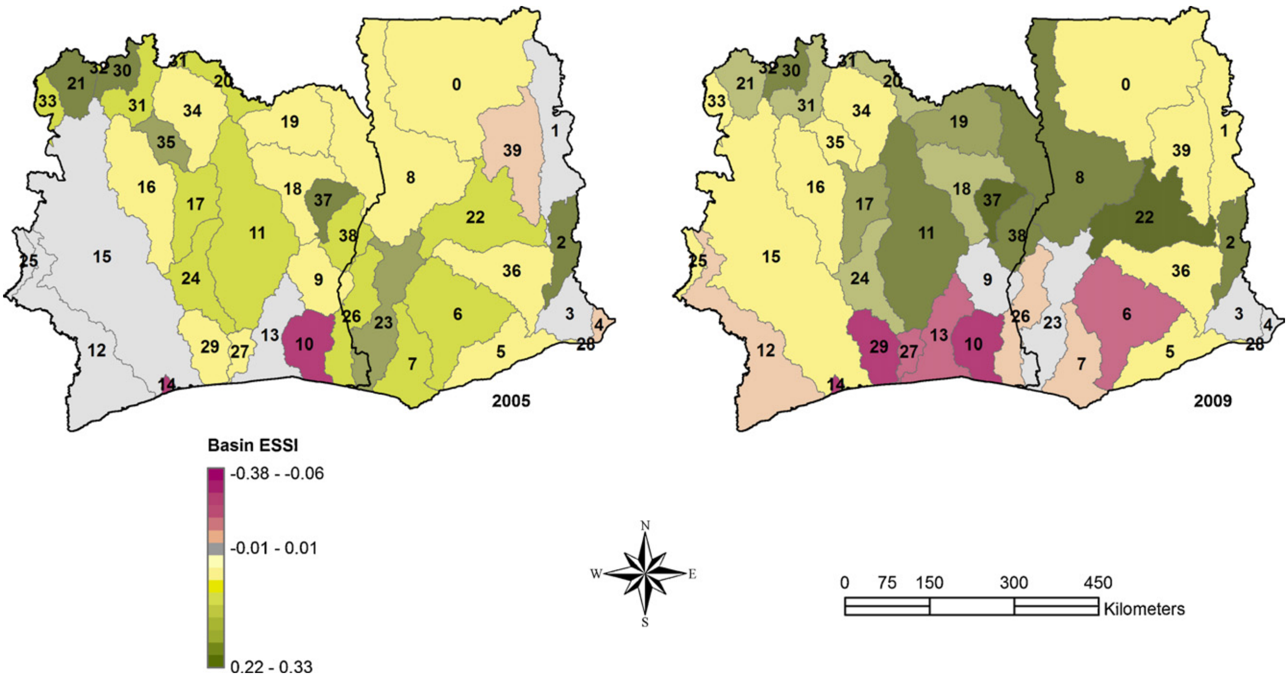

Fig. 8. Ecosystem Services Status Index (ESSI) for numbered major hydrologic basins in Ghana and Cote d'Ivoire for years 2005 and 2009.

data in data scarce tropical regions, often leaves researchers to use data that can be afforded and not what is actually needed (Hansen et al., 2008; Rochon et al., 2005; Avitabile et al., 2011). The main limitation of the InVEST model used in this study is that the processes modeled are simplified without accounting for seasonal variability and feedback (Vigerstol and Aukema, 2011; Tallis et al., 2011). The carbon and water modules for example, do not account for the full carbon and hydrologic cycles (Tallis et al., 2011). Also, the carbon model does not consider the flux of carbon for each of the land use classes while the water model does not consider subsurface flow (Tallis et al., 2011). Further, caution is advised when interpreting the ecosystem service indices which are particularly sensitive to the choice of ecosystem services. We selected four services (water yield, carbon storage, sediment retention and nutrient retention) and biodiversity for our analysis. It is possible that if a different set of ecosystem services (e.g. food provision) were chosen, the results would look significantly different. A lack of data prevented us from modeling all the possible ecosystems services that are available in InVEST. Another challenge in this study was our inability to assess the accuracy of our ecosystem

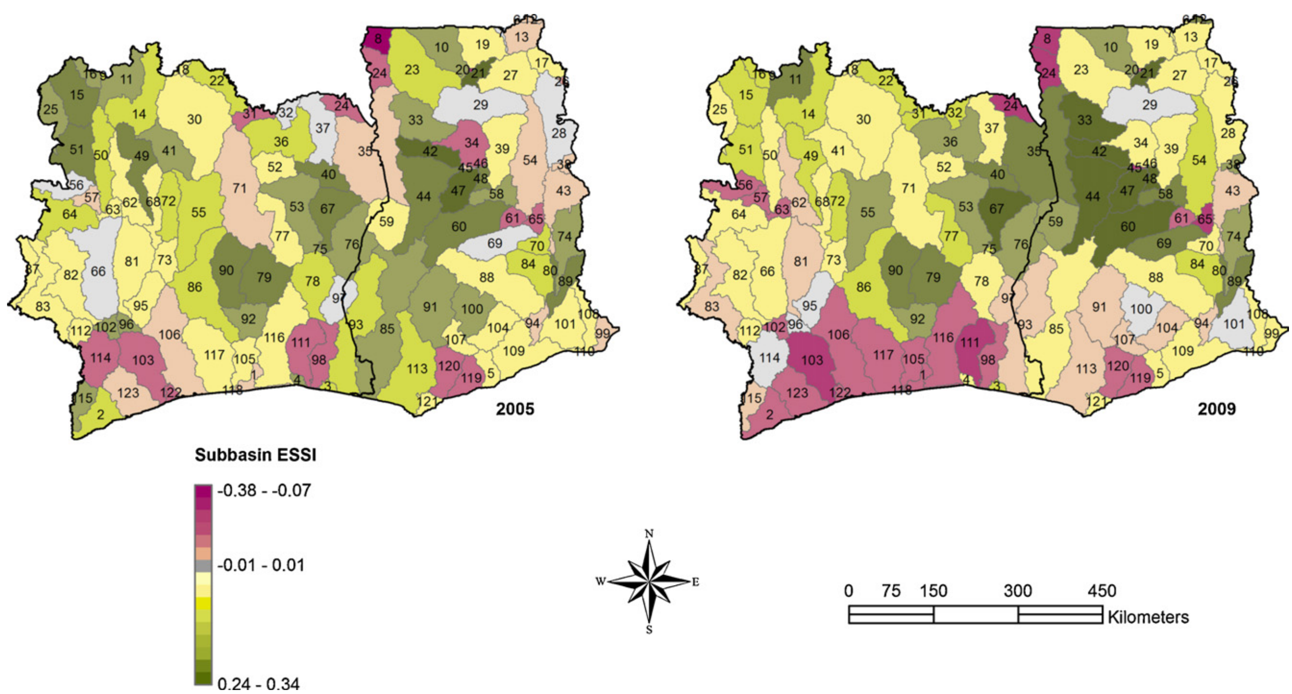

Fig. 9. Ecosystem Services Status Index (ESSI) for numbered hydrologic subbasins in Ghana and Cote d'Ivoire for years 2005 and 2009.

service simulations by field validation. Although limiting, our attempts at validation were mainly graphical and included for example, visually comparing our carbon maps to published carbon maps for the region (Bertzky et al., 2011).

6. Conclusions

The objective of this study was to assess the impacts of land use change on biodiversity and multiple ecosystem services. The study developed quantitative indices to measure ecosystem services states and change at the local and regional scale. This allowed evaluation and assessment of the effects of changing land use on biodiversity and ecosystem services at the management level while showing impacts and spatial variation of impacts at the locale scale. The study showed a general decrease in services from 2000 to 2009. The assessment can be used by land managers in exploring multiple management scenarios and their implications for ecosystem services or “dis-services”. For areas with relatively well established geospatial infrastructures, more accurate predictions with greater spatial resolution could have been possible, however, the ecosystem services assessment outlined in this study may actually prove more useful in areas that lack high resolution geospatial data.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2012.12.001.

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