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Tradeoffs, synergies and traps among ecosystem services in the Lake Victoria basin of East Africa

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ABSTRACT

Lake Victoria is a crucial ecosystem for over 25 million people in Kenya, Uganda, Tanzania, Rwanda and Burundi who live in the basin, and for the greater Nile river system downstream of the lake. Ecosystem management in the Lake Victoria basin has been highly extractive for most of the last 60 years, with the 1990s a period of marked decline in food production, economic contraction, rising poverty, increased burden of human disease, and more frequent floods. Lake Victoria itself is becoming eutrophic, with related problems of species extinctions and invasive species. There is evidence of poverty–environment traps: some households and areas appear to be caught in vicious cycles of low income, low investment in soil management, declines in soil fertility, and soil loss, while other households and areas are able to achieve higher incomes and investments, maintain soil fertility, and conserve soil on their farms.

Concepts and approaches from the Millenium Ecosystem Assessment (MA) were applied in a study of ecosystem service tradeoffs, synergies and traps in two of the river basins that flow into Lake Victoria from Kenya (Yala and Nyando). Hydrologic units are the main geographic unit used in the analysis, with predictions of sediment yield serving as the main measure of regulating services. Provisioning services are evaluated through a spatially disaggregated analysis of agricultural production, yield and area that combines spatial data from aerial photographs with division-level price and yield estimates.

The results illustrate considerable year-to-year variation in land use, agricultural production and sediment yield in the two basins. While overall production appears to be relatively stable at the basin level, there have been shifts in the geographic locus of production toward the upper parts of both basins. A spatial overlay of production and sediment yield indicates that different parts of the basins exhibit tradeoffs, synergies and traps. Results from this study have multiple uses in rural planning, agricultural investment, and watershed management. The results also suggest that the poverty traps conceptual framework may help to enrich the interpretative content of the MA approach.

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1. Introduction

The Millenium Ecosystem Assessment (MA) gave the world several important insights into the inter-dependence of human society and the natural environment. Besides synthesizing expert assessment of the state of human influence on the environment, the MA also provided new ways of conceptualizing human–environment interactions. The integrating concepts of ecosystem services and human well-being have helped to clarify the multiple ways that people depend on natural ecosystems. Sub-global assessments, such as the one conducted for Southern Africa, show how the MA concepts can be applied in empirical studies at multiple spatial scales (van Jaarsveld et al., 2005). An overall result from the MA is that the dominant patterns of demographic, social and economic change generate tradeoffs between provisioning, regulating, support and cultural ecosystem services. In other words, human exploitation of ecosystems for the production of consumptive goods is reducing the long-term quality of the living environment that ecosystems provide (Dasgupta, 2008). The MA report has been criticized by some, however, for painting an overly gloomy picture of the economic development—environment nexus. A range of opportunities exist, it is argued, for development trajectories that improve human well-being while conserving or restoring ecosystem health (e.g. Sachs and Reid, 2006).

The Lake Victoria basin of East Africa is a compelling case for an empirical analysis of the tradeoffs and synergies among ecosystem services in a developing country context. Lake Victoria is a crucial ecosystem for the 30 million residents of Kenya, Uganda, Tanzania, Rwanda and Burundi who live in the basin, and for the Nile river system that draws water from the lake. Lake Victoria is a major economic resource for East Africa, producing fish for a multi-million dollar export industry and millions of local consumers. Lake Victoria is also a major biodiversity reserve, supporting some 400 endemic fish species. Wetlands filter sediment and nutrients from entering the lake, provide habitat for fish breeding, and generate building materials, fuelwood and fodder for a large rural population (Swallow et al., 2003).

The multiple values of Lake Victoria and its basin have deteriorated rapidly over the last 60 years. The Lake is now considered to be eutrophic, with fluctuating water levels, high phosphorus and sediment loads, recurrent invasions of water hyacinth, proliferation of blue-green algae, and record rates of fish species extinction (Scheren et al., 2000; Odada et al., 2004). While there have been geographic pockets of economic advance and declining poverty in the basin, much of the area has experienced deepening poverty, economic decline, environmental degradation, and increasing HIV/AIDS levels (World Agroforestry Centre, 2006). In 2004, the Lake Victoria basin was judged to be one of Africa's worst 'hunger hot spots' by the InterAcademy Council (2004).

Overall it appears that the recent history of the Lake Victoria basin has not been one of increasing provisioning and declining regulating services, as might be suggested by the MA, but rather simultaneous decline of both. One of the propositions advanced to explain the simultaneous degradation of ecosystems and human well-being in the Lake Victoria basin is that the region is caught in a poverty–environment trap (Jalan and Ravallion, 2002; Barrett and Swallow, 2006). Consistent with the poverty trap proposition is the finding of Shepherd and Soule (1998) from the mid-altitude part of the Yala basin that farmers with low and medium resource endowments had low income, made few investments in their land base, and had declining soil quality, while farmers with higher resource endowments were able to make land-improving investments, maintain soil quality through the use of organic and inorganic soil amendments, and generate higher levels of income. Marenya and Barrett (2007) found similar patterns in a nearby study site. These results are consistent with a non-linear relationship between soil fertility and crop production, with increasing marginal returns to soil fertility investments at higher levels of soil fertility. Non-linear and threshold effects in land investments, transportation infrastructure, water management systems, and credit markets may be contributing to a bifurcation of development—environment dynamics. While some households and areas are caught in a poverty–environment trap of ecosystem degradation, low production and low investment, other households and areas are in a synergistic cycle of higher levels of production, adequate investments in land management, and increasing incomes (Barrett and Swallow, 2005, 2006).

The general objective of this paper was to evaluate the evidence base for tradeoffs, synergies or traps between economic development and environmental conservation in the Lake Victoria basin. The study had four specific objectives: (1) to assess the spatial distribution of provisioning and regulating ecosystem services; (2) to provide an empirical basis for more effective and integrated approaches to agricultural extension, irrigation investment, water management, forest conservation, physical planning and environmental protection at local and regional levels; (3) to contribute to more holistic approaches to poverty reduction and environmental management at the national level in Kenya; and (4) to develop and apply an approach to the analysis of the spatial distribution of ecosystem services that could be applied across the Lake Victoria basin and elsewhere.

The paper uses approaches from the Millenium Ecosystem Assessment (MA) to generate empirical estimates of important provisioning and regulating services. The literature on geographic poverty traps suggests that different combinations of provisioning and regulating services may be found in different parts of the basin (Jalan and Ravallion, 2002). Areas constrained by significant threshold effects are likely to exhibit low levels of both provisioning and regulating services. Areas that have been able to surmount such thresholds are likely to have high levels of provisioning and regulating services. High provisioning services with low regulating services, or low provisioning services with high regulating services, would be consistent with the general findings of the MA.

1.1. *Lake Victoria basin*

Lake Victoria, the world's second largest freshwater lake, is located in the upper reaches of Africa's Nile River system. Lake Victoria has a surface area of about 68,800 km^2 and an adjoining basin area of about 184,000 km^2. The lake basin is comprised of 11 river basins and a significant lake-edge area. The largest river basin by far is the Kagera, which drains parts

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of Rwanda, Burundi, Tanzania and Uganda into the Western side of Lake Victoria. The next largest basins are the Mara (Kenya and Tanzania), Gurumeti (Tanzania) and Nzoia (Kenya) (Awiti and Walsh, 2000).

The Lake Victoria basin ecosystem is crucial for the 25–30 million residents of Kenya, Uganda, Tanzania, Rwanda and Burundi who live in the lake basin and for the larger downstream Nile river system. Human population density in the basin is about 170 persons/km^2 and the population growth rate is about 3% per annum (UNEP, 2006). The population mainly depends on extensive rainfed agriculture for domestic and commercial purposes. In addition, the Lake provides hydroelectric power and inland water transport and supports a range of industries in the trade, tourism, wildlife and fishery sectors. Poverty levels are high across the basin.

Ecosystem management in the Lake Victoria basin has been highly extractive for most of the last 60 years, with the 1990s being a period of declines in food production, economic contraction, rising poverty, increased burden of human disease (especially malaria and HIV/AIDS), and increased floods (see Verschuren et al., 2002; World Agroforestry Centre, 2006; Swallow et al., 2007). Lake Victoria itself is becoming eutrophic as high levels of phosphorus and nitrogen have been deposited in the lake from the atmosphere, the surrounding catchment and from municipal centres. Severe erosion in parts of the catchment has increased sediment deposition in waterways and the lake. An invasion of water hyacinth was particularly severe in the late 1990s, affecting fisheries, municipal water supply systems, and transport (Scheren et al., 2000).

1.2. *Nyando and Yala river basins*

This study was undertaken in two river basins of the Lake Victoria basin, the Nyando and Yala. These two basins were chosen because of their similarities and differences. Both basins drain into Lake Victoria from the Kenyan portion of the lake basin, both cover areas between 3000 and 4000 km^2, and both have their headwaters in the Mau range of forested hills in Western Kenya. Both basins vary in altitude from about 3000 m above sea level to 1184 m above sea level where they drain into Lake Victoria. Climate in both basins varies with altitude, with increasing rainfall and decreasing temperatures with increasing elevation. Both have a mix of land tenure types, including settlement areas, sub-divided leasehold farms, large-scale leasehold farms and forest reserves. On the other hand, the basins are occupied by people of different ethnic groups, have different crop mixes, and have different percentages of forests and wetlands. The Yala basin stretches across Nyanza, Rift Valley and Western Provinces, while the Nyando straddles Nyanza and Rift Valley provinces (Onyango et al., 2007). The locations of the Nyando and Yala river basins relative to Lake Victoria and the rest of Kenya are shown in Fig. 1.

From a Digital Elevation Model (DEM) and GIS data on the stream network, we estimate that the Nyando river basin covers 3587 km^2 while the Yala river basin covers 3111 km^2. Mean annual rainfall in the Nyando basin varies from about 1000 mm near Lake Victoria to about 1600 mm in the highlands. In the Yala basin, mean annual rainfall is about 850 mm in the large flat area near Lake Victoria and up to 2000 mm in the highlands.

The potential natural vegetation in the Nyando basin varies from acacia bushland in the lower basin, moist savanna in the mid-altitude area, and moist montane forest in the higher elevation areas. The potential natural vegetation in the Yala basin includes mixtures of broadleaf savanna and evergreen bushland in the lower basin, moist intermediate forest in the mid-altitude areas, and dry montane forest in the higher

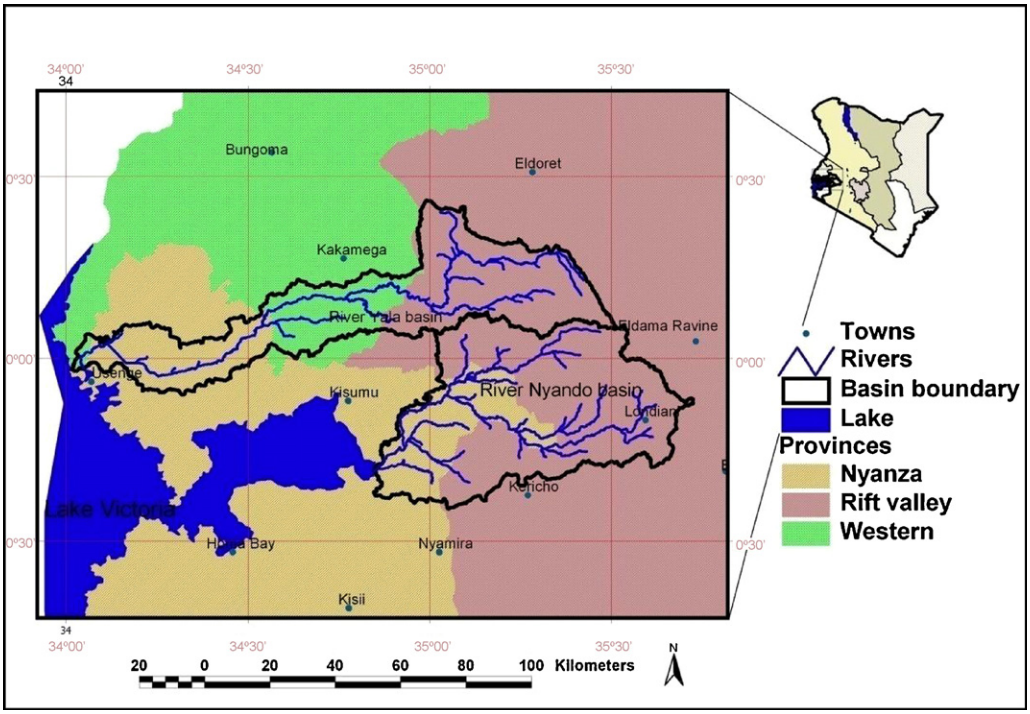

Fig. 1 – Map depicting geographic location of the Nyando and Yala river basins.

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elevation areas (Kindt et al., 2005). At present, however, most land in the two basins has been converted into crop production, with small patches of bushland, forest and wetland remaining (World Resources Institute et al., 2007). The Nyando basin has a small area of intact natural forest in the headwaters and a small fragmented wetland at its outlet into Lake Victoria. About 6000 ha of the 9000 ha Nyando wetland area was converted into irrigated rice production in the 1960s and 1970s (Swallow et al., 2007, pp. 197–198). Sedimentation of the irrigation canals emerged as a serious problem in the mid-1990s (Ong and Orego, 2002).

The forest and wetland ecosystems of the Yala basin are considerably more intact. The Yala swamp is a large wetland area that the Yala river empties into before releasing water into Lake Victoria. The Yala is Kenya's largest freshwater wetland. As of the year 2000, the Yala swamp was degraded but still quite large (175 km^2), providing significant buffering of sediment and water flows between the river system and Lake Victoria. The Yala swamp is being degraded through a number of pressures, including expansion of farming, grazing, macrophyte harvesting, and catchment degradation (Thenya et al., 2006). Between 2005 and 2007, close to 40% of the Yala swamp (69 km^2) was converted to commercial rice production by a single commercial company, Dominion Farms (K) Limited (Kinaro, 2008). Besides a small forest area in the Mau complex, the Yala basin also contains significant forest fragments in the mid-altitude area (Kakamega and South Nandi forests) (see Bleher et al., 2006).

The Nyando and Yala rivers contribute different sediment and nutrient loads into Lake Victoria. Research by the World Agroforestry Centre shows that between 2000 and 2002, turbidity levels were 2–3 times higher in the Nyando than in the Yala (World Agroforestry Centre, 2006, p. 13). While the Nyando basin occupies a relatively small percentage of the overall Lake Victoria basin, it makes a substantial contribution to sediment and nutrient loading of the lake. Flooding is a major problem in the lower Nyando basin, with significant floods reported almost every year.

Land degradation is widespread in both the Nyando and Yala basins, with severe gully erosion in the lower Nyando basin being the most visible sign of land degradation in the area. A study of land degradation in the Nyando basin using the Cesium137 method estimated that 61% of the Nyando basin has experienced significant levels of erosion, with an average erosion loss of 44 tonnes/ha (World Agroforestry Centre, 2006, pp. 14–15). Soil erosion and sedimentation have become increasingly severe over the last 60–100 years as a result of land conversion and farmland degradation. A radionuclide analysis of sediment cores extracted from the Winam Gulf at the mouth of the Nyando River shows that sedimentation rates have increased by three to four times over the last 100 years, with very high levels of sedimentation occurring after times of particularly high rainfall (World Agroforestry Centre, 2006, pp. 14–16). A study in the Yala basin by Awiti et al. (2007) shows continual decline in land productivity and soil conditions in agricultural lands around the Kakamega Forest over the 60 years since conversion from forest.

A GIS analysis of Kenya's 1999 population census data indicates that the Nyando basin had a population of about 656,000 people in 1999, with a population density of 183 persons/km^2, while the Yala basin had a population of about 1,079,000 people, for a population density of about 351 persons/km^2. Population density in the Yala varies from about 100 persons/km^2 near Lake Victoria to 1200 persons/km^2 in the mid-altitude areas of Vihiga District, while population density in the Nyando basin varies from about 50 persons/km^2 in the mid-altitude area (sugar belt) to about 500 people/km^2 in upper parts of the basin adjacent to Kericho town. Absolute poverty rates (also measured for 1999) are high and variable in both basins, with the highest poverty rates found in the lower Yala and parts of the lower Nyando (over 65%) and lowest in upper parts of both basins (35–45%) (World Resources Institute et al., 2007, p. 17). The main agricultural activity is smallholder rainfed mixed farming. The Nyando basin also has about 57 km^2 of irrigated agriculture in the lower areas, large-scale and smallholder commercial sugarcane in the mid-altitude areas, and both smallholder and large-scale tea production in the upper parts of the basin (World Agroforestry Centre, 2006).

A number of environmental and development initiatives have been launched to address specific dimensions of the problems of the Lake Victoria basin. At the broadest level, the Lake Victoria Commission of the East African Community and the Nile Basin Initiative are concerned with all dimensions of development and environmental management in the Lake Victoria basin. The Lake Victoria Environmental Management Programme (LVEMP) focused on understanding and reversing degradation of the lake ecosystem (http://www.gefweb.org/COUNCIL/council7/wp/lakevic.htm). The TransVic project of the World Agroforestry Centre located, quantified, and sought to reverse land degradation in the Kenyan part of the catchment (Swallow et al., 2003), the Western Kenya Integrated Ecosystems Management Project seeks to reverse degradation processes in highly degraded parts of the Nyando, Yala and Nzoia basins, and the Swedish NGO ViAgroforestry is promoting agroforestry development around the lake. The Millenium Village Project is testing integrated approaches to meet the Millennium Development Goals at the household and village levels, working in a small number of villages in the mid-altitude part of the Yala basin (http://www.millennium-villages.org/). At the national level, the Governments of Kenya, Tanzania, Uganda, Rwanda and Burundi have all developed Poverty Reduction Strategy Papers (PRSPs) and National Action Plans for implementing the terms of the Multilateral Environmental Agreements that they have ratified. In the Kenyan portion of the basin, agricultural production has been supported through the National Agricultural and Livestock Extension Programme (NALEP) of the Ministry of Agriculture, while water resource and catchment management are the responsibility of the Water Resource Management Authority (WRMA). Kenya's National Environment Management Authority has overall responsibility for environmental monitoring and planning across the country. Results from this research are being made available to all of these stakeholders through a variety of media.

1.3. *Ecosystem services and tradeoff assessment*

The conceptual framework for the Millenium Ecosystem Assessment (MA) posits that people are integral parts of

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ecosystems and that a dynamic relation exists between people and other components of ecosystems. Changes in human condition drive changes in ecosystems and subsequent changes in human well-being. At the same time, social, economic, and cultural factors external to ecosystems alter the human condition, and several natural forces also influence ecosystems. The MA global assessment reached four general conclusions. First, over the past 50 years humans have changed ecosystems more rapidly and extensively than in any comparable period in human history. Growing demands for food, fresh water, timber, fibre, and fuel have driven substantial and largely irreversible losses in the diversity of life on Earth. Second, changes in ecosystems have contributed to substantial net gains in human well-being and economic development, but at the cost of degradation of many ecosystem services, increased risks of non-reversible changes, and exacerbation of poverty for some groups of people. Third, degradation of ecosystem services could grow significantly worse during the first half of the 21st century and is a barrier to achieving the Millennium Development Goals. Finally, the challenge of reversing the degradation of ecosystems while meeting increasing demands for ecosystem services can be partially achieved under some scenarios, but will require significant changes in policies, institutions, and practices (Millenium Ecosystem Assessment, 2005).

Tradeoffs between ecosystem services arise from management choices made by humans, which can change the type, magnitude and relative mix of services provided by the ecosystem. Tradeoffs occur when the provision of one ecosystem service is reduced as a consequence of increased use of another ecosystem service. In some cases, tradeoffs may be an explicit choice; in others, tradeoffs arise without premeditation or even awareness that they are taking place. Rodríguez et al. (2006) propose that ecosystem service tradeoffs should be classified in three ways: across space, across time, and according to their reversibility.

This paper integrates outputs from geographic, hydrological and economic analysis to assess temporal and spatial tradeoffs among provisioning and regulating services in the Nyando and Yala basins. The provisioning services that are considered are agricultural crops, including the main cereals and the main cash crops. Price and quantity data for the main crops are aggregated into a single measure of the value of agricultural production. Unfortunately, data on the costs of agricultural production or the production of other provisioning services, such as livestock products, fruit, energy and building materials, were not available. The regulating service that is considered is the reduction of sediment yield: sediment yield per hectare is used as an indicator of an ecosystem dis-service. Sediment yield per hectare is estimated at the sub-basin level by SWAT hydrologic models calibrated for each basin. The Soil and Water Assessment Tool (SWAT) is a physically based, continuous-time and distributed-parameter model designed to simulate the impact of management practices on water, sediment and agricultural chemical yield in large and complex watersheds (Jha et al., 2004; Spruill et al., 2000). Sediment yield is of particular concern in the Nyando and Yala basins. High sediment yield increases flood risk by filling in stream beds and plugging drainage canals. High sediment yield also reduces the financial viability of lowland irrigation systems, degrades riparian wetlands, and contributes to sediment and nutrient loading of Lake Victoria. The erosion processes that produce sediment also degrade the productive capacity of farms. The second indicator of regulating service used in this paper is the area of natural vegetation, assuming that natural vegetation tends to provide higher protection of regulating services than does cropping systems.

To be consistent with this emphasis on sediment yield, this study uses the hydrologic sub-basin as the main unit of analysis. A sub-basin is defined in SWAT as a land unit with a physical hydrologic divide and a single water outlet. In the case of the Nyando and Yala basins, the average size of a sub-basin is between 50 and 60 km^2. With average population densities of 180–350 persons/km^2, the average sub-basin contains a human population of between 9000 and 21,000 people. With its focus on tradeoffs at the basin and sub-basin levels, this type of analysis answers very different questions than the plot-level tradeoff studies conducted by the Alternatives to Slash and Burn Programme (Tomich, 2005) or the farm-process modelling of the tradeoff analysis conducted by Antle et al. (2003).

2. Methods and data

This study was conducted at multiple spatial scales, with units defined by scenes from aerial photographs, hydrologic features and administrative boundaries. The smallest spatial unit is the 5 km by 2.5 km area covered by an aerial photograph. Next in size are the hydrologic sub-basin and the division, the smallest administrative area at which agricultural production is reported in Kenya. The largest spatial unit is the river basin. One of the challenges for the study was the re-aggregation of production data from the division scale to the boundaries of the hydrologic units. Data from aerial photographs were used to spread agricultural production across the landscape and these data were aggregated to both the division and sub-basin levels.

2.1. *Hydrologic modelling of regulating and support services*

Sediment yield was simulated using a GIS-based version of the Soil and Water Assessment Tool (SWAT). The SWAT model has previously been used to study the effects of proposed water reservoirs on flood risk and large-scale adoption of conservation agriculture in the lower Nyando basin (Sang et al., 2007), but to our knowledge had not been previously applied in the Yala basin.

SWAT requires information on land use, topography, soils and climate. Topographic data were obtained from a digital elevation model generated from digitized 50 m-resolution topographical maps provided by Survey of Kenya. Land use maps for the two basins were generated from 2003 Aster satellite images. Soil information was obtained from the Kenya Soil Survey (KSS), climate data from the Kenya Meteorological Department, and streamflow data from the Kenya Ministry of Water and Irrigation. A time series of data on climate and streamflow from the present back to the 1960s were collected where possible.

The sediment yield estimates generated by SWAT are based on the Modified Universal Soil Loss Equation which

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contains elements related to topography (LS—calculated from the digital elevation model), soil properties (K—from the soils maps), rainfall (R—from rainfall records), the crop factor (C—from the land use map), and management practices (P—from previous studies conducted in Western Kenya). It should be noted that Mati et al. (2000) and Cohen et al. (2005) suggest problems with applying the universal soil loss equation in Kenyan conditions. Calibration of the SWAT model for the two basins is discussed in more detail in Swallow et al. (2008). Swallow et al. (2008) also shows SWAT model results on water yield. Water yield is a provisioning service and regulation of water yield (i.e. maintenance of dry-season flows and reduction of flood risk) is a regulatory service.

The SWAT analysis identified 67 sub-basins in the Nyando and 54 sub-basins in the Yala. The average size of sub-basins was 53.5 km^2 in the Nyando basin and 57.6 km^2 in the Yala basin.

2.2. Quantification and valuation of agricultural production

Data on agricultural production were collected for two time periods, 1999 and 2005. The year 1999 was chosen because it marked the beginning of several research and development efforts in the Nyando basin, including the TransVic and NALEP projects. The year 2005 was chosen because it was the most recent year of complete data at the time that data collection was undertaken. Agricultural production data were only available for government administrative units, with divisions being the smallest administrative units at which data are recorded in Kenya. Data were collected on total production, area under production, yield, and prices paid by buyers to farmers. A questionnaire was used to collect data from government officers, tea and sugar cane factories, and agricultural purchasing centres, with the questionnaire administered in person by one of the authors with long experience working in the agricultural sector in the study area. Unpublished annual reports of division-level agricultural offices were a key source of information. Once compiled and displayed graphically, the agricultural data were cross-checked through a workshop with about 40 experts and stakeholders in agricultural development in the region. The survey collected data only on the major agricultural crops in each basin. In the Nyando basin this included maize, sorghum, sugar cane, tea, beans, and coffee. In the Yala basin this included maize, sorghum, millet, sugar cane, tea, tomatoes, and cabbages. Unfortunately, comparative data on revenue from fruit trees, timber trees and livestock were not available.

Kenya experienced substantial inflation in consumer prices during 1999–2005 period. The annual rate of consumer price inflation was 5.7% in 1999, 10% in 2000, 5.7% in 2001, 2% in 2002, 9.8% in 2003 and 11.6% in 2005 (Export Promotion Council of Kenya). An aggregate inflation factor of 1.536 was calculated and used to adjust 1999 prices to 2005 terms.

2.3. Spatial data on agricultural production

Data on the spatial distribution and intensity of different enterprises were generated from an analysis of sets of aerial photographs available for the years 1991, 1997 and 2006 from the Kenya Department of Resource Surveys and Remote Sensing (DRSRS). Experts from the DRSRS overlaid a 100 point grid over each 5 km × 2.5 km aerial photograph and assigned each point a unique land use, then assumed that land use in the whole area was proportionate to land use in the 100 sample points. These estimates of land use were then used for calculating the area of different agricultural systems in the divisions and hydrologic sub-basins. These data provided wall-to-wall coverage of the two basins, excluding small areas at the boundaries on the edges of the basin (especially the forested upper catchment areas).

The aerial photography data provided estimates of the percentage cover of the different agricultural systems for each of the 5 km × 2.5 km rectangular areas (scenes) covered by individual photos. GIS software (ArcView) was used to overlay the geographic coordinates of the scenes with the boundaries of the administrative divisions, with 4–10 scenes covering each division. For divisions on the boundaries of the river basins, only the part of the division located in the basin was included in the analysis. Data from the compiled scenes was then used to estimate the area of the different production systems in each division. Area estimates were multiplied by division-level yield estimates to generate production estimates, and production was multiplied by division-level prices to generate estimates of farmer revenue for each crop. Revenue for each crop was summed to produce estimates of total revenue and total revenue per hectare for each division.

To generate estimates of revenue per crop per sub-basin, GIS analysis was used to overlay the boundaries of the sub-basins on the division boundaries. Sub-basins generally included parts of 2–4 divisions. The revenue associated with each crop per sub-basin was calculated as a weighted average of the revenue estimates for the relevant divisions, with weights determined by the proportion of the division located in each sub-basin. One of the limitations of this study was that agricultural production data and production intensity data were available for slightly different years. The aerial photography data for 1997 was therefore used to estimate production intensity in 1999, while the aerial photography data for 2006 was used to estimate production intensity in 2005.

2.4. Tradeoff analyses

Temporal assessment of tradeoffs was generated in three ways. First, an analysis of land use change was conducted on the basis of the aerial photography data from 1991, 1997 and 2006. Second, the disaggregated data on agricultural production for 1999 and 2005 were compared to identify overall and basin-specific trends in yield, area and production. Third, the validated SWAT model was used to simulate annual sediment yields for the 20-year period between 1986 and 2006.

A spatial analysis of tradeoffs and synergies between sediment yield and agricultural production for the year 2005 was generated through a spatial overlay of results on sediment yields and value of agricultural production at the sub-basin level. The sediment yield of each basin was expressed in terms of average sediment yield per hectare. Median sediment yield was calculated, and every sub-basin characterized as having above-median or below-median sediment yield. Similarly, agricultural production in every sub-basin was expressed in

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terms of value of production per hectare, and sub-basins characterized as having above-median or below-median production per hectare. The results were then overlaid and sub-basins grouped into those with high sediment yield/high production, low sediment yield/high production, high sediment yield/low production, and low sediment yield/low production. As discussed in Section 1, high production with high sediment yield is used as an indicator of tradeoffs between provisioning and regulating services, high production/low sediment yield is taken to indicate synergies between economic development and environmental conservation, and low production/high sediment yield is taken to indicate an environment–poverty trap.

3. Results

3.1. *Land use and land use change*

Tables 1 and 2 present aggregate results of the land use analysis for 1991, 1997 and 2006 for the Nyando and Yala basins, respectively. The results for Nyando show large decreases in the area of natural vegetation from 1991 to 1997 and from 1997 to 2006. Overall, the area of natural vegetation decreased from 65 to 56% over the 15-year period, for an average decrease of 0.6% per year. The areas in both crop agriculture and tree production systems increased over these periods. While maize increased most in terms of area of increase (a net increase of 2.4% of the basin), the percentage increases were greatest for rice, sorghum and vegetables. The total area covered by tree crops (4.6%) was constant between 1997 and 2006, with increases in area devoted to tea and fruit roughly matched by a decrease in the area of woodlots and hedges. Overall, the land use data for Nyando indicate tradeoffs between forests and maize in the uplands, and between irrigated crops and intact wetlands in the lowlands. The results for crop agriculture in the Nyando basin show an increase in the already high percentage of agricultural land devoted to maize (88.8% in 1991 to 90.0% in 1997 to 92.9% in 2006), a considerable reduction in the area devoted to a range of minor cereal and cash crops (e.g. millet, pyrethrum, potatoes, cassava, napier grass, wheat), and an increase in higher-value crops requiring irrigation (rice, vegetables).

Table 2 indicates a considerably different land use and land use change situation in the Yala basin. The total area of natural vegetation was relatively constant over the 15-year period between 1991 and 2006, starting at 54% in 1991 and ending at 52% in 2006. During that time, the area of forest and bushland actually increased by about 3%, while the area of grazing, fallow and bare land decreased by about 4%. Total area in foodcrops increased from 1991 to 1997 and decreased from 1997 to 2006. The area of maize, which occupied about 90% of all crop land in all three periods, displayed a similar up-and-down trend. The data indicate that the areas devoted to all tree crops (coffee, tea, fruit, woodlots) decreased marginally from 1991 to 1997. The main change in tree crops from 1997 to 2006 was the large increase in tea, from 2.9 to 5.3% of the area of the basin. The data for sugar cane indicate a surprisingly large increase from 1991 to 1997 and a similarly large decrease from 1997 to 2006. Overall, the data for Yala suggest relatively little net change in the area of natural vegetation, a large drop in the area in sugar cane production and small drop in the area in maize, but a large increase in the area of tea. The spatial tradeoffs appear to be among provisioning services (sugar

Table 1 – Land use in the Nyando river basin, 1991, 1997 and 2006.

	Land cover % in Nyando Basin		
Land use category	1991	1997	2006
Grazing, fallow, bare	37.90	34.00	30.90
Forest and bushland	24.63	24.44	24.38
Water bodies	0.36	0.27	0.19
Wetlands	1.93	0.90	0.40
Total natural vegetation	64.82	59.61	55.87
Ploughed	1.38	0.64	0.28
Maize and maize mixes	12.69	12.94	15.39
Minor crops	0.18	0.32	0.08
Rice	0.00	0.37	0.45
Sorghum	0.01	0.01	0.05
Vegetables	0.02	0.09	0.31
Total crop agriculture	14.28	14.37	16.56
Tea	0.75	1.91	2.89
Coffee	0.24	0.09	0.11
Fruit	0.11	0.07	0.11
Woodlots and hedges	1.57	2.61	1.53
Total tree crops	2.67	4.68	4.64
Sugar cane	7.76	10.75	8.99
No data	9.00	8.70	12.24
Roads and structures	1.51	1.84	1.68
Total all land uses	100.02	99.98	100.00

Table 2 – Land use in the Yala river basin, 1991, 1997, 2006.

	Land cover % in Yala Basin		
Land use category	1991	1997	2006
Grazing, fallow, bare	36.30	36.60	32.20
Forest and bushland	13.67	14.38	16.07
Water bodies	1.30	0.33	0.51
Wetlands	2.42	2.46	3.53
Total natural vegetation	53.69	53.77	52.11
Ploughed	0.85	1.35	0.78
Maize and maize mixes	18.08	19.22	16.38
Minor crops	0.64	1.37	0.68
Rice	0.00	0.00	0.00
Sorghum	0.00	0.02	0.00
Vegetables	0.02	0.04	0.08
Total crop agriculture	19.59	22.00	17.92
Tea	3.51	2.93	5.31
Coffee	0.16	0.06	0.00
Fruit	0.87	0.73	0.82
Woodlots and hedges	4.37	4.04	3.75
Total tree crops	8.91	7.76	9.88
Sugar cane	0.12	6.87	0.40
No data	15.27	7.17	17.50
Roads and structures	2.38	2.27	1.98
Total all land uses	100.00	99.82	100.00

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cane to tea) rather than between provisioning and regulating services.

3.2. *Spatial and temporal analysis of sediment yields*

The estimated sediment yields for the sub-basins of the Nyando and Yala basins are illustrated in Fig. 2a and b. Sediment yield is highest in the mid-altitude parts of the Yala basin, an adjacent area in the upper Nyando basin, and in the southern side of the upper Nyando. The forested areas in the upper parts of both basins have lower levels of sediment yield.

The lower Yala and lower Nyando are shown to be areas of lower sediment yield. It is likely, however that SWAT underestimates sediment yield in those areas, particularly in the lower Nyando. The alluvial soils found in parts of the lower Nyando are known to be particularly prone to severe gully erosion (Sjörs, 2001). It is important to note that the Modified Unified Soil Loss Equation used by SWAT does not consider gully erosion (Cohen et al., 2005).

The SWAT model was also used to evaluate changes in sediment yield between 1986 and 2004 for the Yala and Nyando basins. Year-to-year differences in sediment yield result from the different climatic conditions that prevailed.

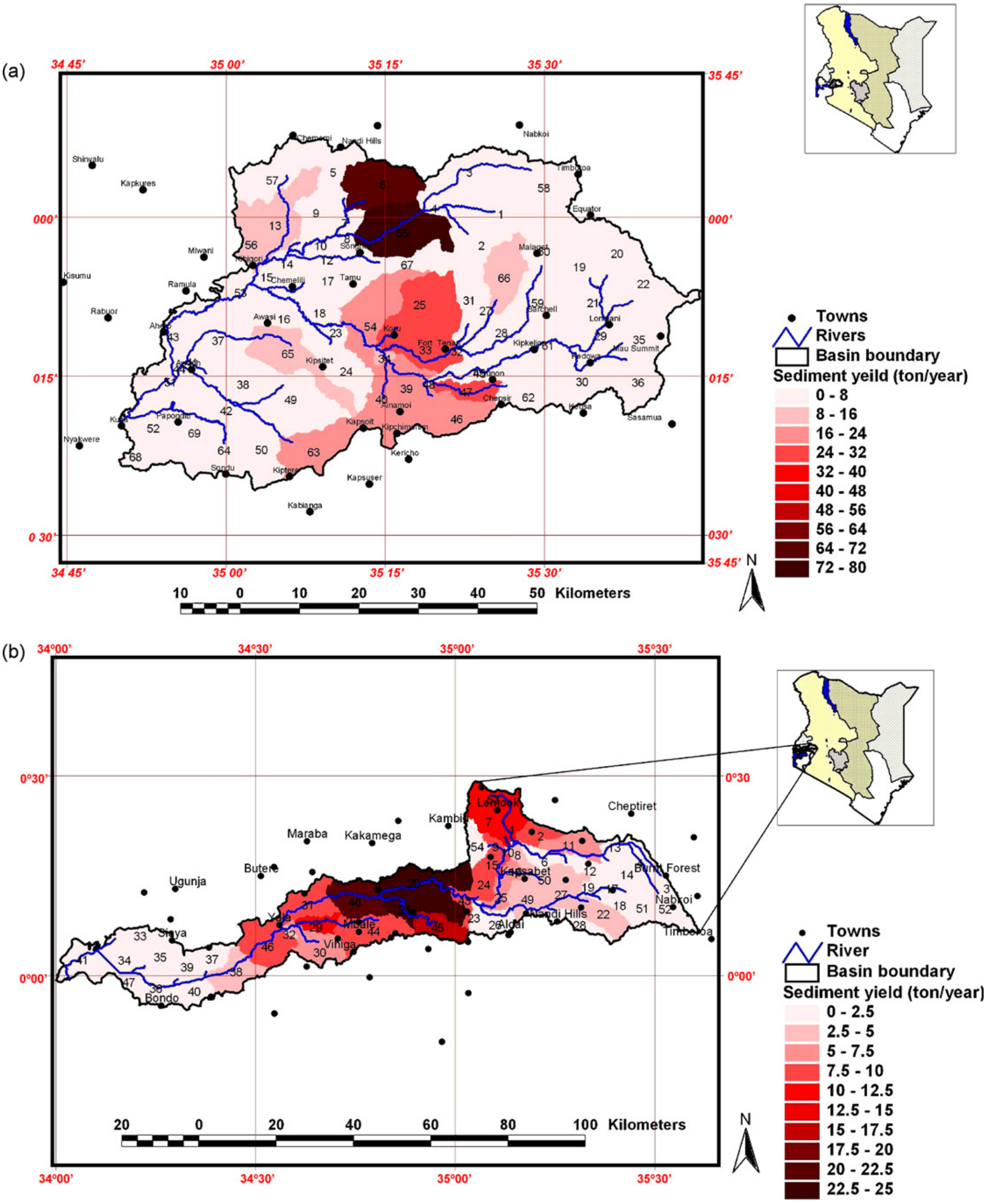

Fig. 2 – (a) Predicted sediment yield by sub-basin in the Nyando river basin. (b) Predicted sediment yield by sub-basin in the Yala river basin.

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The results (not shown) indicate annual sediment yields of between 1 and 3 million tonnes per year in the Nyando, and between 2 and 3 million tonnes per year in the Yala. If climate change results in greater variation in inter-annual and intra-annual rainfall, we should expect greater variation in sediment yield. Years of particularly high rainfall are likely to be coupled with severe flooding, siltation of irrigation canals, and a flush of nutrients and sediment into Lake Victoria.

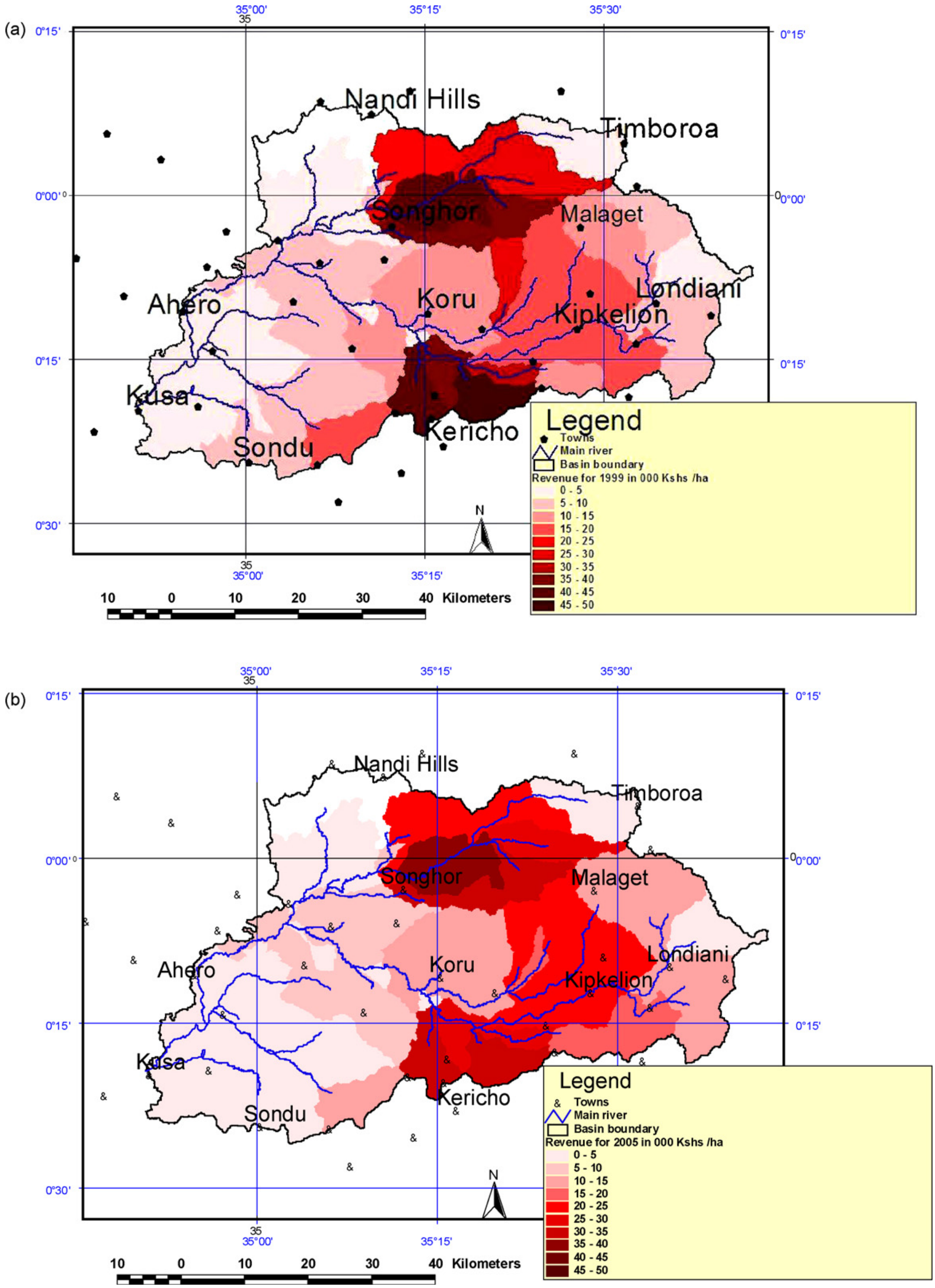

Fig. 3 – (a) Value of agricultural production per hectare per sub-basin in the Nyando basin, 1999 (expressed in thousands of Kenya shillings in 2005 terms). (b) Value of agricultural production per hectare per sub-basin in the Nyando basin, 2005 (expressed in thousands of Kenya shillings in 2005 terms). (c) Ratio of value of agricultural production per hectare in 2005/1999 per sub-basin in the Nyando basin, 2005 (ratios less than one indicate reductions, ratios greater than one indicate increases).

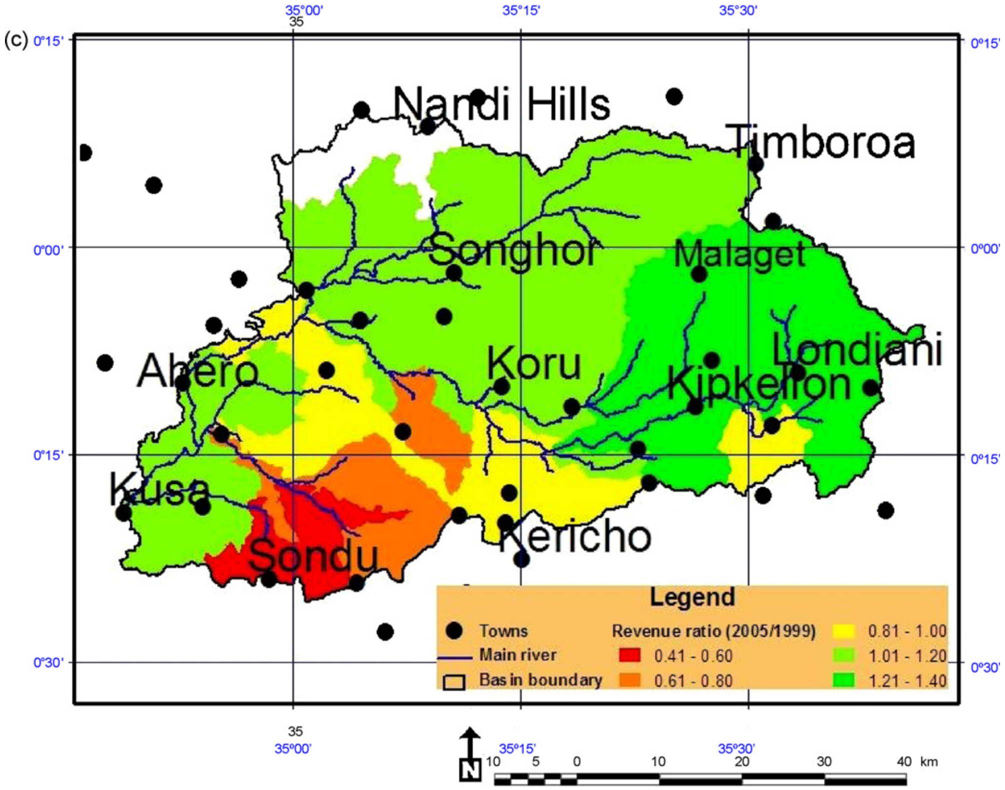

Fig. 3. (Continued).

3.3. *Trends and tradeoffs in agricultural production*

As explained above, this study produced estimates of the quantities and values of major agricultural crops in each administrative division and sub-basin for the years 1999 and 2005. Values are expressed in nominal terms for 1999 and 2005 and in 2005 real terms. Those detailed data are available upon request. For the current purposes, we report two key results. The first result is the geographic distribution of the value of agricultural production in the two basins in 1999 and 2005, aggregated at the sub-basin level and expressed in real 2005 Kenya shillings. The second result is the change in the aggregate value of agricultural production between 1999 and 2005, again aggregated at the sub-basin level.

Results presented for the Nyando basin for 1999 in Fig. 3a show remarkable differences in the value of production across the basin, with the value of production around Ksh 45–50,000 per hectare in the mid-to-upper altitude areas around Kericho town in the southern part of the basin (primarily Anamoi Division) and in the mid-altitude areas in the area around Songhor in northern part of the basin (primarily Tinderet Division). In contrast, value of production was less than Ksh 5000 in the lowest parts of the Nyando basin and Ksh 5000–15,000 per hectare in the mid-altitude sugarcane belt. The areas with highest production include a mixture of tea and mixed smallholder agriculture. (The average exchange rate in 2005 was 75Ksh = US$1.)

The results for Nyando for 2005 in Fig. 3b show a similar spatial pattern of production to that of 1999. The results indicate some reduction in revenue in the areas that had highest revenues in 1999, that is, the tea/mixed agriculture areas near Kericho (Anamoi Division) and Songhor (Tinderet Division). Some of the mid-altitude areas in the sugarcane belt and around Koru and Kipkelion had somewhat higher value of production in 2005 than in 1999. The results for 2005 also suggest that the value of agricultural production was low in 2005 (less than Ksh 10,000 per hectare) in all of the Awach basin in the lower southern part of the basin (Lower Nyakach and Sigowet Divisions).

A more nuanced perspective on changes in the value of agricultural production is provided by Fig. 3c. That figure displays the ratio of the value of agricultural production in 2005 to the value of agricultural production in 1999 (measured in real 2005 terms). The results show a marked decline in Sigowet division in the upper Awach area and smaller declines across much of the mid-altitude and upland area that had the highest value of production in both 1999 and 2005. The results show increases in production (ratios between 1 and 1.6) in the lower Nyando area (although value of agricultural production is still very low in absolute terms), in part of the sugarcane production area, and especially in the highest altitude areas around Kipkelion, Londiani and Malaget.

Similar results on the value of agricultural production were generated for the Yala basin (maps available in Swallow et al., 2008). The Yala results show that the value of agricultural production increases with altitude from the lake shore to the highest altitude parts of the basin near the town of Kapsabet. Results on the ratio of value of production in 2005 to 1999 indicate that the value of production generally declined between 1999 and 2005 in the lower and mid-altitude parts of the basin, while it increased in the highest parts of the basin.

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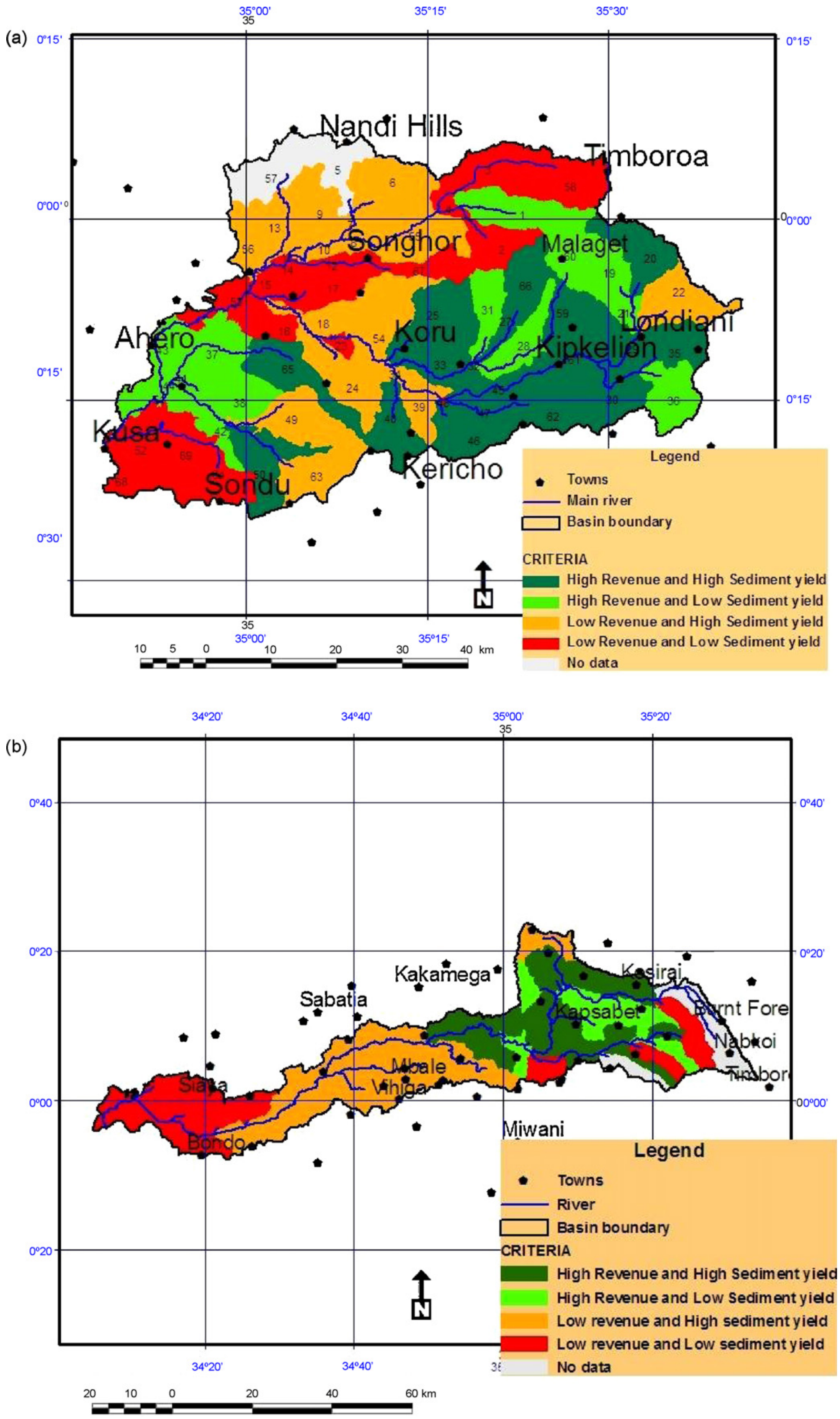

Fig. 4 – (a) Tradeoffs between agricultural revenue and sediment yield, Nyando River basin, 2005. (b) Tradeoffs between agricultural revenue and sediment yield, Yala River basin, 2005.

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The areas around Kapsabet and Kosirai had increases in production per hectare of up to 60% in 2005 real terms.

3.4. *Analysis of tradeoffs between value of production and sediment yield*

The final empirical result presented in this paper is the apparent tradeoff between value of production and sediment yield within sub-basins for the year 2005. First we considered the statistical relationship, estimating a simple linear regression between value of production and sediment yield for each basin. The results (not shown) indicate no significant relationship between sediment yield and value of agricultural production in either basin. Second, we calculated the median sediment yield and median value of production per hectare and characterized each sub-basin as having higher or lower than average sediment yield, and higher or lower than average value of production per hectare. Each sub-basin was thus identified as belonging to one of the four categories: (1) low revenue and low sediment yield (shown in red); (2) low revenue and high sediment yield (shown in brown); (3) high revenue and low sediment yield (shown in dark green); or (4) high revenue and high sediment yield (shown in bright green).

Fig. 4a and b display the results of the overlay of revenue and sediment yield. In the Nyando basin, most of the sub-basins with high revenue are located in the upper part of the basin, with roughly equal numbers characterized as having high and low sediment yield. The rice irrigation area in the lower part of the basin stands out as the only lowland area with high production and low sediment yield. Most of the lower part of the Nyando basin is low revenue, with a mixture of high and low sediment yield. The Yala basin has a more distinct geographic pattern, with the lowest part of the basin having low revenue and low sediment yield, the mid-altitude area having low revenue and high sediment yield, and the upper part of the basin having high revenue and a mixture of high and low sediment yields. Overall, the results indicate tradeoffs, synergies and traps between gain in agricultural production and loss of the regulatory service of sediment control.

4. Conclusions

4.1. *Policy and development conclusions*

The land use change study, based on interpretation of wall-to-wall aerial photographs, shows the dynamic nature of land use in the Nyando and Yala basins between 1991 and 2006. The Nyando basin was particularly subject to land use tradeoffs. In the uplands there was been a large loss of forests and corresponding increases in the area of maize production, while in the lowlands there was an increase in rice and vegetable production and a loss of intact wetlands. The Nyando basin has become even more dependent on maize (and maize mixtures) over the last 15 years, with accompanying drops in area covered by minor crops such as millet, cassava, pyrethrum, potatoes and wheat. Marketing constraints may have been the main cause of this shift toward maize, the major food crop. There were expansions in the agricultural area devoted to vegetables, rice and sorghum, with a particularly large percentage increase in the area of sorghum in the lower Nyando. Sorghum is regarded as being a hardy food crop suitable for labour-constrained families affected by HIV/AIDS. The lower Nyando basin has one of the highest rates of HIV/AIDS in all of Kenya (http://www.faces-kenya.org/photos/hivmap.php).

Tree crops are important in both the Yala and Nyando basins, with expansions in tea and mangoes, and contractions in coffee. The area of woodlots and hedgerows appears to be relatively stable. Tea has become one of the most vibrant sub-sectors of the Kenyan economy, with Kenya becoming one of the world's largest exporters. Tea also produces relatively high revenue for farmers. Coffee, on the other hand, produces very little revenue per hectare and has been largely removed from this part of Kenya. The contraction of coffee is attributed to declines in coffee prices in global markets and mis-management of coffee cooperatives. While apparently stable between 1999 and 2005, there is anecdotal evidence that the area of eucalyptus woodlots on farmland has expanded quickly in recent years, partially due to a ban on logging of trees in government forests (Cheboiwo and Langat, 2008).

The spatial and temporal analysis of the value of agricultural production shows a clear relationship between altitude and value of production. In both basins, value of production is lowest in the areas near to Lake Victoria and highest in the mid-to-upper altitude areas that are suitable to mixed smallholder agriculture and tea. In real 2005 financial terms, the value of agricultural production declined in many of the lower to mid-altitude parts of both basins (especially in the sugar cane areas), while it increased in the upper altitude areas adjacent to the remaining intact forests.

The tradeoff analysis suggests that caution should be taken in accepting generalizations or theoretical propositions that presume particular patterns of tradeoff or synergy between provisioning and regulating services. For the Nyando and Yala river basins, it appears that there are locations where tradeoffs between agricultural production and sediment yield predominate and a roughly equal number of locations where synergies predominate. The theory of poverty traps, which may hold at the household or larger scales of resolution, can help to explain observations of high production with low sediment yield, indicative of a virtuous environment–poverty cycle, and observations of low production with high sediment yield, indicative of a vicious environment–poverty cycle. It is instructive that the mid-altitude part of the Yala basin emerges as a poverty trap area in this analysis, in an earlier study by Shepherd and Soule (1998) and in the recent study by Marenya and Barrett (2007).

Results from this study are relevant to the work of a range of the agencies, both state and non-state, concerned with rural development and environmental conservation in the Kenya portion of the Lake Victoria basin. There is cause for concern for the water resource and environmental agencies responsible for the Nyando and Yala basins. Between 1997 and 2005, there was a considerable amount of land use converted natural vegetable to crop production in the Nyando basin and the most recent data show that there has recently been a large conversion of wetland into irrigated rice in the Yala basin. The environmental costs of these conversions are not calculated in

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this paper, but the results do suggest that there will be increases in sedimentation of waterways in the Nyando and Yala basins. Such sedimentation is very dependent on rainfall patterns: we can expect increased fluctuation in sediment yields and corresponding consequences for phases of flooding and heavy pollution of Lake Victoria.

The main solutions to these problems will not be found in the environment and water sectors alone. Agriculture is the dominant land use in the Nyando and Yala basins and poverty is very high among smallholder farmers. Many farmers, especially in the low and mid-altitude zones, appear to be subject to poverty traps of low income, low investment and high environmental degradation. Breaking out of those traps is possible, and it appears to be happening in at least some of the upper parts of the two basins. Appropriate agricultural development, coupled with the promotion of appropriate land and water management practices, appears to be the main pathway to synergies between economic development and environmental conservation. Within the Nyando and Yala basins there are several areas where special efforts will be needed to help farmers over critical thresholds in production–asset–investment relationships. There is a strong need for environmental management strategies that are part and parcel of agricultural development strategies.

Agricultural agencies should note the overwhelming importance of maize, beans and sorghum as the staple food crops and tea, fruit and vegetables as expanding cash crops in this part of Kenya. Some of these crops, particularly tea and irrigated vegetable production, may be more subject to threshold effects than others and special efforts may be necessary to help smallholder farmers to make those enterprises successful. Improved land management practices—including conservation agriculture practices should be simultaneously promoted to help reduce sediment yield from all crops. Intensified livestock production, which is not explicitly addressed in this study, may be an important part of the agricultural development story for the Nyando and Yala basins. It might be possible to link support for selected agricultural development interventions to compliance with good environmental management through, for example, conditional credit arrangements.

Agricultural agencies should give special attention to sugarcane. Sugarcane occupies a large proportion of the mid-altitude zones of the Nyando and Yala basins. Sugarcane appears to be good for reducing sediment yield, yet the value of production per hectare generated by sugarcane is relatively low and was stagnant between 1999 and 2005. Sugarcane is known to be a crop beset by marketing problems. Can those problems be surmounted to rejuvenate the sector? Should bio-ethanol be given more serious consideration as a possible product of sugarcane? Or should mixed smallholder agriculture be encouraged to replace at least part of the area now dedicated to sugarcane? Policy responses by the Ministry of Agriculture provide opportunities for addressing this array of questions.

4.2. *Research implications*

The concepts and empirical analysis of ecosystem services generated very rich insights into the spatial and temporal patterns of human–environmental interactions in the Nyando and Yala basins in the Western Kenya. Conceptually, the application of the ecosystem services concepts was relatively straightforward: value of agricultural production for the important crops was taken to be an aggregate indicator of provisioning services, sediment yield and loss of natural vegetation were taken to be aggregate indicators of loss of regulating services.

Application of the empirical approach to assess these indicators in the case study area was demanding of both analytical skills and data. Geographic information systems, spatially explicit hydrological modelling, economic analysis and statistical analysis were used by the authors in an iterative manner. Multiple data sources were used including satellite imagery, soils maps, digital elevation models and stream network information from digitized topographic sheets, climate and streamflow data from multiple sources, interpreted wall-to-wall aerial photographs taken at three time periods, and agricultural production and economic data from two time periods. A team approach was essential, with the analysis done in iterations and with review by external experts.

Additional research should be undertaken. Within the Nyando and Yala basins, priority should be given to analysis of the costs of production for the various agricultural products so that the financial returns associated with agricultural production can be estimated. Special attention should be given to the economics of agricultural production in low-asset households and in areas that have emerged as poverty trap areas in this analysis. This would require more household and community-level analyses. It would be instructive to increase the number of ecosystem services to include more provisioning services (e.g. timber, livestock, wetland products, forest products) and more regulating services (e.g. control of disease vectors, pollination). One would expect somewhat different patterns of tradeoff, for example, between the provision of timber and fuelwood and the regulating services provided by crop pollinators. The hydrologic modelling should be improved with more information on the erosion risk factors associated with different land uses and with more information on the risk of gully erosion in the lower Nyando basin.

While the land use change analysis yielded many important insights into the spatial patterns of land use change, relatively little insight has been provided regarding the reasons for those changes. A follow-up spatial analysis could focus on the identification of important drivers of land use change, including relative prices, exhaustion of soil fertility, demographic changes, and policy changes. Such an analysis would require a new round of field work in places with particularly high rates of change.

Additional research should also be undertaken on the linkages between the various ecosystem services and human well-being. Some research on this topic could build directly from the sub-basin level research conducted in this paper, for example, by overlaying poverty (e.g. percentage of households using safe water supplies) and wealth indicators (e.g. percentage of households with iron roofs) onto the measures of provisioning and regulating services. Further measures of human well-being should be considered, particularly the human disease risks (e.g. malaria) associated with environmental management.

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Where there is sufficient data, an appropriate next step would be to expand the geographic scope of the analysis to other basins in the Lake Victoria basin and other regions of Africa. A high priority in the Lake Victoria basin would be the Mara river basin, a larger river basin where there are more obvious tradeoffs between production in the upper basin and biodiversity conservation in the mid-altitude areas (Mati et al., 2006). Other high priority locations might be those where there are distinct opportunities for functional mechanisms of payment for environmental services, such as the Tana River Basin (see World Resources Institute et al., 2007, pp. 109–133).

At the most general level, the analysis presented in this paper suggests that the Millenium Ecosystem Assessment approach to human–environment interactions may be enriched by greater consideration of dynamic poverty traps. As Barrett and Swallow (2006) argue, poverty traps may exist at multiple scales and may interact across scales. In the presence of poverty traps, a variety of environment–development relationships may hold at the same time. Both development and environmental planning should take account of these relationships.

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