

# Aggregate effects on ecosystem services from certification of tea farming in the Upper Tana River basin, Kenya

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## ABSTRACT

Agriculture sustainability standards and certification are increasingly used by the private sector and civil society to incentivize and support environmental conservation and improved rural. However, evidence of impact is limited by methodological challenges that hamper the quantification of certification-induced changes, especially beyond farm level. This paper aims to explore the changes to soil and nutrient regulation ecosystem services from the adoption of Rainforest Alliance tea certification in the Kenyan Upper Tana River watershed. In this study we: i) apply ecosystem service models to simulate the effect of farm-level practices for before and after-certification scenarios, and; ii) evaluate the model applications for their ability to guide future decision making. Our scenario results indicate that a widespread adoption of agricultural practices prescribed in the certification standard reduces sediment export into watercourses. However, an increase in fertilizer use by certified farmers is estimated to result in greater nitrogen and phosphorous loads. Our scenario analyses are highly sensitive to input data and model choice, but show similar relative impacts of tea certification. Opportunities to improve spatial impact measurements to support decision making can be found in the systematic accounting of land management practices by certification organizations and increased remote sensing image accessibility.

## 1. Introduction

After water, tea is the most widely consumed beverage in the world (Mukhopadhyay and Mondal, 2017). Tea production is typically managed intensively in a monoculture, or with light shade cover, and has several potential environmental impacts. The growing demand for tea puts pressure on remnant natural ecosystems to be cleared for tea crops, resulting in biodiversity loss and carbon emissions. Tea expansion continues to be associated with deforestation within Sub-Saharan Africa (Ordway et al., 2017). Once established, intensive production processes of tea have on-farm environmental impacts such as changes to soil chemistry and declines in soil organic content and soil organisms (Zhang et al., 2003), which in turn can reduce farm productivity (Duan et al., 2011). Runoff from tea fields that receive high application rates of fertilizer, pesticide and herbicide can pollute groundwater and downstream waterways (Hirono et al., 2009). The initial land clearance and subsequent management practices such as manual weeding disturb

topsoil and cause erosion that reduces soil integrity and causes downstream river sedimentation and siltation of reservoirs (Zhang et al., 2003; Sahoo et al., 2016)

Several approaches have been designed and promoted to reduce land and water degradation from poor agricultural management practices. Sustainable land management (SLM) – and related concepts such as multi-functional agriculture (Jordan and Warner, 2010), eco-agriculture (Scherr and McNeely, 2008), integrated landscape management (Estrada-Carmona et al., 2014), agroecology (Altieri, 2002), and others (Scherr et al., 2013) – use a holistic and interconnected approach to the management of land for multiple objectives of food production, biodiversity conservation and sustainable rural livelihoods, plus other ecosystem service benefits derived from sustainable stewardship. Evidence shows that SLM practices can improve soil health and reduce soil erosion and downstream sediment and nutrient loads, leading to improved farm productivity and water quality (Bryan and Kandulu, 2009; Lautenbach et al., 2012; Almagro et al., 2016; Doody et al., 2016).

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There is also growing evidence of the ecological and socio-economic benefits of SLM adoption (Rocha et al., 2012; Rueda and Lambin, 2013; Hardt et al., 2015).

While SLM practices are sometimes adopted spontaneously – or based on knowledge shared by extension officers, peers, or otherwise – frequently farmers are reluctant to adopt such practices because of the real or perceived investment costs, implementation challenges, institutional, behavioural and cultural constraints, or negative impacts on yield (Akhtar-Schuster et al., 2010; Grùère and Wreford, 2017). In these cases, incentives may be required to overcome barriers and encourage adoption of SLM. Agricultural standards and certification can provide such an incentive by recognizing farms that adopt SLM practices, thereby aiming to enabling them to realize a price premium for their crop, improve access to markets, or receive other benefits such as training and improved access to inputs (Ochieng et al., 2013). As a market-based mechanism, certification is seen as an important instrument to steer sustainable agricultural practices in areas where governments lack capacity and resources to regulate agriculture effectively (Barrett et al., 2001; Tayleur et al., 2017).

Certification and sustainability standards are increasingly being taken up in agriculture, following and anticipating the growing demand for these products (Tayleur et al., 2017; Oya et al., 2018). One of the largest certification programs active in tropical ecosystems is the Rainforest Alliance certification program which was established in the 1990s (Potts et al., 2017). To become certified, farms must comply with the Rainforest Alliance Sustainable Agriculture Standard (formerly known as the Sustainable Agriculture Network [SAN] Sustainable Agriculture Standard).<sup>1</sup> Compliance is audited by independent certification bodies. The principles and criteria (i.e. requirements) of this standard define different elements of sustainable agricultural production, including nature protection, safeguarding water quality, waste management, and occupational health and safety (SAN, 2010). The standard includes land management criteria to improve ecological processes, such as the protection of streamside buffer zones, maintenance of vegetative ground cover, and optimization of fertilizer use to improve water quality, soil health, and crop productivity.

There is growing interest in the effects of SLM on broader landscape objectives and outcomes, measured using an ecosystem services approach (Reed et al., 2015; IPBES, 2018). Several ecosystem services may be enhanced by on-farm SLM practices which accrue to beneficiaries well beyond the individual farmers. For example, downstream reductions in river and reservoir sedimentation and pollutant loads can help improve human water supplies and hydropower opportunities. Widespread uptake of SLM can also result in landscape-scale improvements in biodiversity, with benefit to people across the landscape and beyond. Despite these important linkages between farm-level SLM interventions and key landscape- and watershed-level policy objectives and outcomes, in general there have been only limited attempts to assess these broader impacts of programs to promote SLM (Ezzine-de-Blas et al., 2016). To our knowledge there are no agricultural certification programs that assess the aggregate ecosystem service effects of certification, driven by the adoption of SLM practices.

This paper aims to help fill this gap by exploring the aggregate ecosystem service effects at watershed level from the adoption of Rainforest Alliance certification by tea growers in the Upper Tana River watershed in Kenya. The study has two objectives: i) apply ecosystem service modelling techniques to simulate the effects of the Rainforest Alliance's farm-level SLM requirements on the landscape-level delivery of key water-related ecosystem services within the study area; and ii) evaluate the model applications used to quantify the ecosystem service

effects to support decision making. To address these objectives, we used a three-step approach: first, we parameterized our ecosystem service models based on a field visit and documentation on SLM uptake; second, we defined and ran SLM practice scenarios; and third, we evaluated the sensitivity, and related decision support implications and opportunities, of the model to assess the impact of tea certification on ecosystem service supply.

## 2. Methods

### 2.1. Study area

Our study area is located in the upper part of the Tana River basin (Upper Tana watershed, Fig. 1) in the equatorial zone of Kenya. The Tana River flows from the mountains of the East African Rift eastwards to the Indian Ocean. The Upper Tana study area is about 9,400 km<sup>2</sup>, with average annual rainfall ranging from 2,000 mm at high altitudes to about 500 mm at lower elevations (Hunink and Droogers, 2015). There are two wet seasons (mid-March to June and October to December) and two dry seasons. Land use is dominated by tea and coffee growing on the slopes and annual crops (rice, corn, mixed subsistence agriculture) in the lower downstream area (Fig. 1). The western part of the Upper Tana area includes two forested national parks, Mount Kenya and Aberdare, located on the highest part of these two mountains (Fig. 1). The protected areas are largely ringed by tea producing areas at the middle latitudes down-slope from these headwater protected areas.

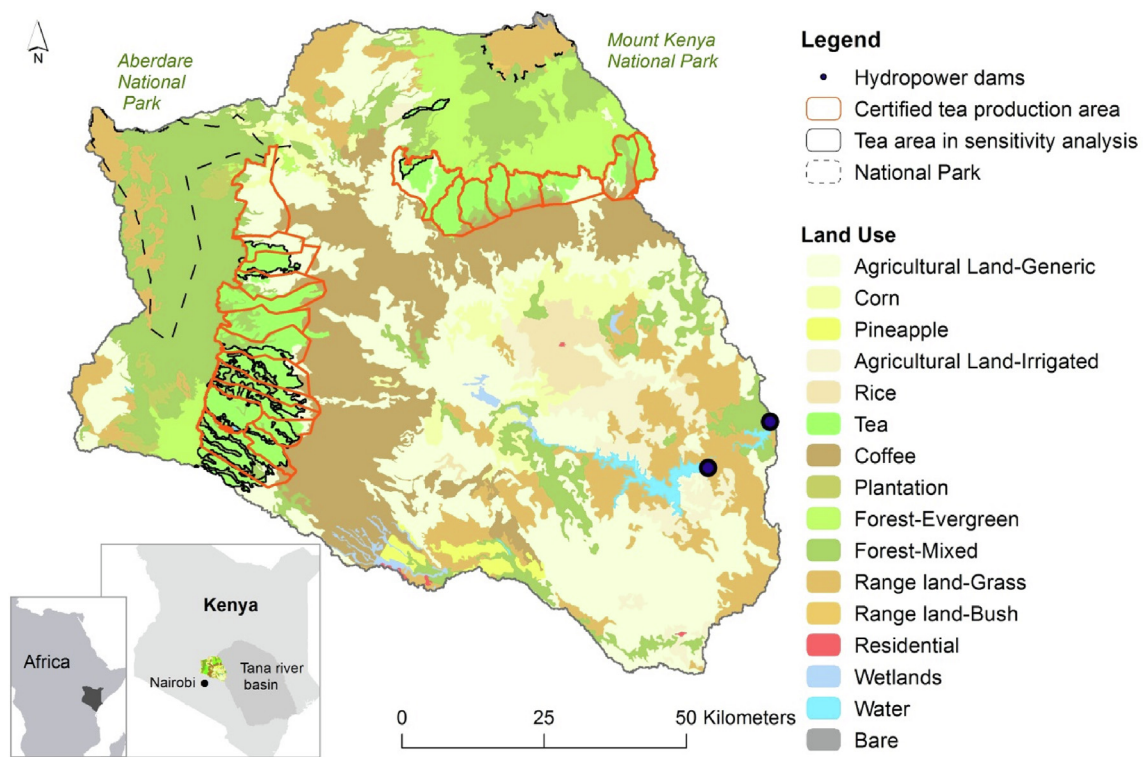
The watershed provides freshwater resources that are essential to local residents and the broader Kenyan populace and economy. The watershed supplies about 95% of Nairobi's domestic water. Additionally, through hydropower infrastructure, the river also provides nearly half of Kenya's energy needs (Hoff et al., 2007). Of the approximate 8 billion cubic meters of water available from rainfall annually in the Upper Tana watershed, about 36% is used for small-holder agriculture, 33% is used for hydropower, 25% is evapo-transpired by forests and natural vegetation, 4% is used for irrigation and 2% is used as Nairobi's water supply (Hunink and Droogers, 2011). However, the quantity and quality of the Upper Tana's water resources are under threat: extensive agriculture development in the 1970s, which saw removal of about 60% of the watershed's original forest cover, continues to impact downstream water quality, water quantity, and water treatment infrastructure (TNC, 2015).

### 2.2. Certification of tea growing

Kenya's Upper Tana watershed has about 250,000 smallholder tea growers that have adopted SLM practices to achieve Rainforest Alliance certification, equating to approximately 95% of all tea growers in the study area (Kenya Tea Development Agency, pers. comm.). Tea growing in the study area started in the 1970s, and in 2010 Rainforest Alliance started training farmers in SLM practices as the basis for certification (Waarts et al., 2012). Training through farmer field schools and lead farmer training ('training the trainers') contributed largely to the uptake of SLM practices (Waarts et al., 2012).

Smallholder tea farmers in the Upper Tana are organized into groups that are managed by the Kenya Tea Development Agency (KTDA) and are certified under the Rainforest Alliance's group certification model. Each smallholder grower supplies tea to the tea processing factory associated with his or her group; of the 65 KTDA factories associated with certified groups, 22 production areas are located in the study area, covering around 110,000 ha (Fig. 1). The tea farms that are currently not certified include large tea estates who do not supply to KTDA factories. In the study area, most farmers first achieved Rainforest Alliance certification between 2010 and 2012 through their membership in KTDA-managed farmer groups associated with each respective KTDA tea processing factory. As with nearly all smallholder tea production in Kenya, tea growing in the Upper Tana watershed is

<sup>1</sup> The 2010 SAN Standard was in effect for the period of time addressed by this study. This standard was superseded in July 2017 by the present standard, which is now known as the Rainforest Alliance Sustainable Agriculture Standard.



**Fig. 1.** The location and land use of our study area, the Upper Tana watershed, in the Tana River basin in Kenya, eastern Africa. The map also shows the area that was used in the sensitivity analysis of the model application. All data are retrieved from the Tana River Basin, Kenya geodatabase and mapping tool (Hussain and Baker, 2016), except for the Africover land use data (FAO, 2003) and Rainforest Alliance tea production areas (own data).

strongly guided by KTDA, which owns the tea factories, manages farmer groups, and provides extension services and facilitates access to inputs for smallholder tea suppliers. As a consequence of this model, smallholder tea production tends to follow relatively uniform practices (Stathers and Gathuthi, 2013; Mbeche and Dorward, 2014)

The 2010 SAN standard includes ten principles addressing a wide range of social and environmental sustainability topics (SAN, 2011, see Table 1). For the purpose of modelling effects on ecosystem services,

this study focuses on the subset of the standard’s requirements in Principles 2 and 9. Principle 2 requirements include the establishment of buffer zones along streams, the protection and/or restoration of all natural ecosystems, and the prohibition on destroying any natural ecosystems. Principle 9 requirements include provisions related to the prevention of soil erosion and the adoption of effective soil and crop fertilization programs (SAN, 2011). Fulfilment of these requirements is hypothesized to influence ecosystem service supply by reducing soil

**Table 1**  
Principles of the 2010 Sustainable Agriculture Network (SAN) Sustainable Agriculture Standard (SAN, 2011).

SAN Principle	Summary of requirements	Considered in this study
1. Social and Environmental Management System	Follow national legislation, effective farm planning and record-keeping, separation of certified and non-certified product	No
2. Ecosystem conservation	No destruction of natural areas buffer zones (3–50 m of natural vegetation) between cropped area and conservation areas and streams planting of native trees to enhance connectivity.	<b>Yes, but not modelled</b>
3. Wildlife protection	No hunting and capturing of animals (exemptions apply), special protection for threatened or endangered species	No
4. Water Conservation	Permits need for water extraction, obligatory water treatment for waste water (e.g. through charcoal pits) or ban (for oils and fecal coliforms), water quality monitory systems continuous discharge. (These requirements relate to water treatment and contamination avoidance, not specific land management practices.)	No
5. Fair treatment and good working condition for workers	Direct hire, minimum wage, prohibited to employ workers younger than 15 years old, special regulations for workers between 15 and 17 years old, well-build workers’ accommodation with sanitary facilities, access to potable water	No
6. Occupational Health and Safety	Restrictions regarding who can apply or handle agrochemicals in combination with health monitoring, adequate storage for agrochemicals, use protective equipment, risk assessment	No
7. Community Relations	Conflict resolution policy in place, needs of local community accommodated, demonstrated land use rights	No
8. Integrated crop management	Inventory of agro-chemical usage, integrated pest management principles applied, no use of illegal pesticides	No
9. Soil management and conservation	Fertilization based on plant needs and soil characteristics. Erosion control and prevention to avoid soil erosion and sedimentation, including the use of vegetative ground cover in addition to minimized use of herbicides.	<b>Yes</b>
10. Waste management	Differentiate organic waste, plastic waste, and empty chemical containers and dispose in adequate ways.	No

erosion and sedimentation, reducing nutrient loads, and improving habitat quality. An analysis of 576 audit reports from Rainforest Alliance certified farms around the globe found that farms in East Africa (including Kenya) showed high levels of compliance with the criteria of the certification standard (Newsom and Milder, 2018).

### 2.3. Field visit

To guide parameterization of ecosystem service models, in August 2017 we visited 15 Rainforest Alliance certified tea farms associated with five KTDA farmer groups (Kiru, Iriaini, Ndima, Mungania and Weru) to gain insight in field-level implementation of SLM practices related to soil management and buffer zones. For each farmer group, a local KTDA extension officer accompanied us and introduced us to the farmers. Per farmer group, the first farmer to be visited was selected by the extension officer, the following two were selected based on proximity, farmer availability, and per farming group we visited at least one farm with a stream on it. The number of visited farmers is very low compared to the total number of tea growers in the area, but for the purpose of guiding scenario development we considered the field observations as indicative for the generally standardized growing practices within strongly organized KTDA groups (Stathers and Gathuthi, 2013; Mbeche and Dorward, 2014). Structured interviews (see Supplementary Material 1) on farm management relative to the requirements of the certification standard were conducted in Kiswahili by a contracted scientist with tea auditing experience. To complement the farm interviews, we used information provided by 10 KTDA tea processing factories on pre- and post-certification fertilizer distribution to members of their farmer groups (of which one was located adjacent to the study area).

### 2.4. Ecosystem service modelling

We used two common models to assess the impact on ecosystem services following adoption of SLM practices associated with certification by tea growers within the study area: i) the InVEST toolbox, to assess impact on sediment and nutrient export after certification; and ii) the Soil and Water Assessment Tool (SWAT) to set reference values and extract parameters for estimating sediment export prior to certification.

#### 2.4.1. InVEST

The InVEST toolbox was used to estimate the effect of changes in land management practices associated with certification. From the InVEST toolbox, we used the Sediment Delivery Ratio model, the Seasonal Water Yield model, and the Nutrient Delivery Ratio model (Sharp et al., 2016).

The Sediment Delivery Ratio model calculates the amount of sediment that leaves the unit of analysis (i.e. raster cell) and reaches the main stream annually. The model uses the Revised Universal Soil Loss Equation (RUSLE) model for soil erosion. Tea certification influences land use/cover and land management, which are reflected in the 'cover management' (C) and 'support practice' (P) factors of the RUSLE. The C factor is the ratio of soil loss from land under the specific crop and management system (i.e., tea) to the corresponding soil loss from land under continuous fallow. The C factor can be used to determine the relative effectiveness of soil and crop management systems in preventing soil loss (the lower the C value, the higher the soil protection). A sensitivity analysis of the RUSLE model by Estrada-Carmona et al. (2017) found that the C factor, along with topography (slope length-gradient), are the most important factors driving predicted soil loss. The P factor is the ratio of soil loss by an improved management practice, such as contouring and terracing, that reduces the amount and rate of water runoff to that of straight-row farming up and down the slope.

The Seasonal Water Yield model calculates the relative contribution of locations (i.e. raster cell) to annual quickflow (surface water runoff during or shortly after rainfall events) and baseflow (movement of

groundwater during drier periods). These values serve as input for the Nutrient Delivery Ratio model, which calculates the amount of nitrogen and phosphorous leaving the unit of analysis (e.g., watershed) via surface and subsurface transport. For the Seasonal Water Yield model, hydrologic soil group curve number (CN) values and monthly crop factors (Kc) values are needed for each land use type. We used CN and Kc values that are typical for each main land use type, as presented in NRCS-USDA (2007) and Allen et al. (1998), respectively. The Nutrient Delivery Ratio model estimates of nitrogen and phosphorous application rates, maximum retention efficiencies, maximum distance of nutrient retention, and proportion of nutrients derived from subsurface flow for each land use type. All input data and parameter settings for the InVEST models are listed in Supplementary Material 4.

#### 2.4.2. SWAT

To set the reference values for sedimentation yield before tea certification, we used a calibrated SWAT model (version 2005) application for the Upper Tana area by Hunink and Droogers (2011). SWAT is considered a state-of-the-art model for modelling hydrological ecosystem services and relationships to land (Droogers et al., 2006; Francesconi et al., 2016). This complex physical model requires a relatively high data input.

Sediment yields in SWAT are estimated with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). In contrast to the (R) USLE applications that use rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield (Hunink and Droogers, 2011). The SWAT model Upper Tana application by Hunink and Droogers (2011) was calibrated using stream flow data and erosion measurements collected between 1980 and 2011; the pre-certification period. Parameters of this model application, including the USLE-K, were adjusted in this calibration process to match the field measurements. These (M)USLE parameters were extracted to parameterize the pre-certification model in InVEST. The validation of this SWAT application showed a R-squared of 0.9 between the average monthly simulated and observed sediment discharge. A full description of SWAT data input can be found in Supplementary Material 3.

SWAT outcome map shows sediment yield (i.e., the sediment transported into the main hydrological channel during a time period) in metric tonnes per hectare per year for each Hydrological Response Unit (HRU). HRUs are the units of analysis used by SWAT which are unique areas of relatively homogenous land use, soil and topography. We aggregated all InVEST outputs to these HRUs to visualize and compare model results.

### 2.5. Scenarios for impact assessment

To assess certification impact, we estimated changes in soil retention (as measured by sedimentation rates) and water quality (as measured by nutrient loading arising from run-off) between two scenarios in the Upper Tana River watershed:

1. A pre-certification scenario reflecting the farming practices prior to 2011; the start of Rainforest Alliance certification (**Scenario 1**).
2. A full certification scenario assuming all tea growers have adopted SLM practices associated with Rainforest Alliance certification (**Scenario 2**).

#### 2.5.1. Scenario 1: Pre-certification

Sediment load in the pre-certification period was calculated based on the InVEST Sediment Delivery Ratio model, using identical C and P factors as the calibrated SWAT model by Hunink and Droogers (2011). The SWAT findings serve as reference estimate of the average yearly sediment yield per hectare (from 2005 to 2011) from tea-sourcing areas prior to certification. For the InVEST application we used global and freely available data as model input, these differed for some variables from the SWAT input data (Supplementary Material 4).

The nutrient exports were estimated using the InVEST Nutrient Delivery Ratio model. The pre-certification nitrogen and phosphorous fertilizer application rates were used as input data. Tea processing factories distribute a mixed NPK product (26%, 5%, 5% respectively) among the farmer groups. Based on the moment factory certification, we used the yearly fertilizer distribution data of the tea processing factories as input for our model to describe the pre-certification fertilizer use (data furnished by certified KTDA factories to Rainforest Alliance, March 2016).

### 2.5.2. Scenario 2: full certification

To estimate sediment export and nitrogen export for the situation in which all tea cultivation areas are certificated as assumed in Scenario 2, we used the InVEST Sediment Delivery Ratio, Seasonal Water Yield, and Nutrient Delivery Ratio models. For these, all biophysical parameters regarding changes in SLM practices after certification were adjusted guided by our field observations and interviews, and tea factory data. We only adjusted the model settings for areas under tea, with all parameters for other land uses in the Upper Tana area remaining the same in both scenarios (Fig. 1).

### 2.6. Sensitivity analysis

To quantify the robustness of the InVEST models in capturing changes and impacts in SLM practices, and as such evaluate the ability to inform decision making, we analysed the sensitivity of the results as follows:

- We compared the sediment yield for Scenario 1 for each HRU as calculated by InVEST with the calibrated and validated SWAT model outcomes. To define the similarities between the more user-friendly InVEST Sediment Delivery Ratio model and the more complex SWAT model outcomes, we carried out correlation analysis and did a visual pattern comparison on the outcome maps.
- We ran the three InVEST models for Scenario 2 again with higher resolution land cover data. The best available land cover data for the full Upper Tana was the Africover dataset (Fig. 1). The resolution of this land cover product does not capture small fields with subsistence agriculture, mixed land uses or linear elements in the landscapes such as buffer zones. To estimate the influence of the land cover resolution on the outcomes, we selected all tea HRUs to rerun all InVEST calculations but with a higher resolution (15 m) land cover map that is available for only a portion of the study area. This higher resolution map was developed by The Nature Conservancy (TNC) and is an update of the Africover map to which more detail was added using Google Earth, ASTER and Landsat sources. There are 31 tea HRUs (from a total of 69 tea HRUs) within the high-resolution land cover map area, and these were used in the sensitivity analysis (see their location in Fig. 1).

## 3. Results

### 3.1. Tea area and model parameters

The area of tea used for model calculations are the 65 tea HRUs (average slope of 14%), which cover around 65,000 ha. The extent of tea based on the HRUs is much lower compared to the certified tea production areas shown in Fig. 1 (i.e. 110,000 ha), as these boundaries are practical divisions of tea sourcing areas based on streams and roads, not actual land cover. The smallholder farms that we observed in the field were each approximately 2 ha, of which a slightly more than half was used for tea production (Table 2), typically grown on the slopes. The remaining land was used for subsistence crops including taro, banana, maize, and cabbage, as well as Napier grass, housing and some natural vegetation. The tea certification standards, however, apply to the whole farm, not just the tea fields (SAN, 2011).

**Table 2**  
Summary of best available evidence of SLM management.

Farm characteristic or practice	Field observations (15 farms)	Factory data (10 factories)
<i>Farm land use</i>		
Tea cultivation	1.2 ha average	
Other crops, natural vegetation, housing	0.9 ha average	
<i>Average fertilizer use (NPK) on tea</i>		
– Before certification		660 kg/ha/year
– After certification		700 kg/ha/year
<i>Erosion control</i>		
Cover crop	All tea area	
<i>Napier grass</i>		
– Before certification	14 m, 33% of farms	
– After certification	14 m, 53% of farms	
Bench/trench for subsistence crop	40% of farms	
<i>Buffer zone along streams</i>		
Before & After certification		
Buffer present	All 11 farms with streams	
• Trees (average width)	50% of all buffers (34 m)	
• Grass (average width)	30% of buffers (10 m)	
• Subsistence crops (average width)	20% of buffers (3 m)	

We set the model parameters for both scenarios by triangulating among three collected sources of information: i) factory records of fertilizer distributed to smallholder farmers pre- and post- certification, ii) field observations and interviews on pre- and post- farm management, and iii) pre-certification field measures for the calibrated SWAT model. Based on these information sources, we characterized three key sets of farming practices that informed the model inputs: i) soil conservation measures; ii) fertilizer use; and iii) a description of the riparian buffer zones.

#### 3.1.1. Soil conservation

The most extensive soil conservation measure in the Upper Tana area is planting of the tea crop itself. After reaching maturity, tea bushes completely cover the soil with canopy and root system as are such considered a cover crop. As a perennial crop, tea is grown as a non-tillage system. Half of the visited farmers grow Napier grass (*Pennisetum purpureum*) on their property to help conserve soil on areas which are not under tea and provide fodder. The amount of Napier grass per visited farm varied considerably, from 60 meter- to 0.6 meter-wide strips along the contours and often in combination with soil conservation structures such as bench terraces and ridges. The average width of these grass strips in the visited farms was 14 m (with average deviation of 14 m). Three of the eight visited farmers with Napier grass did not grow this before certification, equating to a post certification Napier grass uptake of 20% of all visited farms (i.e., three of 15 farms). Six of the 15 visited certified farms across five factories grow their subsistence crops on bench terraces and in trenches. [Supplementary Material 2](#) provides examples of these soil conservation practices.

Based on the SWAT model calibrations, the tea crop pre-certification value (Scenario 1) of the P-factor of the erosion model was set to 1, even though some soil management practices were already in place, and the C-factor to 0.05, which is commensurate with tropical perennial cropping systems with around 80% vegetative cover (Cohen et al., 2005). Based on Hunink and Droogers (2011) and our field observations of erosion control practices, for the tea areas we reduced the P-factor value to 0.85 and the C-factor to 0.04 for Scenario 2 (full certification) to capture the attenuation of soil loss by Napier grass cover (Tables 2 and 3). A P-factor of 0.85 reflects a partial uptake of vegetated contour strips or ridges (P of 0.7 for full uptake by Hunink and Droogers, 2011) The C-factor value of 0.04 is a 20% reduction in the pre-certification C-

**Table 3**  
Value of key model input parameters used for each modelling scenario.

Model Parameter	Scenario 1: pre-certification	Scenario 2: full certification
Tea area	SWAT HRU tea	SWAT HRU tea
C factor, tea	SWAT: 0.05 InVEST: 0.05	InVEST: 0.04
P factor	SWAT: 1 InVEST: 1	InVEST: 0.85
Nitrogen application	InVEST: 172 kg/ha/yr	InVEST: 182 kg/ha/yr
Phosphorous application	InVEST: 33 kg/ha/yr	InVEST: 35 kg/ha/yr

factor, which mirrors the 20% post certification uptake of Napier grass planting in tea observed in visited farms. See [Table 2](#).

### 3.1.2. Fertilizer use

Tea processing factory data furnished by certified KTDA factories to Rainforest Alliance provided an overview of how much mixed NPK product (26%, 5%, 5% respectively) was distributed among the farmer groups by 10 tea processing factories in the Upper Tana region. Based on the year of certification of each farmer group, the average fertilizer distribution per ha was calculated before and after certification. An average of 660 kg of fertilizer per hectare per year before certification was applied. Across the factories, a slight increase in use was reported after certification, from 660 kg/ha to 700 kg/ha ([Table 2](#)). An increase of NPK use was also reported during our field survey. In [Table 3](#) the values for N and P are listed based on the application of the mixed fertilizer product.

### 3.1.3. Buffer zones

According to the certification standard, farmers should maintain an uncultivated buffer of between 3 and 30 meters (depending on stream width, bank slope, and level of input use, as specified in the standard) along each side of perennial and seasonal streams. This requirement appears to be well-respected within the watershed's tea-producing areas: of the 15 visited certified farmers, 11 had a stream on their property, and all of these were fringed by buffer zones. Buffer zones are categorized as either trees (native), grass, or subsistence crops with minimal tillage and no chemical input use ([SAN, 2011](#)). [Table 2](#) reports the average width (one side) of the buffer zones. All farmers with a buffer zone reported already having one before certification, as KTDA has long promoted the implementation of buffer strips. We conservatively assumed that buffer zone prevalence, management, and width did not change with the introduction of certification.

## 3.2. Ecosystem service modelling

### 3.2.1. InVEST scenario outputs

The results from the InVEST toolbox for the Sediment Delivery Model are shown in [Fig. 2](#). The certified tea production areas are also shown on the maps. The amounts of sediment exported from tea growing areas (as defined by the SWAT tea HRUs) into downstream watercourses prior to certification (Scenario 1) averaged 8.8 ton/ha/yr and exceeded 20 ton/ha/yr in some areas ([Fig. 2a](#)). Under the assumed model parameters of Scenario 2 where all tea growers have adopted SLM practices related to Rainforest Alliance certification, sediment export from tea growing areas is nearly 40% lower ([Fig. 2b](#)), averaging 5.5 ton/ha/yr. [Fig. 2c](#) shows the reduction in sediment export between Scenario 1 and Scenario 2. Many tea growing areas see reductions of more than 5 ton/ha/yr, with the average reduction of 3.3 ton/ha/yr. The total amount of sediment exported under tea production in the Upper Tana watershed is estimated at 495,000 ton/yr under Scenario 1 and 311,000 ton/yr under Scenario 2, demonstrating that the modelled adoption of SLM practices associated with Rainforest Alliance certification in the study area resulted in almost 184,000 tonnes of sediment

no longer entering waterways each year.

InVEST model results for nutrient delivery are shown in [Fig. 3 and 4](#). The export of both nitrogen ([Fig. 3](#)) and phosphorous ([Fig. 4](#)) increased slightly from Scenario 1 to Scenario 2 because tea growers apply more fertilizer following certification. The increase in nitrogen export following certification averages 0.53 kg/ha/yr across all tea-sourcing areas ([Fig. 3](#)), resulting in a total of about 30 tonnes of nitrogen additionally exported each year from tea farms following certification. The increase in phosphorous export following certification averages 0.1 kg/ha/yr across all tea-sourcing areas ([Fig. 4](#)), resulting in a total of about 6 tonnes of phosphorous additionally exported each year from tea farms following certification.

### 3.2.2. SWAT baseline output

The average annual sedimentation yield per ha calculated with SWAT for the pre-certification period 2005–2011 is presented in [Fig. 5a](#). While there is sediment export from the upstream areas where tea is grown, the amounts are relatively low compared to some other land uses and crops. The SWAT model showed an average sediment export rate in tea areas of 16 ton/ha/yr.

## 3.3. Sensitivity analyses

### 3.3.1. Model comparison

For the baseline (Scenario 1) models, the SWAT model estimated an average sediment export in tea growing areas of 16 ton/ha/yr with standard deviation (SD) of 19 ton/ha/yr, and the InVEST model estimated an average of 8.8 (SD 8.9) ton/ha/yr of sediment export. The two models use the same C-factor and P-factor parameter values in Scenario 1, but are based on a different sediment estimate equation, erodibility value and weather data. Overall, the HRU values for all land use types in the Upper Tana show a 0.70 correlation (Spearman rank, as data are not normally distributed) between the two models. For the tea areas only, the two modelled values show a 0.51 Spearman rank correlation. In general, the modelled SWAT sediment values for tea are higher compared to the corresponding modelled InVEST values; the beta coefficient of the fitted LM model ( $R^2$  0.64) for InVEST value is 1.8 ( $p < 0.01$ ), meaning that 0.55 ton/ha/yr increase in an InVEST model outcome corresponds to a 1 ton/ha/yr increase for SWAT model. The SWAT model estimates are likely closer to the real sediment loads from tea because the SWAT model was calibrated against field data. Differences in sedimentation estimates from tea between the two models are up to 50 ton/ha/yr. We consider the HRUs in the tea areas with the lowest difference (in yellow, [Fig. 5c](#)) as locations where the InVEST baseline setting is most accurate covering around 32 500 ha (50%) of the total tea area.

### 3.3.2. Land cover resolution

We applied the InVEST models for 31 tea HRUs that were covered by both the land cover datasets (31860 ha). This resulted in substantial differences in the modelled estimates of sediment, nitrogen and phosphorous export from tea sourcing areas ([Table 4](#)). The modelled estimates of sediment and nutrient export are considerably higher under the InVEST model that used higher resolution land cover data compared to the outcomes based on the coarser resolution land cover data. The difference in resolution is illustrated in [Fig. 6](#).

The sedimentation reduction between Scenario 1 and Scenario 2 is less pronounced on a percentage basis in the model with the higher resolution land cover data (22.5% reduction versus 37% reduction) but is relatively similar on an absolute basis (65,200 tonnes reduction versus 76,000 tonnes reduction). Conversely, the nutrient loading models show similar percentage changes between Scenario 1 and Scenario 2 in the model with the higher resolution land cover data. However, the absolute difference is much higher here due to the higher modelled nutrient delivery rates using the high resolution maps. The estimate from SWAT for the total sedimentation of the 31 tea HRUs for

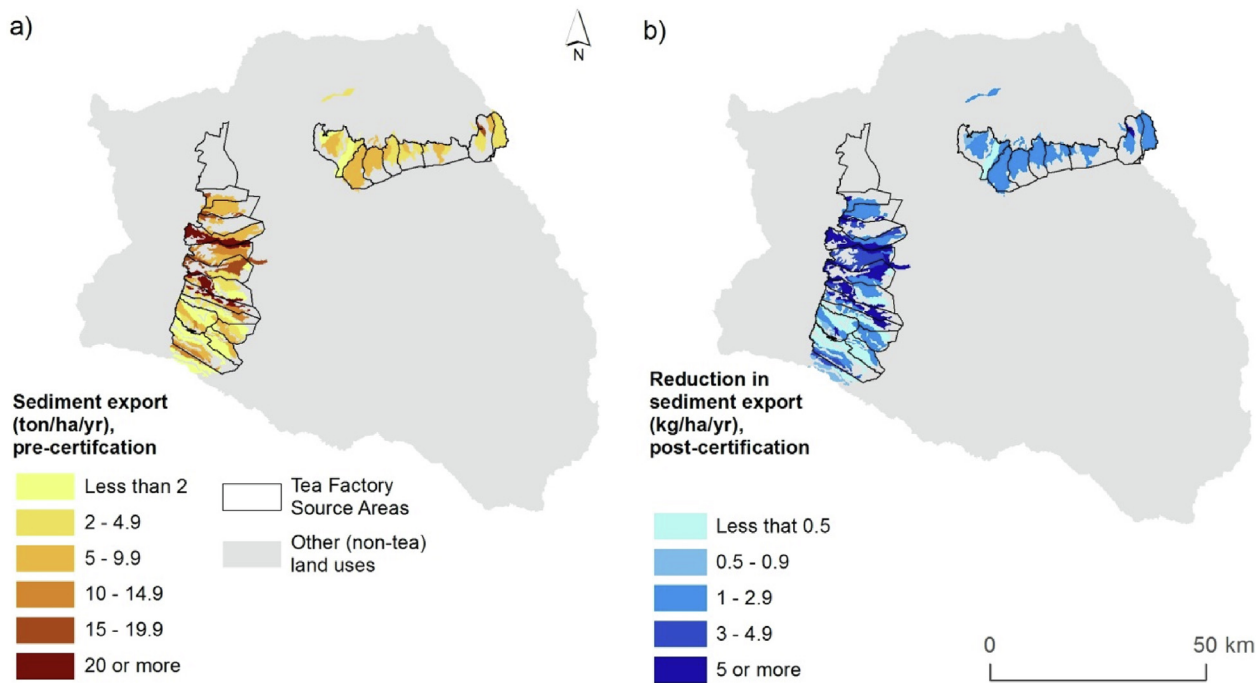


Fig. 2. InVEST model outputs for sediment export: a) Scenario 1 – sediment export with no tea growers adopting SLM practices associated with Rainforest Alliance certification; b) difference in sediment export between Scenario 1 and Scenario 2 (full-certification) for the tea growing areas.

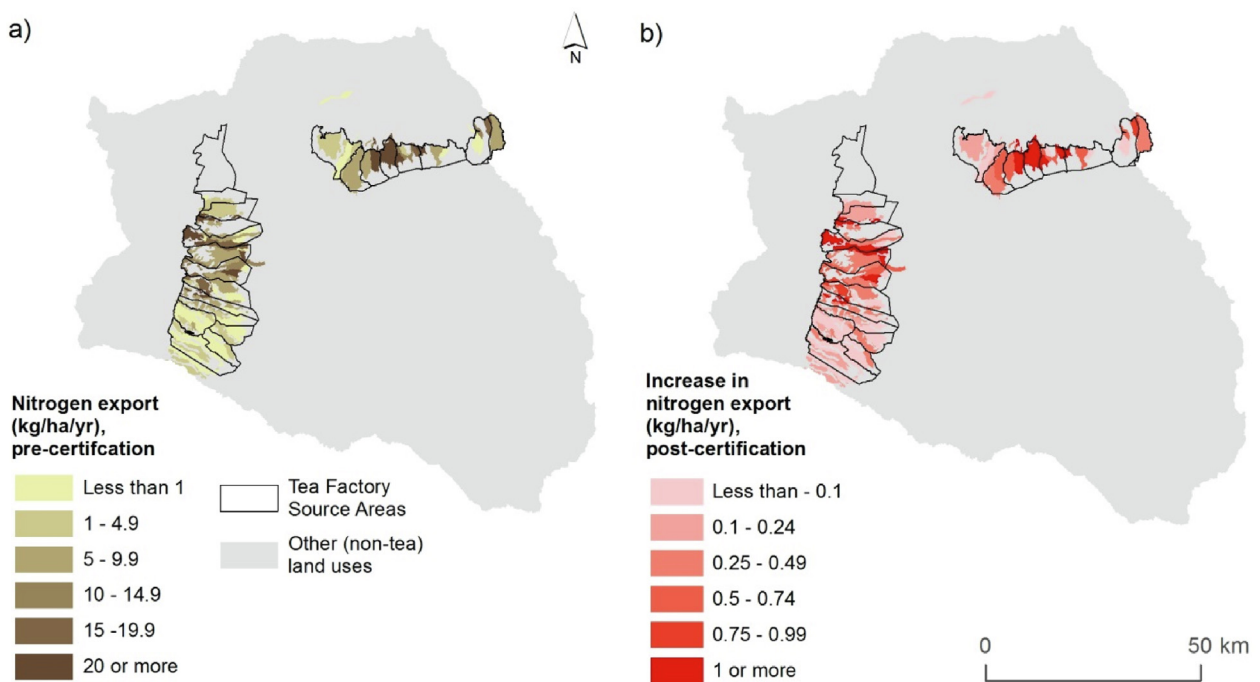


Fig. 3. InVEST model outputs for nitrogen export: a) Scenario 1 – nitrogen export under 172 kg/ha/yr application rate (pre-certification); b) difference in nitrogen export between Scenario 1 and Scenario 2 (full-certification) for the tea growing areas.

Scenario 1 was 465 847 ton/yr. Comparing the values from Table 4 to the values of the calibrated SWAT model, it shows that the InVEST model with the high-resolution land cover better approximates the SWAT outcomes.

#### 4. Discussion

The study results point to several interesting implications, which are elaborated below: 1) the aggregate impact of certification on ecosystem

services in the Upper Tana River watershed; 2) uncertainty of the modelled outcomes in relation to implications for policy, practice, and decision-making, and; 3) opportunities to monitor effects of SLM adoption for ex-post evaluation.

##### 4.1. Aggregate impacts of tea certification in the Upper Tana

Our model outcomes indicate an aggregated impact of Rainforest Alliance certification in the Upper Tana basin: the scenario with

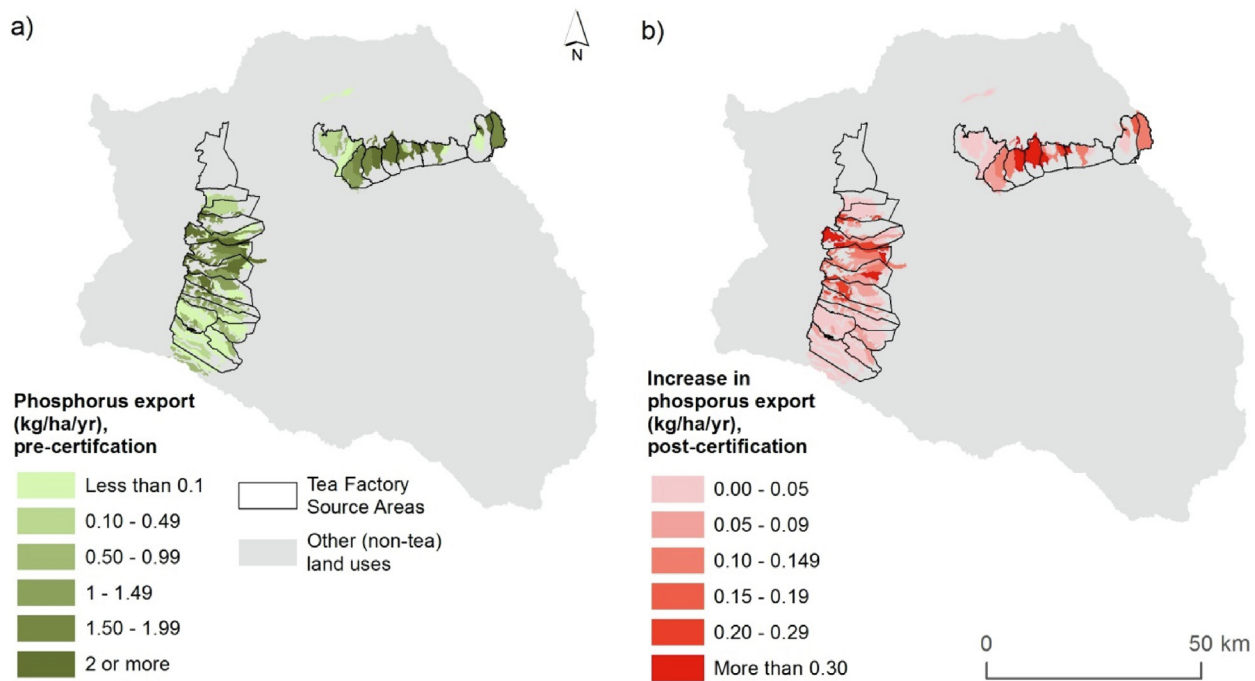


Fig. 4. InVEST model outputs for phosphorus export: a) Scenario 1 – phosphorus export under 33 kg/ha/yr application rate (pre-certification); b) difference in phosphorus export between Scenario 1 and Scenario 2 (full-certification) for the tea growing areas.

widespread certification of tea farms in the region results in a reduction of sediment exported downstream compared to the pre-certification years. In these scenarios only SLM practices related to certification were changed, without incorporation any other factors that could affect ecosystem services supply. These other factors can include policies and regulations of the KTDA, national environmental regulations, and climate (Stathers and Gathuthi, 2013). This modelled reduction and the soil conservation practices that led to it, have beneficiaries on different spatial levels. These include tea farmers experiencing less soil erosion, managers of the downstream hydropower dam contending with less sedimentation of the reservoir, and the citizens of Nairobi benefitting from water and power sources. The inflow of sediments in the Masinga hydropower dam reservoir (the largest water body in Fig. 1) is estimated to be around  $8000 \times 10^3$  ton/yr based on bathymetric surveys (Hunink et al., 2013). In our models the certified farms cover around  $650 \text{ km}^2$  of the  $9400 \text{ km}^2$  Upper Tana watershed (around 7% of the total area). Scenarios estimating the impact of improved soil conservation for this certified tea area estimate a reduction of sedimentation of around  $184 \times 10^3$  tonnes per year (based on the low resolution InVEST model). This is a reduction of around 2.3% of the total sediment inflow in the Masinga reservoir. The sediment reduction indicates a low but clear overall benefit for the hydropower reservoir with an economic value. The Nature Conservancy has identified a range of reduced and avoided costs for the power and water supply facilities in case of lower sedimentation rates in this basin (TNC, 2015).

An early study in the Upper Tana region showed that to obtain similar erosion reduction rates from tea areas (i.e. an average of reduction  $3.3 \text{ ton/ha/yr}$ ) would require significant investment costs to stimulate SLM practices, for example in the form of a payments for ecosystem services scheme (Hunink et al., 2012; Vogl et al., 2017). Such a funding scheme was not implemented at that time because of poor financial and political support in the area (Kauffman et al., 2014). Clear financial benefits for stakeholders and funders are essential to promote long-term watershed conservation with multiple benefits for human well-being and nature (Bremer et al., 2016). Even though Rainforest Alliance does not provide guaranteed prices, the agricultural standards and certification provided and increased incentive for adopting SLM practices by providing market-access for tea producers. Market-access

benefits relate to the sourcing policy of Unilever (owner of the Lipton tea brand) to only purchase Rainforest Alliance certified tea, and an increased leave quality (Stathers and Gathuthi, 2013). Prior to certification, widespread KTDA-led extension services already stimulated uptake of some of SLM practices in Kenya (Waarts et al., 2012; Mbeche and Dorward, 2014).

In the certified tea production area, tea processing factory data and field observations showed an increase in fertilizer use since certification. For our scenario run, this has led to a modelled increase of approximately 6% in N and P outflow from tea areas for which the economic or environment costs were not estimated. The current fertilizer distribution to certified farms (average of  $182 \text{ kg N/ha/yr}$ ), is above the KTDA recommended fertilizer application rate of  $150 \text{ kg N per year}$  (SAN, 2011), although farmers reported that they aim to follow this advice. During our field visit, farmers mentioned two reasons for their change in fertilizer application in the last years: a better understanding of the benefits of NPK fertilizer, and increased purchasing power to buy fertilizer product. This increase in fertilizer use is not an intended outcome of the certification scheme. Rather, the certification standard calls for farmers to conduct soil and/or foliar analyses to help determine optimal fertilization practices (SAN, 2011). During the field visit we asked about management practices regarding organic fertilizer use. It is common and traditional practice for farmers to leave the plant material on the field after pruning (mulching). Some farmers buy goat manure or use manure from their livestock to fertilize their land in addition to NPK use and mulching. Due to poor estimates on overall organic fertilizer use and nutrient contents in the study area, organic fertilizers were not included in our assessment. The nutrient model outcomes therefore show the lower limit of the total nutrient applications.

Our field observations and spatial data lacked information (in terms of spatial and temporal resolution) to make any statements about changes in prevalence and status of buffer zones, as prescribed in the tea certification standard. We therefore could not assess any change in habitat quality related to these natural zones, or their impact on water quality. For the farms visited, certification did not lead to new buffer zones on their property. However, an earlier study of KTDA farmer groups indicated that the prevalence of streamside buffer zones did



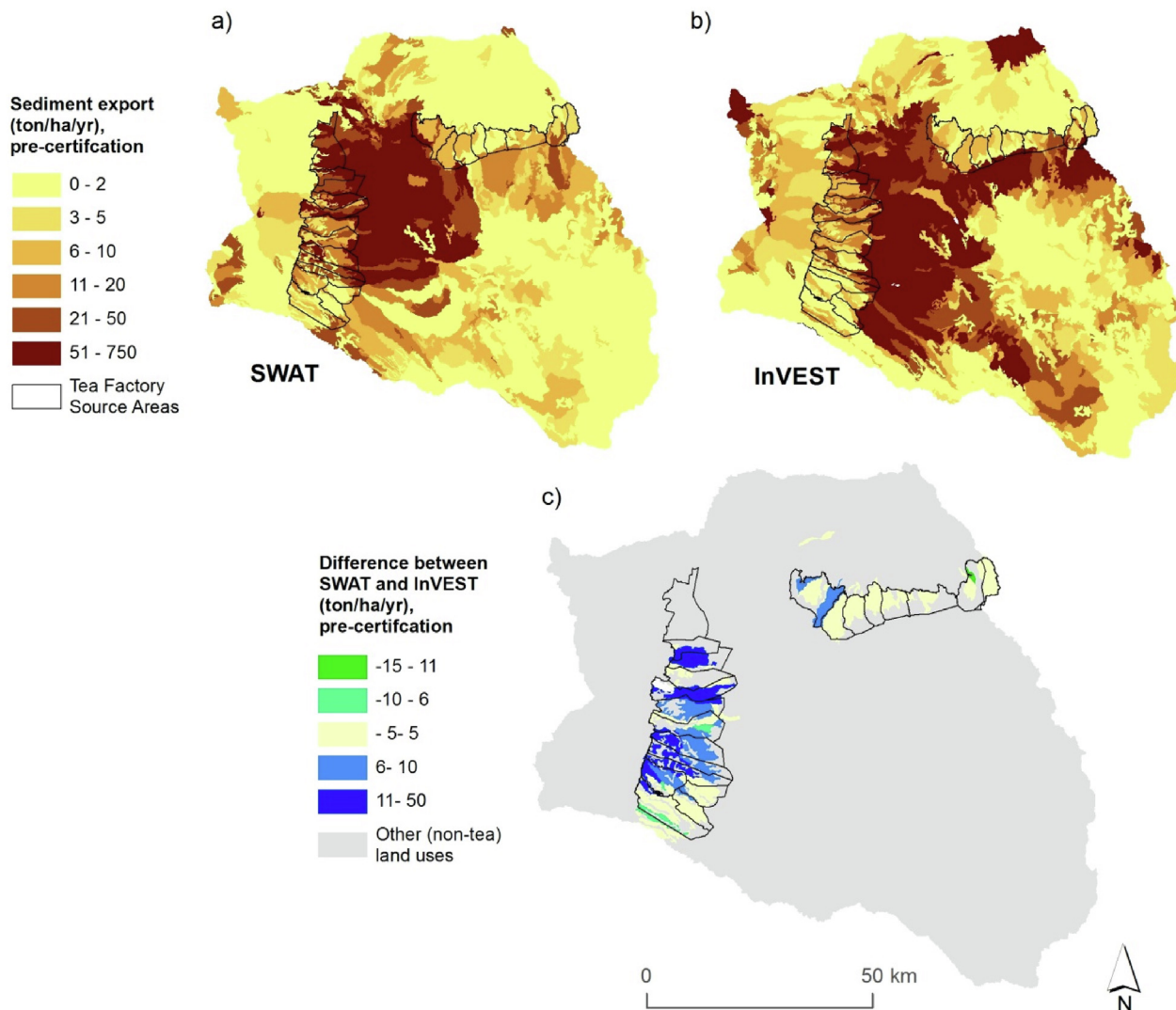


Fig. 5. Modelled sediment yield in the Upper Tana River watershed under Scenario 1 (pre-certification) using a) SWAT, b) InVEST, and showing c) the subtraction of the InVEST from the SWAT model outcomes (Natural Breaks Jenks classification).

increase after certification and that the quality of the buffer area increased (by removing exotic species like Eucalyptus) after farmer training in the context of the certification (Waarts et al., 2012). As we were unable to obtain quantitative information on these changes, we conservatively assumed that buffer zone prevalence, management, and width did not change with the introduction of certification. If one or more of these buffer zones parameters increased, the sediment and nutrient loading would have been less for the full certification scenario.

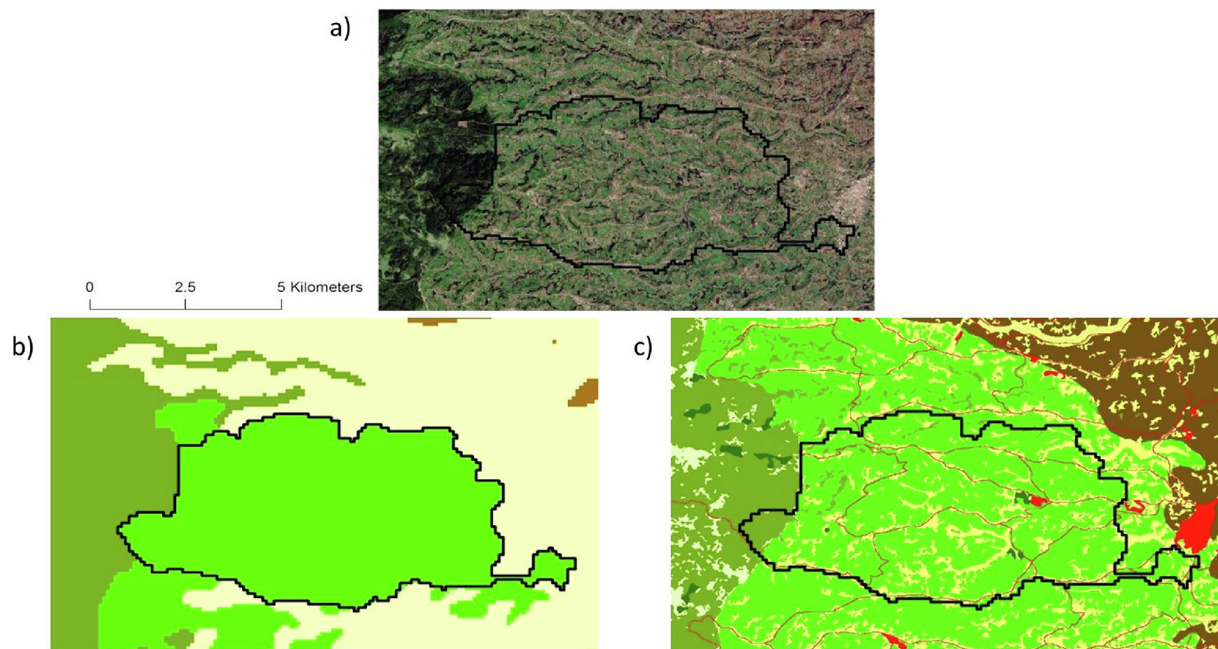
There is much interest in how land use in the Upper Tana basin can

help protect critical economic and social assets (hydropower and domestic water supplies), and what kinds of policies and incentives are effective and cost-efficient to enable the watershed to continue to supply ecosystem services. Market-based incentive programs can contribute to delivering such benefits. The aggregated effect of SLM, stimulated by market incentives though certification, is still limited but could grow considerably if other crop sectors were also included. In the Upper Tana area, the modelled highest average erosion rates are found for coffee (49 ton/ha/yr) and annual crops (37 ton/ha/yr) (Hunink and

Table 4

Comparison of InVEST model outputs applied to different resolution land cover data. The full upper Tana model used the Africover (90 m pixel resolution) land cover data, and the high resolution tea HRUs model used the TNC (15 m pixel resolution) land cover data.

	Full Upper Tana model			High resolution tea HRUs		
	(31 tea HRUs)		% difference (S1-S2)	(31 tea HRUs)		% difference (S1-S2)
	Scenario 1 (S1)	Scenario 2 (S2)		Scenario 1 (S1)	Scenario2 (S2)	
<b>Total sediment delivery</b>						
Sediment exported ('000 ton/yr)	205.2	129.2	-37	290.1	224.9	-22.5
<b>Total nutrient delivery</b>						
Nitrogen exported (ton/yr)	120.5	127.5	5.8	1028.0	1085.1	5.6
Phosphorous exported (ton/yr)	23.1	24.5	6.1	192.7	204.1	5.9



**Fig. 6.** Data challenges to capture tea area and landscape elements, example for HRU280, the black boundary: a) true colour Sentinel satellite image of the area (10 m resolution, December 2016) the dark green shaded show trees, lighter green tea plantations, and red-brown built up areas; b) land cover map used in the InVEST and SWAT modelling: dark green are forest classes, light green is tea, see the Fig. 1 legend; c) high resolution land cover map by TNC.

Droogers, 2011). SLM uptake through the market incentive by certification has most potential for the commodity crop coffee covering a large area of the watershed (Fig. 1). In general, the benefits of SLM for soil and water can be magnified if they are targeted to specific areas that are more environmentally sensitive (e.g., steep slopes) or that directly affect ecosystem service supply (e.g., riparian areas) (Doody et al., 2012; Kaini et al., 2012; Buchanan et al., 2013; Tamene et al., 2014; Chen et al., 2016; Giri et al., 2016; Haregeweyn et al., 2017). Spatially prioritizing certification locations could improve the outcomes of certification, but it could require companies to consider crop sourcing locations with higher production risks (Tayleur et al., 2018). Decisions regarding certification locations and crops and SLM farmer training by Rainforest Alliance and KTDA can as such be guided by spatial modelling efforts as presented in this paper.

#### 4.2. Uncertainty in impact assessments of SLM

This study used three different model applications to estimate the ecosystem service supply for two scenarios in the Upper Tana area: the SWAT model and the InVEST toolbox run with both high and lower resolution land cover data. A comparison of the models showed considerable differences between the model outcomes. For example, the average yearly sediment yield from tea areas pre-certification was estimated to be 16 ton/ha by the SWAT model and 8.8 ton/ha by the full InVEST model. For the area for which we had high resolution data (the 31 HRUs) we found an average of 9.1 ton/ha sediment export when using with high resolution data compared the 6.3 ton/ha using the land cover data used for the complete study area (Table 4, Fig. 5). While our sedimentation estimates are in line with erosion values of tea plantations elsewhere (e.g. in India, Sahoo et al., 2016), small average differences per hectare result in large differences when aggregating values to an entire watershed.

Our multiple model applications show that sediment yield and nutrient loading estimates are highly sensitive to model and data choices. For policy and decision makers like Rainforest Alliance and KTDA it is important to know how much modelling tools and data sources influence the conclusions resulting from ecosystem services assessments (Schröter et al., 2015; Bagstad et al., 2018). In the context of this study,

the purposes include demonstrating the value of farm level SLM for a watershed, priority setting of new SLM practices, exploring the opportunity for monitoring impact of SLM on ecosystem services, or the development of policy instruments. Based on our results, we caution the use of the current set of commonly used SWAT and InVEST modelling techniques for making precise statements on absolute sediment and nutrient loadings over time, and as such, detailed SLM impact statements on a watershed level. The presented SWAT application was calibrated and validated ( $R^2$  of 0.90) based on measured turbidity and sedimentation data, leading to a robust sedimentation map to set benchmark values. This 90% is seen as minimum level of certainty for ecosystem service model outputs to be adequate to support decision making (Willcock et al., 2016). However, the SWAT outcomes are limited to the erosion control ecosystem service before 2011, the pre-certification period. As impact studies like ours lack counterfactuals, the use of scenarios to model impact is crucial (Willcock et al., 2016). Using InVEST we could explore SLM scenarios, but we could not precisely mimic the calibrated SWAT outcomes. For sedimentation yield, we found a low Spearman rank correlation of 0.51 between the SWAT and InVEST estimates for the tea HRUs. This correlation between the outcomes of the modelling tools was 0.70 for all HRU of the Upper Tana area, meaning that InVEST estimates deviated more from the SWAT sedimentation values in the tea areas compared to the rest of the watershed. To understand if higher data resolutions produce more reliable results we ran the InVEST model with two land cover data set: 90 m and 15 m resolution. With higher resolution land cover data, the sediment yield estimates increased and approached the SWAT values. An increase in sediment yield estimates with an InVEST model application using higher resolution maps was also found by other comparative studies (Hamel et al., 2017; Bagstad et al., 2018). While InVEST applications with different land cover resolution gave different results, they showed similar relative changes between the two modelled scenarios (Table 4).

Spatial ecosystem service assessments are model outcomes with different ranges of uncertainty, which are rarely reported (Schulp et al., 2014; Van der Biest et al., 2015; Willemen et al., 2015). With ecosystem service maps becoming an increasingly popular input to decision making, the reporting, quantifying and visualizing of uncertainty of ecosystem service maps needs to be documented. Comparing modelled

results with the outcomes of other models, or comparing to other knowledge sources (Willemen et al., 2017) helps to define hotspots of model agreement (i.e. areas of certainty). Our study showed that the pre-certification sedimentation estimates were most likely correct in the yellow areas in Fig. 5, which are mostly located around Mount Kenya. The quality of the full certification model runs is not quantified because the link to SLM changes to model parameters could not be validated.

#### 4.3. Opportunities to monitor effects of SLM adoption for ex-post evaluation

The increase in land degradation extent and severity, together with the need to improve agricultural production to feed a growing population and increase income, drive the uptake of land management practices that reconcile agricultural production with the maintenance or enhancement of ecosystem service supply in rural landscapes (Mace, 2014; IPBES, 2018). Governments, practitioners, and scientists are calling for more evidence of causal change in ecosystems and human well-being resulting from SLM and other ecosystem-based or landscape interventions (Milder et al., 2014; Díaz et al., 2015; Lovell et al., 2015). It has been shown that the uptake of environmental interventions will be higher when sound evidence on their impact is available (Walsh et al., 2015), especially when investing in common pool resources (Muradian and Rival, 2012).

It is difficult to measure impact of rural landscape interventions such as SLM or sustainability certification on ecosystem services. Only very few empirical studies assess the impact of certified versus non-certified farming practices on social and environmental aspects (Ochieng et al., 2013). Besides the challenge to identify baseline and control values, monitoring and evaluation efforts for large areas typically use insufficient indicators or time span (Lovell et al., 2015; Gurr et al., 2016; Nunes et al., 2016). In addition, defining the appropriate spatial and temporal levels to monitor indicators related to human well-being in complex systems is difficult; it requires the identification of the key landscape processes affected by interventions, and achieving acceptable levels of accuracy while considering inputs such as financial, institutional, and human resource commitments (Singh et al., 2014; Heenan et al., 2016). Monitoring systems must be able to track interventions that often require multiple years to start generating benefits (Kinzig et al., 2011; Fremier et al., 2013), and ideally should identify who benefits from landscape improvements, where, and when (Daw et al., 2011). Awareness of these challenges has led to widespread calls for evidence of causal change in ecosystems and living conditions for people resulting from integrated sustainability interventions (Milder et al., 2014; Díaz et al., 2015; Lovell et al., 2015) and consistent and effective systems for holistic evaluation and monitoring of such interventions (Tallis et al., 2008; Scherr et al., 2012; Mueller and Geist, 2016; Reed et al., 2016).

Sustainability certification programs have the potential to monitor the adoption of SLM practices at multiple scales. At the micro level (i.e. the individual farm or cooperative), annual audits can collect monitoring data to track change over time. When analysed in aggregate or combined with information on the characteristics of certified operations, such monitoring data can be used to assess patterns, trends, and predictors of performance based on factors such as farm/group location, size, crops grown, years certified, biophysical and policy context factors, and others. Group-certification auditing information, as for tea in the Upper Tana area, has not yet reached that potential. A key shortcoming for monitoring is that auditing information for group-certification does not show the performance of individual farmers, since the specific farmers who are audited can change from year to year. Initiatives are underway at sustainability certification organizations aiming to improve the routine collection and reporting of time-series data on practice adoption and selected outcomes (Ochieng et al., 2013; Milder et al., 2016). The use of auditing information for monitoring is restricted to commodity crops for which there is a consumer and company demand for certified products, such as tea, coffee, and

soybean. Products including rice, maize and livestock products are still poorly covered by sustainability standards (Tayleur et al., 2018). At the macro level (i.e. a region or watershed in which a critical mass of certification occurs), efforts such as those conducted in this study build on a small but growing body of work that uses spatial modelling to compare outcomes such as tree cover, forest quality, connectivity and deforestation rates in landscapes dominated by certified agriculture relative to landscapes with little or no certification (e.g. Hardt et al., 2015; Rueda et al., 2015; Takahashi and Todo, 2017). Remote sensing, especially when combined with local knowledge on field locations and land management practices (Mialhe et al., 2015; Rueda et al., 2015; Dutrieux et al., 2016), has a role to play in improved monitoring of impacts. The frequent and detailed observations of new satellite missions delivering freely accessible images, such as the European Space Agency's Sentinel program, will allow for improved information on crop extent and green infrastructure such as buffer zones.

## 5. Conclusions

Voluntary crop certification can steer sustainable farming practices and as such have a potential role in complementing governmental strategies in achieving sustainability goals. Large scale effects of agricultural certification programs on ecosystem services are currently not monitored. This study aimed to explore the effect of adopting farm-level practices prescribed by Rainforest Alliance tea certification on the watershed-level delivery of erosion prevention and nutrient retention ecosystem services and to evaluate the ability of spatial modelling applications to guide future decision making. Our scenario-based study showed that the assumed adoption of practices prescribed in the Rainforest Alliance certification program by all tea farmers would reduce sediment export into watercourses. However, there is an indication that certified farmers' increase their use of fertilizer to boost tea production which is estimated to result in greater nitrogen and phosphorous loads post-certification. Our sediment and nutrient estimates based on the scenario analyses are highly sensitive to model and data choices, but show similar relative impacts of tea certification across multiple models. While the different models showed consistent relative impacts, the very different absolute magnitude of impacts estimated by the different models indicates that the results of this study are not robust enough to yield precise quantifications of certification impacts. Spatial impact studies like ours can be valuable for demonstrating the value of SLM and for setting priorities for new investments in promoting or supporting SLM practices using state-led, private or civil society instruments. Spatially prioritizing certification locations that are more environmentally sensitive or that directly affect ecosystem service supply can improve the outcomes of certification for people and nature. To support the ex-post empirical evaluation of certification as an instrument for sustainable land management, the systematic accounting of farming practices by sustainability certification organizations and use of remote sensing techniques are necessary to improve spatial impact assessments.

### Declaration of Competing Interest

DN, JCM, DH are employed by Rainforest Alliance, LW and NDC received funding from Rainforest Alliance to conduct this study.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoser.2019.100962>. These data include Google maps of the most important areas described in this article.

## References

- Akhtar-Schuster, M., Thomas, R.J., Stringer, L.C., Chasek, P., Seely, M., 2010. Improving the enabling environment to combat land degradation: institutional, financial, legal and science-policy challenges and solutions. *Land Degrad. Dev.* 22, 299–312.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements*. FAO Irrigation and drainage paper 56. FAO, Rome, Italy.
- Almagro, M., de Vente, J., Boix-Fayos, C., García-Franco, N., Melgares de Aguilar, J., González, D., Solé-Benet, A., Martínez-Mena, M., 2016. Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems. *Mitig. Adapt. Strat. Glob. Change* 21, 1029–1043.
- Altieri, M.A., 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agric. Ecosyst. Environ.* 93, 1–24.
- Bagstad, K.J., Cohen, E., Ancona, Z.H., McNulty, S.G., Sun, G., 2018. The sensitivity of ecosystem service models to choices of input data and spatial resolution. *Appl. Geogr.* 93, 25–36.
- Barrett, C.B., Brandon, K., Gibson, C., Gjertsen, H., 2001. Conserving tropical biodiversity amid weak institutions. *Bioscience* 51, 497–502.
- Bremer, L.L., Auerbach, D.A., Goldstein, J.H., Vogl, A.L., Shemie, D., Kroeger, T., Nelson, J.L., Benítez, S.P., Calvache, A., Guimarães, J., Herron, C., Higgins, J., Klemz, C., León, J., Sebastián Lozano, J., Moreno, P.H., Nuñez, F., Veiga, F., Tiepolo, G., 2016. One size does not fit all: natural infrastructure investments within the Latin American Water Funds Partnership. *Ecosyst. Serv.* 17, 217–236.
- Bryan, B.A., Kandulu, J.M., 2009. Cost-effective alternatives for mitigating Cryptosporidium risk in drinking water and enhancing ecosystem services. *Water Resour. Res.* 45.
- Buchanan, B.P., Archibald, J.A., Easton, Z.M., Shaw, S.B., Schneider, R.L., Todd Walter, M., 2013. A phosphorus index that combines critical source areas and transport pathways using a travel time approach. *J. Hydrol.* 486, 123–135.
- Chen, L., Wei, G., Shen, Z., 2016. Incorporating water quality responses into the framework of best management practices optimization. *J. Hydrol.* 541, 1363–1374.
- Cohen, M.J., Shepherd, K.D., Walsh, M.G., 2005. Empirical reformulation of the universal soil loss equation for erosion risk assessment in a tropical watershed. *Geoderma* 124, 235–252.
- Daw, T., Brown, K., Rosendo, S., Pomeroy, R., 2011. Applying the ecosystem services concept to poverty alleviation: the need to disaggregate human well-being. *Environ. Conserv.* 38, 370–379.
- Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan, K.M.A., Figueroa, V.E., Duraipah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P., Mace, G.M., Martín-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez, E.S., Reyers, B., Roth, E., et al., 2015. The IPBES Conceptual Framework — connecting nature and people. *Curr. Opin. Environ. Sustain.* 14, 1–16.
- Doody, D.G., Archbold, M., Foy, R.H., Flynn, R., 2012. Approaches to the implementation of the water framework directive: targeting mitigation measures at critical source areas of diffuse phosphorus in Irish catchments. *J. Environ. Manage.* 93, 225–234.
- Doody, D.G., Withers, P.J.A., Dils, R.M., McDowell, R.W., Smith, V., McElarney, Y.R., Dunbar, M., Daly, D., 2016. Optimizing land use for the delivery of catchment ecosystem services. *Front. Ecol. Environ.* 14, 325–332.
- Droogers, P., Mantel, S., Kauffman, S., 2006. *River Basin Models to Support Green Water Credit Assessments*. Draft Report. FutureWater/SEI.
- Duan, X., Xie, Y., Ou, T., Lu, H., 2011. Effects of soil erosion on long-term soil productivity in the black soil region of northeastern China. *Catena* 87, 268–275.
- Dutrieux, L.P., Jakovac, C.C., Latifah, S.H., Kooistra, L., 2016. Reconstructing land use history from Landsat time-series: case study of a swidden agriculture system in Brazil. *Int. J. Appl. Earth Obs. Geoinf.* 47, 112–124.
- Estrada-Carmona, N., Hart, A.K., DeClerck, F.A.J., Harvey, C.A., Milder, J.C., 2014. Integrated landscape management for agriculture, rural livelihoods, and ecosystem conservation: an assessment of experience from Latin America and the Caribbean. *Landscape Urban Plann.* 129, 1–11.
- Estrada-Carmona, N., Harper, E.B., DeClerck, F., Fremier, A.K., 2017. Quantifying model uncertainty to improve watershed-level ecosystem service quantification: a global sensitivity analysis of the RUSLE. *Int. J. Biodivers. Sci., Ecosyst. Serv. Manage.* 13, 40–50.
- Ezzine-de-Blas, D., Wunder, S., Ruiz-Pérez, M., Moreno-Sanchez, R.d.P., 2016. Global patterns in the implementation of payments for environmental services. *PLoS ONE* 11, e0149847.
- FAO, 2003. *Africover: Multipurpose Landcover database* (<http://www.africover.org>).
- Francesconi, W., Srinivasan, R., Pérez-Miñana, E., Willcock, S.P., Quintero, M., 2016. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: a systematic review. *J. Hydrol.* 535, 625–636.
- Fremier, A.K., Declerck, F.A.J., Bosque-Pérez, N.A., Carmona, N.E., Hill, R., Joyal, T., Keesecker, L., Klos, P.Z., Martínez-Salinas, A., Niemeier, R., Sanfioranzo, A., Welsh, K., Wulffhorst, J.D., 2013. Understanding spatiotemporal lags in ecosystem services to improve incentives. *Bioscience* 63, 472–482.
- Giri, S., Qiu, Z., Prato, T., Luo, B., 2016. An integrated approach for targeting critical source areas to control nonpoint source pollution in watersheds. *Water Resour. Manage.* 30, 5087–5100.
- Gruère, G., Wreford, A., 2017. *Overcoming Barriers to the Adoption of Climate-friendly Practices in Agriculture*. OECD Food, Agriculture and Fisheries Papers, No. 101. OECD Publishing, Paris.
- Gurr, G.M., Lu, Z., Zheng, X., Xu, H., Zhu, P., Chen, G., Yao, X., Cheng, J., Zhu, Z., Catindig, J.L., Villareal, S., Van Chien, H., Cuong, L.Q., Channoo, C., Chengwattana, N., Lan, L.P., Hai, L.H., Chaiwong, J., Nicol, H.I., Perovic, D.J., Wratten, S.D., Heong, K.L., 2016. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nat. Plants* 2, 16014.
- Hamel, P., Falinski, K., Sharp, R., Auerbach, D.A., Sánchez-Canales, M., Denny-Frank, P.J., 2017. Sediment delivery modeling in practice: comparing the effects of watershed characteristics and data resolution across hydroclimatic regions. *Sci. Total Environ.* 580, 1381–1388.
- Hardt, E., Borgomeo, E., dos Santos, R.F., Pinto, L.F.G., Metzger, J.P., Sparovek, G., 2015. Does certification improve biodiversity conservation in Brazilian coffee farms? *For. Ecol. Manage.* 357, 181–194.
- Haregeweyn, N., Tsunekawa, A., Poesen, J., Tsubo, M., Meshesha, D.T., Fenta, A.A., Nyssen, J., Adgo, E., 2017. Comprehensive assessment of soil erosion risk for better land use planning in river basins: case study of the Upper Blue Nile River. *Sci. Total Environ.* 574, 95–108.
- Heenan, A., Gorospe, K., Williams, I., Levine, A., Maurin, P., Nadon, M., Oliver, T., Rooney, J., Timmers, M., Wongbusarakum, S., Brainard, R., 2016. Ecosystem monitoring for ecosystem-based management: using a polycentric approach to balance information trade-offs. *J. Appl. Ecol.* 53, 699–704.
- Hirono, Y., Watanabe, I., Nonaka, K., 2009. Trends in water quality around an intensive tea-growing area in Shizuoka, Japan. *Soil Sci. Plant Nutr.* 55, 783–792.
- Hoff, H., Noel, S., Droogers, P., 2007. *Water Use and Demand in the Tana Basin: Analysis using the Water Evaluation and Planning tool (WEAP)*. Green Water Credits Report 4. ISRIC – World Soil Information, Wageningen.
- Hunink, J.E., Droogers, P., 2011. *Physiographical Baseline Survey for the Upper Tana Catchment: Erosion and Sediment Yield Assessment*. FutureWater Report 112.
- Hunink, J.E., Droogers, P., 2015. *Impact Assessment of Investment Portfolios for Business Case Development of the Nairobi Water Fund in the Upper Tana River, Kenya*. FutureWater, Wageningen, The Netherlands.
- Hunink, J.E., Droogers, P., Kauffman, S., Mwaniki, B.M., Bouma, J., 2012. Quantitative simulation tools to analyze up- and downstream interactions of soil and water conservation measures: supporting policy making in the Green Water Credits program of Kenya. *J. Environ. Manage.* 111, 187–194.
- Hunink, J.E., Niadas, I.A., Antonaropoulos, P., Droogers, P., de Vente, J., 2013. Targeting of intervention areas to reduce reservoir sedimentation in the Tana catchment (Kenya) using SWAT. *Hydrol. Sci. J.* 58, 600–614.
- Hussain, A., Baker, T., 2016. *Tana River Basin, Kenya: Geodatabase and Mapping Tool*. User Guide. International Water Management Institute (IWMI), Colombo, Sri Lanka.
- IPBES, 2018. *Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. R. Scholes, L. Montanarella, A. Brainich, N. Barger, B. ten Brink, M. Cantele, B. Erasmus, J. Fisher, T. Gardner, T. G. Holland, F. Kohler, J. S. Kotiaho, G. Von Maltitz, G. Nangendo, R. Pandit, J. Parrotta, M. D. Potts, S. Prince, M. Sankaran and L. Willemen (Eds.). IPBES Secretariat, Bonn, Germany.
- Jordan, N., Warner, K.D., 2010. Enhancing the multifunctionality of US agriculture. *Bioscience* 60, 60–66.
- Kaini, P., Artita, K., Nicklow, J.W., 2012. Optimizing structural best management practices using SWAT and genetic algorithm to improve water quality goals. *Water Resour. Manage.* 26, 1827–1845.
- Kauffman, S., Droogers, P., Hunink, J., Mwaniki, B., Muchena, F., Gicheru, P., Bindraban, P., Onduru, D., Cleveringa, R., Bouma, J., 2014. *Green Water Credits – exploring its potential to enhance ecosystem services by reducing soil erosion in the Upper Tana basin, Kenya*. *Int. J. Biodivers. Sci., Ecosyst. Serv. Manage.* 10, 133–143.
- Kinzig, A.P., Perrings, C., Chapin, F.S., Polasky, S., Smith, V.K., Tilman, D., Turner, B.L., 2011. Paying for ecosystem services—promise and peril. *Science* 334, 603–604.
- Lautenbach, S., Maes, J., Kattwinkel, M., Seppelt, R., Strauch, M., Scholz, M., Schulz-Zunkel, C., Volk, M., Weinert, J., Dormann, C.F., 2012. Mapping water quality-related ecosystem services: concepts and applications for nitrogen retention and pesticide risk reduction. *Int. J. Biodivers. Sci., Ecosyst. Serv. Manage.* 8, 1–15.
- Lovell, R., Husk, K., Cooper, C., Stahl-Timmins, W., Garside, R., 2015. Understanding how environmental enhancement and conservation activities may benefit health and wellbeing: a systematic review. *BMC Public Health* 15, 1–18.
- Mace, G.M., 2014. Whose conservation? *Science* 345, 1558–1560.
- Mbeche, R.M., Dordard, P., 2014. Privatisation, empowerment and accountability: what are the policy implications for establishing effective farmer organisations? *Land Use Policy* 36, 285–295.
- Mialhe, F., Gunnell, Y., Ignacio, J.A.F., Delbart, N., Oganía, J.L., Henry, S., 2015. Monitoring land-use change by combining participatory land-use maps with standard remote sensing techniques: showcase from a remote forest catchment on Mindanao, Philippines. *Int. J. Appl. Earth Obs. Geoinf.* 36, 69–82.
- Milder, J.C., Hart, A.K., Dobie, P., Minai, J., Zaleski, C., 2014. *Integrated landscape initiatives for African agriculture, development, and conservation: a region-wide assessment*. *World Dev.* 54, 68–80.
- Milder, J.C., Newsom, D., Lambin, E., Rueda, X., 2016. Measuring impacts of certification on biodiversity at multiple scales: experience from the SAN/Rainforest Alliance system and priorities for the future. In: Castka, P., Leaman, D.J. (Eds.), *Policy Matters: Certification and Biodiversity: How Voluntary Certification Standards Impact Biodiversity and Human Livelihoods*. IUCN Commission on Environmental,

- Economic and Social Policy (CEESP), Gland, Switzerland, pp. 12–24.
- Mueller, M., Geist, J., 2016. Conceptual guidelines for the implementation of the ecosystem approach in biodiversity monitoring. *Ecosphere* 7.
- Mukhopadhyay, M., Mondal, T., 2017. Cultivation, Improvement, and Environmental Impacts of Tea. Oxford Research Encyclopedia of Environmental Science. Oxford University Press.
- Muradian, R., Rival, L., 2012. Between markets and hierarchies: the challenge of governing ecosystem services. *Ecosyst. Serv.* 1, 93–100.
- Newsom, D., Milder, J.C., 2018. 2018 Rainforest Alliance Impacts Report. Partnership, Learning, and Change. The Rainforest Alliance.
- NRCS-USDA, 2007. National Engineering Handbook. United States Department of Agriculture.
- Nunes, A., Oliveira, G., Mexia, T., Valdecantos, A., Zucca, C., Costantini, E.A.C., Abraham, E.M., Kyriazopoulos, A.P., Salah, A., Prasse, R., Correia, O., Milliken, S., Kotzen, B., Branquinho, C., 2016. Ecological restoration across the Mediterranean Basin as viewed by practitioners. *Sci. Total Environ.* 566–567, 722–732.
- Ochieng, B.O., Hughey, K.F.D., Bigsby, H., 2013. Rainforest Alliance Certification of Kenyan tea farms: a contribution to sustainability or tokenism? *J. Cleaner Prod.* 39, 285–293.
- Ordway, E.M., Asner, G.P., Lambin, E.F., 2017. Deforestation risk due to commodity crop expansion in sub-Saharan Africa. *Environ. Res. Lett.* 12, 044015.
- Oya, C., Schaefer, F., Skalidou, D., 2018. The effectiveness of agricultural certification in developing countries: a systematic review. *World Dev.* 112, 282–312.
- Potts, J., Voora, V., Lynch, M., Mammadova, A., 2017. Standards and Biodiversity: Thematic Review. International Institute for Sustainable Development (IISD).
- Reed, M.S., Stringer, L.C., Dougill, A.J., Perkins, J.S., Athlopheng, J.R., Mulale, K., Favretto, N., 2015. Reorienting land degradation towards sustainable land management: linking sustainable livelihoods with ecosystem services in rangeland systems. *J. Environ. Manage.* 151, 472–485.
- Reed, J., Van Vianen, J., Deakin, E.L., Barlow, J., Sunderland, T., 2016. Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. *Glob. Change Biol.*
- Rocha, E.O., Calijuri, M.L., Santiago, A.F., de Assis, L.C., Alves, L.G.S., 2012. The contribution of conservation practices in reducing runoff, soil loss, and transport of nutrients at the watershed level. *Water Resour. Manage.* 26, 3831–3852.
- Rueda, X., Lambin, E.F., 2013. Responding to globalization: impacts of certification on Colombian small-scale coffee growers. *Ecol. Soc.* 18.
- Rueda, X., Thomas, N.E., Lambin, E.F., 2015. Eco-certification and coffee cultivation enhance tree cover and forest connectivity in the Colombian coffee landscapes. *Reg. Environ. Change* 15, 25–33.
- Sahoo, D.C., Madhu, M.G., Bosu, S.S., Khola, O.P.S., 2016. Farming methods impact on soil and water conservation efficiency under tea [*Camellia sinensis* (L.)] plantation in Nilgiris of South India. *Int. Soil Water Conserv. Res.* 4, 195–198.
- SAN, 2011. Local Interpretation Guidelines for Sustainable Coffee and Tea Production in Kenya, August 2011. Sustainable Agriculture Network Secretariat, San Jose, Costa Rica.
- SAN, 2010. Sustainable Agriculture Standard. July 2010, Version 2. Sustainable Agriculture Network Secretariat, San Jose, Costa Rica.
- Scherr, S.J., McNeely, J.A., 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of 'ecoagriculture' landscapes. *Philos. Trans. R. Soc. B: Biol. Sci.* 363, 477–494.
- Scherr, S.J., Shames, S., Friedman, R., 2012. From climate-smart agriculture to climate-smart landscapes. agriculture and food. *Security* 1.
- Scherr, S., Shames, S., Friedman, R., 2013. Defining Integrated Landscape Management for Policy Makers. Ecoagriculture Policy Focus No. 10. EcoAgriculture Partners, Washington DC.
- Schröter, M., Remme, R.P., Sumarga, E., Barton, D.N., Hein, L., 2015. Lessons learned for spatial modelling of ecosystem services in support of ecosystem accounting. *Ecosyst. Serv.* 13, 64–69.
- Schulp, C.J.E., Burkhard, B., Maes, J., Van Vliet, J., Verburg, P.H., 2014. Uncertainties in ecosystem service maps: a comparison on the European scale. *PLoS ONE* 9, e109643.
- Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., et al., 2016. InVEST + VERSION + User's Guide. The Natural Capital Project. Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.
- Singh, N.J., Danell, K., Edenius, L., Ericsson, G., 2014. Tackling the motivation to monitor: success and sustainability of a participatory monitoring program. *Ecol. Soc.* 19.
- Stathers, T., Gathuthi, C., 2013. Final Report: Poverty impact of social and environmental voluntary standard systems in Kenyan tea. Natural Resources Institute (NRI), University of Greenwich, London, UK.
- Takahashi, R., Todo, Y., 2017. Coffee certification and forest quality: evidence from a wild coffee forest in Ethiopia. *World Dev.* 92, 158–166.
- Tallis, H., Kareiva, P., Marvier, M., Chang, A., 2008. An ecosystem services framework to support both practical conservation and economic development. *Proc. Natl. Acad. Sci.* 105, 9457–9464.
- Tamene, L., Le, Q.B., Vlek, P.L.G., 2014. A Landscape planning and management tool for land and water resources management: an example application in Northern Ethiopia. *Water Resour. Manage.* 28, 407–424.
- Taylor, C., Balmford, A., Buchanan, G.M., Butchart, S.H.M., Ducharme, H., Green, R.E., Milder, J.C., Sanderson, F.J., Thomas, D.H.L., Vickery, J., Phalan, B., 2017. Global coverage of agricultural sustainability standards, and their role in conserving biodiversity. *Conserv. Lett.* 10, 610–618.
- Taylor, C., Balmford, A., Buchanan, G.M., Butchart, S.H.M., Corlet Walker, C., Ducharme, H., Green, R.E., Milder, J.C., Sanderson, F.J., Thomas, D.H.L., Tracewski, L., Vickery, J., Phalan, B., 2018. Where are commodity crops certified, and what does it mean for conservation and poverty alleviation? *Biol. Conserv.* 217, 36–46.
- TNC, 2015. Upper Tana-Nairobi Water Fund Business Case. Version 2. The Nature Conservancy, Nairobi, Kenya.
- Van der Biest, K., Vrebos, D., Staes, J., Boerema, A., Bodí, M.B., Franssen, E., Meire, P., 2015. Evaluation of the accuracy of land-use based ecosystem service assessments for different thematic resolutions. *J. Environ. Manage.* 156, 41–51.
- Vogl, A.L., Bryant, B.P., Hunink, J.E., Wolny, S., Apse, C., Droogers, P., 2017. Valuing investments in sustainable land management in the Upper Tana River basin, Kenya. *J. Environ. Manage.* 195 (1), 78–91.
- Waarts, Y., Ge, L., Ton, G., Jansen, D., 2012. Sustainable tea production in Kenya: Impact assessment of Rainforest Alliance and Farmer Field School training. LEI report 2012-043. LEI Wageningen UR, The Hague.
- Walsh, J.C., Dicks, L.V., Sutherland, W.J., 2015. The effect of scientific evidence on conservation practitioners' management decisions. *Conserv. Biol.* 29, 88–98.
- Willcock, S., Hooftman, D., Sitas, N., O'Farrell, P., Hudson, M.D., Reyers, B., Eigenbrod, F., Bullock, J.M., 2016. Do ecosystem service maps and models meet stakeholders' needs? A preliminary survey across sub-Saharan Africa. *Ecosyst. Serv.* 18, 110–117.
- Willemen, L., Burkhard, B., Crossman, N., Drakou, E.G., Palomo, I., 2015. Editorial: best practices for mapping ecosystem services. *Ecosyst. Serv.* 13, 1–5.
- Willemen, L., Crossman, N.D., Quatrini, S., Egoh, B., Kalaba, F.K., Mbilinyi, B., de Groot, R., 2017. Identifying ecosystem service hotspots for targeting land degradation neutrality investments in south-eastern Africa. *J. Arid Environ.*
- Williams, J.R., 1975. Sediment-Yield Prediction with Universal Soil Loss Equation Using Runoff Energy Factor. Pages 244–252 Present and Prospective Technology for predicting Sediment Yields and Sources. Proceedings of the Sediment Yield Workshop. Oxford.
- Zhang, Y., Zhang, H., Peng, B.-Z., Yang, H., 2003. Soil erosion and its impacts on environment in Yixing tea plantation of Jiangsu Province. *Chin. Geograph. Sci.* 13, 142–148.