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Assessment of soil erosion in social forest-dominated watersheds in Lampung, Indonesia

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Abstract Social forestry policies grant local communities the right to access protected forest areas contingent upon certain governmental criteria. However, the adoption of social forestry is known to alter land-cover patterns and promote soil erosion. This study assessed the water quality of Sekampung Hulu and Sangharus Rivers in Lampung, Indonesia, based on their total suspended solid (TSS) concentrations. Subsequently, the extent of soil erosion in the two watersheds was determined, and best management practices (BMPs) were recommended for the study area. Water sampling was conducted in 2016 to estimate TSS levels in the two watersheds. Additionally, the Universal Soil Loss Equation (USLE) was integrated with an ArcGIS model to evaluate soil erosion in the watersheds. The results indicated that TSS concentrations in the Sekampung Hulu and Sangharus Rivers ranged from 36–813 mg L^{-1} and 16–146 mg L^{-1}, respectively. Further, the average soil erosion rates in the Sekampung Hulu and Sangharus watersheds were 12.5 Mg ha^{-1} $year^{-1}$ and 5.6 Mg ha^{-1} $year^{-1}$, respectively. The results indicated that young coffee trees increased soil erosion rates, especially in areas characterized by vulnerable soil. The USLE results concurred with the TSS analysis and indicated higher erosion rates for the Sekampung Hulu watershed than the Sangharus watershed. The application of BMPs, including conversion to agroforestry coffee, cover crops, and contour systems, was effective in reducing soil erosion in both the Sekampung Hulu and Sangharus watersheds.

Keywords Erosion · Sangharus watershed · Sekampung Hulu watershed · Social forestry · Total suspended solids

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Introduction

Increasing human population as well as rapid economic growth have resulted in increased demand for land in Indonesia (Liu and Yamauchi 2014). The availability of land is closely linked to the intensity of economic activities, which subsequently impact forest areas. In particular, deforestation can be attributed to illegal logging activities and conversion to agricultural land, plantations, and settlements (Kubitza et al. 2018; Malahayati

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2018; Margono et al. 2014). Conversion of forest land to other land-use types contributes to nonpoint source pollution and significantly threatens water quality in aquatic systems (Gunawardhana et al. 2016).

Forest areas in Indonesia should be sustainably managed by utilizing both canopy and understory vegetation. This would not only maintain the ecological functions of forests but also enhance infiltration, which would decrease the rapid discharge of water as well as the subsequent erosion from mountainous areas to downstream watersheds. The political reformation period of 1998 significantly impacted land use change in the forested areas of Indonesia (Sunderlin 2002). Presently, the Indonesian government is attempting to reduce the effects of deforestation by implementing equitable economic policies through a social forestry program. According to the Ministry of Environment and Forestry (2016), social forestry consists of community forests (*Hutan Kemasyarakatan*, *HKm*), forestry partnerships (*Kemitraan Kehutanan*), adat forests (*Hutan Adat*), village forests (*Hutan Desa*), private forests (*Hutan Rakyat*), and community plantation forests (*Hutan Tanaman Rakyat*). The social forestry policy aims to empower communities surrounding forest areas through provision of environmental services and maintenance of forest functions. This could potentially contribute to local economic growth and improve sociocultural dynamics near forests.

Community forestry and forestry partnerships were implemented in the Sekampung Hulu and Sangharus watersheds in Lampung Province, Indonesia, as part of the social forestry policy. The primary land use in these watersheds is coffee plantation, with nearly 131,501 tons of coffee produced in Lampung Province in 2014 (Statistics of Lampung Province 2017b). Land use changes inside the forests likely influence the environmental functions of the forests. Moreover, a reservoir downstream of the target watersheds contributes to irrigation of paddy fields and supports electricity generation. Thus, erosion hazards in the upstream area could influence the water capacity of the reservoir dam as well (Ran et al. 2013).

Because land use changes can trigger soil erosion and sedimentation (Pilgrim et al. 2015), the conversion of forests to coffee plantations in the study area likely increased soil erosion, which is an indicator of environmental disturbance. Soil erosion is detrimental to optimal soil properties (Ebeid et al. 1995) and causes nutrient loss from soil surfaces (Su et al. 2010). Soil erosion rates depend on the amount and intensity of precipitation (Canton et al. 2001), topographic conditions (Hessel and Jetten 2007), soil characteristics (Panagos et al. 2014), and vegetation (Nicolau et al. 1996). The focal area for this study is characterized by high precipitation and steep slopes in the hilly or mountainous areas (Prawiradisastra 2013).

Assessment of soil erosion can help address land management issues at the plot or watershed scale. In addition, such assessment enables stakeholders to evaluate erosion risks and subsequently determine suitable crop types for the watershed. Furthermore, this information allows government agencies to implement agricultural regulations and forest management policies to minimize land degradation and address related environmental concerns. Soil erosion can be estimated through the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978), which is simple and user friendly. The application of the USLE at the watershed scale can be supplemented by geographic information system (GIS) analysis (Ahmad and Hagos 2016). Recently, GIS has been utilized in studies of natural resource management for efficient data management. The integration of the USLE with GIS allows assessment of soil erosion for each spatial unit.

The study of the effects of land use change on water quality could aid watershed management and planning (Kibena et al. 2014; Xu and Zhang 2016). Somura et al. (2019) conducted a preliminary study on the total suspended solids (TSS) in the target watersheds and concluded that TSS concentrations for the Sekampung Hulu River were higher than those for the Sangharus River. However, this study was conducted during the rainy season (March–May), but detailed investigation of the primary rainy season characteristics and the causes of the apparent differences in TSS concentrations was not conducted. Thus, this study aimed to determine the water quality of the Sekampung Hulu and Sangharus Rivers based on annual estimates of their TSS concentrations for 2016. Subsequently, soil erosion was assessed by utilizing the USLE. Best management practices (BMPs) were also recommended for the study area. The evaluation of soil erosion in both watersheds could potentially aid sustainable land management in the study area.

Materials and methods

Study area

The Sekampung Hulu and Sangharus watersheds are located in the Tanggamus Regency, Lampung Province, Indonesia. These two major watersheds supply water to the Batutegi Dam reservoir (Fig. 1). The study area is situated between latitudes 5°5′37″ S and 5°15′58″ S and longitudes 104°30′34″ E and 104°42′56″ E. The Sekampung Hulu and Sangharus watersheds are spread over 141.3 km^2 and 117.2 km^2, respectively. The study region covers an area of 258.5 km^2, of which social forestry constitutes 244.3 km^2. The remainder area of 14.2 km^2 is private land, which is predominantly located in the Sangharus watershed.

The elevation in the study area ranges from 282 to 1767 masl. The local mean annual precipitation is 1826 mm (Directorate General of Operation and Maintenance Water Resources Mesuji Sekampung [DGOMWRMS] 2017). The mean monthly precipitation during the periods 1998–2010 and 2013–2016 is presented in Fig. 2. No precipitation data is available for 2011–2012 because the equipment was not working.

Based on data from the National Land Agency (2017) and from field observations, land use in the Sekampung Hulu watershed comprised forest (5.8%), young coffee (25.7%), agroforestry coffee (33.9%), shade coffee (34.3%), and river (0.3%), while that in the Sangharus watershed comprised forest (4.6%), young coffee (3.3%), shade coffee (66.3%), agroforestry coffee (25.6%), and river 0.2% (Fig. 3a). Young coffee has less canopy coverage because of the early stage of growth. Shade coffee describes coffee plantations also planted with shade trees such as *Gliricidia sepium*, *Paraserianthes falcataria*, and others. Agroforestry coffee describes multistory coffee plantations with fruit and timber trees such as durian (*Durio* spp.), avocado (*Persea americana*), cloves (*Syzygium aromaticum*), *dogfruit* (*Archidendron pauciflorum*), mahogany (*Swietenia mahagoni*), sonokeling (*Dalbergia latifolia*), *Albizia chinensis*, and others. Agroforestry coffee is distinguished from shade coffee by the inclusion of more than five different shade tree species.

Soil type classifications (Fig. 3b) for the Sekampung Hulu and Sangharus watersheds were obtained from the Indonesian Center for Agricultural Land Resources Research and Development (ICALRD 2016). The Sekampung Hulu watershed comprised the following soil types: Andic Dystrudepts (28%), Typic Dystrudepts (30.6%), Typic Hapludands (16.5%), Typic Hapludox (11.6%), Typic Kanhapludults (3.1%), Typic Udivitrands (2.9%), and Typic Endoaquepts (7.2%). The soil types in the Sangharus watershed consisted of Andic Dystrudepts (43.5%), Typic Dystrudepts (33.2%), Typic Hapludands (19.5%), and Typic Endoaquepts (3.7%). The dominant soils in both watersheds were Andic Dystrudepts and Typic Dystrudepts, which are categorized as Inceptisols.

Water sampling

In this study, water samples were collected from the main streams of the Sekampung Hulu and Sangharus Rivers at two sites each (Fig. 1) and TSS concentrations were subsequently determined. Water sampling was conducted four times during the 2016 rainy season (once in October, twice in November, and once in December). Additionally, data regarding TSS concentrations from March to May 2016 were obtained from a previous study (Somura et al. 2019) to ensure a comprehensive analysis. The TSS parameter was analyzed based on the methods proposed by the American Public Health Association (1999).

Assessment of soil erosion

Soil erosion assessment for the Sekampung Hulu and Sangharus watersheds was conducted using the USLE method (Wischmeier and Smith 1978), which has been applied in several previous studies focusing on the prediction of soil erosion in watersheds (Devatha et al. 2015; Huang 2018; Pham et al. 2018). The USLE equation is expressed as

$$A = R \times K \times LS \times C \times P \tag{1}$$

where A is erosion (Mg ha^{-1} year^{-1}), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K is the soil erodibility factor (Mg ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the slope length factor (dimensionless), C is the crop factor (dimensionless), and P is the soil management factor (dimensionless).

Rainfall erosivity factor (R)

Daily precipitation data were obtained from the Batutegi Dam station for the periods 1998–2010 and 2013–2016

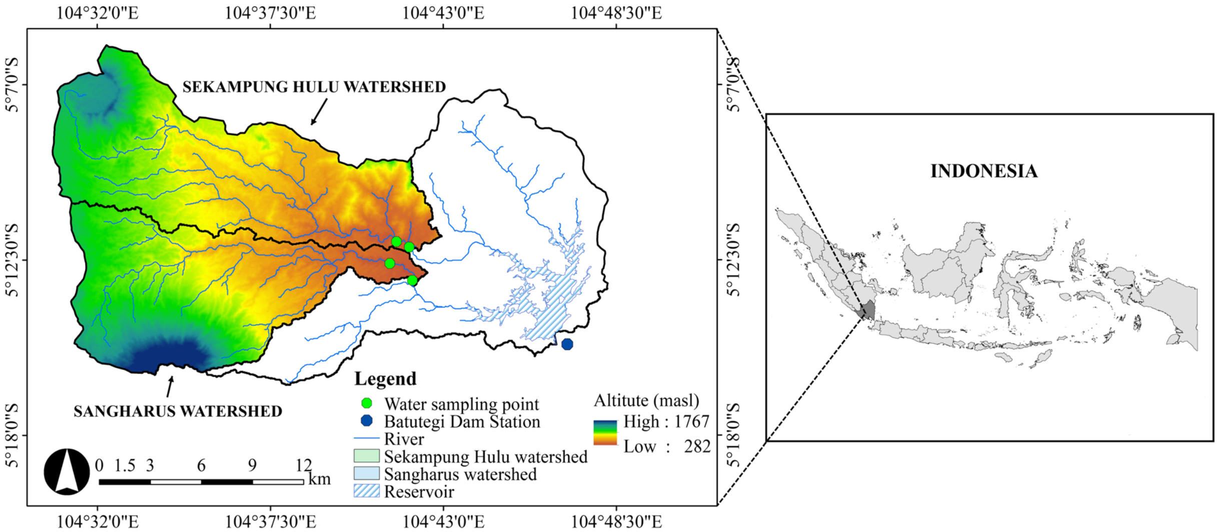

Fig. 1 Location of study area

(DGOMWRMS 2017) and used to calculate R using the Bols equation (Bols 1978). This equation was developed from precipitation data for Indonesia spanning a period of 38 years. The Bols equation is expressed as

$$R_m = 6.119(Rain)^{1.21} \times (Days)^{-0.47} \times (MaxP)^{0.53} \quad (2)$$

where R_m is the monthly erosivity factor, $Rain$ is the total monthly rainfall (cm), $Days$ is the number of rainfall days in a particular month, and $MaxP$ is the maximum rainfall in a particular month (cm).

Soil erodibility factor (K)

K reflects the sensitivity of soil characteristics to erosion. In this study, K was calculated from the following equation (Renard et al. 1997; Wischmeier and Smith 1978):

$$100K = \left(2.71 \times M^{1.14}\left(10^{-4}\right)(12-OM) + 3.25(s-2) + 2.5(p-3)\right)/7.59 \quad (3)$$

where M is (percentage of very fine sand + silt) × (100 − percent clay), OM is the percentage of organic matter, s is the soil structure code, and p is the soil permeability code. The soil properties for the study area were obtained from ICALRD (2016).

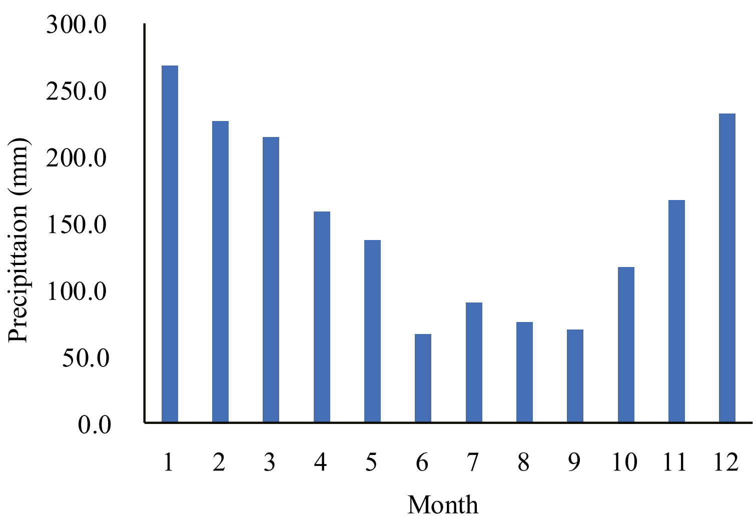

Fig. 2 Mean monthly precipitation, 1998–2010 and 2013–2016

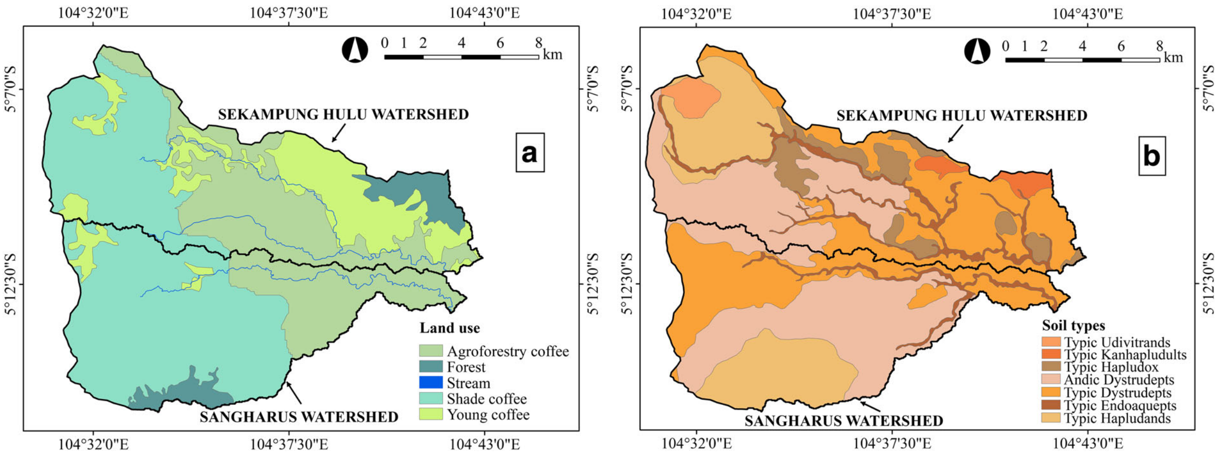

Fig. 3 **a** Land use and **b** soil types in the study area

Topographic factor (LS)

LS consists of the slope-length factor (*L*) and the slope steepness factor (*S*) and represents topographic impacts on the soil erosion rate. Several methods have been suggested to estimate *LS* (Mitasova et al. 1996; Moore and Wilson 1992; Wischmeier and Smith 1978). In this study, *LS* was estimated using the System for Automated Geoscientific Analyses (SAGA), which uses the digital elevation model from the NASA Shuttle Radar Topography Mission (spatial resolution = 30 m). *LS* was calculated based on the equation provided by Desmet and Govers (1996):

$$L_{i,j} = \frac{\left(A_{i,j-in} + D^2\right)^{m+1} - A_{i.j-in}^{m+1}}{D^{m+2} * X_{i,j}^{m} \times 22.13^{m}} \quad (4)$$

where $L_{i,\,j}$ is the slope length factor for the grid cell with coordinates (*i*,*j*), $A_{i,\,j-in}$ is the contributing area at the inlet of the grid cell with coordinates (*i*,*j*) (m^2), *D* is the grid cell size (m), *m* is the slope length exponent, $X_{i,\,j}$ is sin $\alpha_{i,\,j} + cos\ \alpha_{i,\,j}$ ($\alpha_{i,\,j}$ is the aspect direction for the grid cell with coordinates (*i*,*j*)). Further,

$$m = \frac{\beta}{(\beta + 1)} \quad (5)$$

$$\beta = \frac{\frac{\sin\theta}{0.0896}}{3 * \sin\theta^{0.8} + 0.56} \quad (6)$$

where β is the ratio of rill erosion to interrill erosion and θ is the angle of the slope (degrees).

Calculation of *LS* was limited to a slope of 50% or 26.6°. Liu et al. (2000) stated that the slope length exponent did not increase for slope steepness ranging from 40 to 60%. A previous study limited the slope gradient to 50% during calculation of *LS* to determine soil erosion in Europe (Panagos et al. 2015).

Crop and management factor (CP)

The *CP* value combines two factors found in equation (1): crop (*C*) and management (*P*) factors. The *C* factor represents the influence of cover crop type and the *P* factor represents the influence of soil management practices. For some land use categories, such as agroforestry and shade coffee, *C* and *P* values were hard to distinguish separately because these land uses combine both elements simultaneously. Thus, a conjoined *CP* value was employed for this study. *CP* values range between 0 and 1, with 0 indicating good vegetation ground cover and a well-protected soil surface and 1 indicating no vegetation cover and no soil management practices. Values close to 0 indicate good crop and soil conservation practices, which could reduce the rate and influence the direction of runoff and subsequently decrease soil erosion. Forests and young coffee were considered to have *P* factor values of 1 because no soil conservation practices were implemented for these land-use types in the target watersheds.

In this study, the assigned *CP* value was 0.001 for forest areas and 0.005 for agroforestry coffee, which was based on the value for forests with low litter (Hamer 1980). As forests and agroforests have similar above-ground vegetation coverage, soil erosion rates are not significantly different between these land-use types (Kusumandari and Mitchell 1997). The assigned *CP* values for young coffee and shade coffee were 0.3 and 0.1, respectively, based on a report from Roose (1976). Young coffee has less canopy and ground vegetation development than shade coffee, while shade coffee has better coverage because of the inclusion of shade trees. The assigned *CP* values for stream channels in the Sekampung Hulu and Sangharus watersheds were 0.

Impacts of BMPs

Continuous soil erosion contributes to soil degradation, which reduces land productivity. The application of BMPs can potentially decrease soil erosion in the study area. In particular, BMPs can reduce nonpoint source pollution from coffee plantations. The following simulation scenarios were developed in this study to understand the implications of BMPs:

(1) Converting shade coffee and young coffee to agroforestry coffee.
(2) Converting young coffee to shade coffee with subsequent application of cover crop to shade coffee. The *P* value of cover crop was obtained from Roose (1976) (Table 1)
(3) Converting young coffee to shade coffee with subsequent application of contour cropping to shade coffee. The contour system was divided into slopes of 0–8%, 8–20%, and > 20% according to the *P* values obtained from Hamer (1980) (Table 1).

In all scenarios, the conditions for forests and agroforestry coffee were not changed because these land-use types were well-managed. Therefore, the simulations were only applied to shade coffee and young coffee areas. In scenarios 2 and 3, young coffee was converted to shade coffee, and subsequently, all shade coffee areas were simulated with soil conservation techniques.

The agroforestry system scenario was applied in this study because the original land use was forest. Because the agroforestry system has multistory trees, providing nearly the same conditions as forest, applying this scenario could conserve ecosystems and support farmers' economic circumstances. Scenarios converting young coffee to shade coffee were also applied because these land uses were dominant in both watersheds. Subsequent applications of cover crops and contour cropping were simulated to achieve increased protection with respect to runoff and soil erosion.

Application of GIS techniques

Soil erosion was predicted by overlaying raster layers for the *R*, *K*, *LS*, and *CP* factors in ArcGIS 10.4.1. All layers were divided into 30-m grids and all maps were characterized by the WGS 1984 UTM zone 48S projection. Subsequently, soil erosion values were calculated in the raster module.

Statistical analyses

The statistical analyses for water samples collected from the two rivers were conducted using SPSS software (Version 17.0). Descriptive data analysis included reporting of means and standard errors. The Mann-Whitney *U* test was conducted to determine statistically significant differences in the TSS values of the Sekampung Hulu and Sangharus Rivers. A significance value lower than 0.05 indicates significant differences in the water quality of the two rivers at the 95% confidence interval.

Results

Water quality

The Sekampung Hulu River displayed higher TSS concentrations in contrast to the Sangharus River (Table 2). The maximum TSS concentrations in the Sekampung Hulu and Sangharus Rivers were 813 mg L^{-1} (March 26, 2016) and 146 mg L^{-1} (Nov 20, 2016), respectively, while the minimum concentrations were 36 mg L^{-1} (April 23, 2016) and 16 mg L^{-1} (April 23,

Table 1 Soil management factor (*P*) values

Conservation practice	*P* factor value
Cover crop	0.1[a]
Contour cropping, slope gradient 0–8%	0.5[b]
Contour cropping, slope gradient 8–20%	0.75[b]
Contour cropping, slope gradient > 20%	0.9[b]
None	1[b]

[a] Roose (1976)
[b] Hamer (1980)

2016), respectively. Further, as indicated in Table 2, the mean and standard error of TSS concentrations in Sekampung Hulu and Sangharus Rivers were 228 ± 87.5 and 69.3 ± 15.2, respectively. Statistical analysis indicated that the mean TSS concentration for the Sekampung Hulu River was significantly higher than that for the Sangharus River.

Erosion assessment

Rainfall erosivity factor (R)

Rainfall erosivity is one of the climatic factors influencing hydrological properties within a watershed. Daily precipitation data were provided by the Batutegi Dam station for a period of 17 years and were utilized to estimate *R*. The estimated *R* value for both Sekampung Hulu and Sangharus watersheds was 1433.5.

Soil erodibility factor (K)

The *K* factor is affected by the diversity of soil types and their parameters. Therefore, the *K* factor map was extracted from the soil type map (ICALRD 2016). The Sekampung Hulu watershed indicated seven values for *K* ranging from 0.0007 to 0.0341, of which the most prevalent *K* value was 0.0341, accounting for 30.6% of the area. Similarly, the *K* value for the Sangharus watershed comprised four values, of which 0.0103 was the most prevalent with a coverage of 43.5%. The distribution of *K* is presented in Fig. 4a and Table 3.

Table 2 Concentrations of total suspended solids (TSS) in the Sekampung Hulu and Sangharus rivers

Date	TSS concentration (mg L^{-1})	
	Sangharus River	Sekampung Hulu River
3/26/2016[a]	80	813
4/10/2016[a]	71	144
4/23/2016[a]	16	36
5/8/2016[a]	31	196
10/23/2016	62	89
11/6/2016	38	80
11/20/2016	146	220
12/4/2016	110	246

[a] Source: Somura et al. (2019)

Topographic factor (LS)

The distribution of *LS* was determined using SAGA software and is presented in Fig. 4b. The *LS* values ranged between 0 and 9.7. The *LS* ranges 0–2, 2–5, 5–7, and 7–9.7 corresponded to 38.3%, 39.2%, 12.2%, and 10.3% of the total Sekampung Hulu watershed area, respectively, and 36.9%, 45.8%, 10.4%, and 6.9% of the total Sangharus watershed area, respectively. These results indicate that the percent area corresponding to *LS* value greater than seven was higher for the Sekampung Hulu watershed than the Sangharus watershed, thus indicating higher potential erosion rates.

Crop and management factor (CP)

Vegetation cover and land management affect soil erosion rates, as represented by *CP*. The distribution of *CP* was derived from the land use map (Fig. 4c). The dominant *CP* value for both watersheds was 0.1, corresponding to 34.3% and 66.3% of the total area for the Sekampung Hulu and Sangharus watersheds, respectively.

Erosion

The results indicate that erosion rates for both watersheds ranged from 0 to 142 Mg ha^{-1} $year^{-1}$. Average soil erosion rates in the Sekampung Hulu and Sangharus watersheds were 12.5 Mg ha^{-1} $year^{-1}$ and 5.6 Mg ha^{-1} $year^{-1}$, respectively, while the standard deviations were 26.4 and 12.3 Mg ha^{-1} $year^{-1}$, respectively. The spatial distribution of erosion is presented in Fig. 4d. Erosion rates greater than 10 Mg ha^{-1} $year^{-1}$ corresponded to 21.8% and 15.5% of the total area for Sekampung Hulu and Sangharus watersheds, respectively. These results indicate potential soil degradation in the study area.

Simulation of BMPs

The simulation scenarios indicated that BMPs could effectively reduce soil erosion in the following order (from highest to lowest reduction): scenario 1 > scenario 2 > scenario 3 (Fig. 5). Scenario 1 focused on conversion of shade and young coffee to agroforestry coffee, with resulting average erosion rates for the Sekampung Hulu and Sangharus watersheds of 0.4 ± 0.5 Mg ha^{-1} $year^{-1}$ and 0.3 ± 0.4 Mg ha^{-1} $year^{-1}$, respectively. Under this scenario, conversion to agroforestry coffee

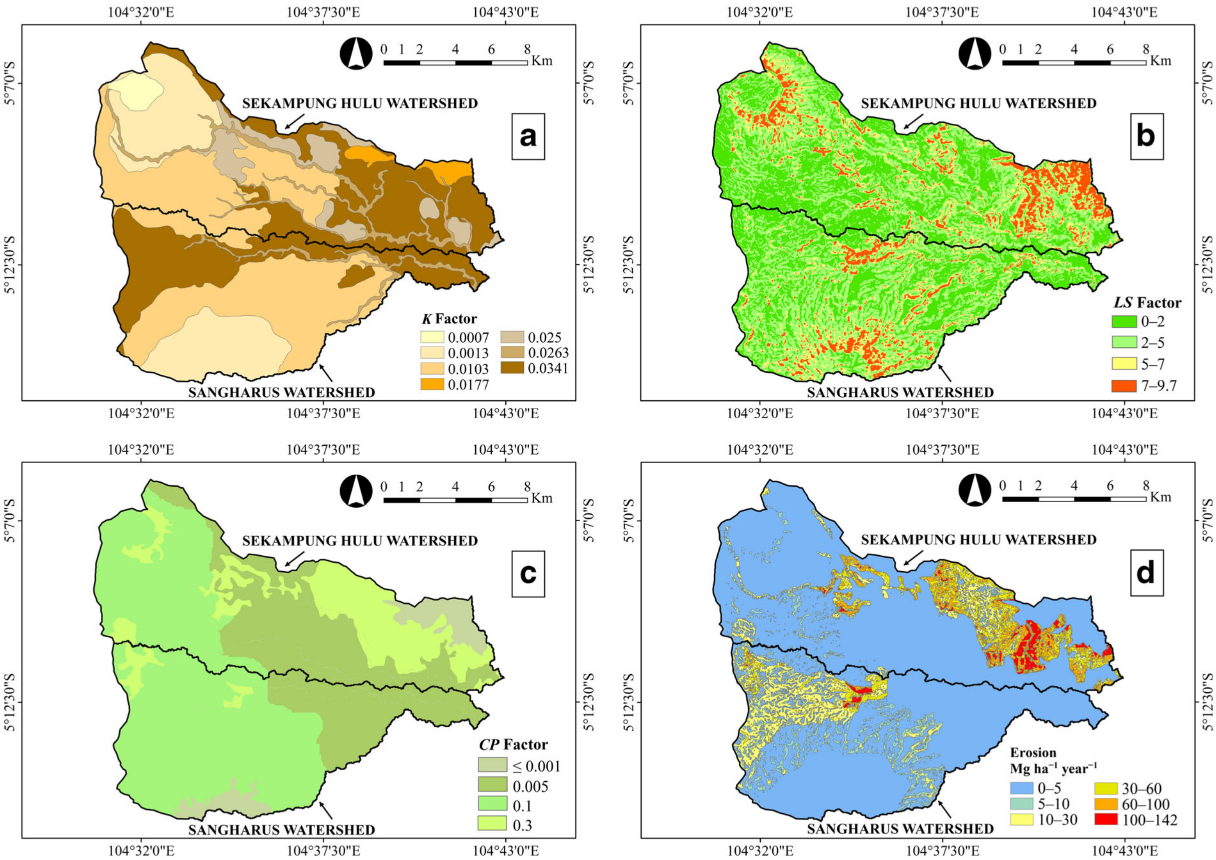

Fig. 4 Distribution maps for **a** soil erodibility factor (*K*), **b** topographic factor (*LS*), **c** crop and management factor (*CP*), and **d** soil erosion

effectively reduced soil erosion by 96.8% and 93.9% in the Sekampung Hulu and Sangharus watersheds, respectively.

Scenario 2 focused on conversion of young coffee to shade coffee with cover crop and resulted in an average soil erosion rate of 0.6 Mg ha^{-1} year^{-1} for both watersheds (with standard deviations of 0.9 Mg ha^{-1} year^{-1} and 0.7 Mg ha^{-1} year^{-1} for the Sekampung Hulu and Sangharus watersheds, respectively). Under scenario 2, soil erosion reduced by 94.9% and 89.8% in the Sekampung Hulu and Sangharus watersheds, respectively. Scenario 3 was based on the application of contour cropping and resulted in the least reduction in soil erosion. This scenario resulted in an average erosion of 4.1 ± 7.8 Mg ha^{-1} year^{-1} and 3.9 ± 6.6 Mg ha^{-1} year^{-1} for the Sekampung Hulu and Sangharus watersheds, respectively. Under scenario 3, adoption of the contour system effectively reduced soil erosion by 67.1% and 29.7% in the Sekampung Hulu and Sangharus watersheds, respectively.

Table 3 Soil types and soil erodibility

Soil type	Soil erodibility factor (*K*)
Typic Dystrudepts	0.0341
Typic Endoaquepts	0.0263
Typic Kanhapludults	0.0177
Typic Hapludox	0.0250
Andic Dystrudepts	0.0103
Typic Hapludands	0.0013
Typic Udivitrands	0.0007

Discussion

The water quality analysis suggested that TSS concentrations in the Sekampung Hulu River were significantly higher than in the Sangharus River, indicating that the Sangharus River exhibited more optimal social forestry conditions. The USLE results indicated higher erosion in the Sekampung Hulu watershed, which agreed with the TSS trends obtained from water quality analysis.

A high soil erosion rate can be detrimental to environmental quality, especially if the erosion rate is greater than the tolerable soil loss. The definition of tolerable soil loss is the amount of soil erosion that does not lead to deterioration of soil functions as long as soil erosion does not greater than soil formation rate (Verheijen et al. 2009). The parameters that influence tolerable soil loss are erosion rate, soil depth, social and economic scenario, evaluation of soil deterioration through soil depth change (Sparovek and Jong Van Lier 1997), and lifetime soil use (Sparovek et al. 1997). The tolerable soil loss for Lampung is 10 Mg ha^{-1} year^{-1} (Dariah et al. 2004). The average soil erosion values for the Sekampung Hulu and Sangharus watersheds as estimated by the USLE method were 12.5 Mg ha^{-1} year^{-1} and 5.6 Mg ha^{-1} year^{-1}, respectively. While 78.2% of the Sekampung Hulu watershed area had an erosion rate less than 10 Mg ha^{-1} year^{-1}, the soil erosion rates for the remaining area were greater than the tolerable soil loss. Similarly, 84.5% of the Sangharus watershed area had a soil erosion rate lower than 10 Mg ha^{-1} year^{-1}, while the remaining 15.5% of the area had erosion rates greater than the tolerable soil loss.

Verbist et al. (2010) studied soil erosion at the plot scale and concluded that the erosion rate in monoculture coffee plantations aged 3 to 5 years was 7–11 Mg ha^{-1} year^{-1}, while that for plantations older than 6 years was 4–6.3 Mg ha^{-1} year^{-1}. Afandi et al. (2002) concluded that the soil erosion rate in two-year-old coffee plantations was 22.7 Mg ha^{-1} year^{-1}. However, the erosion rate declined to 9.1 Mg ha^{-1} year^{-1} and 4.8 Mg ha^{-1} year^{-1} during the third and fourth years of growth, respectively. Widianto et al. (2004) studied soil loss in plots sized 10 m × 4 m with a slope of 30°. The results suggested that coffee trees experience high erosion in the first and second years of growth, that is, 33.6 Mg ha^{-1} year^{-1} and 37.2 Mg ha^{-1} year^{-1}, respectively. However, the erosion rate decreased for older coffee trees; the erosion rate in areas planted with 7-year-old coffee trees was 7.1 Mg ha^{-1} year^{-1} while that for areas with 10-year-old coffee trees was 6.8 Mg ha^{-1} year^{-1}. However, areas in the Sumberjaya, Lampung, planted with monoculture coffee trees younger than 3 years, were found to have a lower soil erosion rate of 1.5 Mg ha^{-1} year^{-1} (Dariah et al. 2004).

Young coffee trees likely contribute to the higher soil erosion in the Sekampung Hulu watershed. According to Mr. Joni Ansonet (village head of Datar Lebuay),

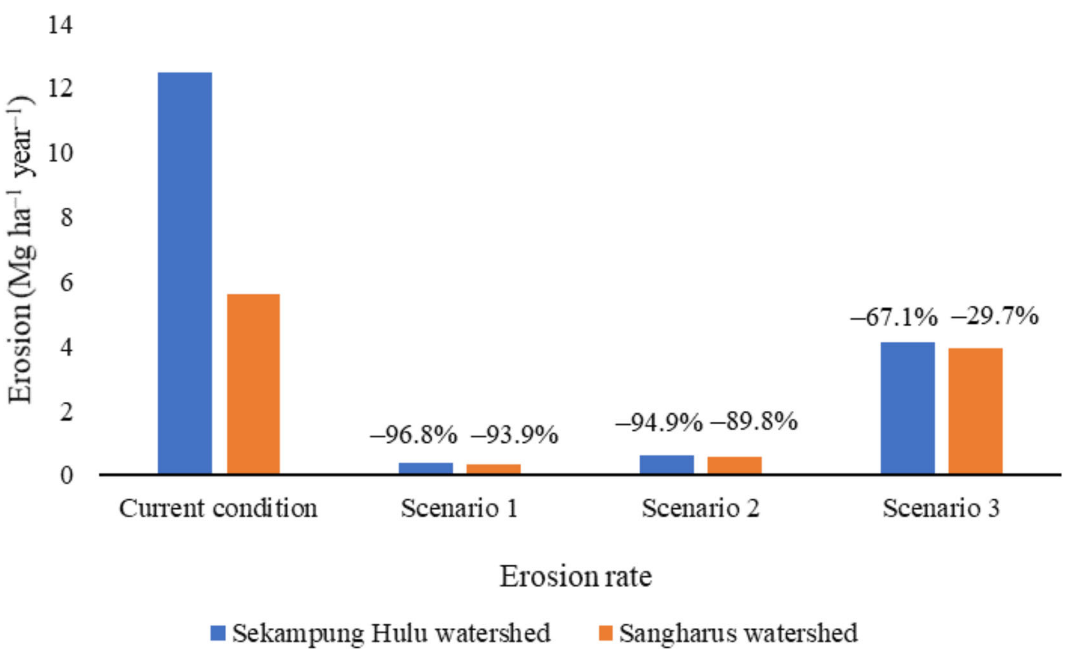

Fig. 5 Impacts of best management practice simulation scenarios: application agroforestry (scenario 1), cover crops (scenario 2), and contour system (scenario 3) on soil erosion rate in the Sekampung Hulu and Sangharus watersheds

several local farmers planted coffee trees in the Wana Tani Lestari and Mandiri Lestari *HKm* areas of the Sekampung Hulu watershed from 2015 to 2016 (personal interview, 2019). The land-use type characterized by young coffee trees offers less coverage than agroforestry coffee and shade coffee. Further, the erosion rates in different areas were influenced by the age of the coffee trees. Therefore, soil loss due to erosion was higher in young coffee plantations (Widianto et al. 2004) due to less canopy cover and ground-layer vegetation. The conditions of land use cover are seen in Fig. 6; Fig. 6d presents the poor surface cover conditions in coffee plantations less than 1 year old. Older coffee trees exhibited larger canopies consisting of leaves, branches, and stems that reduce the kinetic energy of rainfall. Subsequently, rainfall does not disperse soil aggregates in the top layer. Preti (2013) reported that slope stability depends on vegetation type and differences in their root characteristics and coverage.

Physical soil characteristics, such as macropores and permeability, also affect soil erosion rates (Dariah et al. 2003). The dominant soil type in Sekampung Hulu watershed was Typic Dystrudepts (30.6%), which had the highest K value of 0.0341 (Table 3), indicating vulnerability to soil erosion. Further, young coffee trees in this soil type constituted 11.3% of the total area for the Sekampung Hulu watershed. The dominant soil type in the Sangharus watershed was Andic Dystrudepts, which exhibited a lower K value of 0.0103. The lower K value of Andic Dystrudept compared to Typic Dystrudept is due to higher organic matter and permeability. Verbist et al. (2010) reported that the geological characteristics of lithology also influence the soil erosion rate.

Soil erosion rates are also affected by topography. High LS values ranging between 7 and 9.7 were estimated for 10.3% and 6.9% of the area for the Sekampung Hulu and Sangharus watersheds, respectively. Presence of young coffee trees in areas with high LS values resulted in high soil erosion rates. In addition, a high slope gradient indicated higher vulnerability to erosion (El Kateb et al. 2013). Therefore, erosion rates could be reduced by planting coffee on slope gradients less than 30%; however, slope gradients ranging between 50 and 70% could be considered optimal for agroforestry coffee characterized by good management practices (Sepulveda and Carrillo 2015).

Analysis of BMP scenarios indicates that all scenarios could reduce soil erosion. Adoption of agroforestry can reduce soil erosion (Sepulveda and Carrillo 2015) through a well-developed canopy system and supply of litter to the soil surface (Hairiah et al. 2006). Moreover, agroforestry can also decrease pest attacks (Pumarino et al. 2015) and increase carbon stock (De Beenhouwer et al. 2016). The simulation based on adoption of agroforestry indicated a reduction in soil erosion by 96.8% and 93.9% in the Sekampung Hulu and Sangharus watersheds, respectively.

The planting of cover crops (e.g., *Arachis pintoi*, *Calopogonium mucunoides*, *Peuraria javanica*) can reduce soil degradation by protecting the soil surface from rainfall, which can stimulate the breakdown of soil aggregates. The presence of cover crops in coffee plantations can decrease soil erosion by lowering runoff velocity. Therefore, the scenario based on cover crop adoption decreased soil erosion in the Sekampung Hulu and Sangharus watersheds by 94.9% and 89.8%, respectively. Cover crops can also increase the carbon stock of soils (Ladoni et al. 2016) and improve available soil water (Pires et al. 2017). Messiga et al. (2015) reported that a combination of cover crops and amendments could support biological, chemical, and physical soil properties.

The contour system of soil conservation is based on planting trees according to elevational contour lines. Simulation results indicated that the presence of a contour system could reduce soil erosion by 67.1% and 29.7% in the Sekampung Hulu and Sangharus watersheds, respectively. Further, implementation of a contour system could reduce runoff and soil erosion (Aflizar et al. 2010; Alegre and Rat 1996; Shi et al. 2004), especially in sloped areas.

The simulation of BMP scenarios indicated that the adoption of agroforestry and cover cropping would be more effective than the application of a contour system in reducing soil erosion. These results are in agreement with Xiong et al. (2018) who reported that biological techniques of soil conservation were more effective (up to 88%) than engineering techniques (like contour application) in reducing soil erosion.

In summary, adoption of agroforestry coffee is the most effective BMP for reducing soil erosion. Therefore, this practice should be suggested to local farmers. Furthermore, it is crucial to raise awareness regarding the importance of this system, especially with respect to both income generation and environmental conservation, to encourage the adoption of agroforestry among farmers. Moreover, agroforestry coffee is likely to minimize potential economic losses due to crop failure, because farmers can also profit from trees other than coffee.

Conclusions

The implementation of social forestry policies, such as community forests and partnership forests, in the Sekampung Hulu and Sangharus watersheds significantly altered land cover patterns. Consequently, this will influence water quality in the rivers. This study assessed water quality based on TSS concentrations in the two watersheds throughout 2016.

The Sekampung Hulu River was found to have significantly higher TSS concentrations than the Sangharus River during the study period. The higher TSS in the Sekampung Hulu River was aligned with the soil erosion assessment based on the USLE that indicated higher soil erosion in the Sekampung Hulu watershed than in the Sangharus watershed. The higher erosion in the Sekampung Hulu watershed was attributed to the higher presence of young coffee trees in the area. The area occupied by young coffee trees was higher in the Sekampung Hulu watershed because cultivation in the area was recently initiated by several new farmers. In the latest available Google Earth images of the study area from July 2017 (Google Earth 2017), some places were observed to have even less vegetation, and the soil was visible. As 3 years have passed since this research was conducted, the conditions in the Sekampung Hulu watershed may have improved in some areas, because the canopy of young coffee trees and surface vegetation may now be more developed, as several other studies have indicated (Afandi et al. 2002; Iori et al. 2014; Widianto et al. 2004). However, it is also possible that farmers have planted new young coffee trees in other parts of the watersheds after securing permission to use the land. Thus, it is very important to disseminate the idea of BMPs to local farmers.

Adopting BMPs could minimize soil erosion that typically transports nutrients out of topsoil. Lack of nutrients in soil can reduce coffee growth and productivity, thereby reducing yield. Increasing coffee productivity is important because coffee provided the

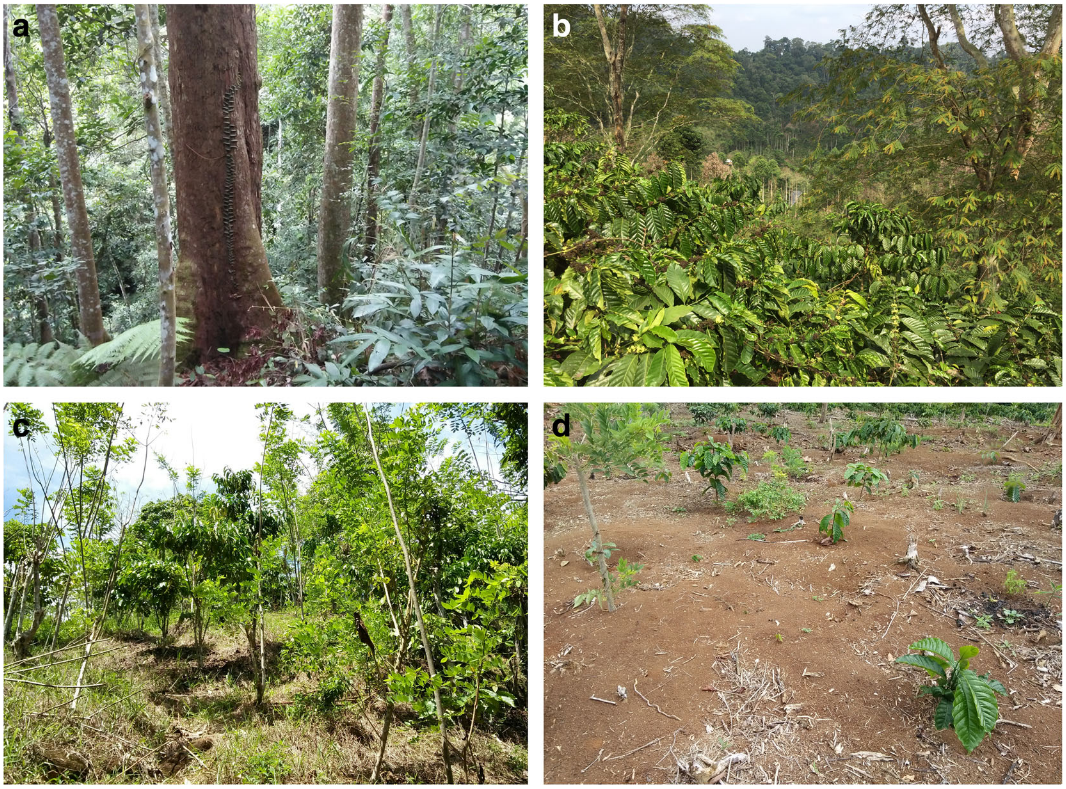

Fig. 6 Land use cover: **a** forest, **b** agroforestry coffee, **c** shade coffee, and **d** young coffee

agricultural and forestry sector in Lampung province with a value of US $435,288,000 in 2014 (Statistics of Lampung Province 2017a). Indonesia is now the fourth largest coffee producer in the world, after Brazil, Vietnam, and Colombia (International Coffee Organization 2019). To maintain high coffee crop productivity in this area into the future, communicating with local farmers and suggesting simple techniques to conserve the environment are crucial for the sustainable maintenance of forest functions.

In our study, the adoption of agroforestry coffee systems, a relatively simple concept and set of techniques, was the most effective BMP scenario for reducing soil erosion. However, our analyses did not consider spatial and temporal land use planning for next several years in the watersheds, because of lack of data. As a next step, this information will be necessary to enter discussions with local farmers about young coffee tree planting.

Additionally, high soil erosion rates can increase sedimentation in reservoirs and subsequently reduce their storage capacities (Fu et al. 2008). The Batutegi Dam in the lower part of the studied watersheds is multipurpose, irrigating an agricultural area of 660 km^2 and contributing to hydroelectric power generation. Therefore, efficient land use management in the watersheds upstream is essential to reduce sediment discharge from the rivers (Mehri et al. 2018) and maximize dam functionality.

As a final word, the concept of "Social Forestry" is ideal to support local farmers and produce products in protected forests with strict rules. On the operational side, we should provide new techniques that combine multiple soil loss prevention methods, especially for areas with steep slope, in addition to agroforestry. This information could be useful for the government as well, to accelerate the improvement of watershed conditions and water quality.

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