Assessing land degradation as the impact of deforestation due to the expansion of oil palm plantation in Rokan Hulu, Riau

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Abstract. In Riau province, Sumatra much of the deforestation has been associated with the extension of oil palm plantations on soils that are particularly vulnerable to soil erosion and land degradation. Most of the deforestation in Riau occurred on highly erodible Ultisols, on slopes steeper than 7 degrees and under a high and erosive rainfall regime, which, when taken together can result in a high risk of soil erosion and land degradation. Land degradation depends on soil erodibility, climatic factors expressed as rainfall erosivity, and slope conditions. This research aims to determine the impact of deforestation, particularly on the risk of land degradation. The rate and extent of deforestation was determined using remote sensing data published from reliable sources. The risk of land degradation assessed through soil erosion analysis in Riau Province by using published soil survey information and data to calculate soil erodibility and by combining this with other factors such as rainfall erosivity for the region and an assessment of slope factors. The estimation of the risk of land degradation has been achieved by a quantitative assessment of the potential soil erosion loss by applying the USLE (Universal Soil Lost Equation) to discrete land facets within Riau Province. The result of this study indicates that slight and moderate risk erosion class were dominant over most of the study area with 239,389 ha (47.92 %) and 129,391 ha (26.23 %), respectively. About 25% of the study area was predicted to suffer from erosion risk of more than 60 ton/ha/year.

1. Introduction
Indonesia, especially Borneo, Kalimantan, Sumatra and Papua, includes the second largest area of tropical rain forest in the world after Amazon rainforest in Brazil. Sumatra's lowland forests, in particular, are recognised as part of the Global 200 Ecoregion, nature legion, landscapes or seascapes that are exceptionally important and symbolic for the survival of rich biodiversity features [12]. According to UNESCO [12], Sumatra's tropical rainforest is home to an estimated 10,000 plant species, more than 200 mammal species and some 580 bird species. However, this situation is rapidly changing due to extensive deforestation and the consequent loss of biodiversity and degradation of ecosystem services during the last decade.

In addition to their contribution to biodiversity, tropical rain forest ecosystems provide other essential ecosystem services (FAO, 2013). Muhammad et al. (2014) identify these as: (1) forest goods and provisioning services, such as fruits, honey, fodder, energy, timber, and medicinal materials, (2) regulating services representing regulation of water purification, climate, air and protection from strong
winds, pollination, crop pest regulation and seed dispensers (particularly for fruit trees), (3) social services representing a place for observing wildlife, and the enhancement of spiritual, cultural and aesthetic values, and (4) supporting services representing sanctuary or habitat for wildlife, soil formation and nutrient cycling that support soil fertility and protection from erosion and landslides.

Hansen et al. (2013) stated that Indonesia as a whole exhibited the most significant increase in a forest lost (1021 km/year) of all countries globally in 2000 – 2012. This has had massive ecological and environmental impacts. The highest rates of deforestation are occurring in Sumatra, where forest cover has been reduced from 58% in 1985 to 29% in 2008/9, constituting an average annual forest clearance rate of 2.1%. In Riau province, Sumatra, much of this deforestation has been associated with the extension of oil palm plantations on soils that are particularly vulnerable to soil erosion and land degradation. Yet, little research has been carried out on such potential environmental impacts, or the loss of other ecosystem services.

Any assessment of the rates and impacts of deforestation and the associated spread of oil palm plantations requires a critical analysis of what is meant by deforestation and how it is assessed as this will affect the data presented. There are several definitions of deforestation. Deforestation may simply be defined as the change of land-cover conditions from forested land cover to non-forested land cover [8]. Other definitions include more precise limits for tree cover on non-forested land. Thus, according to FAO [4] deforestation is the conversion of forest to another land use, or the long-term reduction of tree canopy cover to below the 10% threshold. More specifically, WWF-Indonesia [13] defines deforestation as the process whereby natural forests are cleared through logging and/or burning, either to use the timber or to replace the area for alternative land uses. Whereas Gaveau et. al. [6] define deforestation as the long-term removal of “old growth natural evergreen forest cover”, thus placing more emphasis on the values of primary tropical rain forests for biodiversity.

There are three crucial potential environmental effects of deforestation for the development of oil palm plantation: climate change due to the release of carbon, loss of biodiversity and increased soil erosion [1]. Most of the deforestation in Riau occurred on highly erodible Ultisols, on slopes steeper than 7° and under a high an erosive rainfall regime, which, taken together can result in a high risk of soil erosion and land degradation. Land degradation depends on soil erodibility, and climatic factors expressed as rainfall erosivity and slope conditions. Land degradation is a process where degradation of the overall capacity of the land to produce economic goods and to perform environmental regulating functions occur. The critical point of land degradation is soil degradation. Soil erosion is the most visible and sometimes most destructive form of soil degradation.

This research aims to determine the impact of deforestation, particularly on the risk of land degradation. The risk of land degradation assessed through the analyses of soil erosion in Riau Province using published soil survey data to calculate soil erodibility and by combining this with other factors such as rainfall erosivity for the region and an assessment of slope factors.

2. Materials and Methods
This study assesses the potential risk of erosion in 19 oil palm plantations in Rokan Hulu Regency, Riau Province. The assessment was based on soil erodibility, rainfall erosivity and slope factors from the study area. The research was conducted in Rokan Hulu Regency, Riau Province, Indonesia. The site is situated at latitude of 00°25′20 - 01°25′41 N and 100°02′56-101°56′59 E with an area of 7,604 km². The population of the Rokan Hulu Regency is 517,577 [14]. Rokan Hulu is located at an altitude of 10 – 164 meters above sea level. The lowest area is Bonai Darussalam (10 m above sea level), and the highest area is Rambah Samo (164 m above sea level). This area has a tropical zone climate with a maximum temperature of about 31°C – 32°C and mean annual rainfall (2000 – 2010) of 2888 mm.

2.1. Data sources
The estimation of the risk of land degradation has been achieved by a quantitative assessment of the potential soil erosion loss by applying the USLE to discrete land facets within Riau Province. The data required to fulfill its component factors include relevant soil properties derived from soil survey maps,
rainfall data derived from meteorological records and slope data derived from a digital elevation model (DEM).

The soil data for this study is obtained from the Indonesian Soil Research Institute. The dominant soil types of the study area were Dystrandepts, Dystropepts, Hapludults, Tropahemists and Tropaquest. Soil map unit boundaries and 60 soil data points were used to derive the soil erodibility map which was calculated using the soil properties obtained from the soil map. The soil erodibility factor (K-factor) from 60 soil data points then interpolate to the whole study area based on soil map unit boundaries to create the soil erosion risk map.

The daily rainfall data for the period 2000 to 2011 obtained from seven rainfall stations in the study area were used in this study. Additional data from five rainfall stations close to the study area were also used to increase the accuracy of the result. All the precipitation data for these stations were obtained from the Indonesian Agency for Meteorological, Climatological and Geophysics.

The location of oil palm plantations was assessed from a map covering the study area obtained from the Indonesian Ministry of Industry. There are 19 oil palm plantations in the study area. The slope data was derived from a digital elevation model (DEM). It includes a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals. The DEM data are digital representations of cartographic information of the area. The DEM data files were obtained from the Indonesian Agency for Geospatial Information.

Different data sources may have different data formats, projections and spatial resolution. The use of GIS provides the tool to manage and analyse these data. However, the evaluation and pre-processing of these data such as interpolation and conversion were done before the data were used in the analyses.

2.2. Methodology

2.2.1. Soil erodibility evaluation

The soil erodibility K that measures the influence of physical and organic properties on the soil's susceptibility to erosion was calculated employing the regression equation proposed by Wischmeier and Smith [12]

\[
100 \, K = 2.1 \, M^{1.0} \, (10^{-4})(12 - a) + 3.25 \, (b - 2) + 2.5 \, (c - 3)
\]

where:

- \( M \) is the (%silt + % very fine sand)(100 - % clay)
- \( a \) is the % of organic matter
- \( b \) is the soil structure code (1: very fine granular, 2: fine granular, 3: medium or coarse granular, and 4: blocky)
- \( c \) is the soil permeability class (1: rapid, 2: rapid to moderate, 3: moderate, 4: slow to moderate, 5: slow, 6: very slow)

2.2.2. Rainfall erosivity evaluation

The rainfall erosivity (R) is a measure of the rainfall erosion energy at a certain place. Rainfall erosivity can be calculated based on the data obtained from rainfall rate data. The equation used to determine the levels of rainfall erosivity in this study were [3]

\[
R = 6.119 \, (RAIN)^{1.21} \, (DAYS)^{-0.47} \, (MAXP)^{0.53}
\]

where:

- \( R \) is the mean monthly rainfall erosivity
- \( RAIN \) is the mean monthly rainfall rate (mm)
- \( DAYS \) is the mean number of rainy days per month
- \( MAXP \) is the maximum precipitation for 24 hours in the month

RAIN and MAXP for this study were obtained from daily rainfall data for the period 2000 to 2011 derived from 12 rainfall stations.
2.2.3. LS factor evaluation
The LS factor accounts for the effect of topography on erosion. The slope length factor (L) represents the effect of slope length on erosion, and the slope steepness factor (S) reflects the influence of slope gradient on erosion. In this study, the LS factor estimated from a digital elevation model (DEM). The technique for computing LS requires a flow accumulation and the slope steepness. The flow accumulation was computed from a DEM using watershed delineation techniques. The slope steepness was computed using the DEM.

The slope gradient (S) and slope length (L) can be accurately determined and combined with the incline of the Digital Elevation Models (DEM) to form one factor known as a topographic factor LS. The equation used to determine this parameter was recommended by Morgan [9]:

\[
LS = \left( \frac{x}{22.13} \right) (0.065 + 0.045s + 0.0065s^2)
\]

Where:
- \(x\) is the slope length (m)
- \(s\) is the slope gradient in percent

2.2.4. Mapping soil erosion risks
The soil erodibility map, rainfall erosivity map, LS factor map and oil palm plantation map were constructed using ArcGIS 10.1 software. These were subsequently combined to produce the potential soil erosion risk map for each oil palm plantation. Using GIS, these maps were overlaid with each geographic feature for the study area.

The soil erosion potential was determined by multiplying the respective USLE factors interactively in ArcGIS 10.1. The potential soil loss value obtained were subsequently grouped into five classes using an area distribution analysis, resulting in the potential erosion risk map. The annual potential soil loss map obtained were grouped in the following scales of priority: Slight (0 – 15 ton/ha/yr), Moderate (15 – 60 ton/ha/yr), High (60 – 180 ton/ha/yr), Very High (180 – 480 ton/ha/yr) and Severe (>480ton/ha/yr) annual erosion classes as per guidelines suggested by the Indonesian Ministry of Forestry [8] for Indonesian conditions.

3. Results and Discussion
3.1. Rainfall erosivity
The climate in Rokan Hulu Regency is influenced by maritime wind systems which originate in the Indian Ocean and the South China Sea. In April to August, the climate is influenced by the Northwest wind, while in August to April is affected by the East wind, with a maximum temperature of 36°C and minimum temperature of 15°C. Mean annual rainfall in Rokan Hulu ranged from 2,000 – 3,000 mm. The rainy season usually occurs from September to April, and the dry season occurs from May to August.

Classification of climate in Rokan Hulu based on Schmidt and Ferguson’s climate classification [14], Rokan Hulu has rainfall of A-type (very wet). The climate of Rokan Hulu is classified as Af (tropical wet) climate in the Koppen climate zone system. Meanwhile, according to Oldeman agroclimatic zones, this area is included in the B1 climate zone, which is characterised by the presence of wet months (rainfall >200 mm/month) for 7 – 10 months and dry months (rainfall <100mm/month) for 1 – 2 months.

The distribution of the average annual rainfall of the study area for the 12 years is different from station to station, and the values of R factor used in the USLE are also expected to vary according to rainfall distribution. Rainfall erosivity factor varied from 1605 – 3257 MJ ha/mm/hr/yr. The erosivity factor map (Figure 1A) of the study area was generated in Arc-GIS 10.1
3.2. Topographic factor (LS)

The topographic factors slope gradient and slope length significantly influence soil erosion. A slope and flow accumulation grid were prepared from a digital elevation model (DEM) and presented in Figure 1B. Each grid was considered as a single slope plane. Slope and flow accumulation was calculated using the available spatial analysis function within ArcGIS. An LS factor map was created using raster calculation function. LS factor values range from 0 to 7.19, but over most of the land area are in 0 – 1 range, with some higher values occurring in the hilly areas.

3.3. Soil erodibility

Soil survey work has demonstrated that Inceptisols, Ultisol and Histosols were dominant soils in the study area. In general, the study area seems to have moderate to high erodibility. Moderate erodibility that associated with Inceptisols is located in the northern part of the study area, while high erodibility that associated with Ultisols is located in the southern part of the study.

Table 1. Classification and distribution of soil groups in the study area.

| Order   | Suborder | Groups     | Area (ha) | Area (%) | K-factor |
|---------|----------|------------|-----------|----------|----------|
| Inceptisols | Tropepts | Dystropepts | 500,528 | 68.81 | 0.21 – 0.30 |
|          | Aquepts  | Tropaqupts  | 96,932    | 13.25   | 0.21 – 0.26 |
|          | Andepts  | Dystrandepts | 2,014   | 0.28    | 0.32     |
| Ultisols | Udults   | Hapludults  | 81,934    | 11.26   | 0.31 – 0.39 |
| Histosols | Hemits   | Tropohemits | 43,499    | 5.98    | Peatland, not calculated |

Figure 1. The erosivity factor (A) and the LS factor map (B) of the study area.
Soil erodibility is a quantitative estimation of erodibility of particular soil. One of the main factors affecting the capability of the soil to erode is its soil texture. However, the other factors affecting the K factor are soil structure, permeability, and the organic matter content. The soil erodibility factor map (Figure 2B) was prepared from the soil map of the study area (Figure 2A). The soil distribution in the study area and derived erodibility factors calculated from soil data available from analysed soil profiles used to characterise the soil map units is given in Table 1. The soil erodibility was calculated using the soil properties obtained from the soil map. The soil erodibility factor (K-factor) from 60 soil data points from the study area were interpolated for the whole study area based on soil map unit boundaries to create the soil erosion risk map.

![Figure 2. The soil map (A) and erodibility factor map (B) of the study area.](image)

The value and the extent soil erodibility for each palm oil plantation were calculated from the overlay of the soil erodibility map and oil palm plantation map. Most of the oil palm plantations have values of K-factor ranging from 0.21 to 0.30, except for PT Karyatama Bakti Mulia with almost half of the area having a K-factor value more than 0.

### 3.4. The potential soil erosion risk map

The potential soil erosion risk map for the study area was created from the combination of the rainfall erosivity map, the soil erodibility map and the LS factor map using ArcGIS as shown in Figure 7. Using GIS software, these maps were overlaid with each geographic feature of the study area. The soil erosion potential was determined by multiplying the respective USLE factors interactively in ArcGIS. The potential soil erosion values ranged from 0.15 to 5250 ton/ha/year.

The annual potential soil loss map obtained were grouped in the following scales of priority: Slight (0 – 15 ton/ha/yr), Moderate (15 – 60 ton/ha/yr), High (60 – 180 ton/ha/yr), Very High (180 – 480 ton/ha/yr) and Severe ( >480ton/ha/yr) annual erosion classes as per guidelines suggested by the Indonesian Ministry of Forestry [13] for Indonesian conditions. Figure 3 shows the annual potential soil erosion map of the study area, which is helpful in identifying the areas vulnerable to soil erosion. Table 2 shows the spatial distribution of different erosion classes in the study area.
Table 2. Erosion Potential Classes of the study area.

| Soil Risk Erosion Class | Range (ton/ha/yr) | Area (ha) | Area (%) |
|-------------------------|------------------|-----------|----------|
| Slight                  | 0 – 15           | 236,389   | 47.92    |
| Moderate                | 15 – 60          | 129,391   | 26.23    |
| High                    | 60 – 180         | 50,767    | 10.29    |
| Very High               | 180 – 480        | 38,642    | 7.83     |
| Severe                  | > 480            | 38,094    | 7.72     |

Figure 3. The potential soil erosion risk map of the study area.

In general, soil erosion risk was low in relatively flat areas, where soil loss rates was less than 15 ton/ha/year. Slight and moderate risk erosion class were dominant over most of the study area with 239,389 ha (47.92 %) and 129,391 ha (26.23 %), respectively. About 25% of the study area was predicted to suffer from erosion risk in excess of 60 ton/ha/year. High to severe soil erosion risk occur in the southern part of the study area. However, within the existing oil palm plantation, only 6,669 ha (3.32 %) of the land area was predicted to have high to severe erosion risk. PT Karyatama Bakti Mulia has the largest area (1,561 ha) of land that is predicted to have very high to severe erosion risk.

4. Conclusions

Rokan Hulu is one of the locations of oil palm plantation development in Riau Province, Sumatra. The result of this study indicates that slight and moderate risk erosion classes were dominant over most of the study area, with 239,389 ha (47.92 %) and 129,391 ha (26.23 %), respectively. About 25% of the study area was predicted to suffer from erosion risk of more than 60 ton/ha/year. However, within the existing oil palm plantation, only 6,669 ha (3.32 %) of the land area was predicted to have high to severe
erosion risk. Ultisols dominated the southern part of the study area. These highly erodible soil combined with steep slopes increased the erosion risk. Meanwhile, the northern part of the study area is dominated by peat soils (Histosols) characterised by very poorly drained and acid conditions.

This study applied a tool for modelling soil erosion potential, given the unique physical conditions in the study area. It was possible to predict location-specific soil loss and, in combination with GIS techniques, transform these to erosion risk maps at reconnaissance scales. The application of the USLE principles within the study area based on secondary sources of climatic, slope and soil survey data have provided means of estimating soil erosion risk, which can be extrapolated spatially using GIS as a tool. Data requirements were not too complicated or unattainable provided means of estimating soil erosion risk, which can be extrapolated spatially using GIS as a tool. Data requirements were not too complicated or unattainable in a developing country like Indonesia. The data obtained was compatible with GIS, and it was easy to implement and understand from a functional perspective. This had distinct advantages when attempting to identify the spatial patterns of soil loss. The GIS could be used successfully to isolate and query specific locations to produce vital information about the effect of individual variables in contributing to the observed erosion potential value.

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