Estimation of sediment production in oil palm expansion areas in the Amazon

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A B S T R A C T
Currently, an activity that has become strategic at a national level is the cultivation of oil palm (*Elaeis guineensis*) in the northeast region of the Pará State, in eastern Brazilian Amazon. However, the impacts of this crop expansion on the hydro-sedimentological cycle are still unknown. Therefore, this study estimated the impacts of oil palm crop expansion on sediment production in a sub-basin under consolidated use of this crop. The Soil and Water Assessment Tool (SWAT) model was applied in the Mariquita sub-basin, calibrated by the flow regionalization technique, using data measured in the field with a current meter. Simulation results indicated an increase in sediment production between the years 2008 and 2013, which can be attributed to the large reduction of areas of secondary vegetation that were replaced by pasture, oil palm and general agriculture. Oil palm areas had a lower average monthly sediment yield in the rainiest period in all simulated years, compared with areas of general agriculture and pasture.

Estimativa da produção de sedimentos em áreas de expansão da palma de óleo na Amazônia

R E S U M O
Atualmente, uma atividade que se tornou estratégica a nível nacional é o cultivo da palma de óleo (*Elaeis guineensis*) na região nordeste do estado do Pará, na Amazônia oriental brasileira. Entretanto, se conhece pouco ainda dos impactos da expansão dessa cultura sobre o ciclo hidrossedimentológico. Por isso, este trabalho estimou os impactos da expansão da cultura da palma de óleo sobre produção de sedimentos em uma sub-bacia de uso consolidado dessa cultura. Aplicou-se o modelo hidrossedimentológico Soil and Water Assessment Tool (SWAT) na Sub-Bacia do Rio Mariquita, PA, calibrando o modelo utilizando a técnica de regionalização de vazão, a partir de dados medidos em campo com o molinete hidrométrico. Os resultados das simulações indicaram um aumento da produção de sedimentos entre os anos de 2008 e 2013, podendo ser atribuído à grande redução de áreas de vegetação secundária que foram substituídas pelos cultivos de pastagem, palma de óleo e agricultura geral. As áreas de palma de óleo tiveram uma produção média mensal de sedimentos menor no período mais chuvoso em todos os anos simulados, se comparadas às áreas de agricultura geral e pastagem.

Introduction

Brazilian Amazon region, especially northeastern Pará state, has undergone an accelerated economic development (Becker, 2005), causing a series of socioeconomic and environmental impacts due to the lack of territorial planning. Among these impacts, alterations in surface runoff regime and intensification of erosive processes stand out (Yang et al., 2009), leading to reduction of soil fertility, formation of gullies, contamination of water resources and silting of rivers and reservoirs (Filizola et al., 2011).

Currently, oil palm (*Elaeis guineensis*) cultivation became strategic on a national level for the energy and food production market (Ramalho Filho, 2010). With excellent biophysical, socioeconomic and political conditions, the northeastern region of the Pará state has faced a large expansion of this crop, motivating some studies on the possible environmental impacts. These studies particularly include those related to carbon rates in the soil (Guillaume et al., 2016), planting in deforested or degraded areas (Carvalho et al., 2015), as well as its influence on the dynamics of soil use and occupation (Wicke et al., 2011). However, there is a demand for studies evaluating the impacts of crop expansion on the hydro-sedimentological regime on a water basin scale.

The hydro-sedimentological model SWAT (Soil and Water Assessment Tool) allows to evaluate the impact of different soil uses on surface runoff and sediment production (Zhang et al., 2009; Arnold et al., 2012). This tool has been employed to study the influence of the expansion of oil palm areas on water and sediment yields in Malaysia (Alansi et al., 2009) and Thailand (Babel et al., 2011), presenting important data for the planning of soil use and cover in water basins.

Therefore, the SWAT model was applied to an ungauged sub-basin of the Mariquita River, located in the eastern Brazilian Amazon, to evaluate the impacts of oil palm expansion on sediment production.

Material and Methods

The study was carried out in sub-basin of the Mariquita River (MRSB), with area of 159.94 km^2, tributary of the Acará-Mirim river (Figure 1), located in the Northeast mesoregion of the Pará state, municipality of Tomé-Açu (48º 22' 38" W, 2º 22'

41" S and 48º 30' 42" W, 2º 34' 08" S). The climate of the region is classified as Am, according to Köppen's classification, with mean temperature of 27.9 °C, mean annual rainfall of 2500 mm and relative air humidity of 80%, and the area has predominance of dystrophic Yellow Latosol and declivity from 0 to 13%.

The SWAT model was used to evaluate the impacts on the hydro-sedimentological cycle caused by the changes in soil use and cover, occurred in the years 2008 and 2013. The map of soil use and cover for 2013 was elaborated according to the TerraClass project for the year 2008 (INPE, 2014), using LandSat 8 satellite images. Table 1 and Figure 2 show the data of soil use and cover in the MRSB, in which the year 2008 represents the context before oil palm expansion, and 2013, the context after its expansion.

The Digital Elevation Model was generated from SRTM (Shuttle Radar Topography Mission) images with 90-m resolution. Pedological information on the number of soil layers, organic carbon, sand, silt, clay and rock of the soil profiles, obtained from ZEE-PA (2010) and profiles opened for soil physical and chemical analysis in the MRSB, was used to estimate all the other soil parameters necessary in the SWAT model through pedotransfer functions (Saxton & Rawls, 2006). Some parameters of the uses were adjusted to the characteristics of the region, such as Manning roughness coefficient (OV_N); maximum height of tree canopy (CHTMX), maximum leaf area index (BLAI) and maximum root depth (RDMX). Climate data of rainfall (mm) from 2003 to 2014 were provided by the National Water Agency (ANA) and the other climate data were provided by the National Institute of Meteorology (INMET).

Table 1. Areas for each class of soil use and cover in 2008 and 2013 in the MRSB

Use and cover	Area			
	2008		2013	
	(ha)	(%)	(ha)	(%)
General agriculture	407.0	2.55	916.4	5.73
Oil palm	---	---	2316.5	14.48
Pasture	5455.9	34.11	4222.7	26.40
Forest remnants	4134.2	25.85	3883.0	24.28
Secondary vegetation	5967.6	37.31	4634.3	28.98
Water*	29.3	0.18	2.7	0.02
Urban area	---	---	18.6	0.12
Total	15993.9	100.0	15993.9	100.00

*Area variation in the class "Water" may be linked to classifier interpretation and LandSat image quality
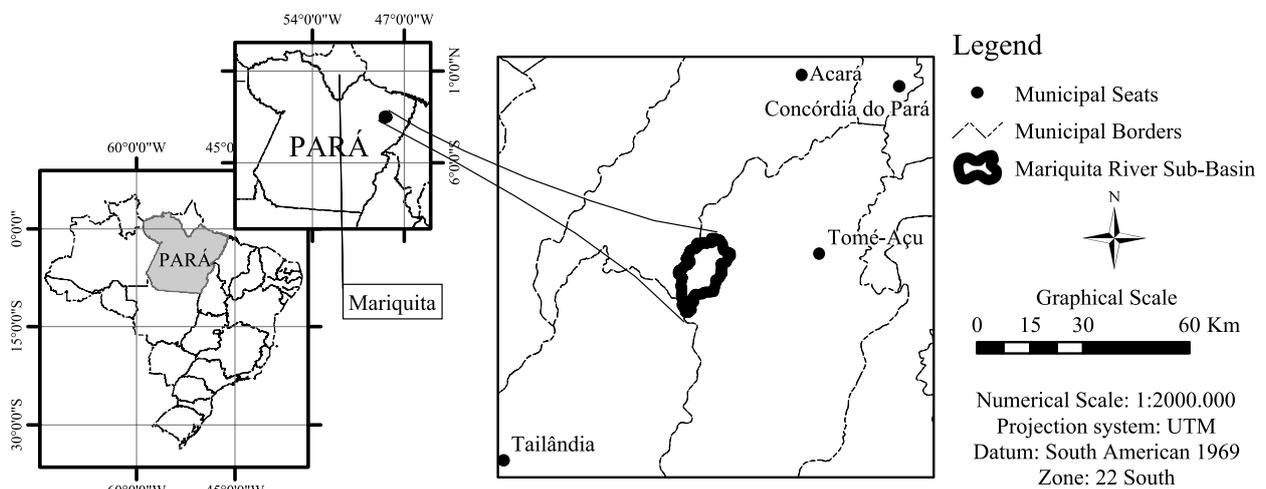

Figure 1. Location map of the MRSB

A.　　　　　　　　　　B.

Legend

- ▨ General Agriculture
- ▨ Oil Palm
- ▨ Pasture
- ▨ Forest Remnants
- ▨ Secondary Vegetation
- ▨ Water
- ▨ Urban Area

Graphical Scale

0　2.25　4.5　　9 Km

Numerical Scale: 1:250.000
Projection system: UTM
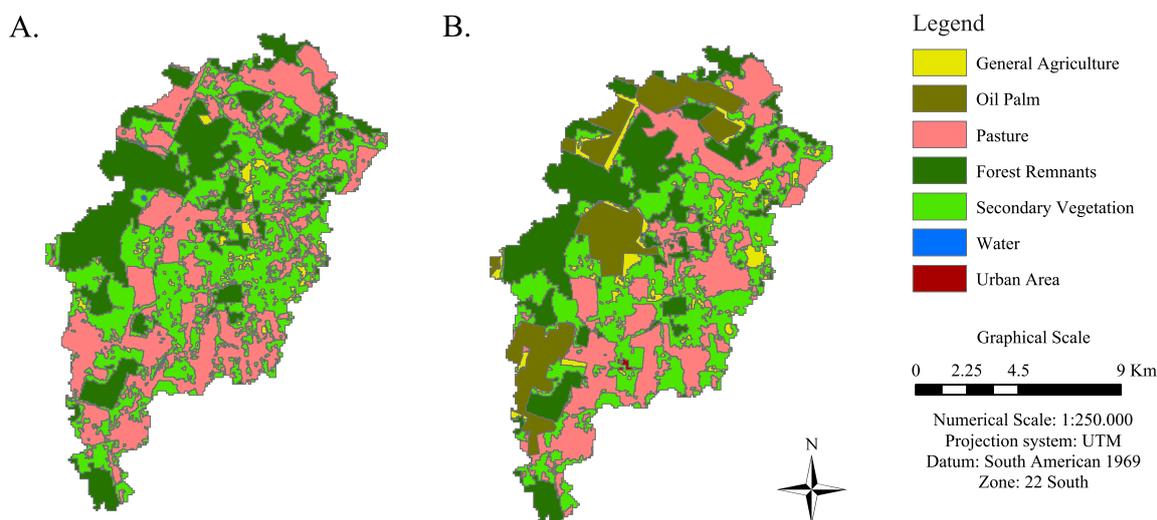Datum: South American 1969
Zone: 22 South

N

Figure 2. Maps of soil use and cover in the years 2008 (A) and 2013 (B) for the MRSB

The MRSB was divided into 11 sub-basins, 62 units of hydrological response and 4 classes of declivity: 0-3, 3-13, 13-20, and from 20% on. For surface runoff and evapotranspiration, the Curve Number (CN) method of the Soil Conservation Service and the Priestley-Taylor equation were respectively used. Three years were used for training (2003 to 2005), five years for calibration (2006 to 2010) automatically performed using the SWAT-CUP software (Abbaspour, 2014) and four years for validation (2011 to 2014).

The flow data relative to the period from 2006 to 2014, used in the simulations, were obtained by the flow regionalization technique, by applying non-linear regression equations (Tucci, 2002) and using as independent variables the basin drainage area (km^2) and mean rainfall (mm) to estimate the long-term average monthly flow and average flow for each month of each year of the series from 2006 to 2014. Data from four fluviometric stations of ANA were used: two in the Guamá River Basin (5005.1 km^2) and two in the Capim River Basin (33384.3 km^2), also located in the northeastern region of the Pará state, under similar geophysiographic characteristics (Goswami et al., 2007).

To evaluate the synthetic series of flow generated by the regionalization and by the SWAT model, flow was measured at the end of the rainy period (May) and dry period (December) in 2014, using a current meter. The correctness of flow measurements was determined using the Nash-Sutcliffe coefficient (NSE) (Moriasi et al., 2007).

Results and Discussion

Validation of regionalization through the test with the Nash-Sutcliffe coefficient (NSE) showed satisfactory results for the Badajós station (0.52) and very good for the stations Fazenda Maringá (0.89), Bom Jardim (0.83) and Vila Capoeira (0.98). After validation, the regionalization equation was applied to generate series from 2006 to 2014 for the MRSB. Statistical results demonstrate the adequacy of the method of calibration and validation regarding the regionalized monthly flow from 2006 to 2014 (NSE = 0.73) and regarding the long-term regionalized average monthly flow (NSE = 0.93). In both analyses, the model showed good results (Moriasi et al., 2007).

An expressive modification occurred between 2008 and 2013 due to the expansion of oil palm (OILP), which changed from 0% in 2008 to 14% in 2013. General agriculture areas increased by approximately 125%, whereas pasture areas (PAST) decreased by 22.6% and secondary vegetation areas (FRSE_VS) decreased by 22.3%. Areas of forest remnants (FRSE_RF) remained virtually unchanged (Table 1).

Sediment production rates in total amounts between 2008 and 2013 in the MRSB increased by about 16%, changing from 41.1 t ha^{-1} year^{-1} in 2008 to 47.7 t ha^{-1} year^{-1} in 2013. Long-term average monthly accumulations (from 2006 to 2014) also demonstrated increase of sediment production in the MRSB from 2008 to 2013 during the rainy period, such as the production peak that occurred in March, 11.9 t ha^{-1} for 2008 and 14.2 t ha^{-1} for 2013. Increase in sediment production (Figure 3) results from the replacement of FRSE_VS areas (CN = 50) by general agriculture areas (AGRL) (CN = 69) and OILP areas (CN = 59), increasing the average value of the Curve Number (CN), as well as increasing surface runoff and sediment production. Influence of CN on surface runoff and sediment production has been confirmed (Kim et al., 2010; Bonumá et al., 2015) and it is important to understand the impacts of agriculture on soil loss and water contamination (Chaubey et al., 2010).

Oil palm expansion occurs particularly in the sub-basins 3, 6 and 10, and the latter two showed large occupation of FRSE_RF and FRSE_VS in 2008 and in 2013, but OILP advanced over the areas of PAST and AGRL. Nevertheless, the replacement of PAST and AGRL areas by OILP does not negatively affect sediment production, only in 2013 for the sub-basin 3, since the OILP advances over the FRSE_VS areas, which lead to lower flow and lower sediment production. Due to the homogeneous declivity, soil use and cover was the main forcing of this distribution of surface runoff and sediment production (Figure 4). The results showed that AGRL areas, followed by PAST, were the ones that most produced sediments in the MRSB (Table 2) and the OILP areas showed lower sediment production compared with AGRL and PAST. Forest areas showed the lowest production rates.

The present study found an average annual sediment production lower than 7 t ha^{-1} year^{-1} (Figure 4), as also reported in the studies of Jesus (2009), in Argisols and with

A.

B.

Legend

	0.80 - 4.15
	4.16 - 7.20
	7.21 - 10.26
	10.27 - 13.32
	13.33 - 16.38

Geographic Scale

0   2.25   4.5   9 Km

Numerical Scale: 1:250.000
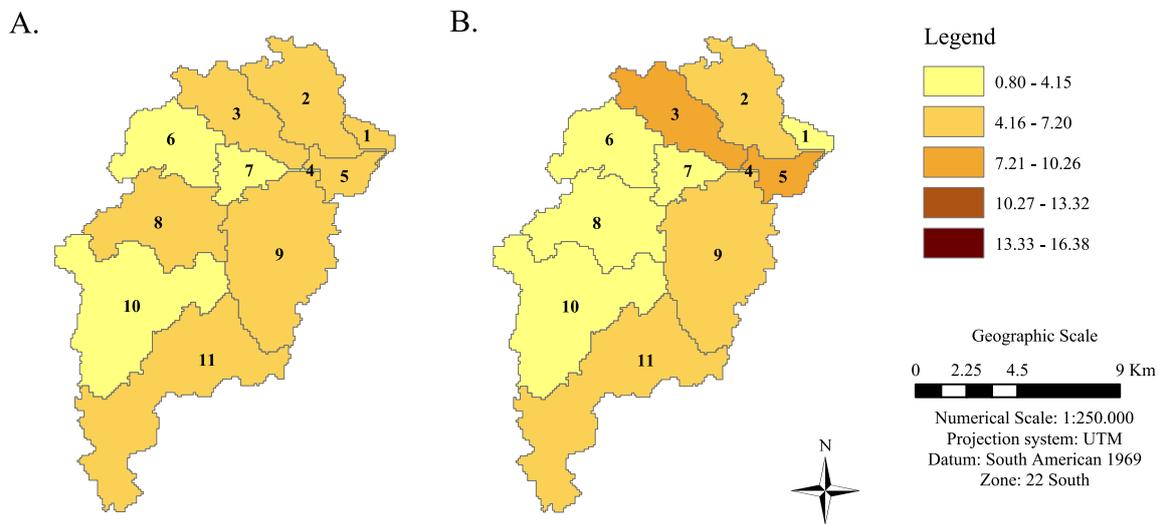Projection system: UTM
Datum: South American 1969
Zone: 22 South

N

Figure 3. Distribution of sediment production (t ha⁻¹) in the MRSB for the years 2008 (A) and 2013 (B)
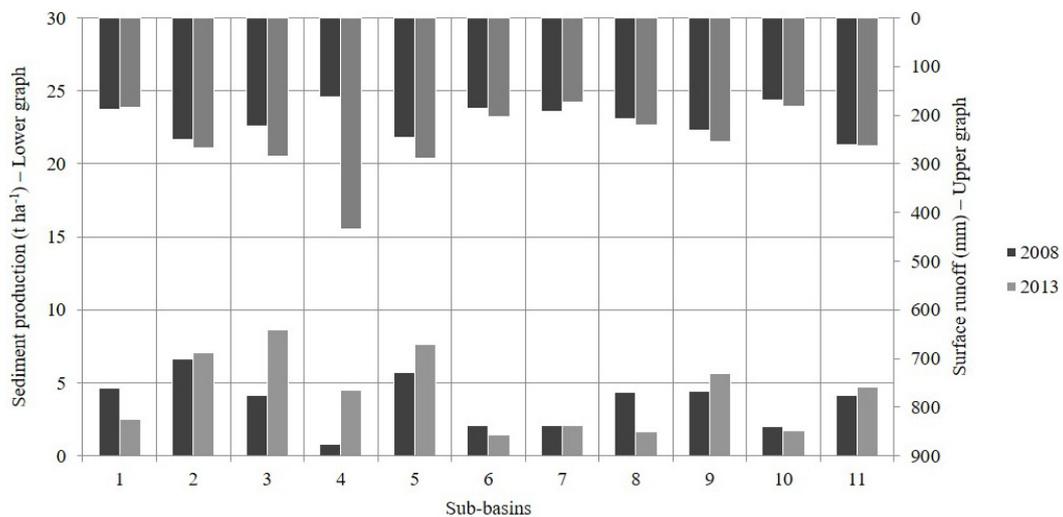

Figure 4. Surface runoff and sediment production in the 11 sub-basins of the MRSB

Table 2. Long-term monthly average and annual sum of sediment production relative to 12 months of the seasonal cycle and for the 6 rainiest months between the simulated years of 2006 and 2014 for the MRSB in both maps of soil use and cover.

Sediment production in the Mariquita River Sub-basin (t ha⁻¹)				
	12 months		6 rainiest months	
	Mean	Sum	Mean	Sum
Map of 2008				
OILP	0.054	0.650	0.099	0.594
AGRL	0.891	10.690	1.512	9.070
PAST	1.346	15.650	2.459	14.757
FRSE	0.004	0.034	0.006	0.034
Map of 2013				
OILP	0.169	2.030	0.306	1.835
AGRL	1.037	12.060	1.705	10.232
PAST	1.267	14.720	2.313	13.878
FRSE	0.004	0.035	0.006	0.035

fewer forest areas, and Santos et al. (2015), with predominance of Latosols and absence of forests, also conducted in the northeastern region of the Pará state. These results demonstrate that sediment production was much lower than the soil loss tolerance limit of 12.7 t ha⁻¹ year⁻¹ (Nunes et al., 2012).

For oil palm, Babel et al. (2011) found that the scenario of oil palm expansion showed insignificant alteration in evapotranspiration and water yield, but observed an increase in nitrate supply, which is linked to the greater supply of nitrogen fertilizer. Conversely, Majid & Rusli (2014) pointed to an increment in surface runoff when forest areas were replaced by rubber tree plantations and then by oil palm in the Muar River Basin (Malaysia). Thus, identifying that the change in soil use and cover has influenced the hydro-sedimentological regime of the MRSB warns for the need to obtain more knowledge on the environmental impact of large agribusiness activities. Therefore, the modeling methodologies applied here combined with the sediment production data provide a range of important information for the region, especially with estimates of sediment production in oil palm areas. In addition, it was possible to identify the importance of secondary vegetation ecosystems for soil conservation and that oil palm plantations require monitoring and environmental management.

Conclusions

1. The results of sediment production estimates are important because they represent a range of information still inexistent for the region.

2. The increment in sediment production in the MRSB is related to the expressive reduction in secondary vegetation and not specifically to oil palm expansion.

3. Oil palm areas showed lower average monthly sediment production in the rainiest period compared with areas of general agriculture and pasture.

Acknowledgments

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