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RESEARCH ARTICLE

Watershed-scale assessment of oil palm cultivation impact on water quality and nutrient fluxes: a case study in Sumatra (Indonesia)

Irina Comte[1,2] · **François Colin**[3] · **Olivier Grünberger**[4] · **Joann K. Whalen**[1] · **Rudi Harto Widodo**[5] · **Jean-Pierre Caliman**[5]

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Abstract High fertilizer input is necessary to sustain high yields in oil palm agroecosystems, but it may endanger neighboring aquatic ecosystems when excess nutrients are transported to waterways. In this study, the hydrochemical dynamics of groundwater and streams under baseflow conditions were evaluated with bi-monthly measurements for 1 year on 16 watersheds. Hydrochemical measurements were related to the spatial distribution of soil and fertilization practices across a landscape of 100 km^2, dominated by oil palm cultivation, in Central Sumatra, Indonesia. The low nutrient concentrations recorded in streams throughout the landscape indicated that the mature oil palm plantations in this study did not contribute to eutrophication of aquatic ecosystems. This was ascribed to high nutrient uptake by oil palm, a rational fertilizer program, and dilution of nutrient concentrations due to heavy rainfall in the study area. Soil type controlled dissolved inorganic N and total P fluxes, with greater losses of N and P from loamy-sand uplands than loamy lowlands. Organic fertilization helped to reduce nutrient fluxes compared to mineral fertilizers. However, when K inputs exceeded the oil palm requirement threshold, high K export occurred during periods when groundwater had a short residence time. For higher nutrient use efficiency in the long term, the field-scale fertilizer management should be complemented with a landscape-scale strategy of fertilizer applications that accounts for soil variability.

Keywords Water quality · Nutrient fluxes · Oil palm · Baseflow · Watershed scale

Introduction

Oil palm (*Elaeis guineensis*) production has expanded rapidly in the tropics during the last decades. As the world's largest palm oil producer since 2007, the government of Indonesia plans to increase production up to 40 million tons of crude oil palm by 2020, mainly in Sumatra, Kalimantan, and West Papua (IMA 2010). The Riau province in Central Sumatra is the largest producer of palm oil in Indonesia, accounting for about 24 % of total national production. From 2004 to 2009, the oil palm area in Riau province increased by 21 % (IMA 2010; Susanti and Burgers 2012). Such rapid expansion of the oil palm industry implies that tremendous land use changes are underway in Indonesia, which raises concern for the environment and human health.

Water quality can be impacted by the oil palm industry, which is why practices and environmental impacts of oil palm

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Responsible editor: Philippe Garrigues

✉ Irina Comte
irinacomte@gmail.com

[1] Department of Natural Resource Sciences, Macdonald Campus of McGill University, 21 111 Lakeshore, Ste-Anne-de-Bellevue H9X 3V9, Quebec, Canada

[2] CIRAD (International Cooperation Centre in Agronomic Research for Development), Avenue Agropolis, 34098 Montpellier Cedex 5, France

[3] Montpellier-SupAgro, UMR-LISAH (Laboratory on Interactions between Soil, Agrosystem and Hydrosystem), 2 Place Pierre Viala, F-34060 Montpellier Cedex 2, France

[4] IRD (Research and Development Institute), UMR-LISAH (Laboratory on Interactions between Soil, Agrosystem and Hydrosystem), 2 Place Pierre Viala, F-34060 Montpellier Cedex 2, France

[5] PT SMART Research Institute (SMARTRI), Jalan Teuku Umar 19, 28112 Pekanbaru, Riau, Indonesia

cultivation must be evaluated. The Roundtable for Sustainable Palm Oil (RSPO), an international organization involving all the stakeholders of palm oil production and utilization (producers, distributors, environmental, and social NGOs, etc.) was created in 2004 to develop and implement new practices for the production of sustainable palm oil (Tan et al. 2009). The RSPO has established sets of principles and criteria for sustainable management of oil palm plantations and mills. As discussed by Lord and Clay (2006), most activities related to oil palm plantation establishment and exploitation (e.g., forest clearing, construction of roads and drainage networks, agrochemical use, wastewater release) present a risk to surface and groundwater quality (ECD 2000; Goh et al. 2003).

Aquatic ecosystems close to plantations are particularly at risk for water quality impairment due to the relatively high rate of fertilizers applied in plantations (Sheil et al. 2009). Water runoff and drainage from newly established (young) palm plantations is controlled by the legume cover crop sown by planters. However, this understory progressively disappears as the canopy closes, leaving the soil with little vegetative cover to retain excess water and nutrient-rich sediments. In addition, the death and subsequent decomposition of the legume cover crop under a dense canopy of mature palms release nitrogen that was previously fixed through biological nitrogen fixation (Breure 2003; Campiglia et al. 2010; Goh et al. 2003). Goh and Chew (1995) confirmed that nitrate leaching losses from the legume cover crop were affected by soil texture and greater losses were recorded in sandier soils. The best practices of RSPO suggest that old fronds of mature palms cut during harvesting and pruning should be left on the ground for decomposition and nutrient recycling. This practice promotes water infiltration and limits surface water runoff. This is further enhanced by growing oil palm on coarse-textured soils and installing appropriate drainage systems. Therefore, subsurface flow is expected to be the dominant pathway for nutrient export from mature oil palm plantations as shallow groundwater was reported to be the major contributor to stream flow in coarse-textured soils of the humid tropics (Malmer 1996) where high soil infiltrability occurs (Banabas et al. 2008; Maena et al. 1979).

The scientific community mainly focused on assessing the impacts of oil palm expansion on deforestation, and the impact on biodiversity losses as well as greenhouse gas emissions due to fire clearing and peatland drainage for oil palm (Carlson et al. 2013; Koh et al. 2011). Relatively few studies have examined how fertilizers applied to oil palm agroecosystems may affect nutrient loading and water quality at the watershed scale (Ah Tung et al. 2009). During the 1970–1980s, some hydrological studies were carried out in oil palm plantations to investigate the percentage of applied fertilizers lost through leaching, but they were done at the field scale only, i.e., a few hectares (Chang and Zakaria 1986; Foong et al. 1983; Maena et al. 1979), whereas plantations managed by companies and farmer cooperatives often cover thousands of hectares. Consequently, there are many cases where oil palm is the major crop in the landscape. This requires large watershed-scale studies to assess the intrinsic variability in soils and nutrient management within plantations and their influence on nutrient loads and water quality. Among the few examples of watershed-scale studies carried out in oil palm agroecosystems was a study by Yusop et al. (2008), which quantified runoff processes on a small watershed of 8.2 ha, and a study by DID (1989) that assessed nutrient exports at the watershed scale (97 ha) after forest clearing and during the first year of oil palm cultivation. It is difficult to extrapolate from these studies to assess streamflow and nutrient fluxes from large-scale, mature oil palm plantations, accounting for spatial variability of soil and in the use of organic vs. mineral fertilizers. A study carried out in Borneo highlighted the negative impact of oil palm cultivation on temperature, oxygen, and sediments in river bodies (Carlson et al. 2014) but did not assess the impact of fertilizer applications on water quality. Gandaseca et al. (2014) studied the spatial and temporal variations of water quality in oil palm plantations and peat swamp forest in Sarawak, Malaysia. While they suspected that fertilizer applications were responsible for the high level of biological oxygen demand recorded in streams, no direct measurements were available to support their assertion. Comte et al. (2012) concluded that few studies provided an integrated view, at the watershed scale, of the agricultural practices and hydrological processes that contribute to nutrient losses from mature oil palm plantations and the consequences for surface and groundwater quality.

The first objective of this study was to characterize water quality in a large area (100 km^2) covered by oil palm plantations. Since water quality assessment under oil palm cultivation remains an under-investigated topic, 15 parameters were measured to obtain baseline data for water quality evaluation in 16 watersheds. Then, this study aimed to assess the effect of soil type and fertilizer management on groundwater chemistry and on nutrient fluxes at the watershed scale under baseflow conditions. To estimate nutrient fluxes, we use modeling method to reconstitute chronological sequences from punctual samplings and measurements.

Material and methods

Description of the study area

The study area was located in the province of Riau in Sumatra (Indonesia), within the Siak watershed (~11,500 km^2) (Fig. 1). This area has a tropical humid climate, with average annual rainfall of 2400 mm year^{-1} (2000–2010). The wet season runs from September to April, and a relatively dry season occurs

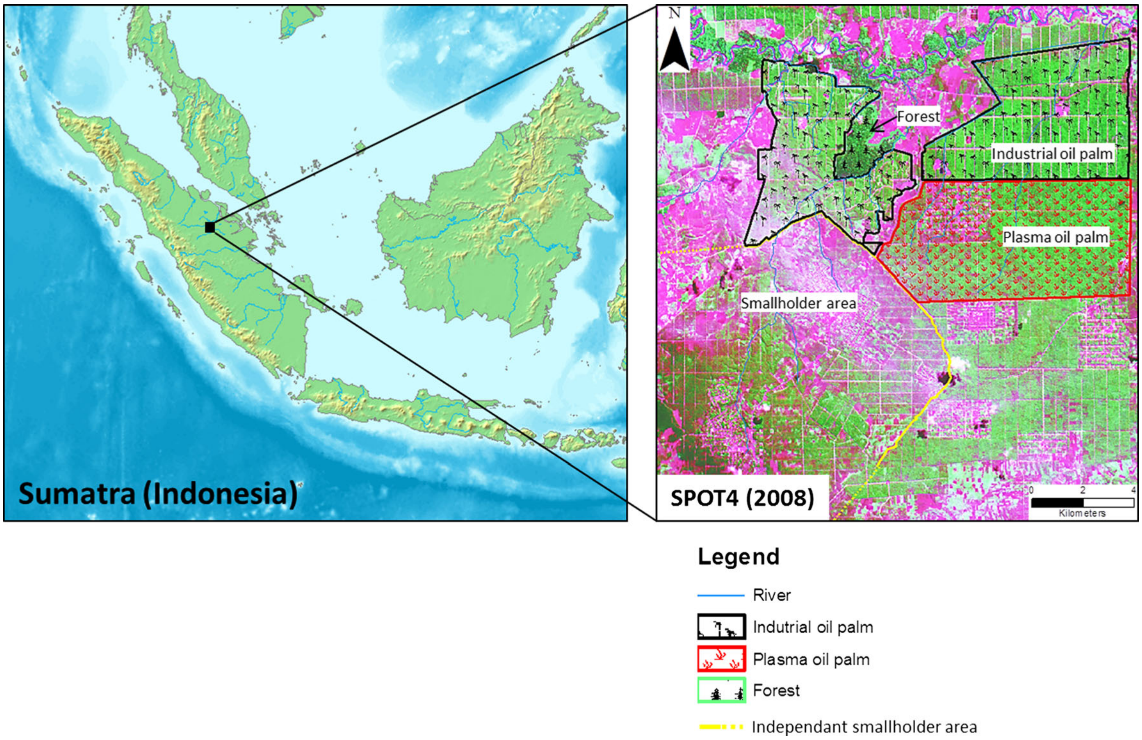

Fig. 1 Location of the study area in Riau province, Indonesia, and identification of land uses from satellite imagery (SPOT4/2008)

from May to August. The average monthly temperature is 26 to 32 °C.

Land use in the study area included a nucleus mature (15 years old) oil palm plantation (35.1 km^2) that will be referred to as "industrial" in the rest of the paper, a plasma mature (15 years old) oil palm plantation (19.6 km^2) referred to as the "plama" in the rest of the paper, independent smallholdings (mosaic of mainly smallholder oil palm plantations, but also rubber (*Hevea brasiliensis*) plantations, housing and garden, 55.2 km^2) that will be referred to as "smallholder" in the rest of the paper, and remaining land was covered by *Dipterocarp* forest (20.2 km^2) (Fig. 2a).

Soils are Ferralsols (FAO/ISRIC/ISSS 1998) that were developed on recent alluvium with peat deposits in small depressions (Blasco et al. 1986). Within the study area, three main soil types were identified: loamy-sand uplands, loamy lowlands, and marginally clayey floodplain with patches of peat in the topsoil (0–10 cm depth), referred to as "peat" soil (Fig. 2b). The physicochemical properties of these major soil types are given in Table 1.

The study area was characterized by high rainfall (R= 2600 mm year^{-1} during the year 2009–2010) and evapotranspiration exceeding 1000 mm year^{-1} (Table 2), which led to high flow according to the water budget equation. Annual water yields (AWY$_1$) were between 1473 and 1539 mm year^{-1} across the studied area.

Soils were coarse-textured and exhibited high infiltrabilities: 9 to 77 cm h^{-1} on loamy-sand uplands, 8 to 13 cm h^{-1} on loamy lowlands, and 24 to 57 cm h^{-1} on peat soils. The plantations under study are on relatively flat topography, with abundant ground cover, including frond piles, and are surrounded by drainage ditches, which limit water ponding at the soil surface and reduce overland flow. Moreover, high water table level (0–2 m below the soil surface) was observed throughout the monitoring period. These field conditions lead us to conclude that infiltration was the primary route for water flow and that stream flow was dominated by baseflow from shallow groundwater.

Throughout the paper, watershed identification codes are designated as follows: land management/soil type.number of watershed (e.g., P/U.1), where Io is the industrial with organic fertilization, Im is the Industrial with mineral fertilization, P is the plasma plantation, S is the independent smallholder plantation, M is the mixed (industrial and smallholder) plantations, U is the loamy-sand uplands, and L is the loamy lowlands. The numbers 1 to 3 represent numbered locations within each land management/soil type.

Fertilizer management and nutrient inputs

Organic fertilizers derived from mill wastes are generally recycled back to the fields in the industrial plantation as organic fertilizer, often on fields close to the mill due to transportation costs; other areas of industrial plantations receive mineral fertilizers, and smallholders rely exclusively on mineral fertilizers. Mineral fertilizers applied in plantations included urea, either rock phosphate (RP), triple super

Fig. 2 **a** Land use classes in the study area. **b** Soil types in the study area. **c** Watershed delineation and hydrochemical monitoring design

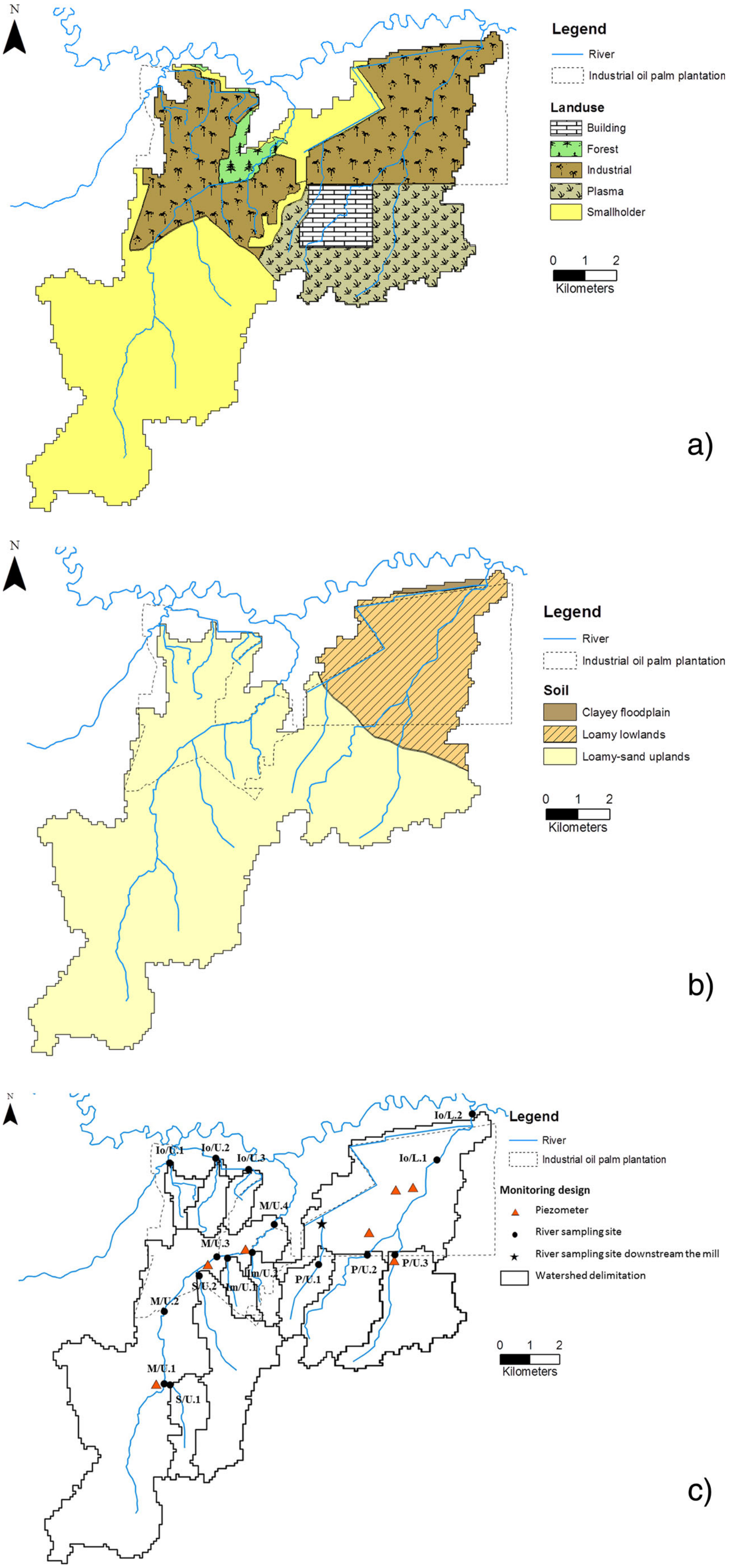

Table 1 Mean values of soil physicochemical properties (0–15 cm depth) from oil palm plantations studied in the Petapahan area, Sumatra, Indonesia

	Unit	Loamy lowlands (*n*=176)	Loamy-sand uplands (*n*=188)	Clayey floodplain (*n*=30)	Peat patch (*n*=21)
Infiltrability[a]	mm h^{-1}	80–130	90–770	6–10	245–565
Sand	g kg^{-1}	500	730	110	–
Silt	g kg^{-1}	340	160	370	–
Clay	g kg^{-1}	160	110	520	–
pH		4.22	4.24	3.74	3.99
OC	g kg^{-1}	61	35	62	145
Total N	g kg^{-1}	3	20	40	50
Total P	mg kg^{-1}	194	122	346	296
Total K	mg kg^{-1}	67	36	212	75
Bray-P	mg kg^{-1}	51	42	36	57
CEC	cmol$_c$kg^{-1}	15.50	8.53	24.80	35.45
Ca^{2+}	cmol$_c$kg^{-1}	0.88	0.45	2.02	1.99
Mg^{2+}	cmol$_c$kg^{-1}	0.59	0.24	0.81	1.63
Na^{+}	cmol$_c$kg^{-1}	0.05	0.05	0.08	0.07
BS	%	11.7	11.2	13.4	14.4
Exch H	cmol$_c$kg^{-1}	0.69	0.55	2.37	1.32
Exch Al	cmol$_c$kg^{-1}	2.74	1.68	10.63	5.48

OC organic carbon, *CEC* cation exchange capacity, *BS* base saturation, *Exch* exchangeable, *WC* water content

[a] *n*=2 for sandy loam lowlands; *n*=2 for sandy uplands; *n*=2 for clayey floodplain; *n*=3 for peat patch

phosphate (TSP), or diammonium phosphate (DAP) as phosphate fertilizers, muriate of potash (MOP) for potassium input, either kieserite or dolomite as magnesium fertilizers, and high-grade fertilizer borate (HGFB). A site-specific rational fertilizer program is implemented by the industrial oil palm plantations and aims to match nutrient inputs with oil palm nutrient demand based on annual leaf analysis at the field scale and results from field experiments (Caliman et al. 2003). The annual nutrient requirements are usually met with two split applications per year to maximize nutrient use efficiency. Given the large area of the industrial plantation, applications of mineral fertilizers are scheduled at a field scale throughout the year.

Table 2 Rainfall and evapotranspiration (mm) measured using two automatic stations (DAVIS) in the Petapahan area, Sumatra, Indonesia

	Station 1*	Station 2**	Average (mm)
Year 2009–2010			
Rainfall			
Annual	2615	2607	2611
Dry season (170 days)	711	777	744
Wet season (195 days)	1904	1830	1867
Reference evapotranspiration			
Annual	1076	1134	1105
Dry season	485	528	507
Wet season	591	606	599
Year 2010–2011			
Rainfall			
Annual	2280	2076	2178
Dry season (212 days)	1122	947	1035
Wet season (153 days)	1158	1129	1144
Reference evapotranspiration			
Annual	1134	1174	1154
Dry season	668	697	683
Wet season	466	477	472

*Coordinates (m E/m N) station 1: 727150/60580 (UTM 47N)

**Coordinates (m E/m N) station 2: 735490/61135 (UTM 47N)

In the industrial plantation, organic fertilizers, consisting of empty fruit bunches (EFBs) and palm oil mill effluent (POME), are regularly applied to dedicated fields close to the mill, due to transportation cost. This results in the field receiving EFB once every 2 years and POME is applied three times. The mill location is usually chosen close to a river (for water availability) on a site with suitable soil physical characteristics to support buildings. The soil fertility or susceptibility to nutrient losses of the nearby fields is generally not taken into account when deciding upon the mill location.

Plasma plantations receive mineral fertilizers only, based on recommendations provided by the industrial oil palm plantation. Additionally, frond pruning occurs year-round in both industrial and plasma oil palm plantations, resulting in frond piles around each palm, but this was considered to recycle nutrients rather than serve as a nutrient input. Unfortunately, no information on fertilization practices could be collected for the independent smallholdings, due to the large number of owners, the high variability of land use and fertilization practices, and inexistent land register.

Fertilizer applications between September 2009 and August 2011 were recorded for each field in the industrial and plasma plantations (field size is 30–40 ha with tree density of about 143 and 130 palms ha^{-1} for industrial and plasma plantations, respectively). The annual input of N, P, K, Mg, and Ca input per field were calculated, based on nutrient content of fertilizers (Table 3). Deposition of nutrients in rainfall was assumed to be uniform in the studied landscape and negligible relative to fertilizer inputs.

Nutrient inputs were generally greater in the industrial plantation than the plasma plantation, especially in fields that received organic fertilizer because EFB and POME tend to supply more N (135 kg N ha^{-1} year^{-1}), P (67 kg ha^{-1} year^{-1}), K (480 kg K ha^{-1} year^{-1}), and Mg (173 kg Mg ha^{-1} year^{-1}) than the average mineral fertilizer applications. The industrial watersheds Io/U.1 to Io/U.3 on loamy-sand uplands and the industrial part of the watersheds Io/L.1 and Io/L.2 on loamy lowlands received from 65 to 93 % of their nutrient input from organic fertilizer (Table 3).

Groundwater and watershed monitoring

Groundwater survey was done with seven piezometers (10 cm dia.) installed to a depth of 3 m, distributed across the study area to obtain representative information for the distinct land uses, soil types, and fertilizer management practiced in the study area (Fig. 2c). Groundwater sampling (September 1, 2010 to June 7, 2011) consisted of discrete water sampling for water quality analysis, plus water table measurements in the piezometers every 2 weeks.

Stream survey consisted of 16 sampling points distributed throughout the study area: 6 points located along the two mainstreams (Petapahan river and Ramalah river) as nested watersheds to represent replicated outlets of diverse land uses and 10 points located at the headwatershed outlets of land under a unique cultural system (five for the industrial, three for the plasma, and two for the smallholder oil palm plantations). In addition, a sampling point was located immediately downstream from the mill for water quality monitoring only (Fig. 2c). Description of the watershed characteristics for sampling points, including dominant land use, soil type, and fertilization practices are provided in Table 4.

Given the large number of sampling points in this landscape-scale study and financial constraints, no watershed could be gauged with an automatic station, so monitoring was carried out manually. For discharge monitoring, a rating curve was constructed from manual discharge measurements taken every 2 weeks from 1 September 2009 to 31 August 2010 using a current meter (Flo Mate 2000, COMETEC, Mandres-les-Roses, France) and hydraulic radius (Rh) calculation. Rh was calculated from manual water level measurements taken along the river section. The rating curves were

Table 3 Nutrient inputs in industrial and plasma oil palm plantations in the Petapahan area, Sumatra, Indonesia

Watersheds	Mineral fertilizers (kg ha^{-1} year^{-1})					Organic fertilizers (kg ha^{-1} year^{-1})					Total fertilizers (kg ha^{-1} year^{-1})				
	N	P	K	Mg	Ca	N	P	K	Mg	Ca[b]	N	P	K	Mg	Ca
Industrial plantation															
Dominant mineral applications															
Section M/U.2 to M/U.4[a]	49	19	13	19	13	4.9	1.4	18	1.5	0.6	54	20	31	20	14
Im/U.1	69	25	25	21	22	0	0	0	0	0	69	25	25	21	22
Im/U.2	83	28	24	25	15	0	0	0	0	0	83	28	24	25	15
Dominant organic applications															
Io/U.1	10	48	4.1	15	47	83	24	301	25	9.4	93	72	305	40	57
Io/U.2	30	38	7.0	12	28	86	25	310	26	9.7	116	63	317	37	38
Io/U.3	7.2	21	1.2	6.1	17	92	34	331	62	8.3	99	55	333	68	26
Io/L.1	56	21	23	13	21	96	54	339	154	3	151	75	362	167	24
Io/L.2	52	23	22	15	25	149	87	527	251	4	201	110	549	266	29
Section P/U.2 to Io/L.1[a]	100	39	39	26	41	212	116	751	321	7.8	312	154	790	348	49
Section P/U.2 to Io/L.2[a]	79	35	33	22	36	227	131	800	376	6.3	305	166	834	398	43
Plasma smallholder plantation															
P/U.1	40	18	21	12	19	0.0	0.0	0.0	0.0	0.0	40	18	21	12	19
P/U.2	48	17	24	7.9	15	0.0	0.0	0.0	0.0	0.0	48	17	24	8	15
P/U.3	76	27	40	13	25	0.0	0.0	0.0	0.0	0.0	76	27	40	13	25

[a] Sections concern the part of the watershed that is only under industrial oil palm plantation

[b] From empty fruit bunched applications only. No data on Ca content in palm oil mill effluent

Table 4 Watershed delineation and sampling points for water quality and discharge monitoring across a landscape dominated by oil palm plantations in the Petapahan area, Sumatra, Indonesia

Watershed	Outlet location (m E/m N)	Area (ha)	Mean slope (%)	Min.–max. elevation (m AMSL)	Dominant land use	Dominant fertilizer source	Dominant soil
Io/U.1	725808/61571	152	11.3	73–160	Industrial	Organic	LSU
Io/U.2	727759/61925	232	9	83–164	Industrial	Organic	LSU
Io/U.3	728889/61545	179	8.3	69–182	Industrial	Organic	LSU
Io/L.1	735304/61690	2505	4.4	82–174	Industrial	Organic	LL
Io/L.2	736659/63491	3801	5.4	41–174	Industrial	Organic	LL
Section P/U.2 to Io/L.1	735304/61690	928	5.2	82–142	Industrial	Organic	LL
Section P/U.2 to Io/L.2	736659/63491	1861	5.8	36–142	Industrial	Organic	LL
Im/U.1	729000/58710	185	8.8	91–173	Industrial	Mineral	LSU
Im/U.2	729360/ 58491	176	8.5	97–173	Industrial	Mineral	LSU
Section M/U.2 to M/U.4	729731/59573	1315	9.0	89–166	Industrial	Mineral	LSU
Mill[a]	731355/59592	563	8.3	91–174	Industrial	Mineral	LSU
M/U.1	726058/54335			114–198	Mixed	Mineral	LSU
M/U.2	726169/56992	3016	3.7	104–198	Mixed	Mineral	LSU
M/U.3	727740/58405	4136	4.3	95–198	Mixed	Mineral	LSU
M/U.4	729731/59573	4795	4.9	89–198	Mixed	Mineral	LSU
S/U.1	726061/54342	456	5.0	117–181	Smallholder	Mineral	LSU
S/U.2	727236/57812	1119	3.5	97–180	Smallholder	Mineral	LSU
P/U.1	731326/58589	310	8.4	104–174	Plasma	Mineral	LSU
P/U.2	732990/58602	726	3.6	92–174	Plasma	Mineral	LSU
P/U.3	734212/58613	851	4.4	89–171	Plasma	Mineral	LSU

Geographical attributes (watershed drainage area, slope and elevation) as well as the dominant land use, fertilizer source and soil type are provided

AMSL above mean sea level, *LSU* loamy-sand uplands, *LL* loamy lowlands

[a] Site immediately downstream the mill. Water quality monitoring only

made using 24 or more single measurements over the course of the year, including dry and wet seasons. The bi-monthly discharge Q was calculated from the rating curve and manual water level measurements at each sampling point, except for site RA2, which was monitored for water quality only. Discrete water sampling at each sampling point was also done every 2 weeks to ensure sufficient replication, while taking account of laboratory capacities and logistical constraints. Many hydrological studies are carried out with monthly sampling frequency (Hamaidi-Chergui et al. 2013; Mueller-Warrant et al. 2012; Raymond 2011), so bi-monthly sampling is considered to be a reasonable frequency given logistical constraints. Polyethylene bottles used for sampling were placed in an icebox for transport to the lab and stored at 4 °C until analysis.

Water sample analysis

Water pH and electrical conductivity (EC) were measured. The chemical oxygen demand (COD) was determined with the closed reflux, colorimetric method (SNI 06-6989.2-2004; APHA 1998). The total organic carbon (TOC) was analyzed using high-temperature combustion method (SNI 06-6989-28-2005; APHA 1998). As the apparatus was not available at the beginning of the work, the TOC concentrations for the year 2009–2010 were calculated from linear regressions between concentrations of COD and TOC (Dubber and Gray 2010) measured from August 2010 ($\mathrm{TOC}=1.53\times\mathrm{COD}-27.54$, $R^2=0.92$, $n=281$). The biological oxygen demand (BOD) (SNI 06-2875-1992; SNI 06-6989.14-2004) and dissolved oxygen were determined (SNI 06-6989.2-2004; APHA 1998). Total phosphorus (TP) was determined using flow injection analysis for orthophosphate (SNI M-52-1998-03; APHA 1998). The concentrations of the cations K^+, Mg^{2+}, Ca^{2+}, Fe^{2+}, and Mn^{2+} were determined using atomic absorption spectrometry (AAS) (SNI 1994). The NO_3-N and NO_2-N concentrations were determined using colorimetry (Yong and Singh 1980). Total alkalinity (TA) was analyzed using titration method expressed as equivalent concentration of $CaCO_3$ (Yong and Singh 1980; APHA 1992). The NH_4-N concentration was determined using Nessler reagent (SNI 06-2479-1991). Dissolved inorganic nitrogen (DIN) was the sum of NO_3-N, NO_2-N, and NH_4-N. Total dissolved solids (TDS) were determined at 105 °C after filtration (45 μm). In addition to water quality parameters, the SiO_2 concentration was analyzed (APHA (3120B modified) 2005), as an indicator of groundwater residence time.

Water baseflow estimation using a reservoir model

We chose a one-compartment reservoir model with a daily time step to estimate daily baseflow discharge since it is a robust and parsimonious method used by many authors (e.g., Birkel et al. 2014; Perrin et al. 2003). Input data were daily rainfall and evapotranspiration. During the study period, rainfall and evapotranspiration (ET) data were recorded using two automatic weather stations (DAVIS Instruments Corp., Hayward, California, USA) located in the industrial plantation (Table 2). Under the tropical humid climatic conditions occurring in the study area, actual ET was assumed to be equal to reference ET, because of the low likelihood of hydric stress (DID 1989; Henson 1999).

Initial condition was initial water storage $S(t=0)$, and the calibration parameters were the contributing zone Cz and the coefficient of groundwater drainage by the hydrographic network α (called drainage coefficient in the rest of the paper). The contributing zone represents the proportion of the watershed area that effectively contributes to the discharge at the outlet. It depends on the topography and on the presence of artificial drainage pathways (e.g., ditches). Cz was derived from field observations and α from manual calibration based on (i) the fitting of daily simulation with point observations (outside storm events) and (ii) the coherence of the α values between watersheds: Similar watersheds (soil, topography, and land uses) were given similar α values. Finally, daily baseflow water yields were summed to get annual baseflow water yield AWY_2.

For Io/U.2, Io/U.3, and Im/U.2, there was insufficient data to calibrate the model, so a regionalization approach was used to select relevant model parameters from another watershed (i.e., having similar size and pedoclimatic conditions) (Parajka et al. 2005). In addition, we verified that the reference watershed was appropriately chosen by examining the correlation between instantaneous discharge measurements from both watersheds on the same date. Io/U.2 and Io/U.3 model calibration used parameters from the Io/U.1 watershed ($r=0.85$ and $r=0.88$, respectively), while the model calibration of Im/U.2 was based on parameters from the S/U.1 watershed ($r=0.88$).

Estimation of baseflow nutrient fluxes in streams

The nutrient flux during a time interval results from the integration of the instantaneous nutrient concentrations weighted by the instantaneous discharges during the same time interval. In this study, we considered the daily time interval to be sufficiently short that the instantaneous measured nutrient concentration was considered constant during each day (Raymond 2011). Daily nutrient concentrations for days when no samples were taken (periods of approximately 13 days) were estimated using the average of values for the previous and subsequent measurement days.

Then, the annual baseflow export for a given watershed was calculated by summing daily fluxes for the study period (1 year). Annual baseflow nutrient export fluxes were calculated for all watersheds (excluding the downstream mill site), and the total fluxes (kg year^{-1}) for sections M/U.2 to M/U.4, P/U.2 to Io/L.1, and P/U.2 to Io/L.2 were calculated by deducting total flux(es) at the inlet(s) from the total flux at the outlet. Then, to compare fluxes between watersheds, specific fluxes (kg ha^{-1} year^{-1}) were calculated, dividing total flux by the watershed area.

Although nutrient exports in stormflow conditions were not considered in this study, we assumed that they would not affect the relative ranking of watersheds with respect to nutrient exports. This assumption is valid because the high soil hydraulic conductivities and the high rainfall redistributions by vegetation promote infiltration instead of overland flow. Then, during a storm event, ancillary measurement of discharge and electrical conductivity, using CTD diver (Schlumberger Water Services) exhibit a dilution of EC by a factor of 4 (Fig. 3). This shows that solute concentrations in stream flow are lower during storm events than in periods dominated by baseflow. Finally, baseflow water yields deduced from the hydrological model, AWY_2, ranged from 1492 to 1563 mm year^{-1}, within 3 % of the total water yields calculated using an annual water budget, AWY_1=rainfall−ET (Table 5). This result confirms that baseflow is the main component of the annual stream flow.

Finally, mean annual pH, EC values, and other water quality parameter concentrations were calculated for each sampling point. Then, stream water quality was assessed by comparing mean annual values from the study area to Indonesian water quality standards (class II) (GR 82/2001). Comparisons between the watersheds were performed on the basis of annual fluxes and annual specific fluxes calculated for each outlet.

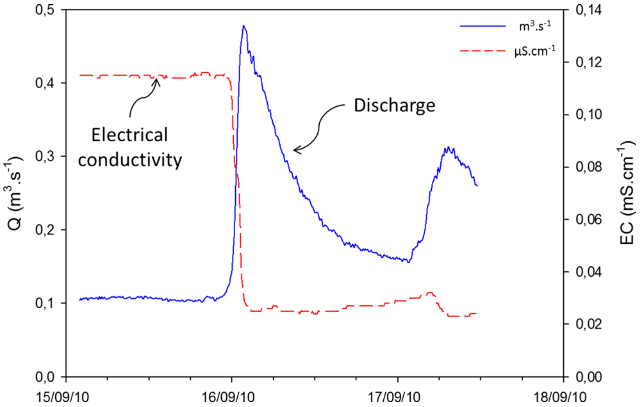

Fig. 3 Ancillary measurement of discharge (Q in m^3 s^{-1}) and electrical conductivity (EC in µS cm^{-1}) during a storm event on September 16–18, 2010 in an industrial oil palm plantation in the Petapahan area, Sumatra, Indonesia

Table 5 Parameterization of the hydrological reservoir model used in the study and water yields for the hydrological year 2009–2010 in the Petapahan area, Sumatra, Indonesia

Watershed	Modelling			Water yields			Difference between AWY_1 and AWY_2
	Initial conditions	Calibration parameters		Annual AWY_2	AWY_2/R	Wet AWY_2/Annual AWY_2	
	$S(t=0)$[a] (mm)	α (day^{-1})	Cz	mm year^{-1}	%	%	%
Io/U.1	53	0.060	0.50	1563	60	83	−1.6
Io/U.2	53	0.060	0.50	1563	60	82	−1.6
Io/U.3	53	0.060	0.50	1563	60	82	−1.6
M/U.1	69	0.055	1.00	1530	59	82	0.6
M/U.2	71	0.055	1.00	1532	60	82	0.5
M/U.3	77	0.050	0.90	1544	60	82	−0.3
M/U.4	73	0.055	1.00	1546	60	82	−0.4
S/U.1	56	0.080	1.50	1549	60	83	−0.7
S/U.2	79	0.040	1.00	1533	60	82	0.4
Im/U.1	15	0.060	0.80	1492	58	85	3.0
Im/U.2	56	0.080	1.50	1549	58	82	−0.6
P/U.1	53	0.080	0.80	1501	58	80	−1.9
P/U.2	53	0.080	1.00	1501	58	80	−1.9
P/U.3	53	0.080	0.70	1502	58	80	−1.9
Io/L.1	46	0.100	0.90	1509	58	80	−2.5
Io/L.2	72	0.050	0.80	1488	57	80	−1.0

AWY_1 annual water yields deduced from water budget, AWY_2 simulated annual water yields, R Annual rainfall (mm year^{-1}), *Wet* AWY_2 simulated water yields during the wet season using reservoir model (mm year^{-1}), S water storage, α drainage coefficient, Cz contributing zone

[a] $t=0$ is Sept 1, 2009

Comparison of water quality and water table levels between piezometers was done statistically for each parameter, using the non-parametric Kruskal-Wallis test due to non-normal data and non-homogeneity of the variances. Statistical tests were performed using R freeware (R Development Core Team 2011).

Results

Stream water quality and nutrient fluxes across the landscape

Water quality

Since water quality assessment under oil palm cultivation remains an under-investigated topic, all measured parameters are presented to demonstrate the global water quality in a large area (150 km^2) dominated by oil palm plantations. In the landscape (excluding sampling sites located downstream the mill), stream water was generally acidic with pH between 4.42 and 5.41. Low EC and TA were measured: 12.8 to 22.7 μS cm^{-1} and 4.28 to 7.53 mg L^{-1}, respectively. Low nutrient concentrations were recorded, with mean annual concentrations across the study region between 0.13 and 1.01 mg DIN L^{-1}, 0.01 and 0.07 mg TP L^{-1}, 0.35 and 2.46 mg K L^{-1}, 0.16 and 0.28 mg Mg L^{-1}, and 0.56 and 1.09 mg Ca L^{-1}, respectively. However, the rivers had high organic matter content, between 13.9 and 18.6 mg TOC L^{-1} (Table 6a, b).

Higher DIN concentrations were recorded in watersheds dominated by industrial plantations than those dominated by smallholder and plasma plantations. In general, higher TOC and K concentrations were measured in watersheds receiving organic fertilizers than mineral fertilizer. Water quality parameters recorded immediately downstream from the mill gave the highest values recorded in this study: fourfold higher EC, 10 times more K, 5 times more Mg, a sixfold increase in Ca, about 35 % greater DIN and 13 % more TDS, and 5 times more TA, compared to the landscape average (sites downstream from the mill). Further downstream at point Io/L.2, the EC, K, Mg, and Ca values were intermediate between the mill sampling site and the landscape average, but all other water quality parameters were similar to the landscape average.

Nutrient fluxes in streams

The DIN fluxes were between 1.88 and 9.17 kg ha^{-1} year^{-1}; fluxes of NO_3-N were between 1.53 and 8.24 kg ha^{-1} year^{-1},

Table 6 Mean annual values of water quality parameters for each sampling site in the Petapahan area, Sumatra, Indonesia

A

Site	Dominant management	Dominant fertilizer type	Dominant soil class	pH	EC	BOD$_5$	COD	DO	TOC	TDS	TA	*n*
					μS cm^{-1}	mg O$_2$ L^{-1}			mg L^{-1}			
Io/U.1	Industrial	Organic	LSU	5.01	18.78	5.78	29.82	7.19	17.77	47.39	6.53	(*n*=27)
Io/U.2	Industrial	Organic	LSU	4.86	21.41	5.82	30.19	6.96	18.31	38.78	6.37	(*n*=27)
Io/U.3	Industrial	Organic	LSU	4.76	22.74	6.04	30.52	7.22	18.63	41.96	6.09	(*n*=27)
Io/L.1	Industrial	Organic	LL	5.20	21.37	5.46	28.73	7.02	16.31	38.29	7.53	(*n*=26)
Io/L.2[a]	Industrial	Organic	LL	5.45	32.08	6.10	30.01	7.27	18.10	35.85	9.95	(*n*=21)
M/U.1	Mixed	Mineral	LSU	5.41	16.44	5.74	28.93	7.00	16.72	45.41	6.03	(*n*=27)
M/U.2	Mixed	Mineral	LSU	5.05	15.76	5.39	28.56	7.00	15.93	47.48	5.89	(*n*=27)
M/U.3	Mixed	Mineral	LSU	5.01	15.84	5.66	28.74	7.06	16.35	52.48	5.95	(*n*=25)
M/U.4	Mixed	Mineral	LSU	4.93	16.13	5.81	28.99	7.07	16.67	41.97	5.83	(*n*=28)
Im/U.1	Industrial	Mineral	LSU	4.55	16.44	5.89	27.67	7.00	14.28	36.78	4.80	(*n*=18)
Im/U.2	Industrial	Mineral	LSU	4.42	22.56	6.44	29.39	7.39	17.30	35.72	4.28	(*n*=18)
S/U.1	Smallholder	Mineral	LSU	4.81	12.82	4.86	27.07	6.50	13.94	44.29	5.53	(*n*=28)
S/U.2	Smallholder	Mineral	LSU	5.17	15.21	5.38	28.33	6.88	15.41	47.75	6.27	(*n*=24)
P/U.1	Plasma	Mineral	LSU	4.60	19.26	4.65	27.96	6.85	15.30	34.96	5.96	(*n*=26)
P/U.2	Plasma	Mineral	LSU	4.88	17.52	4.60	27.42	6.64	14.09	38.15	6.84	(*n*=26)
P/U.3	Plasma	Mineral	LSU	4.97	19.21	4.96	27.86	6.58	14.47	38.92	6.48	(*n*=28)
Mill[a]	Industrial	Mineral	LSU	5.79	91.23	6.42	31.19	7.27	21.36	47.50	34.05	(*n*=26)
Water quality standards												
WHO standards for drinking water				–	–	–	–	–	–	<600	–	
Class I[b]				6–9	–	<2	<10	>6	–	<1000	–	
Class II[b]				6–9	–	<3	<25	>4	–	<1000	–	
Class III[b]				6–9	–	<6	<50	>3	–	<1000	–	

B

Site	Dominant management	Dominant fertilizer type	Dominant soil class	DIN	NO$_3$-N	NO$_2$-N	NH$_4$-N	TP	K	Mg	Ca	*n*
				mg L^{-1}								
Io/U.1	Industrial	Organic	LSU	0.54	0.47	0.01	0.06	0.01	1.05	0.25	0.72	(*n*=27)
Io/U.2	Industrial	Organic	LSU	1.01	0.96	0.01	0.04	0.01	1.16	0.25	0.75	(*n*=27)
Io/U.3	Industrial	Organic	LSU	0.61	0.58	0.01	0.02	0.03	2.46	0.27	0.66	(*n*=27)
Io/L.1	Industrial	Organic	LL	0.30	0.19	0.02	0.10	0.01	1.30	0.28	1.09	(*n*=26)
Io/L.2[a]	Industrial	Organic	LL	0.34	0.22	0.02	0.10	0.02	2.85	0.52	1.57	(*n*=21)
M/U.1	Mixed	Mineral	LSU	0.23	0.19	0.01	0.03	0.03	0.69	0.21	0.93	(*n*=27)
M/U.2	Mixed	Mineral	LSU	0.28	0.25	0.01	0.02	0.05	0.53	0.20	0.71	(*n*=27)
M/U.3	Mixed	Mineral	LSU	0.26	0.23	0.01	0.02	0.06	0.64	0.21	0.76	(*n*=25)
M/U.4	Mixed	Mineral	LSU	0.28	0.25	0.01	0.03	0.03	0.76	0.20	0.69	(*n*=28)
Im/U.1	Industrial	Mineral	LSU	0.33	0.30	0.01	0.02	0.04	0.68	0.19	0.56	(*n*=18)
Im/U.2	Industrial	Mineral	LSU	0.45	0.43	0.01	0.02	0.02	0.56	0.27	0.63	(*n*=18)
S/U.1	Smallholder	Mineral	LSU	0.13	0.11	0.01	0.02	0.05	0.35	0.16	0.58	(*n*=28)
S/U.2	Smallholder	Mineral	LSU	0.19	0.15	0.01	0.04	0.07	0.61	0.18	0.80	(*n*=24)
P/U.1	Plasma	Mineral	LSU	0.15	0.13	0.01	0.02	0.01	0.36	0.20	0.74	(*n*=26)
P/U.2	Plasma	Mineral	LSU	0.17	0.13	0.01	0.03	0.01	0.43	0.20	0.88	(*n*=26)
P/U.3	Plasma	Mineral	LSU	0.17	0.14	0.01	0.01	0.01	0.48	0.23	1.04	(*n*=28)
Mill[a]	Industrial	Mineral	LSU	0.46	0.09	0.01	0.36	0.16	9.22	1.37	5.48	(*n*=26)
Water quality standards												
WHO standards for drinking water				–	<11	<0.09	–	–	–	–	–	
Class I[b]				–	<10	<0.06	–	<0.2 (PO$_4$)	–	–	–	

Table 6 (continued)

Class II[b]	–	<10	<0.06	–	<0.2 (PO_4)	–	–	–
Class III[b]	–	<20	<0.06	–	<1 (PO_4)	–	–	–

LSU loamy-sand uplands, *LL* loamy lowlands, *EC* electrical conductivity, *BOD* biological oxygen demand, *COD* chemical oxygen demand, *DO* dissolved oxygen, *TDS* total dissolved solids, *TA* total alkalinity, *TOC* total organic C, *DIN* dissolved inorganic N, *TP* total P

World Health Organization (WHO, 2011)

[a] Sampling site located downstream the oil palm mill

[b] Indonesian water quality standards. *Class I* drinking water or any other use with similar requirements; *Class II* service water recreational, gardening, or any other use with similar requirements; *Class III* fresh water agricultural, farming, and any other use with similar requirements

and TP fluxes were between 0.05 and 1.16 kg ha^{-1} year^{-1}. Fluxes of the major cations were from 5.4 to 37.9 kg K ha^{-1} year^{-1}, 2.0–5.4 kg Mg ha^{-1} year^{-1}, and 4.5–29.9 kg Ca ha^{-1} year^{-1}.

Annual specific fluxes of nutrients from watersheds dominated by industrial plantations (Io/U.1 to Io/U.3, Im/U.1, and Im/U.2) did not exceed the annual specific fluxes from smallholder watersheds (S/U.1 and S/U.2). Lower fluxes of TP, K, Ca, and NH_4-N were recorded in the industrial headwatersheds compared to the smallholder watersheds. Generally, lower fluxes were recorded in headwatersheds under plasma oil palm cultivation (P/U.1, P/U.2, and P/U.3) on loamy-sand uplands than industrial watersheds on loamy-sand uplands receiving mineral fertilizers (except for Ca and NO_2-N fluxes). Higher fluxes of TOC, K, Mg, Ca, and DIN were recorded in P/U.2 headwatershed, which had a larger area with housing (278 ha) than the other two plasma watersheds (P/U.1 and P/U.3) (Table 7).

Influence of the soil and fertilizer management on water chemistry and nutrient transfers

Influence at the local scale: groundwater hydrochemistry

The lowest annual mean pH was recorded in the piezometer located in peatsoil (pH=4.15). Higher annual mean pH was recorded in piezometers located in the loamy-sand uplands: pH=5.79 under native forest and pH=5.96 under unfertilized rubber plantation. In the loamy-sand uplands under mineral-fertilized oil palm, pH was 5.39, significantly higher ($p<0.05$) than other piezometers in loamy-sand uplands. Intermediate pH values (between peatsoil and loamy-sand uplands) were recorded in piezometers located in loamy lowlands: pH was 4.54 under mineral fertilizer applications, 5.08 under EFB applications, and 5.33 under POME applications. The pH values were significantly ($p<0.05$) different between each piezometer located in loamy lowlands. We observed that pH was negatively correlated with EC when pH<5 ($r=-0.79$, $n=20$) and positively correlated to EC when pH>5 ($r=0.82$, $n=41$) (Fig. 4a).

There was no difference in TP concentrations between piezometers. Higher DIN concentrations ($p<0.05$) were recorded in the piezometer under forest (annual mean: 3.19 mg DIN L^{-1}) than in all piezometer location in oil palm plantations (0.71 to 1.02 mg DIN L^{-1}). Among oil palm plantations, the lowest DIN concentrations were recorded under organic fertilizer applications in loamy lowlands (0.71 to 0.77 mg DIN L^{-1}). Similar DIN concentrations were observed under mineral-fertilized oil palm on loamy lowlands and loamy-sand uplands (1.02 and 1.00 mg DIN L^{-1}, respectively). The DIN concentration was lower ($p<0.05$) in loamy lowlands receiving EFB than in loamy lowlands receiving mineral fertilizers (Fig. 4b).

The piezometer in the POME-amended field had a higher K concentration (9.24 mg K L^{-1}) ($p<0.05$), than other piezometers (1.55 to 3.49 mg K L^{-1}). On loamy-sand uplands, lower K and Mg concentrations ($p<0.05$) were recorded under mineral-fertilized oil palm (1.86 and 0.73 mg L^{-1}, respectively) than forest (3.02 and 1.43 mg L^{-1}, respectively) and unfertilized rubber plantation (2.27 and 0.67 mg L^{-1}, respectively). Higher Mg concentrations ($p<0.05$) were recorded under natural forest (1.43 mg Mg L^{-1}) than most other piezometers, except the piezometer under POME application (0.88 mg L^{-1}). Lowest Mg concentrations ($p<0.05$) were recorded in the piezometer under EFB applications (0.43 mg L^{-1}) and in the piezometer located on peat, compared to other piezometers (Fig. 4c).

Influence at the watershed scale: nutrient inputs and nutrient fluxes

Nutrient inputs and fluxes were plotted for N, P, K, and Mg to assess the effect of soil type, fertilizer source (i.e., mineral vs. organic), and fertilizer application rate on nutrient fluxes (Fig. 5). Three groups clearly appeared: the organic fertilized watersheds on loamy lowlands (Io/L.1 and Io/L.2), the organic fertilized watersheds on loamy-sand uplands (Io/U.1, Io/U.2, and Io/U.3), and the mineral-fertilized watersheds on loamy-sand uplands (Im/U.1, Im/U.2, and section M/U.2 to M/U.4).

Higher nutrient inputs did not trigger higher nutrient fluxes of DIN and TP. Although inputs of N and P were much higher in organic fertilized watersheds on loamy lowlands (up to 200 kg N ha^{-1} year^{-1} and up to 100 kg P ha^{-1} year^{-1}),

Table 7 Specific fluxes of total organic carbon and nutrients during baseflow conditions in the Petapahan area, Sumatra, Indonesia

Site	Dominant management	Dominant fertilizer type	Dominant soil class	TOC	TP	K	Mg	Ca	DIN	NO_3-N	NO_2-N	NH_4-N
				kg ha^{-1} year^{-1}								
Io/U.1	Industrial	Organic	LSU	148	0.12	10.79	2.27	6.16	5.70	5.12	0.12	0.47
Io/U.2	Industrial	Organic	LSU	153	0.09	9.28	2.03	5.55	7.64	7.29	0.07	0.28
Io/U.3	Industrial	Organic	LSU	150	0.26	18.01	2.03	4.48	4.74	4.54	0.06	0.15
Io/L.1	Industrial	Organic	LL	208	0.09	19.32	3.72	13.50	4.06	2.64	0.72	0.71
P/U.2–Io/L.1	Industrial	Organic	LL	200	0.05	28.49	4.21	14.18	5.20	3.04	1.14	1.03
Io/L.2[a]	Industrial	Organic	LL	194	0.15	28.90	5.14	14.81	3.40	2.32	0.10	0.98
P/U.2–Io/L.2[a]	Industrial	Organic	LL	150	0.11	37.86	5.40	12.92	3.40	2.05	0.04	1.28
M/U.1	Mixed	Mineral	LSU	329	0.71	15.79	4.61	18.51	6.42	5.75	0.14	0.53
M/U.2	Mixed	Mineral	LSU	273	0.75	12.55	3.96	14.98	5.12	4.67	0.11	0.39
M/U.3	Mixed	Mineral	LSU	214	0.72	7.96	2.81	29.95	8.87	8.24	0.20	0.42
M/U.4	Mixed	Mineral	LSU	266	0.57	11.85	3.65	12.46	5.74	5.05	0.19	0.52
M/U.2–M/U.4	Industrial	Mineral	LSU	343	0.36	14.42	4.23	11.07	9.17	7.69	0.43	1.00
Im/U.2	Industrial	Mineral	LSU	263	0.22	8.60	4.47	10.06	7.77	7.40	0.09	0.29
Im/U.1	Industrial	Mineral	LSU	188	0.57	8.40	2.73	8.94	3.29	3.02	0.14	0.22
S/U.1	Smallholder	Mineral	LSU	338	0.54	8.84	4.25	14.67	4.02	3.56	0.14	0.32
S/U.2	Smallholder	Mineral	LSU	231	1.16	8.57	3.09	12.15	3.73	3.09	0.21	0.43
P/U.1	Plasma	Mineral	LSU	186	0.15	5.36	2.63	9.67	1.88	1.53	0.11	0.27
P/U.2	Plasma	Mineral	LSU	235	0.14	7.21	3.22	13.82	2.76	2.33	0.17	0.28
P/U.3	Plasma	Mineral	LSU	156	0.16	5.80	3.03	12.49	1.98	1.72	0.18	0.14

LSU loamy-sand uplands, *LL* loamy lowlands, *TOC* total organic C, *TP* total P, *DIN* dissolved inorganic N

[a] Sampling site located downstream the oil palm mill

recorded fluxes of 3 to 5 kg N ha^{-1} year^{-1} and 0.05 to 0.15 kg P ha^{-1} year^{-1} did not exceed fluxes from the other watersheds (3 to 8 kg N ha^{-1} year^{-1} and 0.09 to 0.57 kg P ha^{-1} year^{-1}) that received lower inputs (<120 kg N ha^{-1} year^{-1}). Nonetheless, fertilizer management appeared to be important on loamy-sand uplands where organic fertilized watersheds had lower DIN and TP fluxes despite higher fertilizer application rates than mineral-fertilized watersheds (Fig. 5a, b).

The effect of fertilizer management seemed more important for K (compared to N and P) since K fluxes to streams increased with fertilizer K inputs. Indeed, organic fertilized watersheds on loamy lowlands received the highest inputs (up to 400 kg K ha^{-1} year^{-1}) and exported up to 19 kg K ha^{-1} year^{-1}, more than all other watersheds. On the loamy-sand uplands, watersheds receiving organic fertilizers also received higher K inputs (up to 300 kg K ha^{-1} year^{-1}) and exported higher K fluxes than those receiving mineral fertilizer (Fig. 5c).

Regarding Mg, both the fertilizer management (source and amount) and the soil type affected the exported Mg fluxes. Organic fertilized watersheds on loamy lowlands received highest inputs and exported higher Mg fluxes than organic fertilized watersheds on loamy-sand uplands. Also, within the loamy-sand upland soil type, organic fertilized watersheds exported lower Mg fluxes than mineral-fertilized watersheds despite higher Mg application rates. It is notable that mineral-fertilized watersheds exported more Mg per unit of Mg applied than the organic fertilized watersheds (Fig. 5d).

Discussion

Low concentrations and low fluxes exported in the landscape

The water quality throughout the studied landscape was characterized by an acidic pH, low EC, and low nutrient concentrations. Values in this study were within the range of water quality parameters reported for forested tropical watersheds (DID 1989; Gasim et al. 2006; Yusop et al. 2006; Duncan and Fernandes 2010). The annual average nutrient concentrations recorded in streams did not exceed water quality standards established by Indonesian water quality standards (class I) (GR 82/2001). However, the values of some biological parameters (COD, BOD) were higher than recommended quality standards (class II). Although organic fertilization may have contributed to the COD and BOD values, which should be further investigated, natural sources of organic matter are likely important in the study area. In black rivers of Central Sumatra, Alkhatib et al. (2007) recorded 60 mg DOC L^{-1} in Dumai river, while Baum et al. (2007) reported 23 to 43 mg

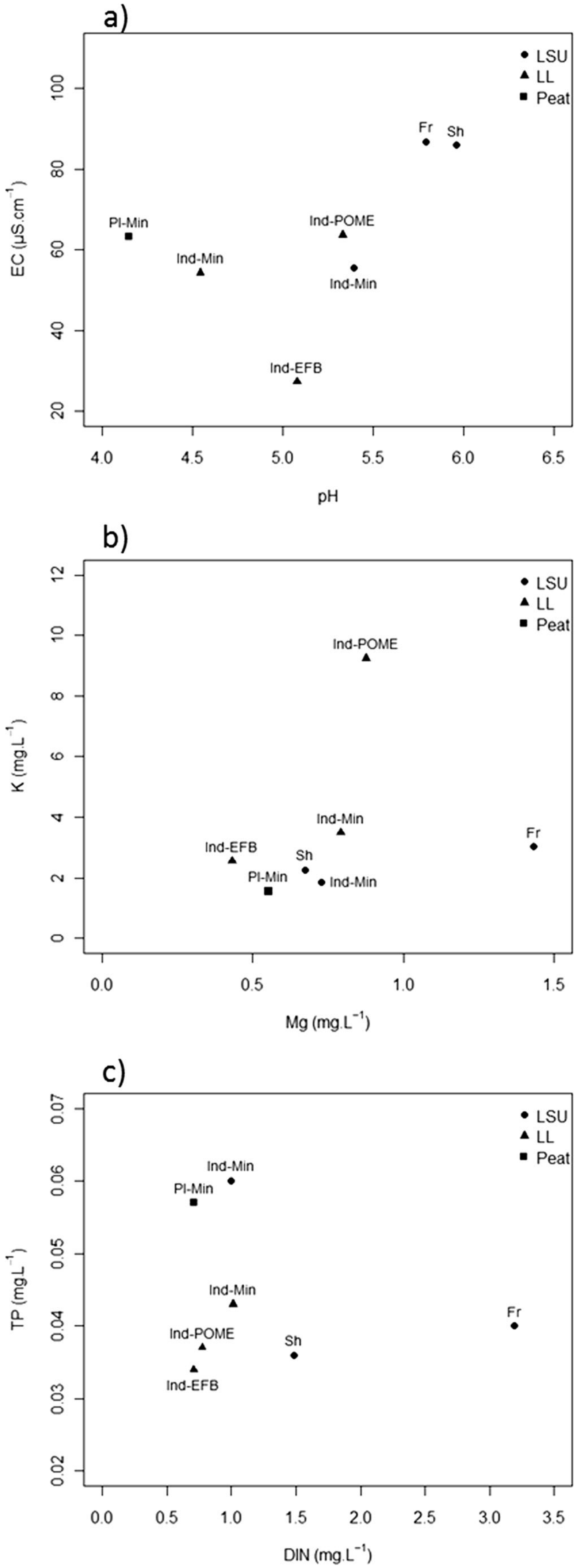

Fig. 4 Annual mean values of water quality parameters measured in groundwater in the Petapahan area, Sumatra, Indonesia. **a** pH vs. electrical conductivity (EC). **b** dissolved inorganic nitrogen (DIN) vs. total phosphorus (TP). **c** Mg vs. K. *LSU* loamy-sand uplands; *LL* loamy lowlands; *Ind-POME* piezometer located in the industrial oil palm plantation, under palm oil mill effluent applications; *Ind-Min* piezometer located in the industrial oil palm plantation, under mineral fertilizer applications; *Ind-EFB* piezometer located in the industrial oil palm plantation, under empty fruit bunch applications; *Pl-Min* piezometer located in the plasma oil palm plantation, under mineral fertilizer applications; *Sh* piezometer located in the independent smallholder area (unfertilized rubber plantation); *Fr* forest (unfertilized)

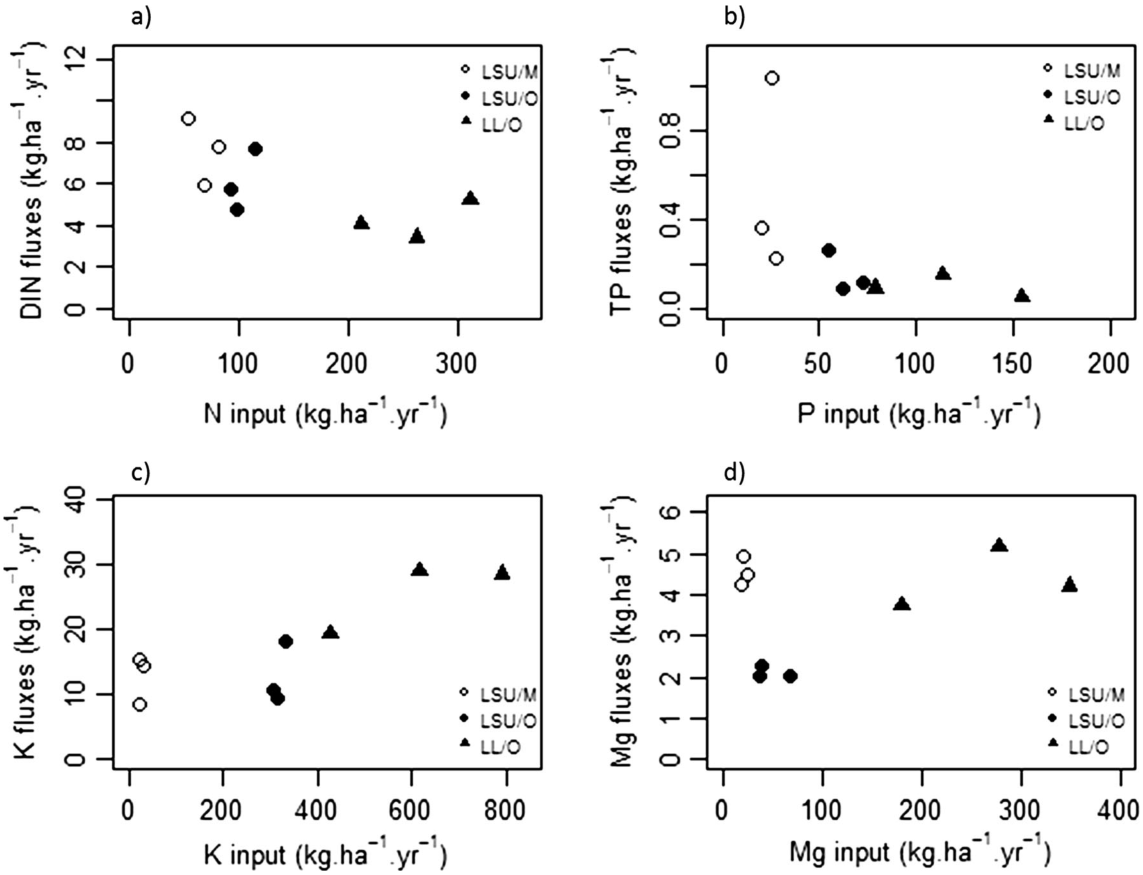

Fig. 5 Nutrient inputs from fertilizers and nutrient fluxes exported to streams during baseflow conditions in industrial oil palm plantation watersheds. **a** N inputs vs. dissolved inorganic N (DIN) fluxes exported; **b** P inputs vs. total P (TP) fluxes exported; **c** K inputs vs. K fluxes exported; **d** Mg inputs vs. Mg fluxes exported. *LSU/M* mineral-fertilized watersheds located on loamy-sand uplands, *LSU/O* organic fertilized (empty fruit bunch only) watersheds located on loamy-sand uplands, *LL/O* organic fertilized watersheds (mainly palm oil mill effluent) located on loamy lowlands

DOC L^{-1} in peat draining Mandau river (tributary of the Siak river), which exceeds the values measured in this study. Peat soil patches within the study area, and the presence of a black river flowing close to the studied watersheds, point to natural sources of organic matter as contributors to the COD and BOD levels in our streams.

Highest pH, EC, nutrient, and dissolved organic matter concentrations ($p<0.05$) were recorded at the site immediately downstream the mill. However, the mill impact on stream water quality was no different at the plantation outlet (Io/L.2) than the overall study area at a landscape level, which suggests considerable in-stream dilution of nutrients downstream from the mill.

Dilution of subsurface drainage water was not the only factor explaining the low nutrient concentrations observed in the streams. The Ferralsols present in the study area had low inherent fertility and low export fluxes, in contrast to higher export fluxes that were reported on richer soils such as volcanic or limestone soil, even under rainforest (Bruijnzeel 1983; Crowther 1987a, b). However, despite high fertilizer application rates, nutrient fluxes were within the range of those reported from forested watersheds on low fertility soils (Ultisols, Oxisols) (Abdul Rahim and Yusop 1987; Malmer 1996; Brinkmann 1985) (Table 8). We concluded that mature oil palm was an effective nutrient sink for applied fertilizer, which limited nutrient fluxes to streams.

Fluxes recorded at the industrial plantation outlet in M/U.4 did not exceed inflows in M/U.2. That suggested a low impact of the industrial plantation on fluxes in streams. However, in this case, the plantation area was small compared to the watershed area (27 %), so the impact may have been obscured. When comparing loamy-sand upland headwatersheds under mineral fertilizer application (Im/U.1 and Im/U.2) to smallholder headwatersheds (S/U.1 and S/U.2) also on loamy-sand uplands, lower exports were recorded from industrial plantation than the smallholder plantation. Unfortunately, we did not get fertilizer application data from the smallholder area, but it is also possible that housing in the smallholder area could increase nutrient fluxes through household livestock and domestic wastes. Indeed, higher fluxes of TOC, K, Mg, Ca, and DIN were recorded in

Table 8 Nutrient fluxes exported to waterways reported in studies carried out in the tropics (including natural forest and oil palm plantations)

	TP	K	Mg	Ca	TN	NO_3-N	NO_2-N	NH_4-N	Source
	kg ha^{-1} year^{-1}								
Tropical Rainforest									
Montane moist evergreen forest, Costa Rica	1.3	17.0	8.7	33.9	4.4	0.23		0.34	Liu et al. 2003
Disturbed rainforest, Amapa, Brazil		4.7	7.5	22.1		0.71		0.18	Forti et al. 2000
Rainforest, volcanic soils		14.9	51	24.8					Turvey 1974 Bruijnzeel 1991
Rainforest, limestone soil				764–795					Crowther 1987a, b
Close tropical rainforest, Guyana, plot scale		5	1	2	4	3		1	Brouwer and Riezebos 1998
Rainforest Amazon, Latosols	0.3		0.5	0.9	29	3.25	0.11	3.7	Brinkmann 1985
Intact forest, Coast Rica, fertile clayey ultisol, plot scale		3.6	8.2	5.5	17.3				Parker 1985
Hill dipterocoarp forest, gleyicpodsol and haplicacrisol	0.65	30.5	5.8	10.1	6.2				Malmer 1996
Tropical cloud forest, Costa Rica						4–6			Brookshire et al. 2012
Oil palm plantation, plot-scale studies									
Unfertilized adult oil palm (22 years), volcanic soil, Nigeria		29	32	123	65				Omoti et al. 1983
Unfertilized young oil palm (4 years), volcanic soil, Nigeria		3	32	165	32				Omoti et al. 1983

TP total phosphorus, *TN* total nitrogen

plasma watershed P/U.2 (including the larger housing area) despite lower agricultural inputs compared to P/U.1 and P/U.3. However, lower fluxes were recorded in the plasma watersheds compared to the smallholder watersheds. This suggested that rational and site-specific fertilizer management practiced in the industrial and plasma plantations helped to reduce nutrient fluxes to streams. Nutrient fluxes recorded in plasma watersheds (on loamy-sand uplands) were also lower than fluxes recorded in mineral-fertilized industrial headwatersheds on the same soil type, which was ascribed to higher nutrient application rates in the industrial watersheds than in the plasma area.

Soil type and fertilizer management influenced groundwater chemistry and nutrient fluxes

Soil type mainly influenced groundwater chemistry, based on the difference in pH and EC values of groundwater related to the soil types where the piezometers were installed. First, a gradation of pH values were observed as follows: piezometer located in peatsoil<piezometers located in loamy lowlands< piezometers located in loamy-sand uplands. Then, EC was negatively correlated to pH at pH<5.5 and positively correlated to pH at pH>5.5. The EC increase when pH<5.5 was ascribed to the dissolution of aluminum since acidic tropical soils such as Ferralsols with high aluminum oxide content may release aluminum through dissolution at pH<5.5 (Larssen et al. 1999; Guo et al. 2007). At pH>5.5, higher EC was generally recorded in piezometers located in loamy-sand uplands than in loamy lowlands, suggesting a better retention capacity of cations contributing to salinity in loamy lowlands relative to loamy-sand uplands. This observation at the local scale was consistent with that at the watershed scale leading to counter-intuitive results: Greater nutrient inputs in the watershed lead to lower nutrient exports at the outlet (with the exception of K, as discussed below).

Aquatic ecosystems health is threatened by N and P since these nutrients trigger eutrophication in streams at high concentrations (Palmer 2010). Lower DIN and TP fluxes were generally recorded from watersheds on loamy lowlands than watersheds on loamy-sand uplands despite higher N and P inputs and mill wastes entering the stream. This is consistent with groundwater observations and confirmed that the soil type may have controlled DIN and TP losses to streams, loamy-sand uplands soil being more sensitive to losses than loamy lowlands soil; this is also consistent with the higher nutrient retention in loamy lowlands, which have higher clay content and organic matter content than loamy-sand uplands (Comte et al. 2013). Another reason for lower DIN fluxes exported from loamy lowlands could be because denitrification resulted in N losses to the atmosphere rather than to aquatic ecosystems. Denitrification was not assessed in this study; however, it has been demonstrated that the accumulation of soil moisture and soil organic matter down the slope increases soil denitrification rates (Florinsky et al. 2004). Denitrification also occurs in water bodies, which may explain the low DIN fluxes recorded throughout the study area (Mulholland et al. 2009). It is well-known that clay and aluminum oxide content in the soil are responsible for P adsorption (Muljadi et al. 1966; Udo and Uzu 1972; Brennan et al. 1994), so the high aluminum oxide content in the Ferralsols within the study area could adsorb and limit P leaching into groundwater, particularly in loamy lowlands that have a greater clay content than loamy-sand uplands. Since our results were restricted to soluble TP in streams, future work should also assess whether particulate P (bound to sediments) is entering streams in the study area.

Fertilizer sources (mineral vs. organic) also influenced DIN and TP losses, although to a lesser degree than soil type. In loamy-sand uplands, lower DIN and TP fluxes were exported from organic fertilized watersheds than mineral-fertilized watersheds, despite higher nutrient application rates in the former. This suggests that organic fertilization may help to reduce DIN and TP losses to streams compared to mineral fertilization. Unlike mineral fertilizers, the organic fertilizers used in oil palm plantations constitute a progressive-release fertilizer that requires mineralization to liberate water-soluble nutrients, which favors plant uptake while avoiding nutrient losses via leaching (Kasim and Abd Majid 2011). This was consistent with groundwater observations. However, lower DIN concentrations were measured in the piezometers under organic fertilizer applications compared to mineral fertilization in the loamy lowlands in the following order: EFB-fertilized plot< POME-fertilized plot<mineral-fertilized plot. The same order was observed for TP concentrations, but the differences were not statistically different, likely due to very low TP concentrations detected throughout the year as a result of P adsorption/fixation reactions within the soil profile.

An exception to this trend concerns K fluxes: With greater K application rates, a larger K flux was exported at the watershed outlets, regardless of the soil type (mineral fertilizers on sandy upland<EFB fertilizers on loamy-sand uplands< POME fertilizers on loamy lowlands). POME and EFB applications result in extremely high K inputs, such that POME application can deliver 2175 kg K ha^{-1} and EFB applications give 324–486 kg K ha^{-1}. POME was applied on loamy watersheds while organic fertilized watersheds on loamy-sand uplands received EFB applications only. Thus, higher K fluxes recorded on loamy watersheds compared to all others suggest that once the K application rate exceeds the threshold for oil palm K uptake, higher K fluxes will be exported regardless of soil type. The same was true for EFB-fertilized watersheds on loamy-sand uplands, although to a lesser extent than POME-fertilized watersheds. This was consistent with groundwater observations that showed significantly higher K concentrations in POME-fertilized plots compared to other piezometers in the oil palm plantations.

Although EFB fertilizer applications result in higher Mg input (+135 %) than mineral fertilizer applications, lower Mg fluxes were recorded from the EFB-fertilized watersheds, suggesting that EFB applications helped to reduce Mg losses. EFB fertilizer application provided ample Mg, but it did not exceed oil palm Mg requirements, so there appeared to be little risk of excess Mg loss to the environment. Indeed, Mg is solubilized from EFB fertilizer at a lower rate than K, with 80 % of the total Mg becoming plant available in the first year after it is applied, while 100 % of K content in EFB is released within 90 days after application only (Caliman et al. 2001). Higher Mg fluxes recorded from POME-fertilized watersheds on loamy lowlands compared to EFB-fertilized watersheds on loamy-sand uplands suggest that POME applications likely exceeded oil palm Mg requirements. However, Mg fluxes from POME-fertilized watersheds that did not exceed Mg fluxes recorded from mineral groundwater observations in the piezometers also showed that higher EC, DIN, and Mg concentrations were recorded in the piezometers under forest and unfertilized rubber plantation compared to piezometers under oil palm. This is likely due the high nutrient demand of oil palm (Ng 2002) and highlighted the efficiency of the rational fertilizer program that avoided excess nutrient losses to streams (except K losses under organic fertilizer applications). Groundwater and watershed-scale observations were consistent, and both revealed the high nutrient uptake of oil palm and importance of a rational fertilizer program in limiting nutrient losses to streams. The soil type controlled nutrient losses to streams (because stream flow is mainly fed by groundwater contribution), with loamy-sand uplands being more susceptible to nutrient losses than loamy lowlands. The ability of soil to buffer nutrient losses is tempered by the fertilizer management since organic fertilizer applications resulted in lower DIN, P, and Mg fluxes to streams than mineral fertilizer applications.

Agronomic and environmental implications

Mature oil palm cultivation that relies on high fertilizer inputs did not pose a risk to water quality in the study area. Low nutrient concentrations in streams, compared to water quality standards, were partly explained by dilution due to the high volume of water draining through soil in these humid tropical climatic conditions. However, the dilution effect occurring throughout the study area did not fully explain the low nutrient fluxes exported at the watershed scale nor did the low inherent fertility of the Ferralsols. High nutrient uptake by oil palm seemed to play a crucial role as nutrient sink, which may explain why low nutrient exports were observed despite high fertilizer inputs.

Our study indicates that the site-specific and rational fertilizer management practiced in the industrial and plasma plantations can efficiently reduce the risk of nutrient losses to aquatic ecosystems. In particular, the application of organic fertilizers seemed to be effective in reducing the exported fluxes of DIN, TP, and Mg despite higher nutrient inputs when organic fertilizer sources are used, compared to mineral fertilizers. In this study, the loamy-sand uplands appeared to be more susceptible to leach nutrients into streams compared to loamy lowlands. This is likely due to the more acidic pH, lower CEC, and coarser texture in loamy-sand upland soil type that favored leaching, compared to soil in the loamy lowlands. In our previous study, we demonstrated a general improvement in soil fertility status with organic fertilizer applications compared to mineral fertilizer applications, and a decline in some soil fertility parameters when organic fertilizers were applied in frequently over a 7-year period. Particularly, the loamy-sand uplands benefited more than loamy lowlands from organic fertilizers but requested annual organic fertilizer applications to maintain the soil fertility improvement (Comte et al. 2013). Thus, organic fertilizer should be preferentially applied on loamy-sand soils to maintain soil fertility at the plantation scale and prevent non-point source pollution of waterways.

We recommend the development of a spatial strategy of fertilizer application that accounts for the soil variability across the entire plantation, for maximum agronomic and environmental benefits. Fertilization management (even rational fertilization) is generally performed at the plot scale and the organic fertilizers usually applied in the plots surrounding the mill due to transportation cost without taking account of the soil type and fertility. The choice of the mill location needs to consider the spatial strategy for organic fertilizer applications in the future. Consequently, industrial producers must investigate the spatial distribution of soils throughout the plantation with detailed soil surveys that identify and map the more sensitive soils (e.g., those that should receive organic fertilizers for agronomic benefits and environmental protection purposes) when establishing a new plantation. In conclusion, the plot-scale fertilizer management should be complemented with a landscape-scale strategy of fertilizer applications for higher efficiency in the long term.

Further research is needed to better understand the impact of oil palm cultivation on hydrochemical processes. Indeed, the low impact of mature oil palm cultivation on water quality should be confirmed in other areas, particularly those with drier climatic conditions. In the context of global climate change, oil palm plantations may experience lower rain amounts and thus have less dilution of the nutrients in water that runs off and leaches through the plantation. Still, lower rainfall would also result in lower water flow and lower nutrient losses through leaching, runoff, and erosion. Similarly nutrient losses and water quality in areas with different soil types (i.e., clayey soils with low infiltration capacity) should be investigated. Moreover, supplementary data on the temporal change in SiO_2 concentration revealed short residence time of water with renewal of shallow groundwater after wet periods in our study area. When this occurs, nutrients can be quickly flushed to streams and could potentially increase nutrient concentrations detected in stream water quality monitoring programs, particularly when a storm even occurs shortly after fertilizers are applied. This leads us to recommend that the industry consider water quality assessment as part of their best management practices for maintaining ecological health at the landscape and watershed scales. On the other hand, potential soil degradation (acidification and nutrient depletion due to high nutrient uptake by oil palm) in case of under-fertilization should be investigated. Finally, this study detected high COD and BOD due to the presence of degradable organic matter in streams, likely due to natural conditions (presence of peatsoil patches within the study area and a black river close to the study area). Streams with high organic matter loads merit additional study because many pesticides bind to organic matter and are then readily transported from agroecosystems to streams (Vereecken 2005), making the dissolved organic matter load a possible indicator of exported pesticide fluxes (Page and Lord 2006; Reichenberger et al. 2007).

Oil palm being a perennial crop with a 25–30 years lifespan, particular attention should be dedicated to the plantation spatial design to enhance ecosystem services in the long term. Actions should be undertaken to (i) implement a nutrient management taking account of soil variability, (ii) preserve riparian vegetation as a buffer zone to protect streams from non-point source pollution, and (iii) include forested patches and corridors within the plantation to preserve the biodiversity. This requires going beyond the field-scale management and implementing best management practices at the landscape or watershed scale. Recently, RSPO redefined the Principles and Criteria for the Production of Sustainable Palm Oil that, among other, encourages the implantation of management strategies to minimize environmental impact of oil palm plantations, including a nutrient recycling strategy (criteria 4.24), a management strategy for fragile and problem soils (criteria 4.3.6), and the protection of water courses by maintaining and restoring riparian and other buffer zones (criteria 4.4.2) (RSPO 2013). RSPO already encourages planters to implement best management practices, but stronger measures are needed to encourage planters in designing new plantations in a more sustainable way and to put recommendations into practice. Beyond environmental considerations, socioeconomic aspects should also be taken in account to improve strategy management at the supra-farm level. For example, industrial planters use the fruit bunches sold by smallholders as organic fertilizers without either returning some organic fertilizer to smallholders or including the price of the fertilizer in the trade. A more equitable share of available resources should be encouraged by policy makers. Also, oil palm mills are able to produce more energy than needed to drive their turbines and may provide electricity to surrounding villages if local government would put the necessary infrastructure in place. All these actions should be included in a policy strategy that prioritizes sustainable development at the watershed scale and supra-farm level.

Conclusion

This study provided a comprehensive, year-long report on water quality in an oil palm-dominated landscape and assessed nutrient fluxes exported from 16 watersheds while accounting for variability in soil type and fertilizer management. Low nutrient concentration recorded in the streams throughout the landscape indicated that mature oil palm plantations in the study area did not contribute to eutrophication of the aquatic ecosystems. This was ascribed to high nutrient uptake by oil palm, a site-specific and rational fertilizer program that aimed to closely match fertilizer applications to oil palm nutrient requirements, and nutrient dilution due to heavy rainfall in the study area. Subsequent investigations should provide a nutrient budget for the oil palm trees and ground cover, which could also consider gaseous nutrient losses (e.g., denitrification).

The spatial design of the study (with pseudoreplicated watersheds) permitted analysis of the influence of soil type and fertilization management on nutrient fluxes, and results were consistent with our observations deducted from groundwater chemistry analysis at the local scale. The soil type appeared to control DIN and TP fluxes, loamy-sand uplands being more susceptible to losses than loamy lowlands. Organic fertilization helped to reduce nutrient fluxes compared to mineral fertilizers, especially N and P loads. However, when K inputs exceed the oil palm requirement threshold, high K fluxes can be expected, especially when groundwater has a short residence time and is the dominant source of subsurface water contributing to baseflow.

Finally, our hydrochemical study carried out at the watershed scale highlighted number of agroenvironmental implications and led to a number of recommendations for oil palm planters and policy makers.

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