

RESEARCH ARTICLE

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Key Points:

- Hydrological function is measured in five streams along a land-use gradient
- Oil palm streams are warmer and export more sediment than other streams
- Base flow periods are significantly warmer than times of stormflow

Supporting Information:

- Tables S1–S3 and Figures S1–S4

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Influence of watershed-climate interactions on stream temperature, sediment yield, and metabolism along a land use intensity gradient in Indonesian Borneo

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Abstract Oil palm plantation expansion into tropical forests may alter physical and biogeochemical inputs to streams, thereby changing hydrological function. In West Kalimantan, Indonesia, we assessed streams draining watersheds characterized by five land uses: intact forest, logged forest, mixed agroforest, and young (<3 years) and mature (>10 years) oil palm plantation. We quantified suspended sediments, stream temperature, and metabolism using high-frequency submersible sonde measurements during month-long intervals between 2009 and 2012. Streams draining oil palm plantations had markedly higher sediment concentrations and yields, and stream temperatures, compared to other streams. Mean sediment concentrations were fourfold to 550-fold greater in young oil palm than in all other streams and remained elevated even under base flow conditions. After controlling for precipitation, the mature oil palm stream exhibited significantly greater sediment yield than other streams. Young and mature oil palm streams were 3.9°C and 3.0°C warmer than the intact forest stream (25°C). Across all streams, base flow periods were significantly warmer than times of stormflow, and these differences were especially large in oil palm catchments. Ecosystem respiration rates were also influenced by low precipitation. During an El Niño–Southern Oscillation-associated drought, the mature oil palm stream consumed a maximum 21 g O₂ m^{−2} d^{−1} in ecosystem respiration, in contrast with 2.8 ± 3.1 g O₂ m^{−2} d^{−1} during nondrought sampling. Given that 23% of Kalimantan's land area is occupied by watersheds similar to those studied here, our findings inform potential hydrologic outcomes of regional periodic drought coupled with continued oil palm plantation expansion.

1. Introduction

Agriculture is a major driver of change in freshwater quality and quantity globally [Carpenter *et al.*, 2011; Rosegrant *et al.*, 2009]. Croplands span ~12% of the world's land surface, and increased food demand from altered diets and growing population is expected to lead to crop expansion and intensification, especially within tropical regions [Foley *et al.*, 2011; Tilman *et al.*, 2011]. Because rivers are spatially nested complex systems [Allan, 2004], the influence of agricultural land use change on tropical freshwater streams depends on multiple interactions among physical, chemical, and biological conditions occurring across spatial and temporal scales [Ponette-González *et al.*, 2010a, 2010b; Uriarte *et al.*, 2011]. Directly assessing these interactions is necessary to evaluate how agricultural land use change affects downstream ecosystems [Beman *et al.*, 2005; Bennett *et al.*, 2001; Diaz and Rosenberg, 2008].

Tropical forest clearing and agricultural land use affect streams in diverse ways. Forest conversion to cropland often results in increased water yield due to associated changes in canopy interception, evapotranspiration (ET), and soil infiltration [Brauman *et al.*, 2012; Coe *et al.*, 2011; Costa *et al.*, 2003; Giambelluca, 2002; Hayhoe *et al.*, 2011; Nik, 1988]. Agricultural conversion also affects stream physical and biochemical properties. For example, stream temperatures tend to be higher in agricultural than forested catchments [Macedo *et al.*, 2013; Neill *et al.*, 2013], while sediment concentration and load are typically elevated after land clearing [Bruijnzeel, 2004; Douglas *et al.*, 1999]. Enhanced sediment production is often sustained through activities

such as tilling and road use [Dunne, 1979; Ziegler et al., 2002, 2004]. Reduction in riparian zone vegetation modifies stream light availability and organic matter inputs [Heartsill-Scalley and Aide, 2003; Lorion and Kennedy, 2009]. This combination of hydrological, physical, and biochemical alterations induced by land use change may impact stream metabolism, an integrative indicator of stream ecosystem structure and function [Bernot et al., 2010; Davies et al., 2008; Gücker et al., 2009; Mulholland et al., 2001; Young and Huryn, 1999].

Nonintact yet forested land uses may also alter stream ecosystems. Compared to streams draining intact forest catchments, logged forests typically generate enhanced sediment loads [Douglas, 1999; Douglas et al., 1999; Walsh et al., 2011]. In Malaysian Borneo, Iwata et al. [2003] found that even after 9–20 years of regrowth, swidden fallows can produce higher sedimentation and lower benthic biodiversity compared with intact forested watersheds. In contrast, others have reported that the hydrological impacts of long-fallow swidden systems are inconsequential [Ziegler et al., 2009]. Establishment of plantation forests on nonforest land has also been found to enhance ET and reduce runoff; the magnitude of these effects may change as stands mature from open- to closed-canopy systems [Giambelluca, 2002; Guardiola-Claramonte et al., 2010; Jackson et al., 2005; Ponette-González et al., 2014]. These studies suggest that conversion of nonintact or managed forests to plantation agriculture (compared to intact forest to plantation trajectories) may impart distinctive outcomes on freshwater stream ecosystems.

Oil palm (*Elaeis guineensis*) plantations are expanding throughout the tropics, especially in Southeast Asia. In Kalimantan, Indonesia, this extensive contiguous (~130 km² per plantation) and perennial (~25–30 year rotation) tree crop is developed mainly over mineral soil lowland (<100 m above sea level (asl)) areas and is primarily replacing forests [Carlson et al., 2013]. From 1990 to 2010, Carlson et al. [2013] found that ~50% of Kalimantan oil palm plantation expansion converted intact forest. Another 20% replaced logged forest, while ~20% occurred on mixed swidden smallholder agricultural lands, typically mosaics of rain-fed rice gardens, fallows, fruit agroforests, and tree crops such as rubber [Carlson et al., 2012; Lawrence et al., 1998; Mertz et al., 2009].

Given the rapid and extensive conversion of forests and mixed agricultural systems to oil palm, and projected plantation expansion within allocated leases [Carlson and Curran, 2013; Carlson et al., 2013, 2012; Curran et al., 1999, 2004], we examined stream hydrological conditions along a land use gradient from intact forest to mature oil palm plantation in Kalimantan. We addressed the following questions: (i) Do streams draining watersheds dominated by intact forest, logged forest, mixed agroforest, or oil palm plantation differ in stream conditions including temperature, sediment concentration and yield, and oxygen and metabolic dynamics? (ii) If so, do conditions measured in a stream draining a mature oil palm catchment (>10 years) differ from those recorded in a young oil palm watershed (<3 years)? (iii) How does climate, including precipitation and temperature, influence observed stream conditions?

2. Study Region Description

This study was conducted in Ketapang District, on the southern coast of West Kalimantan province, Indonesia (Figure 1). The focal region, centered at 110°20'22"E, 1°12'31"S, spanned five streams draining ~84 km² within and surrounding Gunung Palung National Park (GPNP). While West Kalimantan contains peat and white sand substrates [RePPProT, 1990], we limited our investigation to watersheds on mineral soils. These regional soil formations include alluvial deposits near river banks and nutrient-poor soils derived from sedimentary (40–150 m asl) and granite bedrock (>150 m asl) [Paoli and Curran, 2007]. Precipitation has been reported at ~3600–4500 mm yr⁻¹, with June through September generally drier than other months [Curran and Leighton, 2000; Lawrence and Schlesinger, 2001]. The El Niño Southern Oscillation (ENSO) drives interannual precipitation variability. At the onset of warm ENSO events (El Niño), monthly precipitation may decline to <100 mm [Paoli and Curran, 2007], with elevated precipitation occurring during cold ENSO (La Niña) periods.

3. Materials and Methods

3.1. Stream Selection

Our experimental design included six land uses at five sample sites. We selected five streams in similarly sized watersheds in Ketapang to represent dominant regional land uses (Table 1 and Figure S1): Intact forest (FOR), selectively logged forest (LOG), mixed agroforest (AG), and oil palm agriculture (OP). Oil palm was divided

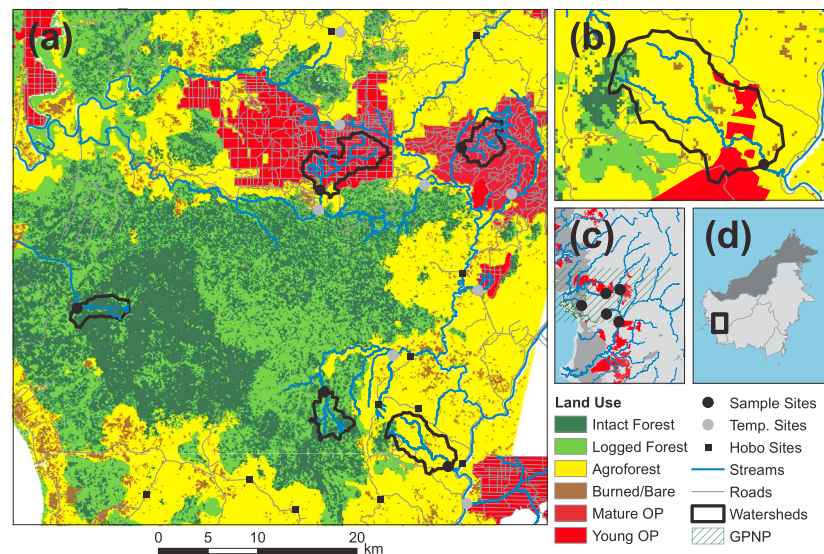


Figure 1. Study region in Ketapang District, West Kalimantan, Indonesia (110°25'E, 1°10'S). (a) In 2008, focal watersheds were dominated by major regional land use classes derived from Landsat imagery [Carlson *et al.*, 2012]: intact forest, selectively logged forest, mixed agroforest, young oil palm plantation <3 years postclearing in 2008, and mature oil palm plantation >10 years postclearing in 2008. Five focal stream sample sites are indicated by black circles; eight supplementary temperature measurements are denoted with grey circles. (b) In July 2011, clearing for oil palm commenced in the agroforest watershed; by June 2012, ~14% of the watershed was converted. The study region is centered around Gunung Palung National Park (GPNP) and is nested within (c) the Pawan River watershed on the southwestern coast of (d) the island of Borneo. Kalimantan, Indonesia, is light grey; the Federation of Malaysia (Sarawak and Sabah) and Negara Brunei Darussalam are dark grey.

into recently cleared and planted oil palm (young oil palm, OPY, <3 years post clearing in 2008) and mature oil palm (OPM, >10 years). In the AG watershed, clearing and planting for oil palm began in July 2011. This transition (TRANS) treatment allowed an assessment of stream condition changes with conversion from extensive swidden agriculture to intensive oil palm. To allow for inclusion of agroforest and transitional treatments within a single watershed, we use the term “land use treatment” when reporting our results. We chose watersheds without permanent human settlements or oil palm factories.

Each land use class is represented by only one watershed. This sampling design may confound the hydrological effects of land use with impacts of other watershed-specific factors including land cover pattern and extent, disturbance history, elevation, soil type, aspect, and stream geometry. To reduce uncertainty about the transferability of our findings to other watersheds, we control for watershed-specific factors to the extent possible; we highlight these controls in the methods section.

3.1.1. Intact Forest

Dipterocarpaceae, a diverse tree family with species that typically reproduce synchronously in supraannual cycles, dominates mineral soil forests in West Kalimantan [Cannon *et al.*, 2007; Curran *et al.*, 1999; Curran and

Table 1. Focal Watershed Descriptions in Kalimantan, Indonesia^a

Watershed Classification	Area (ha)	Elevation (m)	Slope (deg)	1996 Land Use (%)						2008 Land Use (%)					
				FOR	LOG	AG	B/B ^b	OPY		FOR	LOG	AG	B/B ^b	OPY	OPM
Forest (FOR)	1065	492	(42–1112)	17	(0–33)	97	3	0	0	85	15	0	0	0	0
Logged Forest (LOG)	1148	128	(52–441)	9	(0–31)	89	11	0	0	40	60	0	0	0	0
Agroforest (AG/TRANS)	2297	103	(19–519)	7	(0–31)	58	10	31	0	3	4	90	3	0	0
Young Oil Palm (OPY)	2621	41	(19–91)	2	(0–10)	71	29	0	0	0	0	6	3	72	19
Mature Oil Palm (OPM)	1283	47	(27–104)	3	(0–13)	1	1	0	99	0	0	1	0	0	99

^aWatershed characteristics for five focal watersheds, including means with ranges (parentheses), and percentage land use in 1996 and 2008. Classes were derived from Landsat TM and ETM+ satellite imagery as reported in Carlson *et al.* [2012].

^bB/B indicates the burned and bare land use class.

Leighton, 2000]. In the 1990s and 2000s, logging, coupled with fires and oil palm development, resulted in extensive degradation and conversion of these forests [Carlson *et al.*, 2013, 2012; Curran *et al.*, 1999; Curran and Webb, 2000]. By 2008, only a few watersheds dominated by intact forest were suitable to serve as experimental controls; all of these watersheds were located within GPNP and were characterized by relatively high elevation and slope.

3.1.2. Logged Forest

The logged forest catchment was selected from Gunung Tarak Protected Forest (*Hutan Lindung*, 240 km²), adjacent to GPNP. From 1990 to 2012, primarily nonmechanized commercial timber extraction not sanctioned by the government occurred throughout this protected area [Carlson *et al.*, 2012; Curran *et al.*, 2004]. Loggers manually constructed ~5 m wide trails by placing small poles or wooden tracks on the ground, and used these trails to pull or skid logs to streams for export by river. Logging in this catchment was especially intense in the mid-2000s; from 2007 to 2008, aboveground biomass in logged-over areas declined 30% [Carlson *et al.*, 2012].

3.1.3. Agroforest

Regional rural communities maintain extensive agroforests and agricultural fallows [Carlson *et al.*, 2012]. In these managed lands, 1–5 ha patches of wetland and dryland rain-fed rice agriculture are intermixed with rice fallows, fruit gardens, and rubber stands. Forest and fallow clearing for rice cultivation occurs in June–July, followed by burning and rice planting from August to September. Rice harvest spans February–May. Networks of unpaved footpaths as well as larger unpaved roads are present throughout agroforests. Fertilizers are rarely applied to agroforest lands.

3.1.4. Oil Palm Plantation

In the 1990s and early 2000s, land clearing for oil palm agriculture employed mechanized logging, followed by burning, to remove residual vegetation (L. M. Curran, personal observations, 1996–1997 and 2001–2002). Mature oil palm catchments received this logging and burning treatment. Within young oil palm watersheds, field visits indicated that land preparation included logging residual commercial timber, piling remaining vegetation into rows, and targeted burning of these stacks. Although Indonesian regulations designate 50–100 m riparian buffers as protected areas [Republic of Indonesia, 1990], clearing typically occurs to the stream edge. On flat lands, drainage systems are used to achieve 50–75 cm water table depth, while hills are terraced to prevent erosion [Corley and Tinker, 2003]. A grid of nonpaved roads is created throughout a plantation. Oil palm seedlings are planted with recommended densities of ~140 individual palms per hectare, and leguminous ground cover is often used to reduce erosion and improve soil nitrogen status [Pahan, 2010]. To achieve high yields, fertilizer application to tree bases should occur ~1–2 times per year [Pahan, 2010]. Frequently applied fertilizers include NPK mixtures, urea, ammonium sulfate, triple superphosphate, magnesium sulfate, and potassium chloride. Empty fruit bunches and pruned fronds are used as organic fertilizer sources.

3.2. Land Use Classification

Regional land use change was quantified by classifying Landsat imagery as described by Carlson *et al.* [2012]. Eleven Landsat images (30 m; path 121/row 61) were acquired from 1989 to 2008. Because all were somewhat cloudy, scenes from adjacent years were merged to create a time series of seven images. Carnegie Landsat Analysis System–Lite (CLASlite) was used to convert Landsat data to reflectance and to apply a probabilistic spectral unmixing model, yielding pixel fractional cover [Asner *et al.*, 2009]. Land uses were identified by applying image segmentation and nearest-neighbor classification to CLASlite data. Oil palm plantations were manually digitized from Landsat reflectance data. We assessed 2008 to 2012 oil palm expansion by manually delineating oil palm from a July 2012 Landsat ETM+ image.

3.3. Watershed Land Use Characterization

From April to July 2012, we field-mapped stream reaches, moving upstream from the sample site until no water flow was present. The AGREE surface reconditioning system, implemented within Dinamica EGO, was used to adjust surface elevation of a 90 m Shuttle Radar Topography Mission digital elevation model (DEM) to be consistent with mapped stream vectors [Hellweger, 1997; Jarvis *et al.*, 2006; Soares-Filho *et al.*, 2009]. Watersheds were delineated by applying ArcGIS hydrology tools to the reconditioned DEM [Environmental Systems Research Institute, 2010]. To assess historical land use in these watersheds, land use was extracted from classified 1996 and 2008 Landsat imagery.

3.4. Identification of Similar Kalimantan Watersheds

To assess the representativeness of sampled watersheds, we applied the ArcGIS hydrology tools to identify all Kalimantan watersheds falling within the range of area, mean slope, and mean elevation of our sample watersheds. We excluded watersheds overlapping with peatlands [Wahyunto *et al.*, 2004]. We then intersected catchment polygons with a 2010 Kalimantan land cover map created by Miettinen *et al.* [2012]. These Kalimantan-wide land-cover classes, which do not include logged forest, were translated into land use classes represented by sample watersheds. The large-scale palm plantation class was combined with the 2010 oil palm plantation layer from Carlson *et al.* [2013] to represent oil palm. Lowland and montane forests represent forest and logged forest; plantation/regrowth and mosaic symbolize agroforest and agricultural fallow; open and urban denote burned or bare land. To estimate potential future conversion of these watersheds to plantations, we intersected representative watersheds with oil palm lease maps, which indicate future locations of oil palm development; we also examined whether these watersheds fell within protected areas [Carlson *et al.*, 2013].

3.5. Regional Climate

In 12 village settlements across the study region, air temperature (°C, hourly) and rainfall (mm, continuous) measured with 20.32 cm diameter tipping buckets (RainWise, Rainew 111) were recorded with event-temperature loggers (Onset, UA-003-64). To estimate mean rainfall and temperature in each watershed, we applied an inverse distance weighting method with a search radius the size of the study region:

$$w_i = d_i^2 \left(\sum_{j=1}^N d_j^2 \right)^{-1} \quad (1)$$

where w_i is the weight of event logger i , d is the distance from the watershed centroid to event logger i , and N is the total number of event loggers. The Multivariate ENSO Index was used to identify El Niño and La Niña events [NOAA Earth System Research Laboratory, 2013].

3.6. Stream Monitoring

From 2009 to 2012, we used the YSI 6600 multiparameter sonde [YSI Incorporated, 2008] to collect hourly unattended continuous samples for 18–42 days, 1–4 times per land use treatment (Figure 2). Our sampling regime included expanded monitoring at the TRANS treatment from August 2011 to March 2012 ($n = 4$ month-long measurements) to capture potential changes in stream condition during the transition from agroforest to oil palm.

3.6.1. Discharge

Because of the remote nature of our field sites, we devised a simple discharge sampling protocol. A barometric pressure sensor (Onset, S-BPA-CM10), installed in a protected, indoor area <2 km from each stream, measured hourly atmospheric pressure recorded by a data logger (Onset, H21-002). Water depth (m) was estimated as the difference between sonde-measured water column pressure (kilopascals, kPa) and atmospheric pressure, correcting for water temperature (°C), which alters water density. Depth measurements were refined by shifting all calculated measurements by the difference between sonde-calculated and human-measured water depth at the start of each sonde deployment period. We manually sampled stream discharge ($\text{m}^3 \text{s}^{-1}$) 3–10 times during each long-term sample depending on deployment duration, and once during each scoping sample, totaling 7–56 measurements per site. Stream width at the location and time of measurement was divided into four equidistant intervals, and stream depth was measured at each interval. Stream velocity (m s^{-1}) was estimated by timing the passage of a floating tennis ball along 5 m in the stream center.

We developed rating curves using relationships between manually recorded measures of discharge and water depth:

$$Q = aD^z \quad (2)$$

where Q is stream discharge ($\text{m}^{-3} \text{s}^{-1}$), D is stream depth (m), and a and z are fitting parameters. Rating curves were developed for each stream and were applied to sonde-measured water depth to generate time series estimates of discharge during sonde deployment. In the intact forest stream, z did not contribute significantly to the regression, so we applied a simple linear relationship between discharge and depth.

Our sampling protocol did not aim to capture high-flow events, but sampled stream depth at regular intervals during sonde installation. To determine the degree to which this methodology captured the full

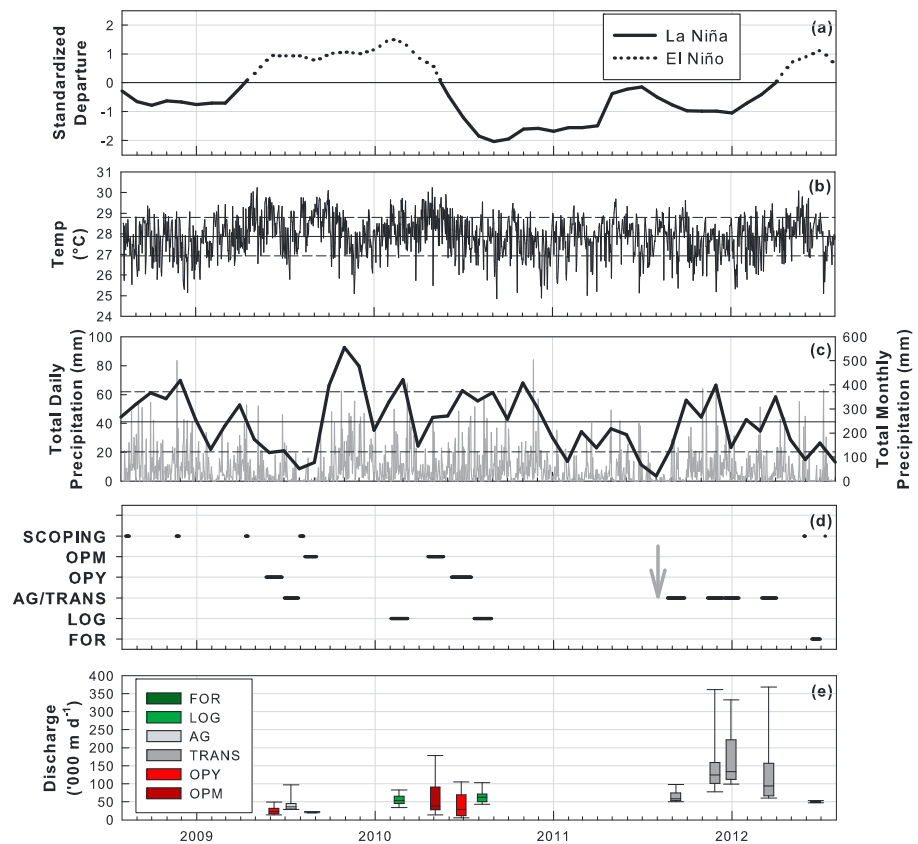


Figure 2. ENSO cycles, regional temperature and precipitation, sampling scheme, and water discharge across six watershed land use treatments in Kalimantan, Indonesia. (a) Standardized departure values identify warm (El Niño) and cold (La Niña) ENSO periods [NOAA Earth System Research Laboratory, 2013]. (b–c) Temperature and precipitation averaged across tipping bucket rainfall and temperature loggers distributed throughout the study region. Solid and dotted horizontal back lines indicate mean and standard deviation of daily temperature and monthly precipitation. (d) Sampling regime for streams draining five watersheds representing six land use classes: FOR = intact forest, LOG = logged forest, AG/TRANS = mixed agroforest before and during conversion to oil palm, OPY = young oil palm, and OPM = mature oil palm. The grey arrow indicates initial conversion of AG/TRANS to oil palm. A submersible sonde was deployed 1–4 times at each land use treatment; total suspended solids and stream discharge were also collected during scoping surveys across multiple sites (“SCOPING”). (e) Stream water discharge during sonde deployments. Line demarcates the median of all daily samples; shaded upper and lower bounds indicate 25th/75th percentiles; whiskers represent 10th/90th percentiles.

range of sonde-sampled depth, we compared maximum sonde-sampled stream depth to maximum manually sampled depth (Table S1). Maximum manually sampled depth at the FOR, TRANS, and OPY sites was >90% of maximum hourly sonde-sampled stream depth; all other maximum manual depth measurements were ~60–70% of maximum sonde-sampled depth.

We separated stream flow hydrographs into base and event flow components using the base flow separation function in the EcohydRology package in R [Fuka et al., 2013].

3.6.2. Suspended Solids

Water turbidity (Nephelometric Turbidity Units, NTU) was measured with YSI’s optical wiped turbidity probe (6136), which has a suggested application range of 0–1000 NTU. Because heterogeneity in particle size causes spikes in turbidity readings, we activated the sonde option to generate a NTU output reflective of the overall cloudiness of the sample. This option applies a mathematical filter to raw data and is recommended by YSI for unattended, long-term deployment [YSI Incorporated, 2008]. Turbidity data were additionally filtered by replacing each turbidity sample greater than twice the value of adjacent samples with the mean of adjacent samples. Optical probes have a tendency to drift; to overcome this problem, the 6136 sensor was factory-calibrated each year during the sampling regime.

Total suspended solids (TSS, mg L^{-1}) samples were collected at least four times per stream, including samples during scoping surveys of multiple sites in 2008, 2009, and 2012, as well as at the onset and completion of each sonde deployment. Water samples were collected with a 140 mL syringe, which was washed 3 times with stream water before collection. TSS was estimated by filtering a known volume of stream water (140–280 mL) through a preweighed 47 mm glass fiber filter. Filter dry weight was calculated after drying filters at $\sim 104^\circ\text{C}$ for 1 h, cooling to room temperature, and weighing with a digital analytical scale (resolution 0.1 mg). This procedure was repeated until each filter reached a constant weight. We derived TSS from the difference between dry mass and presample filter mass.

To generate hourly TSS estimates from turbidity measurements, we developed a linear regression (y intercept $[\alpha] = 0$) between TSS grab samples and sonde NTU and applied this equation to filtered sonde turbidity data ($\beta = 0.61$, $r^2 = 0.93$, $n = 39$). Suspended sediment loads (mg h^{-1}) were calculated by multiplying TSS concentration (mg L^{-1}) by water discharge ($\text{m}^3 \text{s}^{-1}$) and converting these measures to hourly loads. Sediment yield ($\text{mg h}^{-1} \text{ha}^{-1}$) was estimated by dividing sediment load by watershed area.

3.6.3. Stream Temperature and Dissolved Oxygen

Temperature was measured using the YSI 6560 conductivity/temperature probe [YSI Incorporated, 2008]. Dissolved oxygen (DO) concentration ($\text{g O}_2 \text{m}^{-2}$) and saturation (%) were quantified with YSI's wiped ROX optical DO sensor (6150), which measures the partial pressure of oxygen, reported as percent air saturation. The sonde compensates for the difference between calibration temperature and measured temperature ($\sim 1.27\%$ per $^\circ\text{C}$) and for the temperature-dependent relationship between oxygen saturation and solubility [Standard Methods for the Examination of Water and Wastewater 21st Edition, 2005]. The sonde uses conductivity sensor measurements to account for salinity. Before each deployment, the DO sensor was calibrated in a closed, pressure-released chamber of water-saturated air.

To assess whether focal stream temperatures were similar to regional stream temperatures, we measured temperature in eight additional streams, including two replicates of streams draining four land uses: logged forest, agroforest, young oil palm, and mature oil palm (Figure 1). From August 2008 to August 2009, we measured temperature in each of these streams 4–5 times, for a total of 33 data points.

3.7. Metabolism

Daily ecosystem respiration and gross primary production were measured using the single-station method developed by Odum [1956], which assumes that surface and groundwater inputs have a negligible influence on DO concentration:

$$dC/dt = P - R + E \quad (3)$$

where dC/dt is the aerial rate of change of DO ($\text{g O}_2 \text{m}^{-2} \text{h}^{-1}$), P is gross primary production ($\text{g O}_2 \text{m}^{-2} \text{h}^{-1}$), R is ecosystem respiration ($\text{g O}_2 \text{m}^{-2} \text{h}^{-1}$), and E is the gas exchange with the atmosphere ($\text{g O}_2 \text{m}^{-2} \text{h}^{-1}$) between consecutive DO measurements. Gas exchange with the atmosphere (E) was modeled as

$$E = k_a \times (C_s - C) \times D \quad (4)$$

where k_a is the first-order stream reaeration coefficient (h^{-1}), C_s is the saturated DO concentration ($\text{g O}_2 \text{m}^{-3}$), C is the DO concentration ($\text{g O}_2 \text{m}^{-3}$), and D is stream depth (m).

Because oxygen diffusion is highly sensitive to the reaeration coefficient, generating respiration estimates from open-channel data requires accurate estimates of k_a . Common estimation techniques include semiempirical formulae based on hydraulic parameters [e.g., Raymond et al., 2012], in-stream measurement with tracer gases [Tsivoglou and Neal, 1976], DO balance methods [Chapra and Ditoro, 1991], and the nighttime drop in DO from respiration [Hornberger and Kelly, 1975]. We chose to apply a nighttime regression technique, which has been shown to generate accurate estimates of k_a when reaeration rates are low and productivity is high [Cox, 2003]. This method fits a least-squares regression to nighttime measurements of dC/dt and $(C_s - C)$. The slope of the nighttime regression is $k_{a(20^\circ\text{C})}$, which was corrected by stream temperature T ($^\circ\text{C}$) to k_a [Elmore and West, 1961]:

$$k_a = k_{a(20^\circ\text{C})} \times 1.024^{(T-20)} \quad (5)$$

We subset the metabolism data set to whole days with positive k_a values and with base flow composing $>90\%$ of total discharge. Thus, our results are applicable only to base flow conditions. We also report the gas transfer velocity k (m h^{-1}), which a product of k_a and depth.

During the night, gross primary production is 0 and R is the difference between dC/dT and E . Daytime R was calculated by interpolating nighttime R between the hours before dawn (05:00) and after dusk (18:00). Total daily ecosystem respiration (ER , $g\ O_2\ m^{-2}\ d^{-1}$) was the sum of nighttime R and photoperiod R from 00:00–24:00 h. During the photoperiod, we determined total daily gross primary production (GPP) by summing the difference between observed total metabolism (dC/dt) and interpolated daytime R . Net daily metabolism (NDM, $g\ O_2\ m^2\ d^{-1}$) was the difference between GPP and ER . Positive values of ER and NDM indicate oxygen consumption. We discarded days with negative or zero GPP, ER , or NDM values.

3.8. Statistical Analysis

To determine if sample data were derived from normally distributed populations, we examined quantile-quantile plots. Sample distributions that were highly right-skewed were log-transformed for use in models and back-transformed for presentation in text and figures. Transformed variables comprised 24 h and 7 day precipitation metrics as well as TSS, sediment yield, ER , GPP, NDM, and GPP:ER.

We used linear regression to evaluate whether land use treatment, as well as interactions between land use treatment and environmental variables, were significant predictors of hourly stream temperature, O_2 concentration and saturation, TSS, sediment yield, and daily metabolic measurements (i.e., GPP, R , NDM, and GPP:ER). Because all response variables are affected by current as well as antecedent precipitation, we considered mean hourly precipitation calculated across periods spanning 24 h, 7 days, 30 days, and 180 days prior to a given sonde measurement. In the stream temperature model, we also considered ambient temperature and mean watershed elevation. For dissolved oxygen, we included air temperature and TSS as potential predictor variables. Metabolic models incorporated stream temperature. Posthoc tests applied to the chosen models were used to examine pairwise differences among land use treatments. We compared treatments using the *testInteractions* function and Holm p-adjustment method within the R package *phia* [De Rosario-Martinez, 2012; Holm, 1979]. Model fit is reported with the adjusted coefficient of determination (r^2). To determine whether watersheds had significantly different precipitation or temperature for the entire 2009–2012 period, we applied linear regression to evaluate whether watershed was a significant predictor of total monthly precipitation and mean monthly temperature.

To assess whether hydrological patterns were maintained during base flow and stormflow conditions, we analyzed temperature and O_2 saturation and transformed TSS in hours with >95% base flow and >20% stormflow. The FOR site was excluded from the stormflow data set because measurements in this stream included only 1 day with >20% stormflow.

Data analysis was performed in R [R Development Core Team, 2013]. We report the standard deviation of the sample mean ($\bar{x} \pm sd$).

4. Results

4.1. Watershed Land Use Change

All focal watersheds were dominated by forest in the early 1990s yet incurred considerable land use change by 2008. The OPM plantation was developed from a forested timber concession in ~1994 [Carlson *et al.*, 2012]. By 1996, >98% of this OPM watershed was planted with oil palm. From 1996 to 2008, the FOR and LOG catchments incurred increases in logged area, from 3% to 15% and from 11% to 60%, respectively. The AG/TRANS watershed contained 68% intact and logged forest in 1996; by 2008, this watershed was dominated by 90% agroforest. In July 2011, land clearing for oil palm commenced in this catchment. By June 2012, ~14% of the watershed was cleared for or planted with oil palm. Land clearing occurred ~0–2 km from the stream edge (Figures 1b and S1d). The OPY catchment was 100% intact and logged forest in 1996; from 2007 to 2008, 72% of this watershed was cleared for and planted with oil palm. From 2008 to 2012, all but the AG/TRANS catchment experienced minimal land use change.

4.2. Kalimantan-Wide Watershed Analysis

Focal watersheds are well-represented at the Kalimantan-wide scale (Figure S2). A total of 6902 watersheds, 23% of Kalimantan land area ($538,346\ km^2$), have similar area, slope, and elevation as focal watersheds. About 17% of total representative watershed area falls within protected areas. In 2010, representative watersheds with >90% of their area in a single land cover included 2052 intact and logged forest catchments (6.8% of Kalimantan area),

Table 2. Stream Conditions Across Six Watershed Land Use Treatments in Kalimantan, Indonesia^a

Treatment ^b	Dep. (#)	Days (Total)	Hours (Total)	Base Flow (%)	Temperature (°C)	TSS ^c (mg L ⁻¹)	Sediment Yield ^c (mg h ⁻¹ ha ⁻¹)	O ₂ Concentration (%)	O ₂ Saturation (mg L ⁻¹)
FOR	1	18	432	0.99 ± 0.011	25 ± 0.63	0.15 ± 0.036	290 ± 24	A 7.9 ± 0.18	95 ± 2.0
LOG	2	73	1752	0.81 ± 0.15	26 ± 0.52	7.6 ± 3.9	16000 ± 2100	6.9 ± 0.28	84 ± 3.6
AG	1	30	720	0.86 ± 0.17	25 ± 0.67	3.3 ± 1.7	2500 ± 330	A 6.4 ± 0.72	AB 78 ± 8.7
TRANS	4	130	3120	0.87 ± 0.12	27 ± 1.1	6.4 ± 2.2	13000 ± 1400	5.6 ± 0.79	A 69 ± 10
OPY	2	76	1824	0.77 ± 0.21	29 ± 1.8	80 ± 24	32000 ± 4800	4.6 ± 1.3	60 ± 17
OPM	2	58	1392	0.8 ± 0.24	28 ± 1.5	21 ± 7.9	20000 ± 3400	5.3 ± 2.3	B 67 ± 29
All	12	385	9240	0.83 ± 0.18	27 ± 1.7	10 ± 7.5	13000 ± 2200	5.8 ± 1.5	72 ± 18

^aWe report the number of individual sonde deployments (Dep.), total days and hours sampled, and hourly mean ± standard deviation for six stream parameters. Nonsignificant differences between land covers are identified with identical letters. We did not apply these pairwise comparisons to base flow.

^bFOR = intact forest, LOG = logged forest, AG = mixed agroforest, TRANS = mixed agroforest during conversion to oil palm, OPY = young oil palm, and OPM = mature oil palm. "All" describes conditions across all treatments.

^cTotal suspended solids (TSS) concentration and sediment yield were log-transformed for analysis and back-transformed for reporting.

1662 agroforest (5.5%), and 47 oil palm (0.15%) catchments. Only 3.9% of representative watershed area was planted with oil palm in 2010. Overlap with plantation leases indicates that another 17% of this area is allocated to future oil palm development. Specifically, 4.4% of representative forest catchment area and 27% of agroforest catchment area is slated for conversion to plantations.

4.3. Climate and Stream Discharge

Mean annual precipitation measured from 2009 to 2012 was 2900 ± 610 mm yr⁻¹, ~20–35% lower than two 1990 era measurements reported for the same region [Curran and Leighton, 2000; Lawrence and Schlesinger, 2001]. Maximum precipitation was recorded in November 2009 (560 mm), while minimum precipitation occurred in August 2011 (21 mm). Consecutive months with precipitation <100 mm included August–September 2009, July–August 2011, and August–September 2012. Mean monthly air temperature ranged from 27 to 29°C.

Land use-independent differences in watershed heat and water inputs may affect stream temperature, metabolism, and sediment yields. We detected no significant between-watershed differences in mean monthly precipitation (mm month⁻¹) or mean monthly temperature (°C) measured from 2009 to 2012 (Table S2; $n = 240$ months, $p > 0.05$). In contrast, climate conditions varied substantially across watersheds during sonde deployment (Figure S3). The LOG watershed received the most precipitation during sonde deployment. The least 24 h and 7 day precipitation occurred in the FOR watershed. The AG and TRANS treatments received the least total rainfall during 180 day periods antecedent to sonde deployment.

Across all streams, discharge displayed regular diel cycles during dry periods, likely because of diurnal variation in ET (Figure S4). Median base flow across all treatments and dates was 0.56 m³ s⁻¹, contributing a median 91% of total discharge ($n = 385$ days; Table 2).

4.4. Stream Temperature

The OPY watershed exhibited the highest hourly mean stream temperature (29 ± 1.8 °C, $n = 9240$ h), while FOR maintained the lowest mean temperature (25 ± 0.63 °C; Table 2 and Figure 3a). Ambient temperature and mean watershed elevation explained only 14% and 22% of stream temperature, respectively (Table S3). A linear model fit to land use treatment as well as interactions between land use treatment and ambient temperature, and all antecedent precipitation metrics, explained 70% of variation in stream temperature. Pairwise comparisons from this model suggest that after controlling for climate, stream temperatures were significantly different across land use treatments ($p < 0.05$). Temperature in the AG/TRANS stream increased from 25 ± 0.67 °C before land clearing to 27 ± 1.1 °C post land clearing.

Eight regional streams have temperatures comparable to temperatures measured in focal streams with similar land use. Regional logged forest and agroforest streams were cooler (25 ± 1.0 °C and 26 ± 0.72 °C, respectively), while mature oil palm (28 ± 2.5 °C) and young oil palm streams (29 ± 2.6 °C) tended to be warmer.

Mean base flow temperature was significantly greater than stormflow temperature across all streams ($p < 0.05$, Wald's two sample t test with 95% CI). Differences were especially large in OPY (2.1°C) and OPM (1.2°C) and

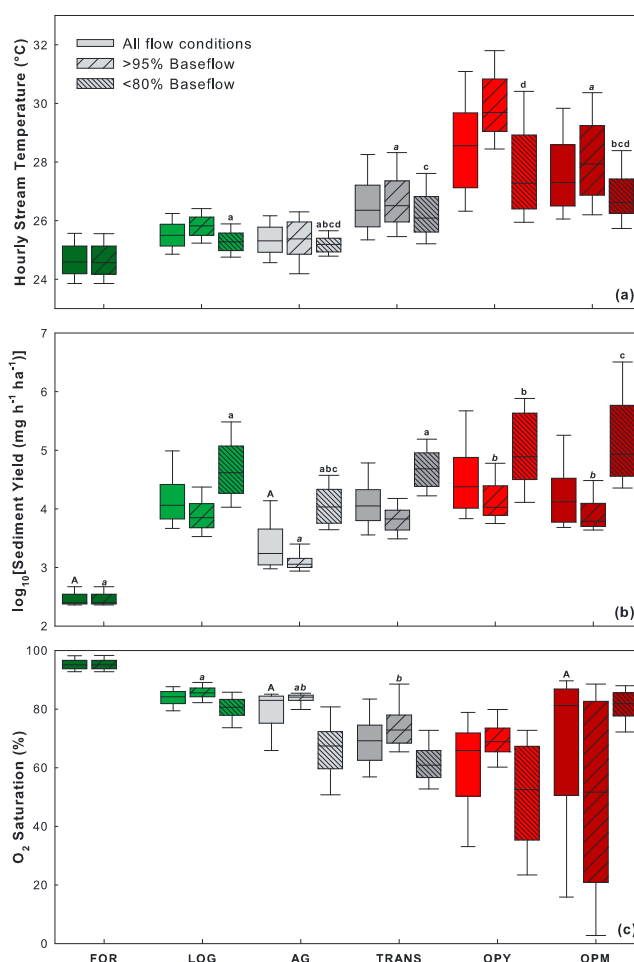


Figure 3. Conditions in streams draining six catchment land use treatments in Kalimantan, Indonesia. (a) Mean hourly stream temperature, (b) log-transformed sediment yield, and (c) O₂ saturation. Nonsignificant differences between land covers are identified with identical letters. FOR = intact forest, LOG = logged forest, AG = mixed agroforest, TRANS = mixed agroforest during conversion to oil palm, OPY = young oil palm, and OPM = mature oil palm. Line demarcates the median of all hourly samples; shaded upper and lower bounds indicate 25th/75th percentiles; whiskers represent 10th/90th percentiles.

relatively small in LOG (0.52°C), TRANS (0.39°C), and AG (0.12°C). Applying the linear model derived from the full temperature data set to base flow conditions ($n = 3419$ hours), we found that between-treatment temperature differences were maintained, except between TRANS and OPM treatments ($p > 0.05$). In contrast, there were few significant differences between land use treatments during stormflow conditions ($n = 2327$ h); only the LOG and oil palm watersheds (TRANS, OPY, OPM) as well as TRANS and OPY treatments differed during storms, when $>20\%$ of water input is estimated to occur in the form of overland flow ($p > 0.05$).

4.5. Total Suspended Solids and Sediment Yield

Total suspended solids concentration varied substantially among land use treatments (10 ± 7.5 mg L⁻¹; Table 2). A linear model including land use treatment and land use treatment interaction with all antecedent precipitation metrics explained 75% of variation in TSS (Table S3). From this model, all differences in TSS between land use treatments were highly significant ($p < 0.01$).

To normalize for differences in watershed area and the magnitude of precipitation events during sonde deployments, we also analyzed sediment yield (mg h⁻¹ ha⁻¹), which averaged $13,000 \pm 2200$ mg h⁻¹ ha⁻¹ across all sites and dates (Table 2 and Figure 3b). During stormflow conditions, mean within-site sediment yield increased significantly ($p < 0.001$, Wald's two sample t test). A model incorporating land use and all interactions with precipitation explained 66% of variation in sediment yield; land use treatment alone

Table 3. Stream Metabolic Parameters Across Six Watershed Land Use Treatments in Kalimantan, Indonesia^a

Treatment ^b	Days (Total)	Reaeration Coefficient (k_a ; h ⁻¹)	Gas Transfer Velocity (k ; m h ⁻¹)	Ecosystem Respiration (ER; g O ₂ m ⁻² d ⁻¹)	Gross Primary Production (GPP; g O ₂ m ⁻² d ⁻¹)	Net Daily Metabolism (NDM; g O ₂ m ⁻² d ⁻¹)	GPP:ER (P:R)
FOR	10	0.26 ± 0.15	0.16 ± 0.069	2.0 ± 2.4	0.50 ± 0.49	1.5 ± 3.4	0.25 ± 0.058
LOG	0	NA	NA	NA	NA	NA	NA
AG	18	0.13 ± 0.060	0.039 ± 0.0094	1.4 ± 3.1	0.0099 ± 0.0034	1.3 ± 3.2	0.25 ± 0.058
TRANS	99	0.15 ± 0.066	0.080 ± 0.028	5.1 ± 3.0	0.62 ± 1.8	4.1 ± 3.0	0.12 ± 0.061
OPY	18	0.16 ± 0.082	0.087 ± 0.037	5.0 ± 2.6	0.76 ± 1.5	4.1 ± 2.7	0.15 ± 0.037
OPM	18	0.16 ± 0.083	0.068 ± 0.014	4.4 ± 3.9	0.76 ± 5.4	3.1 ± 3.4	0.17 ± 0.11
All	163	0.15 ± 0.072	0.076 ± 0.027	4.1 ± 3.0	0.41 ± 0.85	3.3 ± 3.0	0.10 ± 0.059

^aWe report the number of days sampled and the daily mean ± standard deviation of six metabolic parameters. All variables were log-transformed for analysis; here, we report back-transformed statistics. Nonsignificant differences between land covers are identified with identical letters. We did not apply pairwise comparisons to k_a or k .

^bFOR = intact forest, LOG = logged forest, AG = mixed agroforest, TRANS = mixed agroforest during conversion to oil palm, OPY = young oil palm, and OPM = mature oil palm. "All" describes conditions across all treatments.

accounted for only 40% of this variation (Table S3). This model suggests that after controlling for precipitation, sediment yields from the OPM catchment were slightly greater than those from the OPY watershed ($p = 0.022$). This difference was driven by stormflow events; during base flow conditions, OPY and OPM sediment yields did not differ significantly.

We applied this predictive sediment yield model to a scenario of high antecedent 24 h rainfall (+2 standard deviations above the full data set mean) while holding lagged 7, 30, and 180 day precipitation constant at the overall mean. Under this scenario, the OPM and OPY watersheds yielded 580,000 mg h⁻¹ ha⁻¹ and 310,000 mg h⁻¹ ha⁻¹ sediment, 24 to 1500 times the sediment yields from FOR, LOG, and AG watersheds under identical precipitation inputs (380, 13,000, and 950 mg h⁻¹ ha⁻¹, respectively). Clearing for oil palm agriculture in the AG/TRANS watershed generated a >2000% increase in sediment yield in this high-rainfall scenario, producing 20,000 mg h⁻¹ ha⁻¹ in the TRANS treatment.

4.6. Dissolved Oxygen

Mean O₂ saturation (72 ± 18 %) and concentration (5.8 ± 1.5 mg O₂ L⁻¹) exhibited strong diurnal variation during dry periods (Table 2 and Figures S4 and 3c). The OPY catchment had the lowest mean hourly saturation and concentration (60 ± 17 %; 4.6 ± 1.3 mg O₂ L⁻¹), while highest oxygen levels were measured in the FOR catchment (95 ± 2.0 %; 7.9 ± 0.18 mg O₂ L⁻¹). Oxygen saturation and concentration were best predicted with a model incorporating land use treatment as well as interactions with all lagged precipitation metrics and ambient temperature; models explained 63% of O₂ saturation and 67% of O₂ concentration (Table S3). Significant differences were detected in all pairwise comparisons between land use treatments, except between AG and OPM for both metrics, and between AG and TRANS for concentration ($p > 0.05$).

Dissolved O₂ saturation was 6% to 27% lower during stormflow compared to base flow periods across all sites except the OPM stream, where mean O₂ saturation was 57% greater during stormflow. This result was driven by median 45% O₂ saturation at OPM recorded during the ENSO-related drought in August 2009 ($n = 25$ days). Contrasts suggest that O₂ saturation differs significantly across treatments during stormflow conditions. However, under base flow the LOG and AG treatments and AG and TRANS treatments did not have significantly different O₂ saturation ($p > 0.05$). Results for O₂ concentration are similar, and therefore are not reported separately from O₂ saturation.

4.7. Metabolism

We assessed stream metabolism because it is an integrative measure of resource availability and stream function. The LOG watershed was excluded from metabolism calculations because of frequent storm events, which limited viable sample size to <5 days. For the other five land use treatments ($n = 163$ days), treatment was a highly significant predictor of ER, GPP, NDM, and ER:GPP ($p < 0.001$).

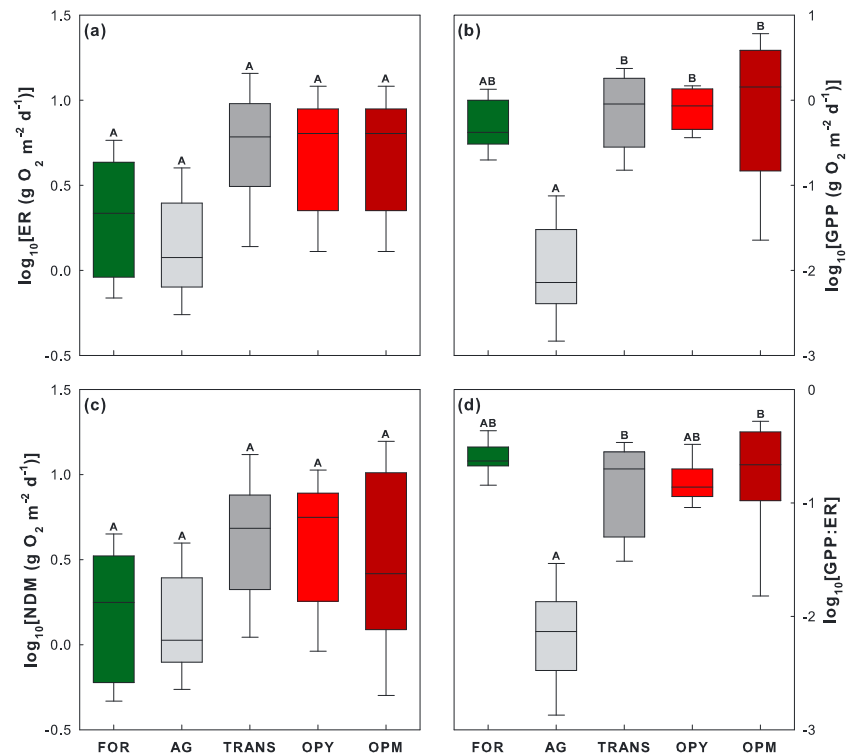


Figure 4. Metabolic measures in streams draining six catchment land use treatments in Kalimantan, Indonesia. (a) Mean daily ecosystem respiration (ER), (b) gross primary production (GPP), (c) GPP:ER ratio, and (d) net daily metabolism (NDM). Nonsignificant differences between land covers are identified with letters. FOR = intact forest, LOG = logged forest, AG = mixed agroforest, TRANS = mixed agroforest during conversion to oil palm, OPY = young oil palm, and OPM = mature oil palm. Line demarcates the median of all daily samples; shaded upper and lower bounds indicate 25th/75th percentiles; whiskers represent 10th/90th percentiles.

Mean ER across all dates and treatments was $4.1 \pm 3.0 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$ (Table 3 and Figure 4a). The AG treatment had the lowest ER ($1.4 \pm 3.1 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$), while TRANS displayed the greatest ER ($5.1 \pm 3.0 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$). No significant differences in ER were detected across treatments ($p > 0.05$). In linear regression analysis, only land use treatment and interaction of treatment and 7 and 180 day lagged precipitation were significant predictors of ER (Table S3).

Mean rates of GPP were lower and more dispersed than ER ($0.41 \pm 0.85 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$) (Table 3 and Figure 4b). The AG treatment had the lowest mean GPP ($0.0099 \pm 0.0034 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$), while the greatest mean GPP was recorded at OPY ($0.76 \pm 1.5 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$). Pairwise contrasts suggest that GPP in the AG stream was significantly lower than in TRANS, OPY, and OPM streams ($p < 0.01$). Interactions between land use treatment and previous 7 and 30 day rainfall, and TSS, as well as land use treatment, were the best predictors of GPP (Table S3).

Across treatments, mean NDM ($3.3 \pm 3.0 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$) reflected ER measurements, with the greatest mean daily oxygen consumption occurring at OPY ($4.1 \pm 2.7 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$), and the lowest oxygen consumption measured at AG ($1.3 \pm 3.2 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$; Table 3 and Figure 4c). NDM was similar among all treatments ($p > 0.05$). Like ER, land use treatment and land use treatment interaction with 7 and 180 day rainfall were the most significant and parsimonious predictors of NDM (Table S3).

Gross primary production to ER ratios < 1 indicate that all study streams were heterotrophic (0.10 ± 0.059 ; Table 3 and Figure 4d) [Odum, 1956]. A model incorporating land use treatment interaction with 7, 30, and 180 day lagged rainfall, and ambient temperature, as well as land use, was an excellent predictor of GPP:ER (Table S3). Pairwise contrasts suggest that GPP:ER was similar across treatments, except slightly lower ratios in AG compared to TRANS and OPM ($p < 0.05$).

We sampled during an extreme drought at OPM in August–September 2009, months that received only 26% of mean monthly precipitation (MMP) (Figure 2). Extremely high daily DO amplitude and ER were observed from 31 August to 3 September 2009 (saturation $51 \pm 50\%$, $n = 96$ h; ER 14 ± 1.9 g O₂ m⁻² d⁻¹, $n = 3$ days; Figure S4). The same OPM treatment experienced moderate DO saturation and ER during other dates sampled ($75 \pm 26\%$, $n = 1728$ hours; ER 2.8 ± 3.1 g O₂ m⁻² d⁻¹, $n = 25$ days). No other such hyperoxic event was recorded during sampling across other streams and dates, despite relatively low water inputs to the TRANS site in August–September 2011 (32% of MMP) and the FOR site in June 2012 (37% MMP).

5. Discussion

Our study assessed five streams draining watersheds representing typical Kalimantan land uses. Compared to the stream draining an intact forest watershed, two catchments dominated by oil palm plantation agriculture had warmer stream temperatures, increased suspended sediment concentration and yield, and reduced oxygen saturation. Despite spatially heterogeneous annual land clearing and burning associated with swidden agriculture within the mixed agroforest watershed, and selective timber harvest and road building within the logged forest catchment, these streams were cooler and had lower sediment yield than oil palm streams.

5.1. Transferability to Other Watersheds

If watershed-level differences are driven entirely by differences in land use, our results might be extrapolated to at least 23% of the Kalimantan land area similar to our sampled watersheds (Figure S2). In particular, our findings could be applied to predict how development of oil palm leases allocated across 17% of this watershed area might influence stream temperature and sediment export across Kalimantan.

Because agricultural productivity depends on climate and soil properties, agricultural land use frequently covaries with natural factors including topography and parent geological material. When land use is associated with a natural gradient, considering only anthropogenic influence may overstate the effects of land use on streams [Allan, 2004]. In Kalimantan, oil palm covaries with elevation—in 2010, most plantations were located in lowlands <100 m asl [Carlson *et al.*, 2013]. Protected areas, which harbor the majority of intact mineral soil forests in our study region, tend to be high in elevation and far from roads and cities [Joppa and Pfaff, 2009]. Reflecting these large-scale tendencies, our focal forest watersheds were located in protected areas and had higher elevation and slope than focal agricultural watersheds. However, interpolation of temperature and precipitation measured around the study region indicates that all catchments received similar amounts of precipitation and maintained comparable temperatures during the study period (Table S2). While land use history can affect current stream conditions [Harding *et al.*, 1998], our streams have similar land use histories; all watersheds were mainly forested in the early 1990s (Table 1). Taken together, these similarities in climate and land use history suggest that the patterns observed in our limited sample represent associations between land use and stream conditions. This suggestion is further supported by broader trends in stream temperature; our results show that temperature measured in eight regional streams reflects the heat gradient recorded within five focal streams, with oil palm streams warmer than agroforest and forest streams.

Nevertheless, numerous potentially critical variables, not documented in this study, affect stream temperature, sediment concentration and yield, and metabolism. These include stream aspect and size, soil type and nutrient status, bedrock characteristics, and the degree of surface–subsurface water exchange [Findlay, 1995; Finlay, 2011; Mohamoud, 2004]. Land conversion location and pattern also affect stream hydrology [Allan, 2004; Ziegler *et al.*, 2006]. For instance, while oil palm plantation land-clearing activities affected a small portion of the AG/TRANS watershed, they intersected with the stream ~2 km upstream from the sample site, directly altering riparian zone vegetation structure (Figures 1 and 2d). As a result, changes in temperature and sediment dynamics were discernible when <15% of this agroforest catchment was converted to oil palm (Figure 3). Watershed land use replicates, combined with consideration of land-cover configuration, are needed to pinpoint how watershed characteristics interact with land use pattern and extent to produce hydrological outcomes.

5.2. Influences on Stream Temperature

Like numerous previous studies [Brown, 1969; Kaushal *et al.*, 2010; Mohseni and Stefan, 1999], we found that air temperature is correlated with water temperature. However, air temperature has low variability in this

equatorial region; mean hourly air temperature was $28 \pm 3.3^{\circ}\text{C}$ across dates sampled. Watershed land use treatment, which integrates a suite of factors influencing stream thermal regimes such as riparian vegetation, stream orientation, ET, and upland shading, was the single best predictor of stream water temperature (Table S3). Specifically, the land use intensity of a catchment appears to be inversely related to stream temperature, with oil palm streams maintaining $1.0\text{--}3.9^{\circ}\text{C}$ greater mean temperatures than all other streams (Table 2).

Research in small temperate headwater catchments suggests that most energy exchange occurs at the air–water interface [Evans *et al.*, 1998] and that riparian vegetation cover plays a critical role in stream water temperature regulation [Lorion and Kennedy, 2009]. In the Brazilian Amazon, studies have found significant warming in soybean and pasture compared to forested catchments; higher temperatures were driven, in part, by reductions in riparian vegetation [Macedo *et al.*, 2013; Neill *et al.*, 2013]. Increased stream surface radiation from reduced shading in oil palm plantations is likely to be a contributor to these thermal dynamics [Caissie, 2006].

Our high-frequency measurements allowed us to discern how watershed characteristics and precipitation interact to affect stream temperature. We found that significant differences in stream temperature among catchments remained during base flow-dominated periods but diminished during stormflow measurements (Figure 3). Especially within oil palm streams, base flow periods were warmer than times of stormflow. Reduced leaf area in agricultural lands leads to reduced ET and associated evaporative cooling, influencing groundwater temperatures [Sinokrot and Stefan, 1993]. Thus, groundwater exchange and subsurface contributions may be critical for stream temperature budgets.

5.3. Sediment Yield and Oil Palm Plantations

Previous work in tropical regions describes elevated sediment export from recently cleared agricultural catchments [Bramley and Roth, 2002; Douglas *et al.*, 1999; Dunne, 1979; Hunter and Walton, 2008]. Similarly, we found that mean sediment yield was greater in the young oil palm stream than in mixed agroforest, logged forest, and intact forest sites (Figure 3). During an intense storm, the young oil palm stream is expected to yield >800 times more sediment than the forest stream. Although sediment yield was higher during stormflow conditions across all watersheds, sediment yield in the young oil palm stream remained elevated over nonplantation land uses even under base flow conditions.

Stream sediment concentration and yield in the >10 year old oil palm plantation was also elevated above nonplantation catchments (Figure 3). Surprisingly, this mature plantation yielded more sediment than the young oil palm catchment during storm events. Although recovery of soil hydraulic properties, increased interception and ET, and plantation management (e.g., hillside erosion control and ground cover) may inhibit sediment export from maturing oil palm stands, we suspect that dense road networks within plantations drive sustained high sediment yields [Dunne, 1979; Hunter and Walton, 2008]. Research in northern Thailand indicates that total sediment input to streams from unpaved roads is similar to that from annual croplands, even though roads cover a small fraction of watershed land surface [Ziegler *et al.*, 2002]. Unpaved roads are disproportionate contributors of sediment because their compact surfaces generate Horton overland flow after small amounts of rainfall and disturbance by vehicles and road maintenance tends to renew surface sediment supply [Ziegler *et al.*, 2004]. While riparian buffers can reduce stream sediment concentrations [Ziegler *et al.*, 2006], in our study region, buffers were not typically present in oil palm plantations. Frequent road/stream intersections enable road runoff to drain directly to streams [Ziegler *et al.*, 2004]. Because roads are required for oil palm fruit harvest and transport, elevated sediment yield may be a permanent feature of oil palm plantations, although riparian buffers could mitigate the impact of roads on sediment inputs.

5.4. Stream Metabolic Dynamics

We report stream ecosystem respiration rates that appear to be among the greatest recorded worldwide: ER reached $21\text{ g O}_2\text{ m}^{-2}\text{ d}^{-1}$ on 2 September 2009 during an ENSO-related drought in the mature oil palm stream. To our knowledge, these rates are exceeded only by mean ER measured in an Argentinian Pampean stream ($\sim 21.5\text{ g O}_2\text{ m}^{-2}\text{ d}^{-1}$) that was neither light nor nutrient limited [Acuña *et al.*, 2011]. High stream respiration rates were particularly surprising because they occurred in a nonforest catchment. Previous studies suggest that forested catchments produce the greatest respiration rates as a result of high organic matter inputs from riparian vegetation and a tendency for pristine streams to retain organic matter [Delong and Brusven, 1994; Gücker *et al.*, 2009; Wantzen *et al.*, 2008; Young and Huryn, 1999]. Our forest watershed

exhibited relatively low mean ER rates ($2.0 \text{ g O}_2 \text{ m}^{-1} \text{ d}^{-1}$, Table 3), well within the range reported for other tropical streams ($<0.1\text{--}8.0 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$, $n = 6$ studies) [Gücker *et al.*, 2009; Hunt *et al.*, 2012; Mulholland *et al.*, 2001; Oliver and Merrick, 2006; Ortiz-Zayas *et al.*, 2005; Townsend *et al.*, 2011]. In the mature oil palm stand in August 2009, low flow rates resulted from little antecedent precipitation. In addition, this stream probably receives organic (e.g., palm fronds) and nutrient (e.g., fertilizer) inputs, while lack of riparian buffers may result in high light availability. These conditions likely enabled high ER rates during the 2009 drought. The temperature dependence of respiration is a topic of considerable debate [Perkins *et al.*, 2012]. We found no significant influence of stream temperature on ER in these warm headwater catchments. Instead, our models suggest that precipitation, which mediates water volume, is an important determinant of stream respiration.

At our focal streams, estimated rates of GPP ranged from $0.00026 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$ to $13 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$, exceeding the range of GPP recorded across six tropical studies ($0.10\text{--}4.6 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$) [Gücker *et al.*, 2009; Hunt *et al.*, 2012; Mulholland *et al.*, 2001; Oliver and Merrick, 2006; Ortiz-Zayas *et al.*, 2005; Townsend *et al.*, 2011]. Available light has been identified as a strong contributing factor to high GPP, especially in reference streams [Bernot *et al.*, 2010; Mulholland *et al.*, 2001; Young and Huryn, 1999]. The lowest GPP was measured in agroforest and forest streams, with riparian buffers potentially reducing light input compared with the oil palm streams. In the oil palm streams, high GPP may be explained by a combination of higher light and nutrient availability. In Queensland and Puerto Rico streams that were not light limited, nutrient availability has been shown to influence GPP [Mosisch *et al.*, 2001; Mulholland *et al.*, 2001]. Specifically, greater algal production maintained by high nutrient inputs (e.g., fertilizers) would lead to higher GPP. Quantification of stream canopy cover and light availability, coupled with a full nutrient budget approach, is required to discern how light inputs and nutrient flux are altered by oil palm plantations and how these changes influence stream metabolism.

5.5. Sources of Uncertainty

Technological innovation in the form of field-deployable sondes enables measurements of hydrologic conditions at frequent intervals and across relatively long time scales. These technologies are generating novel information about highly dynamic catchment processes [Kirchner *et al.*, 2004] and are well suited to remote tropical regions. Nevertheless, the unattended nature of sonde deployments, combined with our goal to rely on analyses that could be conducted in the field, generated several sources of uncertainty.

The optical dissolved oxygen sensor maintained excellent long-term stability during multiday deployments, recording dynamic O_2 concentrations that would not be observed in time series limited to just a few hours or days. Yet because metabolic measurements are highly sensitive to the reaeration coefficient k_a , measuring reaeration with tracers would enhance the accuracy of stream ER and GPP estimates.

Installation of permanent gauging stations, as well as more detailed characterization of stream geometry, would improve stream discharge estimates. Although our manual depth and discharge sampling captured 61–99% of the maximum sonde-measured depth across watersheds, we were unable to develop depth–discharge relationships for very high flows in the logged, agroforest, and mature oil palm catchments (Table S1). In addition, variable stream cross-section geometry may result in noncontinuous rating curves. Overbank flow events, in which discharge might increase without great variation in depth, are not captured in our models. If such events occurred during sampling, our findings represent underestimates of total discharge as well as sediment yield. Nevertheless, our relatively crude methods allowed us to discern base flow and stormflow from discharge measurements.

Turbidity is affected by suspended particles other than sediment, and readings may vary across streams based on water color and particle size and composition [Anderson, 2005]. We sampled TSS across turbidity spanning 0.40–713 NTU, a range which includes ~91% of all filtered turbidity values in the full data set. Developing individual stream TSS–turbidity relationships, and ensuring that sampling methods capture the full range of TSS, would reduce uncertainty around TSS estimates. In addition, the 6136 sensor saturates at ~1000 NTU. Only 3% of filtered turbidity samples were at the high end of the range (>950 NTU), indicating that the sensor was rarely saturated. Nevertheless, high sediment concentrations may have been underestimated due to sensor limitations. This ambiguity, combined with extrapolation of rating curves for high flows in select watersheds, means that our estimates of sediment export during storm events are associated with great uncertainty.

Nonsimultaneous measurements in multiple streams hindered our ability to directly characterize and contrast interactions between land use and climate events such as droughts. For example, are the high respiration rates observed in the mature oil palm stream during drought typical within streams draining lands recently cleared for oil palm? In Kalimantan, where variation in precipitation is driven by interannual ENSO events and where land use and land-cover change can be highly punctuated (e.g., forest conversion to oil palm) or very gradual (e.g., oil palm growth), continuous measurements of many streams simultaneously would be ideal to describe the complex influences of land use and climate on stream ecosystems.

6. Conclusions

By 2020, 35% of West Kalimantan lowland area (<300 m asl) is projected to be converted to oil palm [Carlson *et al.*, 2013]. If the differences measured between watersheds in our study can be translated into differences between land uses, conversion will produce warmer, more turbid streams. Stream warming has been shown to impart significant and often deleterious effects on aquatic organisms [Hester and Doyle, 2011], while thermal regime changes alter whole-stream metabolic processes, affecting stream nutrient and carbon cycling [Butman and Raymond, 2011; Demars *et al.*, 2011]. Increased sediment flux is of particular concern in Indonesia, which has few impoundments that prevent sediment transport to the ocean [Syvitski *et al.*, 2005]. While dam-building has diverse consequences for ecosystems [Dudgeon, 2000; Macedo *et al.*, 2013; Stickler *et al.*, 2013], Kalimantan's lack of impoundments may amplify the effects of land use change on coastal zones compared to other tropical regions. Improved maintenance of riparian buffers may mitigate plantations' thermal effects and sediment export. Yet, our results indicate that climate interacts with land use to influence stream conditions. Changes in water flux, especially alterations in ENSO frequency and intensity [Corlett, 2011], may exacerbate or dampen the influence of plantation land use on stream ecosystems. Longitudinal monitoring is required to assess how changing climatic conditions coupled with other anthropogenic land uses such as mining interact with oil palm agricultural estate practices to alter Bornean stream ecosystem function.

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