Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution

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Edited by Mario J. Molina, University of California at San Diego, La Jolla, CA, and approved September 3, 2009 (received for review July 8, 2009)

More than half the world's rainforest has been lost to agriculture since the Industrial Revolution. Among the most widespread tropical crops is oil palm (*Elaeis guineensis*): global production now exceeds 35 million tonnes per year. In Malaysia, for example, 13% of land area is now oil palm plantation, compared with 1% in 1974. There are enormous pressures to increase palm oil production for food, domestic products, and, especially, biofuels. Greater use of palm oil for biofuel production is predicated on the assumption that palm oil is an "environmentally friendly" fuel feedstock. Here we show, using measurements and models, that oil palm plantations in Malaysia directly emit more oxides of nitrogen and volatile organic compounds than rainforest. These compounds lead to the production of ground-level ozone (O_3), an air pollutant that damages human health, plants, and materials, reduces crop productivity, and has effects on the Earth's climate. Our measurements show that, at present, O_3 concentrations do not differ significantly over rainforest and adjacent oil palm plantation landscapes. However, our model calculations predict that if concentrations of oxides of nitrogen in Borneo are allowed to reach those currently seen over rural North America and Europe, ground-level O_3 concentrations will reach 100 parts per billion (10^9) volume (ppbv) and exceed levels known to be harmful to human health. Our study provides an early warning of the urgent need to develop policies that manage nitrogen emissions if the detrimental effects of palm oil production on air quality and climate are to be avoided.

air quality | land use change | sustainable development | biofuel

Ground-level ozone (O_3) is a priority air pollutant that damages human health, plants, and materials, reduces crop productivity, and has direct and indirect effects on the Earth's climate system (1). It is formed in the atmosphere by reactions involving oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. The terrestrial biosphere is a major source of both these families of trace gases; in fact, the great majority of reactive VOCs globally are of biogenic origin (2). Here we show, using integrated and fully comprehensive measurements of biosphere-to-atmosphere trace gas fluxes and atmospheric composition, together with atmospheric chemistry modeling, that conversion of tropical rainforest to oil palm plantations results in much greater emissions of these reactive trace gases that lead to O_3 formation. Increased NO_x emissions will cause severe ground-level O_3 pollution (> 100 ppbv), but this pollution could be prevented by strict control of emissions of reactive nitrogen species to the atmosphere. Our study shows the importance of quantifying the current and future effects of land use change on air quality when assessing the "environmental friendliness" of palm oil and other biofuel crops. Of course, air quality is only a single consideration; in assessing the consequences of biofuel production, effects on greenhouse gas emissions and climate change, deforestation, biodiversity, water pollution and freshwater availability, and food prices and food security are all important (3); these factors are not considered here. Specifically, our study provides an early warning of the urgent need to develop policies that manage nitrogen emissions to the atmosphere from the tropics if the detrimental effects of palm oil production on air quality and climate are to be avoided.

Results

Our study comprises a truly integrated and fully comprehensive set of biosphere-to-atmosphere flux measurements, atmospheric composition measurements, and atmospheric chemistry modeling in the tropics for 2 distinct but contiguous land use types. The project was based in Sabah, Malaysian Borneo, during April through July 2008. Our measurements (Table 1) show that emissions of VOCs from the rainforest and oil palm plantation landscapes are dominated by emissions of isoprene (2-methyl-1,3-butadiene). On a land area basis, isoprene emissions from the plantation (27 tonnes of isoprene per km^2 per year) are 5 times greater than from the rainforest. Isoprene and other VOC emission rates depend, in part, on leaf temperature (4). Temperatures were higher at the oil palm site than at the rainforest site (campaign averages 27.9 °C and 25.7 °C, respectively), but this difference in temperature explains only 7% of the observed difference in isoprene emission rates; the remainder is the result of the higher biogenic VOC emission rates from oil palm (*Elaeis guineensis*) trees (5) compared with rainforest tree

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Author contributions: C.N.H., A.R.M.K., M.E., D.F., A.C.L., P.S.M., J.A.P., and C.E.R. designed research; C.N.H., A.R.M.K., M.E., D.F., J.D.L., E.N., and C.E.R. analyzed data; P.D.C., C.F.D.M., J.R.D., M.W.G., J.R.H., C.E.J., B.L., J.D.L., A.C.L., S.F.L., J.M., P.M., S.J.M., E.N., D.E.O., S.M.O., G.J.P., T.A.M.P., J.R., J.S., U.S., and D.J.S. performed research; and C.N.H., A.R.M.K., D.F., and J.A.P. wrote the paper.

Conflict of interest: The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0907541106/DCSupplemental.

Table 1. Fluxes of isoprene, monoterpenes, reactive oxides of nitrogen, and nitrous oxide

Site		Isoprene: flux at the canopy scale (10.00–16.00 h) (mg/m²/h)	Monoterpenes: flux at the canopy scale (10.00–16.00 h) (mg/m²/h)	Reactive oxides of nitrogen: flux from soils (00.00–24.00 h) (mg N/m²/h)	Reactive oxides of nitrogen: flux at the landscape scale, inferred from model (00.00–24.00 h) (mg N/m²/h)	Nitrous oxide: flux from soils (00.00–24.00 h) (mg N_2O–N/m²/h)
Rainforest	Mean	1.55 ± 0.39	0.38 ± 0.20	0.14 ± 0.115	0.009	0.036 ± 0.041
	Variability	1.22	0.34	0.035		N/A
	n	619	619	5509		89
Oil palm plantation	Mean	7.77 ± 1.94	0.09 ± 0.20	N/A	0.019	0.051 ± 0.040
	Variability	7.68	0.35			N/A
	n	164	37			101

Fluxes of isoprene, monoterpenes, reactive oxides of nitrogen, and nitrous oxide from the Bukit Atur rainforest site and the Sabahmas oil palm plantation site, with an estimate of their uncertainty, their temporal variability (calculated as the standard deviation of the 30-min or hourly measurements) and the number of observations (n) on which they are based.

species. Isoprene has a 5 times greater potential for photochemical ozone creation than the weighted average of VOC compounds emitted by urban anthropogenic activity (6). After normalizing for this difference in VOC reactivity, the effective emissions of VOCs from the oil palm canopy per unit land area exceed those of a typical European city, such as London (7).

Our observations show that the plantation landscape and associated agro-industrial activities give rise to NO_x emissions several (≈2.5) times greater than from the rainforest on a land area basis (Table 1). The 3 major NO_x sources responsible for this increase are all linked to agro-industrial activity—vehicle exhaust, combustion at the palm oil processing plant, and substantial soil nitrogen fertilization in the plantations (≈0.5 tonnes of nitrogen per hectare per year). Aircraft measurements of acetylene, a well-established combustion tracer (8), show no significant enhancement in the boundary layer over the plantation landscape compared with the rainforest landscape. This finding is a strong indication that non-combustion sources make the major contribution to the elevated NO_x concentrations observed over the plantation landscape. Further corroboration of enhanced denitrification of oil palm plantation soils is given by the N_2O emissions from these soils, which are ≈50% larger than those from the rainforest soils (Table 1).

As well as dominating VOC emission flux rates, isoprene is the dominant (> 80%) reactive VOC by atmospheric mixing ratio in both landscapes. The concentrations of isoprene were 2 to 5 times higher over the plantation landscape than over the rainforest (Fig. 1), consistent with the observations of fluxes. The C_{10} monoter-

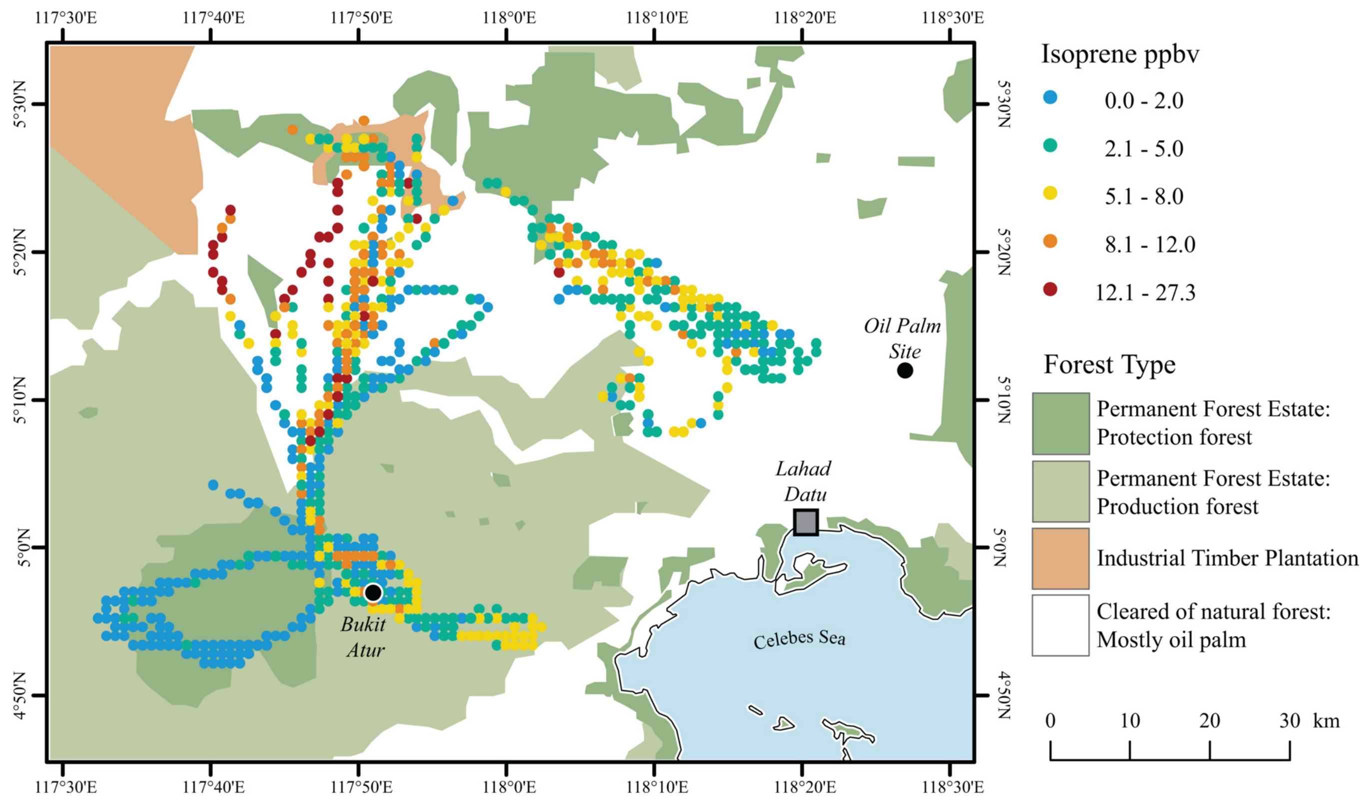

Fig. 1. The aircraft flight tracks in the boundary layer for the data averaged in Fig. 2, colored by isoprene concentrations (ppbv). The markers are at 10-s intervals with the 15-s isoprene data merged onto this time stamp. Each marker represents a single measurement, and there are only a small number of instances, mostly around 5.05° North, 117.8° East, where several points overlay each other.

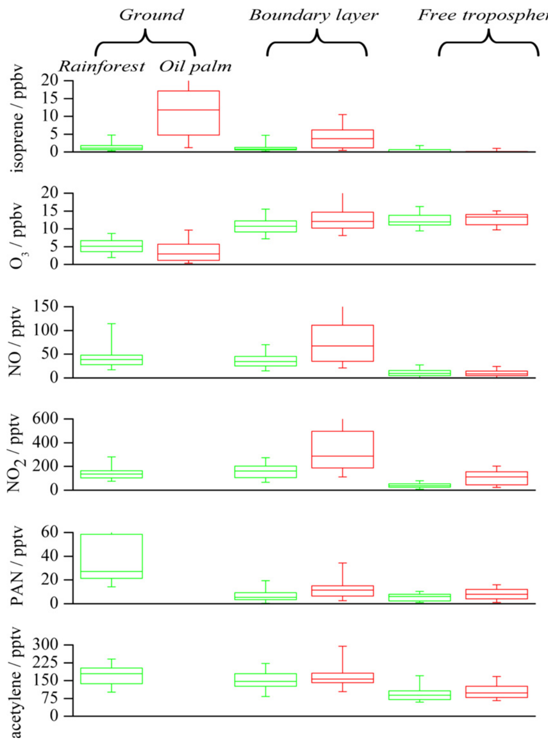

Fig. 2. Isoprene, ozone, nitric oxide, nitrogen dioxide, peroxyacetyl nitrate, and acetylene measured between 10.00 and 16.00 hours local time at ground sites (2 left columns), from the aircraft flying within the boundary layer (500–800 m above ground level) (2 middle columns), and from the aircraft flying in the free troposphere (3,000–6,000 m above ground level) (2 right columns). The green symbols show data from the rainforest landscape, and the red symbols show data from the oil palm plantation landscape. Symbol boxes show median and quartile values, with the whiskers showing 95th and 5th percentiles. Measurements of NO, NO_2, PAN, and acetylene were not made on the ground at the Sabahmas oil palm plantation and therefore do not appear in the figure. Information on sampling frequency and averaging is given in the SI.

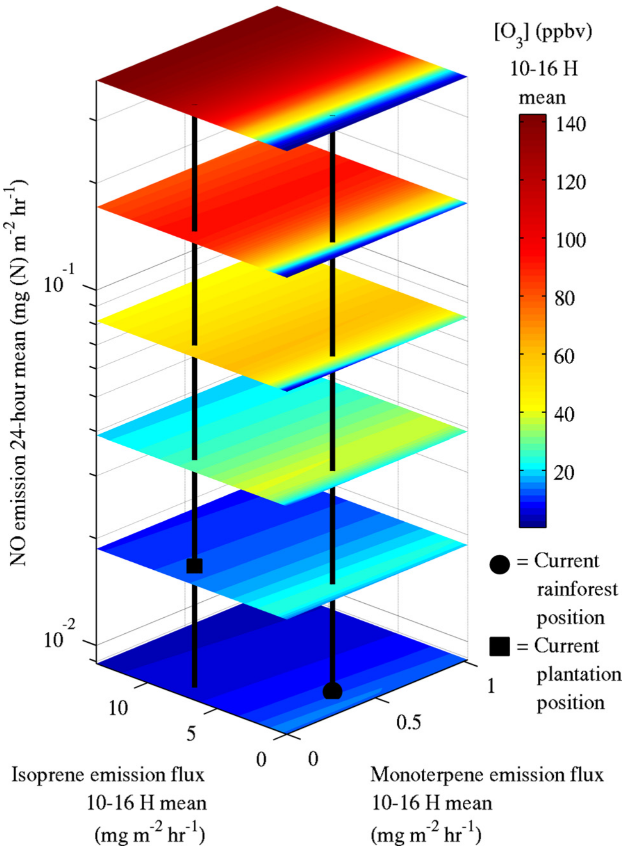

Fig. 3. Sensitivity of mean mixed boundary layer ozone concentrations (from 10.00–16.00 hours) to fluxes of isoprene, monoterpenes, and NO, as computed by CiTTyCAT. VOC fluxes are the mean over 10.00–16.00 hours; NO fluxes are the mean over a 24-hour period. The black lines show the rainforest and plantation VOC emission scenarios. The current rainforest and plantation positions are determined by observed VOC emission rates and ozone concentrations.

penes are the second most important group of biogenic VOCs. At both the rainforest and the plantation sites, γ-terpinene, α-pinene, and limonene dominate the emissions and concentrations of the C_{10} compounds, giving an approximately equal split between more and less reactive monoterpenes (9).

Fig. 2 shows that the differences in emission rates in NO_x and isoprene between the rainforest and the oil palm plantations give rise to differences in concentrations throughout the boundary layer and into the free troposphere. Over the rainforest, median boundary layer mixing ratios of NO, NO_2, and isoprene were 35, 161, and 767 parts per trillion (10^{12}) by volume (pptv), respectively, and over the plantation the median mixing ratios were 67, 288, and 3870 pptv, respectively. Surprisingly, ozone concentrations were similar over both landscapes in the boundary layer (rainforest: 11 ppbv; oil palm plantation: 12 ppbv). The ozone measurements at the Bukit Atur Global Atmosphere Watch station confirm that our measurement period is typical of the long-term record at this site. However, the concentrations of peroxyacetyl nitrate (PAN) increased from 6 pptv in the boundary layer over the rainforest to 12 pptv over the plantation landscape, demonstrating enhanced photochemical processing of the increased NO_x and VOC emissions and concentrations over the plantations.

To understand current and future ozone levels over these 2 landscapes, we have used the CiTTyCAT box model of atmospheric photochemistry (10–12). These computations explore the sensitivity of atmospheric composition in the boundary layer to VOC and NO_x emission rates for the calm, nonprecipitating, atmosphere, consistent with conditions during the measurement period.

Fig. 3 shows the model-calculated average boundary-layer ozone concentrations between 10:00 and 16:00 hours as a function of isoprene, monoterpene, and NO_x emission rates. The model has been enhanced by the inclusion of monoterpene oxidation to capture the rainforest chemistry. Monoterpenes are not yet generally included in atmospheric chemistry models such as those used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (13).

Although the 2 landscapes currently have different NO_x and VOC concentrations, the model predicts similar ozone concentrations, as confirmed by our measurements. The ozone concentrations are similar because ozone production, although driven by increased NO and VOC emissions and oxidation, is moderated here by the rapid sequestering of reactive nitrogen to form organic nitrates that deposit to the surface and by ozone destruction resulting from its direct reaction with monoterpenes.

Fig. 3 also suggests that ozone concentrations at the 2 locations respond quite differently to increasing NO_x emissions and concentrations. In both landscapes, NO_x concentrations will increase with increasing fossil fuel consumption, associated with industrialization, across the region. Additionally, NO_x concentrations will increase in the plantation landscape with increased mechanization, fossil fuel use, and fertilizer application. Total VOC emissions in these landscapes will not be so sensitive to

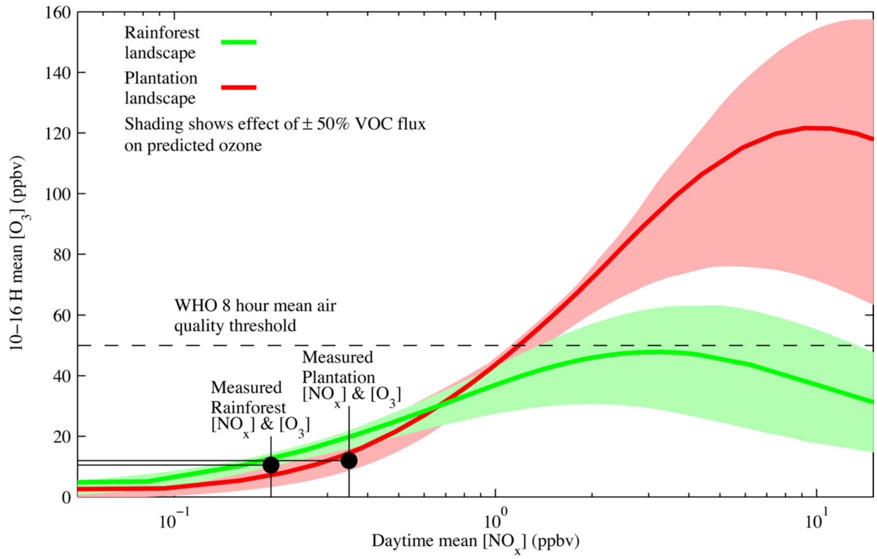

Fig. 4. Sensitivity of daytime (10.00–16.00 hours) average ozone concentration to concentrations of NO_x in the boundary layer, for the isoprene and monoterpene emission rates measured at the rainforest and oil palm landscapes, as computed by CiTTyCAT. Each model run has a similar shape but with a different point of inflection, so the solid lines are not always in the centre of the shaded region. Current measured concentrations of NO_x and O_3 in the rainforest and plantation are marked.

industrialization because of the current large biogenic VOC emission rates (Table 1).

Fig. 4 shows the sensitivity of ozone to NO_x concentrations for the VOC emission rates specific to the 2 locations. The nonlinearity in the chemistry becomes more apparent when the model results are presented this way. Our model predicts that ozone concentrations in the rainforest most probably will not exceed 50 ppbv (except by advection of ozone and its precursors from outside the rainforest landscape), irrespective of NO_x concentration, whereas in the oil palm landscape ozone concentrations will exceed 100 ppbv when NO_x concentrations reach 3–5 ppbv. Such NO_x concentrations are currently widely observed in rural areas of Western Europe (14), North America, and Asia (15). Ozone at 100 ppbv has significant detrimental effects on human health and crop yields and enhances global warming through its strong radiative forcing (1).

Discussion

Our measurements show that the conversion of rainforest to oil palm plantation substantially increases VOC and NO_x emissions and concentrations. The increase in VOC emission rates comes directly from the oil palm plants. The increase in NO_x emission rates comes from agro-industrialization, especially from fertilized soils. These differences in emission rate have increased the concentrations of some photochemical pollutants, notably PAN. Fortunately, they have not, to date, increased the ground-level concentrations of the most hazardous photochemical air pollutant, ozone. However, ozone will increase substantially in this region as NO_x emissions rise with industrialization and economic development.

The degree to which oil palm production will contribute to poor air quality in the future will depend almost entirely on the emission rates of nitrogen oxides. Although ozone concentrations in the rainforest are predicted to remain below 50 ppbv, regardless of the development path taken with respect to emissions of NO_x, there is the potential for ozone concentrations in the plantation landscape to greatly exceed the current World Health Organization 8-hour mean air quality threshold of 50 ppbv. Only stringent controls on emissions to maintain NO_x concentrations below those currently observed in rural parts of Western Europe and North America will prevent this increase from occurring. Controlling nitrogen emissions at both the local (plantation) and regional scales is necessary to prevent large-scale palm oil production from having very serious effects on regional air quality. Genetic modification of the oil palm cultivar to extinguish isoprene emissions (as already demonstrated for poplar [ref. 16]) would also avoid ozone air quality exceedances at any NO_x concentration (see Fig. 3). Without NO_x emissions controls or genetic modification, palm oil production for biofuel and other uses will incur significant future costs in terms of human health effects and crop yield reductions that have yet to be included in sustainability criteria for the industry. The utility of palm oil as an environmentally friendly crop may be therefore severely time-limited.

Methods

The project was based in Sabah, Malaysia, April through July, 2008. Ground-based measurements were performed at the 100-m-high Global Atmosphere Watch tower at Bukit Atur (4° 58′ 49.33″ North, 117° 50′ 39.05″ East, 426 m above sea level) and at the Sabahmas oil palm plantation (5.2° North, 118.45° East), 70 km east-northeast of Bukit Atur. Airborne measurements were made from the Natural Environment Research Council/U.K. Meteorological Office's BAe 146–301 large atmospheric research aircraft, which was based at Kota Kinabalu International Airport. Kota Kinabalu (population 580,000) is the largest city in Sabah and is 250 km northwest of Bukit Atur. Sandakan (population 430,000) and Tawau (population 370,000) are about 100 km north and south of Bukit Atur, respectively. The southern part of Sabah and the adjoining region of Indonesia are largely pristine, and selectively logged, rainforest and local anthropogenic emissions are insignificant. The lowland parts of northern and coastal Sabah are largely oil palm plantations. These plantations are serviced by processing mills, mainly powered by biomass (oil palm husks). No attempt was made to avoid or preferentially to sample the visible mill plumes from the aircraft. The boundary layer was sampled from the aircraft using low-level runs following the terrain, originating above the plantations and terminating above the pristine rain forest. Flying time totaled 68 hours. Measurements included trace gas concentrations and fluxes. Modeling was carried out using the CiTTyCAT box model of atmospheric chemistry. Full details of the measurement and modeling methods used are given in the supporting information (SI).

ACKNOWLEDGMENTS. We dedicate this paper to the memory of Kate Furneaux, a core member of the OP3 project team, who was killed in a traffic accident while cycling in Leeds on 28 July 2009. We thank the Malaysian and Sabah Governments for their permission to conduct research in Malaysia; the Malaysian Meteorological Department for access to the Bukit Atur Global

Atmosphere Watch station and its long-term ozone record; Wilmar International Ltd for access to and logistical support at their PPB Oil Palms Bhd Sabahmas Estate; Waidi Sinun of Yayasan Sabah and his staff, Glen Reynolds of the Royal Society's South East Asian Rainforest Research Programme and his staff, and Nick Chappell and Brian Davison of Lancaster University for logistical support at the Danum Valley Field Centre; the ground staff, engineers, scientists, and pilots of the Natural Environment Research Council/U.K. Meteorological Office's BAe 146–301 large atmospheric research aircraft; Nick Chappell, Gemma Davies, Virginia Nicolas-Perea, and M.H. Phua for drawing and validating Fig. 1; and all the members of the OP3 project team for their support and individual and collective efforts. The work was funded by the Natural Environment Research Council Grants NE/D002117/1 and NE/E011179/1.

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