BIOGEOCHEMICAL RESPONSES TO LAND COVER CHANGES IN COASTAL PEATLAND CATCHMENTS: SPATIAL AND TEMPORAL FLUXES IN GREENHOUSE GAS EMISSIONS AND PEAT SUBSIDENCE, JAMBI PROVINCE, SUMATRA.

Final report to the Southeast Asia Regional Committee for START (SARCS) & United Nations Office for Project Services (UNOPS) [Theme 3: Assessing impacts of environmental changes in terrestrial ecosystems on coastal zones and marine ecosystems]

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Transmigration scheme, study area, 2000

David Taylor and Mochamad Ali
Southeast Asia Regional Committee for START (SARCS) & United Nations Office for Project Services (UNOPS)

Theme 3 *Assessing impacts of environmental changes in terrestrial ecosystems on coastal zones and marine ecosystems*

Final Research Report (April 2001)

**Title of project:** Biogeochemical responses to land cover changes in coastal peatland catchments: spatial and temporal fluxes in greenhouse gas emissions and peat subsidence

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**Correspondence address** *(Principle Investigator, PI):* Dr. David Taylor*
Professor of Geography
Department of Geography
Trinity College
University of Dublin
Dublin 2, Ireland

*formerly of National University Singapore

**Collaborating author’s address:** Dr. Mochamad Ali
Fakultas Pertanian
Universitas Jambi
Kampus UNJA
Mendalo
Jambi 36361. Indonesia
SUMMARY

This research project built upon existing collaborative links between the PI (Trinity College, University of Dublin) and staff in the Department of Geography, National University Singapore (NUS), and Dr. Mochamad Ali and colleagues in the Department of Soil Science, Universitas Jambi, Indonesia. The research aimed to:

(1) develop GIS and remote sensing skills among researchers and practitioners in Southeast Asia and encourage their application to studies of environmental changes and management. The PI addressed the first part of this aim through a five day long training workshop (“Fundamentals and applications of remote sensing and GIS”) at NUS in June 2000 that attracted a full compliment of 20 participants from Southeast Asia.

(2) determine spatial and temporal variations in emissions of carbon dioxide \( (\text{CO}_2) \) (an important greenhouse gas) and peat subsidence from an area of lowland peat swamp to the east of the provincial capital of Jambi on the Indonesian island of Sumatra. The study area incorporates a range of different land covers, many of which have been derived from peat swamp forest through a process of land preparation involving fire-assisted clearance and draining. Peat is high in organic matter, which readily decomposes under the aerobic conditions associated with improved drainage, particularly when temperatures are sufficiently high to permit biological and chemical activity. Decomposition results in shrinkage of the peat body (usually manifest as ‘subsidence’ of the peat surface) and the release of the more labile fractions of organic matter, e.g. \( \text{CO}_2 \) and nitrous oxide \( (\text{N}_2\text{O}) \), to the atmosphere.

This research project attempted to gain insights into variations of \( \text{CO}_2 \) effluxes and peat loss in the study area via a field programme that accommodated a range of land covers and both diurnal and inter-monsoon – monsoon season cycles. Environmental data collected during the field programme comprised information on the extent of different land covers and soils in the study area (from Landsat and SPOT satellite data and 1:250,000 soils maps) and changes in the extents of these from 1989 to 1999. Data were also collected from seven sample plots located on peat in the study area over the period 15-17/09/00 to 15/04/01 on: (a) chemical and physical properties of peat; (b) fluctuations in depth of water table and air and soil temperatures; and (c) variations in \( \text{CO}_2 \) effluxes and peat subsidence.

Subsequent analyses confirm: published relationships between daily mean \( \text{CO}_2 \) effluxes and the temperature of the peat surface and depth of the water table; peat subsidence at all sites, and particularly at those that have been deforested and drained; higher daily mean \( \text{CO}_2 \) effluxes during the main wet (northeast or ‘winter’ monsoon) season from peat cleared of its forest cover than from peat that has remained forested (albeit disturbed by selective logging), and a
possible reversal of the this pattern during the inter-northeast monsoon period; levels of CO$_2$ emissions similar to those published for equivalent, modified peatlands in Malaysia; and estimates of total CO$_2$-C emissions (kg/hr) in the study area for peats beneath selectively logged swamp forest and in areas recently cleared of their forest cover.

Fieldwork for the project was held-up by a delay in the provision of research funds by the UNOP. These funds were required to purchase essential field equipment and to pay for fieldwork costs (including the salaries of field assistants). A severe malfunctioning of the equipment used to collect CO$_2$ efflux data caused a further delay, this time during the period of field data collection. The malfunction required the return of the equipment to its UK-based manufacturer for repair and resulted in no CO$_2$ efflux data being collected for the period mid November 2000 to end of February 2001 (early part of the wet season in the study area).

CO$_2$ efflux and associated environmental data will continue to be collected until June 2001 in order to add information for the drier, inter-northeast monsoon period to the existing database.
A “Fundamentals and applications of remote sensing and GIS” training workshop was held at NUS from June 19 to June 23 2000. The PI, Dr. Heather Holden (who lectures in GIS/remote sensing at NUS) and Ms. Poonam Saksena (Marine Information Technology Laboratory, NUS) jointly organised the workshop, which was attended by nationals from five countries in the Southeast Asia region. A total of 20 participants attended the workshop (see Appendix I), seven of whom received full funding (workshop fees, accommodation, meals and travel to/from Singapore from/to country of origin) through the SARCS/UNOP award (the total number of participants was fixed at 20 before bookings opened, in order for all participants to be guaranteed access to their own PC computer and software during the workshop). Participants attending the workshop with SARCS/UNOP support came from Cambodia (two people), Indonesia (two people), Malaysia (two people) and Vietnam (one person).

All participants at the workshop received a training package (including a CD with pre-loaded copies of the lectures and practicals from the workshop), in addition to hands-on experience in the use of ARCVIEW and ENVI computer software.

**Variations in Land Cover Change, CO$_2$ Effluxes and Peat Subsidence Background**

Soil is a major global-scale sink for organic carbon (1.5 to 3 times as much organic carbon is bound in soils as in vegetation (Rosenzweig and Hillel 2000)). Soils are therefore important in the sequestration of greenhouse gases, such as CO$_2$ and methane (CH$_4$). Increased oxidation, as a result of disturbance and drainage, together with increased microbial activity following the application of fertilisers, have the potential to release organic carbon to the atmosphere by facilitating processes such as decomposition and respiration. Estimates of carbon emissions from soils are difficult to make and fraught with errors. One estimate (IPCC 1996) indicates that agricultural sources, including cultivated soils, contribute around 20% of total anthropogenic emissions of greenhouse gases, with changes in land cover, often associated with agricultural development, accounting for a further 14%. More recently, Fearnside (2000) estimated that changes in tropical land covers alone might represent around 29% of the total anthropogenic emissions of carbon. Furthermore, the effect of climate on carbon effluxes, through its influence over soil temperature and moisture availability, has been demonstrated in a range of field (e.g. Hogg et al. 1992, Magnusson 1993, Moore and Dalva 1993, 1997, Updegraff et al. 1995, Chapman and Thurlow 1996, Yavitt et al. 1997, Ball et al. 1999) and laboratory (Silvola et al. 1996, Bhardwaj 1997, Bubier et al. 1998, Scanlon and Moore 2000) studies. Indeed, soil temperature and moisture (or more accurately oxygen availability) are thought to be among the most important environmental factors controlling the rate of CO$_2$ production in soils (Lessard et al. 1994). The effect of continued global warming and anthropogenically-induced changes to these variables therefore may be a shift in the status of
soils from being sinks of organic carbon to sources (Gorham 1991). Thus carbon emissions from soils may be both implicated in and driven by future climate change, and serve as an example of a positive feedback mechanism in the greenhouse effect (Waelbroeck 1993, Rosenzweig and Hillel 2000).

The potential to act as a source of greenhouse gases is greatest in those soils containing abundant organic residues (mainly the remains of plants) (Aerts and Ludwig 1997). The most organic-rich soils are commonly referred to as peat. Peat forms where rates of decomposition of organic matter are reduced, generally as a result of a combination of anaerobic (i.e. waterlogged) conditions and high acidity (Moore et al. 1991).

Peat swamps, or peatlands, in the tropics cover an estimated 30 million ha, or around 6% of the world total (Inubushi et al. 1998). Around two thirds of tropical peatlands are located in Southeast Asia, where they form deposits up to several metres deep that blanket the coastal plains and lower parts of many river valleys. Peatlands in Southeast Asia have been extensively and intensively modified over the last two to three decades, usually through the clearance and drainage of peat swamp forest in association with the development of commercial logging and plantation agriculture. Studies of the environmental impacts that can follow the conversion of large areas of tropical peat swamp forest to other land covers are, however, relatively few. The UNOP/SARCS-funded research described below aimed to determine spatial and temporal variations in CO$_2$ effluxes from peat and rates of peat subsidence for an area of peatland in Southeast Asia that had been subjected to extremely high rates of environmental changes over the preceding decade or so. Furthermore, the use of satellite images of the study area in combination with CO$_2$ efflux data provided a means of roughly estimating landscape-scale, total yields of CO$_2$-C from peats associated with two major forms of land cover in southeast Sumatra, and indeed much of lowland parts of the western islands of Indonesian, namely selectively logged and recently cleared peat swamp forest. The landscape-scale estimates are useful first approximations only, and come no-where near accounting for the full range of spatial variations within and between the two land covers. Constraining the uncertainties associated with spatial variations ought to be a focus of subsequent research.

**STUDY AREA**

The study area comprises the catchments for two rivers (Sungai Lagan and Sungai Mendahara) draining coastal wetlands in southeast Sumatra, Indonesia. Soils in the study area mainly comprise peat over alluvium, with the latter exposed towards the coast and along rivers, although outlies of Ultisols are present in the southwest and east (Figure 1). Peat and alluvium in the study area are believed to be Holocene in age and to date to episodic progradation following marine transgressions, the last major phase of which impacted upon southeast Sumatra from around 1500 years ago (Furukawa 1994: 29). There is anecdotal evidence from fisher people
in the study area to suggest that the coastline is still actively prograding, with new mud banks rapidly colonised by an advancing front of mangrove forest taxa. This evidence corroborates with observations from elsewhere in eastern Sumatra, where estimates place the modern rate of progradation from around 30 to 125 m year$^{-1}$ (Macnae 1968, Sobur et al. 1977), with more than 200 m year$^{-1}$ reported in some deltaic areas (Guelorget et al. 1996).

Mean annual precipitation in the study area is 2490 mm yr$^{-1}$ (calculated over the period 1989-1999 using data from the airport at Jambi, which at ca. 70 km away from the study area is the closest, reliable meteorological station). There is no pronounced dry season, although mean monthly rainfall figures indicate that the wettest period is associated with the northeast monsoon (generally from late October through to April) and the driest with the southwest monsoon (usually May through to October).
The catchments for the Sungai Lagan and Sungai Mendahara have been extensively modified through the replacement of peat swamp and coastal (mangrove) forests with plantation agriculture (Figure 2). This first occurred in the form of a major transmigration scheme during the late 1970s and early 1980s. Initially farmers who were part of the transmigration scheme grew rice. However, it was evident from discussions with farmers in the transmigration area that yields have dropped dramatically to around 20 percent of their original levels, largely as a result of the acidification of cultivated soils. Falling productivity, together with low profit margins for rice sold at market, have encouraged farmers to diversity and many now co-plant rice with other crops, notably banana, cassava, coconuts, coffee and (most recently) oil palm. Low incomes and the isolated nature of many farmsteads have meant that fertilisers are rarely if ever used. The transmigration scheme was expanded following the major peat swamp forest fires in 1996-1997 (Frontplate and plates 1 and 2), although many of the new farmsteads remain

Figure 2: The extents of land covers in the study area, based on mosaicked SPOT satellite data for February 1999 (see Figure 3).
Plate 1: Peat swamp forest in the study area destroyed during the 1996-1997 forest fires.

Plate 2: Farmsteads in the study area, forming part of an extension to a large transmigration scheme that followed major peat swamp forest fires in 1996-1997.
unoccupied or were quickly abandoned. Many of the inhabitants of those farmsteads that are still occupied supplement their incomes through the illegal logging of remaining areas of peat swamp forest.

All remaining peat swamp forest in the study area, though nominally protected, has been either selectively logged-out or is in the process of being selectively logged. This logging is labour intensive and is carried out by both locals and peripatetic ‘teams’ of non-local loggers. Commercially valuable trees are first marked before being cut down using powered chain saws. Once felled, trees are de-branched and the trunks dragged to the margins of the forest along skid tracks (Plate 3). Most of the trees felled supply local sawmills (Plate 4). A local break down in implementing environmental regulations and an improved infrastructure that has developed along with the exploitation of oil reserves in the area has facilitated transportation of illegally cut timber to sawmills in and around the study area.

Established, relatively old settlements are located in the lower parts of the two rivers in the study area (Plate 5). Although inhabitants of these settlements practice some agriculture, generally rice and coconuts grown in smallholdings on alluvial soils, aquaculture and fishing provide the main sources of employment and income. A significant proportion of the catch is exported to Riau Province and Singapore.

Plate 3: Illegal logging of ‘protected’ peat swamp forest in the study area.
Plate 4: Riparian sawmill on the Sungai Mendahara.

Plate 5: Established coastal settlement in the study area; Mendahara Ilir, at the mouth of the Sungai Mendahara.
METHODS

Data collection
Seven permanent sample plots (each with dimensions 20m x 6m [120m²]) were located on peat beneath three different land covers; selectively logged forest [three plots], newly established cultivated land [two plots] and established agricultural land (part of a major transmigration scheme) [two plots]. Plots were located close to one another, in order to facilitate sampling in the field and to minimise differences in physical and chemical properties between the peat deposits. The newly established, cultivated land was cleared of its original forest cover, burned and drained (Plate 6) seven months prior to the start of field sampling, before being planted with cassava and rice. By comparison, land in the part of the transmigration area sampled during the present research was cleared of its forest cover during the major forest fires of 1996-1997 and is now planted with banana, cassava, coconuts and rice. Fertilizers have never been applied to any of the sample plots located on cultivated land.

Fieldwork commenced in September 2000 and continued on a fortnightly basis to January 2001, after which point fieldwork was temporarily halted because of equipment malfunction. A review of previously collected data indicated that the faulty equipment may have been malfunctioning since mid-November 2000, and therefore that the measurements collected from

Plate 6: Peat in the settled agriculture part of the study area, showing evidence of subsidence.
mid-November to January were suspect. Fieldwork recommenced at the beginning of March 2001, following repair of the faulty equipment by its UK-based manufacturer, and will continue to mid June 2001, in order to obtain data for as complete a monsoon – inter-northeast monsoon cycle as possible. Data collected in the field comprised geo-locational information using hand-held and differential GPSs, water table depth, temperature of air (1 m above the surface) and soil (at 20cm depth), physical and chemical characteristics of peat, including the amount of subsidence, and measurements of effluxes of CO$_2$. Up to five measurements per plot were made (ten for peat subsidence).

Bulk densities of peat in the sample plots were determined by measuring the volume and dry weight of ring core samples (5cm diameter x 5cm thickness). Peat subsidence was determined by measuring the amount by which the peat surface in each sample plot had lowered relative to ten erosion pins. These pins had been inserted so that their tops were flush with the surface of the peat at the beginning of the field-sampling period.

Effluxes of CO$_2$ were determined in situ through a dynamic, ‘closed chamber’ approach (Janssens et al. 2000), as opposed to micrometeorological methods where the vertical flux of CO$_2$ measured at a reference height is assumed to be identical to efflux from the soil (Mosier 1990). The closed chamber was adopted partly because of the limited funds available (micrometeorological methods are generally far more expensive to deploy than those using closed chambers), but mainly because of conditions in the field (lack of an homogenous ‘fetch’ for air containing emitted CO$_2$ and problems over ensuring the security and safety of large pieces of field equipment) and the need to restrict efflux data to emissions from the soil surface/ground vegetation layer. The measurement of CO$_2$ efflux from peat – a primary aim of the present research – as separate from other contributions to atmospheric carbon is problematic in micrometeorological methods (Goulden and Crill 1997). Techniques of determining effluxes of CO$_2$ using closed chambers are not problem free, however, and may suffer from ‘chamber effects’ (sensu Mosier 1990). For non-permanent closed chambers, these effects include soil disturbance, causing CO$_2$ to be released from disrupted pore spaces (Matthias et al. 1980), alteration of diffusion rates between the peat surface and ‘atmosphere’ in the chamber space (Healey et al. 1996, Rayment and Jarvis 1997), and an inability to separate the various potential sources of ground-level emissions of CO$_2$, such as organic matter decomposition and root and above ground plant respiration (Chapman and Thurlow 1996).

The dynamic closed chamber approach adopted in the present research involved placing a PVC chamber (SRC-1, PPSystems UK) of 150mm height and 100mm diameter on the peat surface, making sure that an airtight seal was made with the surface (by pressing the chamber firmly into the peat so that a stainless steel perimeter ring around the chamber was partially embedded) while ensuring that any disturbance of peat was minimised. The rate of CO$_2$ increase in the
chamber was then determined over a 120sec period using a portable, infra-red Environmental Gas Monitor (EGM-3, PPSystems UK) fitted with a water vapour equilibrator (Plate 7). The relatively short sampling period eliminated problems due to major variations in temperature, pressure and humidity. The EGM-3s used in the present research had previously been calibrated for work at or near sea level and efflux data gathered were effectively ‘dry’ gas concentrations and required no temperature conversion.

Assuming a well mixed, sealed system, CO$_2$ effluxes can be determined from:

$$ R = \frac{(C_n - C_0)}{T_n} \times \frac{V}{A} $$

where,

- $R$ = soil respiration rate (efflux of CO$_2$/unit area/unit time)
- $C_0$ = CO$_2$ concentration at onset of sampling (T0)
- $C_n$ = CO$_2$ concentration at end of sampling (Tn)
- $A$ = the area of soil exposed ($78.55 \text{ cm}^2$)
- $V$ = the total system volume ($1178.25 \text{ cm}^3$)

Replicate measurements of CO$_2$ efflux were made at each of the seven sample plots over a two-day period to January 2001 and over a single day from the beginning of March 2001.

**Plate 7:** Collection of CO$_2$ efflux data in the field as part of the present research project.
Measurements were made at three different times during the day, around daybreak (5.30am to 7.30am), midday (11.00am to 2.00pm) and evening (4.00pm to 6.00pm). Measurements were made hourly at plots located in the swamp forest and transmigration areas over the period October 16 to 17 2000 in order to obtain an understanding of diurnal variations in CO₂ emissions.

**Satellite data**

Unpublished land cover information for the study area, in the form of geo-referenced SPOT satellite data that have previously been extensively checked against conditions on the ground, were made available through collaboration with a related research project, led by Geraldine Lee (Centre for Remote Imaging, Sensing and Processing (CRISP), NUS).

Four February 1999 images from the SPOT satellite were acquired for a 14,400 km² (120km x 120km) swathe of land that includes the study area and mosaicked together (Figure 3). The

![Figure 3: Mosaicked SPOT satellite data for February 1999 for a 120km x 120km swathe of southeast Sumatra that includes the study area (area within box).](image)
mosaic of image data were automatically enhanced using a standard deviation stretch and classified into 14 categories of land cover following an extensive field survey during 1999 and Laumonier (1997) (Geraldine Lee pers. comm.). The two catchments forming the study area for the present research were ‘cut’ from the mosaicked data and the number of land covers revised down to six categories. A comparison of the estimates of land cover data determined from the mosaicked SPOT images with estimates for the same categories of land cover from a Landsat TM satellite image for April 1989 that included the study area provided evidence of the extent and rate of changes in the study area over the past decade.

Data analysis
Figures 4a and 4b illustrate diurnal variations in environmental measurements at plots located in, respectively, logged peat swamp forest and settled agriculture over a 24-hour period from October 16 to October 17 2000. Sampling coincided with heavy rains that marked the beginning of the northeast monsoon (the rains started earlier in 2000 than in previous years); water tables were higher at the plots in logged peat swamp forest (around 30cm below the surface) than at those in the settled agriculture area (around 50cm below the surface). Minimum and maximum air temperatures were similar at the two sites (although the range for the settled agriculture area, at 21 to 35 °C, was wider than for the logged peat swamp forest, at 22 to 34 °C) with maximum air temperatures at both sites, not surprisingly, occurring during the hours of daylight and particularly at and shortly following midday. Soil temperature ranged from 25 to 27 °C for plots in logged peat swamp forest and 28 to 29 °C for those in the settled agriculture area.

![Figure 4a: Diurnal variations in environmental data measured at the plots in logged peat swamp forest during the period October 16-17 2000.](image-url)
Mean diurnal CO$_2$ effluxes at the two sites ranged from -0.68 (i.e. CO$_2$ uptake) to 36.38 mmol CO$_2$/m$^2$/hr for logged peat swamp forest and 15.91 to 59.85 mmol CO$_2$/m$^2$/hr for the area of settled agriculture. Mean CO$_2$ effluxes from peats beneath selectively logged swamp forest soils were generally lower and varied less over the diurnal period of study than from those supporting settled agriculture, although CO$_2$ effluxes at both sites appear to track mean air temperatures.

Data expressed in tables 1 and 2 and illustrated in Figure 5 are the means or ranges of data for sample plots collected during fortnightly periods of fieldwork from mid-September 2000 to mid-April 2001. Table 1 indicates the level of similarity in physical and chemical properties between peats in the sample plots clustered according to land cover. The C:N ratios for peats beneath selectively logged swamp forest are relatively high, indicating lower levels of decomposition of organic carbon than in recently cleared and settled agriculture areas (Kalbitz et al. 1999), which also explains the differences in rates of subsidence measured for the three clusters of plots.

Table 2 includes estimates of daily mean CO$_2$ efflux data expressed in various forms, thus allowing comparisons with published values (there are no universally-accepted units of greenhouse gas efflux data). Two populations of daily mean CO$_2$ efflux data are evident. One coincides with the latter stages of the inter-northeast monsoon period, when water tables reached their lowest levels at all sites and particularly at the plots located in peat swamp forest, and

**Figure 4b:** Diurnal variations in environmental data measured at the plots in the settled agriculture area during the period October 16-17 2000.
represents raised levels of daily mean CO$_2$ efflux at these plots when compared to those located in newly cleared and settled agriculture areas. A second population correlates with higher water tables, especially for plots located in the selectively logged peat swamp forest, and the occurrence of the northeast monsoon, which is responsible for the main wet season in the study area. This second population of data is characterised by relatively low CO$_2$ effluxes from peats beneath swamp forest when compared to those that have been cultivated, and direct and inverse relationships between CO$_2$ effluxes and, respectively, air temperatures and depth of the water table.

**Table 1:** Summary of physical and chemical properties of peat in the sample plots

<table>
<thead>
<tr>
<th>Sample plots</th>
<th>Peat depth (m)</th>
<th>Depth of water table (cm)*</th>
<th>Bulk density (g/cm$^3$)</th>
<th>C/N ratio</th>
<th>pH (H$_2$O)</th>
<th>Subsidence (cm)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest plots</td>
<td>&gt; 2^</td>
<td>0 - 65</td>
<td>0.26 – 0.30</td>
<td>12.3- 13.4</td>
<td>3.9 – 4.0</td>
<td>0.9 – 1.1 [1.5 – 1.9]</td>
</tr>
<tr>
<td>Recently cleared plots</td>
<td>&gt; 4^^</td>
<td>20 - 65</td>
<td>0.29 – 0.35</td>
<td>5.0</td>
<td>3.8 – 4.0</td>
<td>1.3 – 1.7 [2.2 – 2.9]</td>
</tr>
<tr>
<td>Transmigration plots</td>
<td>&gt; 4^^</td>
<td>30 - 125</td>
<td>0.35 – 0.45</td>
<td>5.2 – 6.8</td>
<td>3.9 – 4.0</td>
<td>1.5 – 2.0 [2.6 – 3.4]</td>
</tr>
</tbody>
</table>

- = measured spatial range within sample plots, unless otherwise stated  
* = measured range over period of study (15/09/00 to 15/04/01 (7 months))  
** = measured total between 15/09/00 and 15/04/01 (7 months)  
^ = too woody for peat corer to penetrate further  
^^ = beyond the maximum depth of the peat corer used

**Figure 5:** Environmental data measured at the seven sample plots over the period 15-17/09/2000 to 15/04/2001.
Table 2: Measurements of efflux of CO₂ from peat surface, temperature of air and soil (20 cm below the surface) and depth of water table for the three clusters of sample plots in the study area.

<table>
<thead>
<tr>
<th>Date of field measurement (cluster at S 1° 15', E 103 37')</th>
<th>Forest plots</th>
<th>Recently cleared plots</th>
<th>Transmigration plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux Mean temp °C Air/Soil Depth cm of WT</td>
<td>Flux Mean temp °C Air/Soil Depth cm of WT</td>
<td>Flux Mean temp °C Air/Soil Depth cm of WT</td>
<td></td>
</tr>
<tr>
<td>15/09 – 17/09</td>
<td>1.39* 8.78** 31.61* 3.79** 1828010</td>
<td>27.7/ 26.3 53-65</td>
<td>0.85* 5.37** 19.33* 2.32** 366710</td>
</tr>
<tr>
<td>02/10 – 04/10</td>
<td>1.57* 9.91** 35.68* 4.28** 206435</td>
<td>28.2 / 27.0 40-60</td>
<td>1.41* 8.9** 32.04* 3.84** 606810</td>
</tr>
<tr>
<td>16/10 – 18/10</td>
<td>0.63* 3.98** 14.33* 1.72* 829600</td>
<td>26.6 / 26.3 20-50</td>
<td>1.71* 10.8** 38.88* 4.67** 937990</td>
</tr>
<tr>
<td>03/11 – 05/11</td>
<td>0.79* 4.99** 17.96* 2.16** 1041820</td>
<td>28.0 / 26.0 8-15</td>
<td>1.54* 9.72** 34.99* 4.20** 663700</td>
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<tr>
<td>13/11 – 15/11</td>
<td>0.99* 6.25** 22.5* 2.77** 1302280</td>
<td>27.3 / 26.3 5-15</td>
<td>1.13* 7.13** 25.67** 3.08** 486710</td>
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<tr>
<td>01/03</td>
<td>0.48* 3.03** 10.91* 1.31** 631850</td>
<td>28.5 / 25.8 5-25</td>
<td>0.58* 3.66** 12.18** 1.58** 249680</td>
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<tr>
<td>15/03</td>
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<td>26.3 / 25.6 5-10</td>
<td>0.97* 6.12** 22.03** 2.64** 417180</td>
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<tr>
<td>01/04</td>
<td>0.34* 2.15** 7.74* 0.93** 448560</td>
<td>27.3 / 25.3 0-5</td>
<td>0.86* 5.43** 19.55** 2.35** 371350</td>
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<tr>
<td>15/04</td>
<td>0.39* 2.46** 8.86* 1.06** 511260</td>
<td>26.9 / 25.4 10-12</td>
<td>0.66* 4.17** 15.01* 1.80** 284440</td>
</tr>
</tbody>
</table>

= Fieldwork was suspended between January 2001 and March 2001 because of faulty equipment. Subsequent analysis of previously collected data revealed that the equipment may have been malfunctioning since mid-November 2000 and therefore the accuracy of data collected during the period mid-November 2000 to January 2001 could not be relied upon (see text for details).

* = day-light mean g CO₂/m²/hr
** = day-light mean µmol CO₂/m²/sec
++ = day-light mean mmol CO₂/m²/hr
⊗ = estimated total CO₂-C emissions (kg/hr) in the study catchments (based on areas of land covers determined from mosaiced SPOT satellite data for the month of February, 1999) [see Table 3 for areas of different land covers]
⊗* = settled agriculture, including transmigration areas, located on alluvium was not distinguished on the satellite data from those areas over peat in this analysis.
Estimates of the areas of the six categories of land cover in the study area – as of February 1999 - are given in Table 3. Table 3 also indicates the extent of changes in land cover during the period April 1989 to February 1999, based on a comparison of the mosaicked SPOT and Landsat TM satellite data. Two categories of land cover not seen on the SPOT images were visible on the Landsat TM image (undisturbed peat swamp forest and logged dry land forest), and two categories visible on the SPOT images were not observed on the Landsat TM image (established plantations on dry land soils and recently burnt forest). According to Table 3, it seems that the majority of logged dry land forest had been converted to plantations or incorporated within smallholder farms by 1999, while large extents of peat swamp forest were logged or burnt during the same period.

Discussion
The results obtained to date represent spatial and temporal variations in CO\textsubscript{2} effluxes between and within the three clusters of sample plots. These variations appear to track fluctuations in air temperature, with highest effluxes generally during daylight hours. The depth of the water table also appears to have a strong influence on CO\textsubscript{2} effluxes. The most obvious explanation is that air temperature is a reflection of temperature at the surface of the soil, which directly influences chemical processes leading to the emission of CO\textsubscript{2} (such as respiration and decomposition), while depth of the water table has an impact upon degree of aeration and

<table>
<thead>
<tr>
<th>Land cover</th>
<th>1989 area (ha)</th>
<th>1999 area (ha)</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undisturbed peat swamp forest</td>
<td>9960.8</td>
<td>Not present</td>
<td>- 100</td>
</tr>
<tr>
<td>Logged peat swamp forest</td>
<td>49989.8</td>
<td>48232.5</td>
<td>- 3.5</td>
</tr>
<tr>
<td>Logged dry land forest</td>
<td>35719.0</td>
<td>Not present</td>
<td>- 100</td>
</tr>
<tr>
<td>Mangrove forest</td>
<td>1599.0</td>
<td>1630.1</td>
<td>+ 1.9</td>
</tr>
<tr>
<td>Settled agriculture (including established transmigration schemes) on wetland soils</td>
<td>54592.4</td>
<td>53548.8</td>
<td>- 1.9</td>
</tr>
<tr>
<td>Established plantations on dry land soils (ultisols)</td>
<td>Not present</td>
<td>24943.4</td>
<td>---</td>
</tr>
<tr>
<td>Forest (mainly peat swamp forest) burn scars</td>
<td>Not present</td>
<td>15802.3</td>
<td>---</td>
</tr>
<tr>
<td>Secondary growth dry land forest mixed with crops</td>
<td>17135.4</td>
<td>21852.6</td>
<td>+ 27.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>168996.4</strong></td>
<td><strong>166009.7</strong></td>
<td>- 1.8</td>
</tr>
</tbody>
</table>

Table 3: Extent of major categories of land cover in the study area (catchments for the Sungai Lagan and Sungai Mendahara), based on Landsat TM (April 1989) and mosaicked SPOT (February 1999) satellite data. The difference in the total areas is probably largely a result of differences in resolution between the SPOT and Landsat TM satellite data. Similarly, changes in extent of land covers of less than around 5 percent are probably not significant.
therefore decomposition-linked emissions. According to Silvola et al. (1996), surface temperature of the peat (at -2cm) and the depth of the water table proved to be the best predictors of CO$_2$ emissions among a range of variables observed.

Measured daily mean CO$_2$ effluxes ranged from 7.74 to 35.68mmol CO$_2$/m$^2$/hr (or 340 to 1570mg CO$_2$/m$^2$/h) over the seven months of the study, and were generally highest for the plots on recently cleared and settled agriculture land during the northeast monsoon season. Measured emissions are therefore close to those determined for Malaysian peats beneath various established land covers (7.43 to 26.1mmol CO$_2$/m$^2$/hr) (Murayama and Bakar 1996) and for ombrotrophic peatlands in Scandinavia during the summer months (600mg to 1500mg CO$_2$/m$^2$/h) (Silvola et al. 1996). They are also within the range of those determined for eutrophic and mesotrophic peats subjected to varying levels of oxygen availability under laboratory conditions (Aerts and Ludwig 1997).

One noticeable feature of the emissions data is that effluxes of CO$_2$ at the forest and agricultural sites appear out of phase in their response to seasonally determined, environmental variables. Thus one of two populations of data evident in the results and appearing to coincide with the later stages of the inter-northeast monsoon period is characterised by low water tables at all sites and by raised levels of daily mean CO$_2$ efflux from the plots located in the peat swamp forest area. A second population, associated with the northeast monsoon period, is characterised by relatively high water tables, especially for plots located in the selectively logged peat swamp forest, and low CO$_2$ effluxes from peats beneath swamp forest. It is possible that the first of the two populations of data are in error; only a small part of the inter-northeast monsoon period was sampled (hence a continuation of field sampling through to mid-June 2001). However, the data could conceivably be accurate as there is evidence from other work to suggest that forested organic-rich soils can emit more CO$_2$ per unit area than cultivated examples of the same soils. For example, measured CO$_2$ effluxes from forested, organic-rich soils in Ottawa, Canada were three times higher than from cultivated soils of the same type (Lessard et al. 1994).

Spatial differences in the amount of peat subsidence over the period of fieldwork are also apparent. Measured levels of peat subsidence varied from 1.5 to 3.4cm/year, and were highest for the agricultural plots, especially those in the settled agriculture area, presumably because of increased drainage-determined shrinkage and decomposition. Levels of peat subsidence for the agricultural plots (2.2 to 3.4 cm/year) are within the range calculated for newly modified, large peatlands in Malaysia (2 to 4cm) (Murayama and Bakar 1996), where the cause of peat subsidence has largely been ascribed to increased aeration and greater microbial activity following drainage. One consequence of peat subsidence in the study area will be further reductions in agricultural productivity, as the modified peat surface (and any associated crops) is brought closer to acidified groundwater, thus also increasing the incidence of flooding. If
farmers respond by applying fertilisers and improving drainage, a positive feedback may develop in which resultant increased aeration and microbial activity lead to further decomposition, subsidence and reduced agricultural productivity, and consequently the need for more fertilisers and deeper drainage channels.

From the comparison of Landsat TM and SPOT satellite data for the study area, the conversion of forest (mainly on peat) to agricultural land and plantations has been the most dramatic of the land cover changes documented for the period 1989-1999. The overall effect of this conversion on emissions of CO$_2$ from soils remains uncertain for the time being (higher levels of certainty await the collection of additional field data particularly for the climatically relatively dry, inter-northeast monsoon period). One affect appears, however, to have been increased effluxes of CO$_2$ during the wet season. An expansion in the area of recently burnt vegetation is also evident, with selectively logged forest likely to have been particularly prone to burning, as was generally the case in Sumatra during the forest fire event of 1997-1998 (Stolle and Tomich 1999). A huge initial burst in emissions of CO$_2$ must have occurred along with major forest fires (Crutzen and Andreae 1990, Tinker et al. 1996), especially if the peat substrate was also ignited. CO$_2$ emissions are likely to have remained relatively high, as data collected in the present study indicate effluxes from peat recently cleared of its forest cover are generally around 30 to 100% greater than from selectively logged peat swamp forest.

Results from the present research also indicate the existence of a relationship between levels of CO$_2$ effluxes and temperature and depth of water table. One implication of this is that emissions are likely to be influenced by future climate changes. Although global circulation models (GCMs) predict relatively small increases in temperatures in the tropics during the coming 50 to 100 years, compared to more temperate parts of the Northern Hemisphere for example, rises in mean annual temperature of up to 3 °C are expected (Taylor and Sanderson in press). One estimate indicates that a similar increase in temperature (2.5 °C) would increase emissions of CO$_2$ from two areas of peat in Scotland by 36% and 59% (Chapman and Thurlow 1996). The relationship between temperature and CO$_2$ release from temperate peatlands may not be directly applicable to the tropics. However, a review of global CO$_2$ effluxes under different climate and vegetation regimes by Raich and Schlesinger (1992), which reported values of Q$_{10}$ (a multiplier denoting the increase in rate of a reaction due to a 10 °C increase in temperature) between 1.3 and 3.3, suggests that levels of warming predicted for the tropics are likely to have a significant impact on rates of decomposition of organic carbon, and therefore on emissions of CO$_2$ and the amount of subsidence of peatlands. This will be particularly the case if the availability of soil moisture becomes less, as predicted by some GCMs. In Southeast Asia, where extensive areas of peat at low altitude are being rapidly transformed, further subsidence of the peat surface will inevitably increase vulnerability to global warming-induced rising sea levels and increased storminess.
CONCLUSION

The analysis of environmental data collected over the seven month period 15-17/09/2000 to 15/04/2001 indicates spatial and temporal variations in emissions of CO$_2$ from, and subsidence of, an area of modified, lowland peat swamp in southeast Sumatra.

Specifically, data collected as part of this UNOPS/SARCS-funded research project:

- confirm published relationships between daily mean CO$_2$ effluxes from the surface of peat and the temperature of peat surface and depth of the water table, and thus implies a potential global warming affect on CO$_2$ effluxes from tropical peatlands;
- provide evidence of peat subsidence at all sites, and particularly at those that have been deforested and drained, at rates similar to those published for modified peatlands in Malaysia;
- indicate diurnal and seasonal variations in daily mean CO$_2$ effluxes from different land covers, with highest emissions associated with daylight hours when temperatures and the activity of organisms are highest;
- suggest higher daily mean CO$_2$ effluxes during the main wet (northeast or ‘winter’ monsoon) season from peat cleared of its forest cover than from peat that has remained forested (albeit disturbed by selective logging) and a possible reversal of this pattern in the later stages of the inter-northeast monsoon period;
- provide estimates of mean daily CO$_2$ effluxes (range from 7.74 to 35.68mmol CO$_2$/m$^2$/hr, or 340 to 1570mg CO$_2$/m$^2$/h) that are similar to those published for equivalent, modified peatland systems in Malaysia; and
- provide a first estimate – albeit highly uncertain – of total emissions of CO$_2$ –C from two major types of land cover in the study area, and in southeast Sumatra generally.

ACKNOWLEDGEMENTS

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REFERENCES CITED


## APPENDIX 1

### Participants in the workshop

**“Fundamentals and Applications of GIS and Remote Sensing”**

**NUS, June 19-23 2000**

<table>
<thead>
<tr>
<th>NAME</th>
<th>EMAIL</th>
<th>ADDRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Keo Veasna</td>
<td><a href="mailto:neap@forum.org.kh">neap@forum.org.kh</a></td>
<td>Ministry of Environment, #48, Samdech Preah Sihanouk Ave., Chamkarmon, PNH, Cambodia.</td>
</tr>
<tr>
<td>2  Sao Sythuon</td>
<td><a href="mailto:neap@forum.org.kh">neap@forum.org.kh</a></td>
<td>Ministry of Environment, #48, Samdech Preah Sihanouk Ave., Chamkarmon, PNH, Cambodia.</td>
</tr>
<tr>
<td>3  Elia</td>
<td>Elia G [<a href="mailto:elia@mesra.net">elia@mesra.net</a>]</td>
<td>MSc Student Bioresource Information Technology Faculty of Forestry Universiti Putra Malaysia</td>
</tr>
<tr>
<td>4  Nguyen Thi Kim Cuc</td>
<td><a href="mailto:merd@netnam.org.vn">merd@netnam.org.vn</a></td>
<td>Mangrove Ecosystem Research Division CRES Vietnam National University, Hanoi 7 Ngo 115, Nguyen Khuyen, Hanoi, Vietnam</td>
</tr>
<tr>
<td>5  Dr. Mochamad Ali</td>
<td>mochamad ali [<a href="mailto:moch.ali@jambi.wasantara.net.id">moch.ali@jambi.wasantara.net.id</a>]</td>
<td>Fakultas Pertanian Universitas Jambi, Jambi</td>
</tr>
<tr>
<td>6  Harzany Jamaluddin</td>
<td>Harzany Jamaluddin [<a href="mailto:Harzany@netscape.net">Harzany@netscape.net</a>]</td>
<td>Technical Manager Centre for Precision Agriculture &amp; Bioresource Remote Sensing Institute of Bioscience, University Putra Malaysia 43400 Serdang, Malaysia</td>
</tr>
<tr>
<td>7  Mr Otto Fung</td>
<td><a href="mailto:NPARKS_Training@NPARKS.gov.sg">NPARKS_Training@NPARKS.gov.sg</a></td>
<td>Contact person: Iqbal Sanjiman National Parks Board Headquarters Singapore Botanic Gardens 1 Cluny Road Singapore 259569</td>
</tr>
<tr>
<td>8  Mr Ahmad Riteby</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9  Mr Robert Teo</td>
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<td>10 Mr Tay Soon Lian</td>
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<td>11 Mr Oi Keng Hunt</td>
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<td>12 Mr Daniel Tay</td>
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<tr>
<td>13 Mr Sim Cheng Hai</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Ms Peggy Koh</td>
<td><a href="mailto:TAN_Bee_Choo@URA.gov.sg">TAN_Bee_Choo@URA.gov.sg</a></td>
<td>Maritime &amp; Port Authority of Singapore, 460 Alexander Rd # 18-00 PSA Building, Singapore 119963</td>
</tr>
<tr>
<td>15 Ms Ng Mui Lin, Alicia</td>
<td><a href="mailto:HO_Soh_Tin@MOE.gov.sg">HO_Soh_Tin@MOE.gov.sg</a></td>
<td>Ministry of Education</td>
</tr>
<tr>
<td>16 Ms. Ho Soh Tin and Mr. Lee Suat Hui</td>
<td><a href="mailto:tdp@moe.edu.sg">tdp@moe.edu.sg</a></td>
<td>St. Andrew’s Junior College</td>
</tr>
<tr>
<td>17 Mr. Rambe (Yulia Morsa Said)</td>
<td>mochamad ali [<a href="mailto:moch.ali@jambi.wasantara.net.id">moch.ali@jambi.wasantara.net.id</a>]</td>
<td>Universitas Jambi, Jambi</td>
</tr>
<tr>
<td>18 Ms. Sia Bee Leng</td>
<td>Yak-Foo Sheau Yang [<a href="mailto:yak_sheau_yang@nygh.moe.edu.sg">yak_sheau_yang@nygh.moe.edu.sg</a>]</td>
<td>Nanyang Girls High School</td>
</tr>
</tbody>
</table>

NB Those names in **red** received support from the UNOP/SARCS award to participate in the workshop.