Effects of agricultural projects on nutrient levels in Lake Bera (Tasek Bera), Peninsular Malaysia

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A B S T R A C T

Lake Bera is the largest natural lake in Peninsular Malaysia and was designated as its first Ramsar site in 1994. The lake has a total catchment area of 593.1 km$^2$, although approximately 340 km$^2$ of the original tropical rain forest cover has been converted to oil palm and rubber plantations since 1972. Research was conducted to determine the soil nutrient contents in the areas of developed land and to correlate historical variations in nutrient concentrations and eutrophication at the lake with anthropogenic activities. Thus, soil samples in areas of different land use in the catchment area were collected in addition to two cores in the bottom sediments of Lake Bera. In total, 132 samples were analyzed for total carbon (TC) and total nitrogen (TN) contents as well as fallout $^{210}$Pb and $^{137}$Cs radionuclide activities. Sediment profile dating was performed using the constant rate of supply (CRS) model; the resultant sediment ages were verified by $^{137}$Cs horizons. Soils in cleared forest areas exhibited the lowest average nutrient content and $^{137}$Cs inventory with an average loss of carbon, nitrogen and $^{137}$Cs, of 54.6%, 31.2%, and 74%, respectively, in comparison with soils in areas of undisturbed forest. Clear-felling and burning during forest conversion were identified as the two main mechanisms that disrupted the nutrient cycles in the lake catchment. The total concentrations of nutrients in the bottom sediment profiles in the main open water and in the north of Lake Bera decreased in the order of TOC > k$^+$ > TN > $>$ Mg > Ca. The results highlight a clear correlation between variations of nutrient contents in the lake sediments with anthropogenic and natural events during the CRS model; the C/N ratio has remarkably increased four times since oil palm plantations were developed in 1981. This result indicates an upward increase in eutrophication during and following land-use changes. The results also suggest long-term increasing acidic conditions in Lake Bera, leading to a reduction in exchangeable cation contents (Ca, Mg, and K), organic matter preservation, and an incremental addition of SO$_4$ (sulfate) and NO$_3$ (nitrate) ions, particularly in the top layer of the sediment column. This situation will result in Lake Bera being on the verge of considerable ecological risk, as illustrated by very low dissolved oxygen contents, high levels of nitrate, and a reduction in fish population.

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1. Introduction

1.1. Background and scope of work

Agronomic development projects have significantly modified the original tropical rainforest cover of Malaysia. Increasing global demands for oil palm and favorable agro-climatic conditions have resulted in a rapid increase of agricultural development projects since 1961 and have led to the establishment of almost 20 million hectares of oil palm plantations. Although oil palm cultivation has long been advocated as a sustainable farming practice (Basiron, 2006), it does have significant effects on the nutrient contents in soils and lake sediments (MPOC, 2007; Chiew and Rahman, 2002; ECD, 2002; Wakker, 2004).

Historical variations in the nutrient contents of soil profiles have been the scope of several studies (Craft and Richardson, 1998; Guo et al., 2003; Mabit et al., 2008b; Martinez et al., 2010) because of the importance of nutrients for sustainable agriculture and the tracing of anthropogenic activities in the catchment area. Lake sediments

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have also been widely investigated to detect such historical varia-
tions and to trace eutrophication in watershed areas and their
association with heavy metal contamination (Ueda et al., 2009;
Flower et al., 2009; Rippey et al., 2008; Routh et al., 2007; Alve-
raz-Iglesias et al., 2007; Bonotto and de Lima, 2006; Coway and
Beck, 2001; Hongve et al., 1995; Nagao et al., 1999).
Previous studies in Peninsular Malaysia (Tanaka et al., 2009;
Sultan and Shazili, 2009; Neergaard et al., 2008; Wüst et al., 2003;
Phillips and Bustin, 1998; Midmore et al., 1996; Malmer, 1990)
have mainly emphasized the importance of nutrient contents in
soils and sediments as indicators of soil erosion and deposition
and eutrophication. Neergaard et al. (2008), for instance, used the
\(^{137}\)Cs technique to investigate soil erosion resulting from the con-
version of forest land into agricultural areas, although these authors
did not examine the geochronology of deposition of the sediments
in sink areas. A literature review also highlighted this absence of
work in the application of radioisotopes to detect historical varia-
tions in nutrient contents and eutrophication in lake sediments.
The main aim of this research was therefore to investigate the effects of
anthropogenic activities on the nutrients in the catchment area and
to trace historical variations in nutrient contents in the sediments
at Lake Bera using radioisotopes.

1.2. Study area

Lake Bera and its catchment area (BLC) are located in the cen-
tral part of Peninsular Malaysia, between latitudes 2°53’00” N and
3°10’00” N and longitudes 102°30’30” and 102°47’00” E (Fig. 1).
The catchment area covers approximately 600 km\(^2\) and was origi-
nally covered by primary rainforest, although five Federal Land
Development Authority (FELDA) schemes from 1870 to 1995 have
resulted in 292.86 km\(^2\) of the original forest being converted into
oil palm and rubber plantations (Henson, 1994; MPOC, 2007). The
BLC was designated under the Convention of Wetlands as the first
RAMSAR Site in Malaysia in 1994 with the FELDA districts being
called buffer zones. Soil conservation management practices, how-
ever, have never really been applied within the buffer zones either
before or after establishment of the RAMSAR site. A recent land use
map of the Bera Lake catchment prepared with the aid of the geo-
igraphical information system (GIS) technique and a satellite image
(SPOT 5, 2009) of 10-m spatial resolution further demonstrates
that there has been agricultural development and encroachment
into the RAMSAR site by local residents. Because the local resi-
dents have cleared an area of 47.14 km\(^2\) since 1994, the total area
of cleared natural forest within the Lake Bera catchment reached
a maximum value of 340 km\(^2\) in 2010. The remaining area is cov-
ered by wetlands and pristine lowland rain forests (forest and reed
swamps).

Lake Bera and its catchment are located between the eastern
and western mountain ranges of the Peninsula with the highest
hills being only approximately 140 m above sea level (Wüst and
Bustin, 2004). A digital elevation model (DEM) of the catchment
area indicates that as much as 50% of the area comprises low lands
where the slope varies between 0° and 4°.

Lake Bera and its catchment were separated into 12 hydrological
sub-catchments; open water was only observed in the northern-
most part in sub-catchment 3. The overall flow of streams in the
catchment is northwards with sub-catchments 4–12 draining into
the southwestern end of Lake Bera. Two other streams from sub-catchments
1 (Kelantang stream) and 2 drain into the middle and northern
part of the Lake, respectively. Lake Bera drains through an outlet
stream in its northernmost part into the Bera River, which flows
northwards into the Pahang River.

The study area has a humid tropical climate with two
monsoon periods. Heavy rainfall occurs during the Northeast
(November–March) and Southwest (June–August) monsoons,
while there is less rain in April, May, September and October. The
mean annual temperature is approximately 30 °C and ranges from
25 °C to 38 °C (Chee and Peng, 1998). Rainfall records from 1970
to 2009 at the Fort Iskandar Station, which is located at the mid-
point of the catchment, indicate that the minimum and maximum
annual rainfall was 1000 and 2602 mm, respectively. Field obser-
vations and laboratory analyses indicate that the soils within the
catchment are ferralsols; the soils have brownish-yellow, yellow
and red colors and developed on Triassic as well as post-Triassic
continental sedimentary rocks. These ferralsols have maximum and
average thicknesses of 1.0 m and 0.2 m, respectively.

In the catchment area, carbonaceous shale, siltstone and rhy-
olitic tuff of the Triassic Semantan Formation are observed to
overlie thick bedded to massive mudstone, tuffaceous sandstone
and siltstone of the Permian Bera Formation. The Semantan Forma-
tion is overlain by post-Triassic conglomerate, pebbly sandstone
and sandstone of the Redbeds Formation (Hutchison and Tan,
2009). Outcrops demonstrate that these sedimentary strata are
located on the right flank of a broad NW-SE trending syncline, with
the strata dipping 45°–60° toward SE. Within the wetlands and open
waters of Lake Bera, organic and peat deposits have accumulated
from approximately 4500 BP (Morley, 1981).

2. Materials and methods

2.1. Sampling

Thirty-five soil samples were collected with a bulk core sampler
to a depth of 25 cm at sites of different land use in the Lake Bera
catchment. To investigate nutrient depth profiles near the main
body of open water, soil sample were collected at 2-cm intervals
using a rectangular metal frame of 875 cm\(^2\) in area and a scraper
plate at a depth of 24 cm, where rock fragments were the main soil
component and there was little clay content.

Two core samples of the Lake Bera sediments were also collected
using a newly developed core sampler that was designed to collect
a 2-m undisturbed sample with a high recovery rate and minimum
sediment column compaction. A portable Hydro Lab 5 unit was also
used to determine the water quality of Lake Bera.

2.2. Sample preparation and analytical methods

2.2.1. Total organic and total carbon analysis

The sediment cores were preserved in a freezer at a tempera-
ture of 4 °C before being sliced at 2.0 ± 0.2-cm intervals. The soil
and sliced core samples were dried at 60 °C and then ground for fur-
ther analytical procedures. A total of 65 samples of 1.0–1.5 g each
from Cores 1 and 2 were then weighed and mixed with 1–2 ml
of 1 M hydrochloric acid to remove inorganic carbon before being
dried at 100–105 °C for approximately 10h to remove the acid
(Schumacher, 2002). Samples of 0.5–2.0 mg were then weighed
and analyzed for total carbon (TC) and total nitrogen (TN) using a Perkin
Elmer 2400 Series II CHNS/O Elemental Analyzer.

An organic analytical standard (acetonilide-C6H5NH) was used for
quality control and quantitative analysis. For the quality con-
trol procedure, the acetonilide standard sample was used as the
conditioner with testing of five blank-tin aluminum samples. Cali-
bration was continued until positive results of C < 50, H: 100–200,
and N < 16 were obtained. Three replicate acetonilide samples
of 0.5–2.0 mg were then weighed and analyzed using the Perkin Elmer
2400 Series II CHNS/O Elemental Analyzer. The calibration fac-
tors for carbon, hydrogen and nitrogen were determined to be
71.09 ± 0.3%, 6.71 ± 0.3%, and 10.36 ± 0.3%, respectively, accord-
ing to instrumental instructions. The organic analytical standard
of acetonilide was run for every four samples. CHN analysis was
continued when the Acetanilide samples gained in the range of calibration factors.

2.2.2. Gamma-ray spectrometry
A total of 65 samples from Cores 1 and 2 were packed into containers, tightly sealed and stored for 3 weeks to allow $^{226}\text{Ra}$ to achieve secular equilibration with $^{222}\text{Rn}$ and its shorter half-life daughter isotopes. The specific activities of $^{210}\text{Pb}$ and $^{137}\text{Cs}$ in the samples were then measured with a well-type hyper pure germanium (HpGe) detector coupled to a gamma spectrometer at Nuclear Malaysia. The spectrometer was calibrated using an multi-radionuclides standard solution with the same sample-detector geometry. The lower limit of detection with 95% confidence for 24-h measuring time is 0.3 Bq.

Disequilibrium between $^{210}\text{Pb}$ and its parent isotope in the $^{238}\text{U}$ series, $^{226}\text{Ra}$, arises through emission of the noble gaseous isotope $^{222}\text{Rn}$ (half-life = 3.8 days). The isotopes $^{222}\text{Rn}$ released to the atmosphere naturally decays to $^{218}\text{Po}$, a metallic radionuclide, which precipitates on the earth with dust and rain within a few hours or days. Many daughter radioactive isotopes then decay within minutes, and $^{210}\text{Pb}$ or unsupported $^{210}\text{Pb}$ (half-life = 22.3 year) is produced. Supported $^{210}\text{Pb}$ in each sample was assumed to be in equilibrium with the in situ $^{226}\text{Ra}$, and the unsupported $^{210}\text{Pb}$ was calculated by subtracting $^{226}\text{Ra}$ activity from the total $^{210}\text{Pb}$ (Appleby, 2000).

The lake sediment chronology was determined using the constant rate of supply (CRS) model of Appleby and Oldfield (1978). The CRS model is the generally preferred model and assumes that the flux of excess $^{210}\text{Pb}$ supply to sediments is constant with time at a particular location. The CRS dating model is expressed as follows (Appleby and Oldfield, 1978):

$$A_t = A_0 e^{-\lambda t}$$

(1)

where $A_t$ is the cumulative $^{210}\text{Pb}_{\text{ex}}$ below the level representing time $t$, $\lambda$ is the $^{210}\text{Pb}$ decay constant of $^{210}\text{Pb}$ (0.03114) and $A_0$ is the total cumulative $^{210}\text{Pb}_{\text{ex}}$ inventory at the point where the $^{210}\text{Pb}_{\text{ex}}$ activity reaches radioactive equilibrium with the supporting $^{226}\text{Ra}$. In addition, the age of the sediments at any depth is given by

$$t = \frac{1}{\lambda} \ln \frac{A_0}{A}$$

(2)

Recommended methods for validation of the resultant dates are by reference to independent records of artificial radionuclides such as $^{137}\text{Cs}$ (Pennington et al., 1973) or by correlation with known natural or man-induced events in the catchment area. Known dates of $^{137}\text{Cs}$ horizons, i.e., the first appearance in sediment columns (1952–1954) and fallout maximum (1963–1964) from
the atmospheric testing of atomic bombs, were used for validation of the 210Pb dates.

3. Results and discussion

3.1. Lake sediment stratigraphy

A close examination of the core samples indicates that the top 1 m of the Lake Bera bottom sediments contains five separate layers (Fig. 2). The first layer (1) is a gray mud with little organic matter and an average thickness of 25 cm. From its muddy texture, clay, silt and sand size components have average contents of 18 ± 2.5%, 35 ± 1.7%, and 48 ± 2.5%, respectively are observed. Two charcoal horizons were recorded in this layer. The second layer (2) comprises a light to dark gray sandy mud having an average thickness of 25 cm and characterized by abundant partially rotten roots, bark, stems, charcoal and other organic debris. Two charcoal horizons were also recorded in this second layer whose clay, silt and sand size components are on average 11 ± 2%, 61 ± 15%, and 28 ± 15%, respectively. The third layer (3) is an erosion-induced deposit of white color and with a sandy mud texture. The contribution of silt size particles is increased to 58 ± 5%, while the clay and sand portions are reduced to 11 ± 2% and 32 ± 7%, respectively, on average. Six charcoal horizons were recorded in this third layer at 1. The fourth layer (4), at the top of the sediment profile, is composed of organic-rich to peat deposits with an average thickness of 25 cm and a total organic carbon content of 5–20%. Three charcoal horizons were recorded in this fourth layer. The fifth layer (5) of 2–4 cm thickness is composed of organic-rich deposits with terrestrial material, has a muddy sand texture and serves as a remarkable indicator of a major flood that occurred in December 2007. Note, however, that there are some differences in nutrient concentrations and charcoal horizons within these recognizable layers due to their different origins and events.

3.2. Nutrient contents in soil samples

The nutrient contents and physical properties of the soil samples as well as the radionuclide inventories in the four types of land use exhibit clear differences, with the lowest nutrient contents are observed for the cleared and newly opened lands (Table 1; Fig. 3a and b). In addition, the average percentage loss of organic carbon and nitrogen were calculated to be 54.6% and 31.2%, respectively.

Several mechanisms may have contributed to the reducing nutrient contents in the Lake Bera catchment during land clearing. Soil disturbance after clear-felling and burning are the two major problems inland preparation phases for the planting of oil palm by FELDA (Tan et al., 2009). Malmer (1996) reported that concentrations of nutrients in the suspended sediment load during the phase of forest felling and burning increased by 10–100 times compared with those during normal conditions. Trammell et al. (2004) has stated that the adverse effects of forest burning in terms of nitrogen loss are equivalent to 4.5 years of atmospheric input. Oxidation and volatilization of nutrients stored in all types of forest vegetation, leaching, surface run-off and convection of ash are the main mechanisms that promote nutrient loss from ecosystems during and after the burning of deforested land (Fisher and Blinkley, 2000). In addition, Grigal and Bates (1992) have proposed that forest burning is one of the main reasons for the consumption of nutrients, especially nitrogen and some phosphorus, by volatilization before escaping into the atmosphere.

Another destructive effect of forest burning in the process of land clearing as reported by DeBano et al. (1998) is the significant decrease in the hydrological properties of the soil. Loss of aggregation from the destruction of binding organic matter decreases pore volume and thus impedes the flow of air and water through the soil. This process has remarkably affected cleared land in the Lake Bera catchment with a 10% increase in bulk density on average.

Developed oil palm and rubber plantations are one land use that has already experienced a phase of land clearing and a developing (maturing) period. The nutrient content has thus only marginally improved. The mean value of TOC and TN were calculated to be 1.22 ± 0.62, and 0.13 ± 0.07% with CV of 51% and 53%, respectively. On average, the loss of TOC and TN from soil profiles in developed oil palm plantations is 49% and 18.75%, respectively.

Developing land was identified as the land use group that is mainly covered by rubber plantations. The mean TN loss in developing land is quite similar to that in developed lands, while the mean TOC loss was calculated to be 44.6%. The main reason for the lower percentage loss of TOC in developing land is the removal of tree trunks, fallen leaves, tree stumps and roots of felled palms, and other organic matter during replanting. This reason has been validated by Chiew and Rahman (2002), who showed that the empty fruit bunches (EFB) remaining in oil palm plantations rebuild the nutrient cycle and increase N, P, K and Mg levels.

In areas under original tropical rainforest, the mean values of TOC and TN were calculated to be 2.4% and 0.16%, respectively, with maximum concentrations in the surface layers (up to 2 cm depth). A strong negative correlation with an r-value of −0.92 was observed between the nutrient contents and depths in the Lake Bera original forest land. Despite government regulations stipulating that any project involving more than 500 hectares should have an approved Environmental Impact Assessment Report (EIAR) (ECD, 2002), the local residents have disregarded this regulation by deforesting smaller areas in the RAMSAR site since 1994, thus continuing to have destructive effects on the lake catchment ecosystems.

Historical variations in nutrient contents in Lake Bera sediments

The total organic carbon value of sediment samples involves both the TOC value as well as particulate organic carbon (POC), which is usually observed in specific layers. Pieces of charcoal, roots, bark and stems (POC) are considered to be indicators of environmental events in the catchment area. Field and Carter (2000) reported that high percentages of organic matter in lake sediments originate from forest clearing and burning activities. Therefore, during the first storm after forest clearing, almost 56% of suspended charcoal is carried into the sink.

Clear variations in anomalies of TOC and TN values are recorded in the Lake Bera sediment columns. Concentrations of other important nutrients (K, Mg, Ca) from the same sediment cores in the lake have been reported by Gharibreza et al. (2012). The sulfur contents of sediments in the wetlands and open waters of Lake Bera has been reported to be between 0.05% and 0.5%, an indicator of freshwater peat deposits (Wüst et al., 2003). The total concentrations of nutrients in the sediments of the Lake Bera (pH 4.2 and 5.2), as reported by Wüst et al. (2003), was confirmed by in situ water chemistry analyses during this study.

The results indicate that the rate of nutrient supply and physico-chemical conditions at Lake Bera have significantly controlled nutrient contents in the bottom sediment profiles. The Ca, Mg, and K contents were sensitive to physico-chemical conditions in the catchment, while the TOC and TN contents were indicators of nutrient supply rates from source areas (Figs. 4 and 5). The lake catchment has also experienced changes in the rate of eutrophication since 1972 during several natural disasters with variations in details being in good agreement with anthropogenic and natural events that correlate well with dates estimated using 210Pb dating.

Scattered deforestation of small areas has also been performed by local residents from 1995 until the present. Note that the duration of land clearing and preparation for the planting of some 2000 hectares of oil palm is usually 14 months (Tan et al., 2009). Thus, long-term and continuous exposure of weathered Triassic and post-Triassic bed rock occurred during the FELDA projects, resulting in surface erosion and transport of several tons of sediments into the Lake Bera open waters and wetlands. The accumulation of erosion-induced sediments in Lake Bera is marked by deposition of white sandy mud (layer, 3). Correlation of $^{210}$Pb dates in the lake sediment column and nutrient contents (Figs. 4 and 5) demonstrate a clear relationship between the dates of the FELDA projects and the rate of nutrient fluxes.

The mean organic carbon percentage in sediments of Core 1 was calculated to be 4.2 $\pm$ 0.8% with a CV value of 18%. Core 1 in the deepest part of Lake Bera has three major influxes of nutrients (Fig. 4), with pre-1949 deposits (Layer 1) exhibiting a remarkable TOC content of 14.1% at a depth of approximately 66 cm. No definite reason, however, can be attributed to this nutrient influx, which appears to have occurred during the Second World War (1942–1945). The second influx of nutrients in approximately 1969 is revealed in layer 3, with a TOC content of 11.2%, and marks the beginning of the first FELDA land development project. A minor TOC content of 0.5% marks a third influx of nutrients associated with the fifth FELDA project, with a dramatic increase in TOC and TN contents and C/N ratios at Core 1 starting in 1991 when the organic carbon content increased to 21%. This trend is associated with the accumulation of organic-rich deposits in the uppermost layer (4) of the lake sediment profile.

A similar pre-1949 influx of nutrients is also exhibited by Core 2 in the north of Lake Bera (Fig. 5). The second influx of nutrients observed in Core 1 is also observed in Core 2 by the remarkable

### Table 1

<table>
<thead>
<tr>
<th>Land use</th>
<th>Bulk density (kg m$^{-1}$)</th>
<th>TC (%)</th>
<th>TN (%)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed oil palm and rubber plantations (n = 12)</td>
<td>1400</td>
<td>1.22</td>
<td>0.13</td>
<td>5.72</td>
<td>37.66</td>
<td>56.62</td>
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<td>1.22</td>
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<td></td>
<td>5.72</td>
<td>37.66</td>
<td>56.62</td>
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<td></td>
<td>2.41</td>
<td>3.13</td>
<td>15.21</td>
</tr>
<tr>
<td>CV</td>
<td>19</td>
<td></td>
<td></td>
<td>42</td>
<td>35</td>
<td>27</td>
</tr>
<tr>
<td>Developing oil palm farms (n = 8)</td>
<td>1369</td>
<td>1.33</td>
<td>0.13</td>
<td>8.45</td>
<td>44.22</td>
<td>47.33</td>
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<td></td>
<td>3.80</td>
<td>14.33</td>
<td>16.07</td>
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<td></td>
<td></td>
<td>45</td>
<td>32</td>
<td>34</td>
</tr>
<tr>
<td>Cleared land (n = 5)</td>
<td>1326</td>
<td>1.09</td>
<td>0.11</td>
<td>8.29</td>
<td>46.43</td>
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<td>46.43</td>
<td>45.29</td>
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<td></td>
<td>3.21</td>
<td>8.77</td>
<td>11.11</td>
</tr>
<tr>
<td>CV</td>
<td>20</td>
<td></td>
<td></td>
<td>39</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>Natural forest (n = 9)</td>
<td>1254</td>
<td>2.40</td>
<td>0.16</td>
<td>7.21</td>
<td>45.74</td>
<td>46.31</td>
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<tr>
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<td></td>
<td>7.21</td>
<td>45.74</td>
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<td>CV</td>
<td>19</td>
<td>48</td>
<td>31</td>
<td>26</td>
<td>22</td>
<td>26</td>
</tr>
</tbody>
</table>

TN: total nitrogen; TOC: total organic carbon; Cs-137: caesium inventory.

Fig. 2. Stratigraphic layers in Lake Bera sediment columns.
C/N ratios that indicate maximum timber harvesting during the first Malaya Development Plan (1960–1965). Increasing world demands for wood products, especially by Japanese companies, also increased timber harvesting in Malaysia between 1962 and 1965 (Tachibana, 2000).

The rate of nutrient influx in the northern part of the lake also significantly increased in 1981 in association with the accumulation of white sandy mud during the third FELDA phase. Nutrient fluxes also continued with deposition of dark organic-rich sediments (layer 4) at depths of 7–11 cm during and after the fifth
FELDA project phase. There is thus clear enrichment of organic carbon, Ca and Mg since 2000 due to the encroachment by local residents in the catchment area.

The main reason for the accumulation of organic-rich sediments in more recent years, i.e., after 1985, is due to the high biomass production from mature oil palm plantations. The Malaysian Palm Oil Council (MPOC, 2007) has reported that oil palm plantations annually accumulate 8.3 tons of biomass, a value which is 2.5 tons more than the value a rain forest can produce. Furthermore, the annual dry matter production of an oil palm plantation is almost 36 tons, compared with approximately 26 tons for a typical rain forest. Although there have been many encroachments into areas of existing natural forest by local residents in the last two decades, the earlier established (pre-1994) FELDA land development projects have now been in existence for several years, and the sediment run-off thus has a high organic content. Nutrient contents in the lake have therefore increased and reached three times the original natural forested value.

Periodic burning of felled trees during land clearing phases is likely to be the main reason for nitrogen enrichment and eutrophication of lake sediments. This phenomenon has been proven by Field and Carter (2000), who demonstrated that nitrate and ammonium loss is greatly increased during the first 3 months after forest burning and gradually decreases with time. The use of fertilizers is another factor that contributes to the increased supply of nutrients from a catchment area. Fertilizer application has also increased over the years with changes in the Malaysian agricultural sector (Zin and Tarmizi, 2007). Common sources of nitrogen in fertilizers are ammonium sulfate (21% N), ammonium nitrate (26% N), ammonium chloride (25% N) and urea (46% N), all of which have been widely used in the rubber and oil palm plantations of the catchment area of Lake Bera.

Field observations reveal a chemical stratification in the water column, with high acidity (pH values of 4.4–5) dominating the deeper layers. This feature may be due to the decomposition of organic matter (release of carbon dioxide) or incremental additions
of SO4 (sulfate) and NO3 (nitrate) ions resulting in the reduction of exchangeable cation contents (Mg, and K) or organic matter preservation in the top layer of the bottom sediments.

Furthermore, statistical analyses support the chemical analyses presented in Figs. 4 and 5, with hierarchical cluster analysis indicating similarities and dissimilarities between the TOC and TN values and other nutrients in terms of the chemical condition of the deposition media (Fig. 6). A strong negative correlation with a r-value of −0.9 was recorded between nutrient (TOC, TN) contents and Mg and K values, while a clear upward depletion in concentrations of Mg and K in sediment profiles of the lake is associated with organic-rich accumulation. Calcium, however, shows a positive correlation with TOC in the lake sediments. Furthermore, ionic concentrations influence the lake’s ability to assimilate pollutants and keep nutrients in solution. For example, calcium carbonate (CaCO32+) in the form known as marl can precipitate phosphate from water and thus remove this important nutrient (Horne and Goldman, 1994). This process most likely has dominated to precipitate TOC, TN and other micronutrients such as Fe, Zn, and Mn in the Lake Bera sediments.

The high affinity of organic matter with 137Cs inventory has been reported by several researchers including Martinez et al. (2010), Mabit et al. (2008a), Guo et al. (2003), Covay and Beck (2001) and Craft and Richardson (1998). FELDA land development projects, which are well associated with the accumulation of organic-rich sediments in Lake Bera, have also played an important role in controlling the rate of 137Cs supply from the catchment area. Individual peaks of transported 137Cs were recorded in 1976, 1980, 1988, and 1994 in the sediment profile of Core 1 in the deepest point of Lake Bera; these dates correspond with the second, third, fourth, and fifth FELDA land development projects. Similar peaks of transported 137Cs appear in 1976, 1986 and 1994 in Core 2 in the northernmost sediment profile of the lake and are consistent with the second, fourth, and fifth FELDA projects. The highest 137Cs peak, however, is related to a major flood in December 2007, which played a significant role in transporting nutrient contents and 137Cs radionuclides into the open waters and wetlands of Lake Bera.

4. Conclusions

The overall evidence clearly demonstrates the role of FELDA land development projects from 1972 to 2000 and that of local residents since 1994 in influencing the nutrient cycle at Lake Bera. The effects of land clearing and the burning of felled trees are remarkably manifested in the nutrient contents of the soil profiles and the lake bottom sediments. The mean TOC in the soil profiles decreases in the order of 2.4 ± 1.1%, 1.3 ± 0.3%, 1.2 ± 0.6%, and 1.1 ± 0.2% in the areas of natural forest, developing oil palm/rubber plantations, developed (mature) oil palm/rubber plantations, and cleared lands, respectively. A similar trend in the mean TN value in soil profiles was also recorded for these areas of land use with 1.6 ± 0.1%, 0.1 ± 0.02%, 0.1 ± 0.7%, and 0.1 ± 0.02%, respectively. The unique fate of nutrients in the lake sediments is observed in the total concentration of nutrients in the main open water and in the north of Lake Bera, decreasing in the order of TOC > K > N > Mg > Ca. Lake Bera also significantly retains nutrients, especially in the organic-rich deposits in the uppermost layer of the sediment column, with recycling being associated with an upward eutrophication and increase of C/N ratios. Nutrient influxes into the lake have been confidently documented with 210Pb dating and CRS model resultant dates. The geochronology of the nutrient influxes was also verified by 137Cs horizons and supported by charcoal remnants and POC horizons. Hierarchical cluster analysis also revealed a strong similarity between the contents of nutrients (TOC, TN) and the concentrations of micro-nutrients (Fe, Mn, and Zn). A strong negative correlation between the levels of nutrients (TOC, TN) and Mg and K values was also revealed. Clear eutrophication, particularly in the north of the basin, indicates that Lake Bera is on the verge of considerable ecological risk with an anticipated expected algal bloom, reduction of dissolved oxygen, a high level of nitrates and a reduction in fish populations.

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