Degradation and Sustainable Management of Peat Soils in Indonesia

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Summary: The 14.9 million ha Indonesian peatland is under pressure for economic use on one hand and for conservation on the other. Peat degradation is associated with compaction (shrinkage and consolidation) and CO₂ emissions caused by aerobic microbial decomposition (due to drainage) and by peat fire. CO₂ emission is the main national and global concerns. However, the level of uncertainty is very high in estimating the amount of emitted CO₂ from peat fire and peat microbial decomposition. There is a pressing need for the availability of affordable remote sensing technique to support the estimate of the actual peat burn scar area, rather than the hot spot area, and burn scar depth at high enough (≤5 cm) vertical resolution. For peat microbial decomposition, the recent 2013 IPCC Supplement for Wetlands segregates emissions based on land cover types. However, peat properties and environmental condition and water and soil management systems seem more dominant determinants of the emission, but these have been the knowledge gaps that need to be addressed in future research. Sustainable peat soil management is defined as the management systems causing minimum environmental effects and providing feasible economic return. Minimizing the depth of drainage to the level tolerable by crops for optimum production or selecting economic crops that tolerate shallow water table reduces the management impacts to the environment. Fire control is inevitable in sustainable peat management. Agronomic management techniques comprising of water table control, amelioration and fertilization are available for profitable crop production under drained peat systems, leading to a high opportunity cost of peat forest conservation. Unfortunately, crop production under undrained systems are not as economically competitive. Therefore, a combination of incentive and regulatory measures as well as implementation of environmentally friendly management systems are needed for the win-win environmental and economic objectives.

Keywords: Subsidence, burning, drainage, CO₂ emission, burn scar

1. Introduction

Indonesia has the largest tropical peatland area of about 14.9 million ha (Mha) [1]. About half of this area is still covered by forest but the remaining area has been used for agriculture, forest plantation or being idle and covered by shrub or being bare. The area of shrubland and bare peatlands is estimated as large as 3.8 Mha [2] and these lands are not only unproductive, but also the source of emissions due to drainage influence.

There are two contrasting direction in today’s use of peatlands. On the one hand, clearing and draining of peat forest trigger peat decomposition processes which ends up in carbon dioxide (CO₂) emission and peat subsidence. Subsidence also entails the loss of peat hydrological functions [3]. Furthermore, drained peat is also associated with susceptibility to peat fire which contributes further and often more significantly to subsidence and carbon loss [4]. The concern of environmental problems due to peat fire are not only associated with the high amount of CO₂ emissions and subsidence, but also the haze and health problems. On the other hand, drained peat has enabled the production of various kinds of high economic value crops such as oil palm, vegetables, fruits, rubber and grain crops [5, 6, 7]. Profitability derived from peatland, at least for the short term accounting, matches that of mineral land [7].

Science are advanced enough on the management techniques of peatland for increasing farm profitability. Management techniques are also available for reducing the negative environmental effects, but the opportunity costs seem very high for implementation. Furthermore, there are knowledge gaps in inventorizing the most important global environmental concern of peat soil uses under drained conditions, i.e. CO₂ emissions caused by decomposition and fire.

This paper discusses the processes associated with peat subsidence and peat fire. To a lesser detail profitability from the use of peatland will also be explained. Research gaps and the way forward will be elaborated.
2. Land use and land use change as the drivers of degradation

The increasing demand for land resources has lead to a high pressure for the use of peatlands for producing various kinds of agricultural commodities, as well as for settlement and mining [8]. The conversion and draining of peat forests to create favorable conditions for aerobic crops change the peatland role from a C sink to C source [3]. However, not all of the converted and drained peat forest are used for production purposes. About 3.8 Mha of the cleared areas become idle. They are covered by shrub or grasses or being bare [2]. This lands lose both their environmental and economic functions. The peat shrubs become carbon sources due to drainage influence as opposed to natural forests which are considered as near carbon neutral [9]. The rate of shrubland subsidence and CO₂ emission may even exceed those of agricultural land because, not only that it shrink and decompose, but it’s also a subscriber to peat fire during the dry period, which in turn add to the amount of CO₂ emissions and subsidence [7, 10, 11].

Oil palm plantation is one of the most important and rapidly expanding agricultural uses on peatland. Oil palm plantation on peatland has been increasing rapidly from 4% in 2000 to 6% in 2005 and to 10% in 2010 relative to the total Indonesian peatland area [10]. This is attributed to the ease of market accessibility and profitable use of the land. Peatlands are also used for rubber, vegetables and paddy rice. So far none of the other commodities excel oil palm plantation with an estimated area of 1.7 Mha on peatland. Abandoning agricultural practices and restoring the land to natural conditions are often discussed, but this would imply severe socio-economic consequences [12] unless high value crops can be produced on a mass basis on rewetted environment.

3. Peat Degradation Processes

In the general term, degrading peat is the one undergoing accelerated subsidence due to land clearing and draining. For the practical purpose, however, land cover with thin biomass density remote sensing images consisting of peatshrub, bareland and grassland have been delineated using the geographical information system (GIS), and classified as degraded peatlands [2, 5, 7, 8, 10]. What is considered as the degrading peat from the environmental angle may be perceived as the productive land and the source of income by the producers because various lucrative agricultural commodities may be produced on drained peatland. As the peat surface subsides, it loses functions as the carbon storage [9] and hydrological control which stores water during the rainy season and releases it gradually during the dry season, and the niche for peat specific fauna and flora [9, 13].

Subsidence is associated with peat compaction, consolidation and CO₂ emissions caused by aerobic microbial decomposition under drained condition and by peat fire. Subsidence normally happens as the peatland is converted from the natural forest to economic uses involving land clearing, draining, and sometimes, burning. The higher the rate of subsidence, the shorter the timespan of the use of peatland.

Subsidence depends on the peat type, the rate of decomposition, the density and thickness of peat layers, drainage depth, climate, land use, and time since the peatland is converted from forest [3, 14, 15]. Total subsidence from these several causes is indicated by the lowering of the peat surface. There are three main processes contributing to subsidence, i.e. peat decomposition, peat consolidation and shrinkage, and peat fire.

3.1. Peat Decomposition

Draining of peat causes escalation of CO₂ emission by aerobic bacteria [3, 10, 13]. Water saturation and too dry condition lead to the low CO₂ emission [16]. Likewise, neither saturation, nor too dry condition is ideal for most of high value economic crops, implying a high CO₂ emissions under agronomically favorable soil moisture content and water table depth. Recommended water table depth for oil palm is between 50 and 70 cm [11] although in practice it may reach 100 cm, especially during the dry period of the year. Within this range of water table depth, CO₂ emissions from microbial decomposition increases with the water table depth [17].

Drösler et al. (2014) [9] segregated drained-peat CO₂ emission factors (EF) into different land cover types under the Tier 1 (Table 1). As such, there are significant EF differences between lands covered by oil palm plantation, long rotation plantation such as rubber, and short rotation land cover such as Acacia. However, studies in Sumatra, Indonesia demonstrated no significant different emission rates from different land cover types. An oil palm plantation, a secondary forest, an Acacia plantation, a rubber plantation, and a bareland as the land cover types in Riau research sites did not emit different emission rates (Table 2). Rather, they were the sites, which were associated with different climate and peat properties that lead to the variation of the emission levels [18, 19]. Water table depth is the dominant determinant of CO₂ emission from microbial decomposition [17] suggesting that where and whenever possible, the drainage depth should be kept minimum. Furthermore, diurnal variation is also high while most closed chamber measurements of CO₂ emission are biased towards daytime measurement during which the emission is relatively higher [20]. These shows that there are wide gaps of knowledge and lack of data of CO₂ emission estimate for supporting to the more convincing Tier 2/Tier 3 EF of peat decomposition. Regionalized
research on CO₂ emission covering a wide range of peat properties and climate variation as well as range of crops for generating CO₂ emission versus water table relationship will be needed.

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>Emission factor</th>
<th>95% Confidential Interval</th>
<th>Number of research sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drained peat forest or peat shrub</td>
<td>5.3</td>
<td>-0.7</td>
<td>9.5</td>
</tr>
<tr>
<td>Long rotation plantation</td>
<td>15</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Short rotation plantation, such as Acacia</td>
<td>20</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>Oil palm plantation</td>
<td>11</td>
<td>5.6</td>
<td>17</td>
</tr>
<tr>
<td>Plantations with &lt;0.3 m drainage</td>
<td>1.5</td>
<td>-2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Annual crops, bareland</td>
<td>14</td>
<td>6.6</td>
<td>26</td>
</tr>
<tr>
<td>Annual crop, paddy</td>
<td>9.4</td>
<td>-0.2</td>
<td>20</td>
</tr>
<tr>
<td>Grassland</td>
<td>9.6</td>
<td>4.5</td>
<td>17</td>
</tr>
</tbody>
</table>

n.a. = data not available

<table>
<thead>
<tr>
<th>Land use</th>
<th>Code</th>
<th>Mean ± STD CO₂ flux (Mg CO₂ ha⁻¹ year⁻¹)</th>
<th>Mean ± STD WT (cm)</th>
<th>Mean ± STD temperature (°C)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Palm</td>
<td>J-OP-6</td>
<td>38±2</td>
<td>54±22</td>
<td>27±1.3</td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td>J-OP-15</td>
<td>34±16</td>
<td>n/a</td>
<td>29.1±2.9</td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td>J-OP-14</td>
<td>45±25</td>
<td>n/a</td>
<td>26.7±1.7</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>R-OP-4a</td>
<td>66±25</td>
<td>72±37</td>
<td>30.6±2.7</td>
<td>[18]</td>
</tr>
<tr>
<td>Acacia</td>
<td>R-Ac-3</td>
<td>59±19</td>
<td>81±24</td>
<td>28.6±1.0</td>
<td>[18]</td>
</tr>
<tr>
<td>Secondary forest</td>
<td>R-SF</td>
<td>61±25</td>
<td>81±25</td>
<td>27.3±2.5</td>
<td>[18]</td>
</tr>
<tr>
<td>Rubber</td>
<td>R-Rb-6</td>
<td>52±17</td>
<td>67±25</td>
<td>28.6±2.8</td>
<td>[18]</td>
</tr>
<tr>
<td>Bareland</td>
<td>R-BL-p</td>
<td>67±24</td>
<td>67±27</td>
<td>29.8±3.1</td>
<td>[18]</td>
</tr>
<tr>
<td></td>
<td>R-BL-q</td>
<td>56±26</td>
<td>74±23</td>
<td>30±3.2</td>
<td>[18]</td>
</tr>
<tr>
<td></td>
<td>R-BL-r</td>
<td>66±27</td>
<td>69±29</td>
<td>31±2.2</td>
<td>[18]</td>
</tr>
</tbody>
</table>

In column 2, research sites J = Jambi and R = Riau; land uses OP = Oil Palm, Ac = Acacia plantation, SF = Secondary forest, Rb = Rubber (Rb) and BL = Bareland; the numbers at the end of column 2 indicate plant age, where applicable. STD = standard deviation; WT = water table depth.

3.2. Peat consolidation and shrinkage

Peat consolidation is a mechanical compression of saturated peat below the water table caused by the drawdown of water table level that increases the overburden pressure of the overlying peat layer and increases pressure beneath the water table. Peat shrinkage is the reduction of peat volume above water table. The shrinkage rate is very rapid in the first few years after the drainage begins and then slows down with time [14, 21]. Peat subsidence is often used as a proxy for estimating peat emission from decomposition, with peat compaction (the sum of peat consolidation and shrinkage) factorized in the total subsidence [21, 22]. We believe that the compaction/subsidence ratio should be based on a carbon balance and subsidence monitoring, but most previous studies did not include sufficient direct measurement of carbon balance, leading to a compromised certainty of emission estimate. Regionalized research on peat subsidence, fully supported by peat carbon balance monitoring will be the key to improving the certainty of emission factors.

3.3. Peat fire

Peat fire emission is perceived as one of the biggest sources of CO₂ emissions. However, the uncertainty is high, especially in relation to the activity data. Under the Tier 1 of IPCC (2014) [23], only burnt area is required as the activity data. These data are normally generated from the hotspots which are based on the moderate resolution imaging spectroradiometer (MODIS) (with 250, 500 or 1000 m pixel resolution) interpretation. However, not only that the MODIS resolution is relatively low, but the hotspots are not always associated with peat fire, i.e. the fire that actually reaches the peat soil. Therefore, assessment of peat fire area remains a source of uncertainty and require a better support of advance remote sensing technologies.
Under controlled burning, IPCC (2014) [23] calculation of peat fire emission at Tier 1 is as high as 72 Mg C ha⁻¹. With about 570 Mg C ha⁻¹ contained in 1 m layer of hemic maturity peat [11], such level of emission translates to average burn scar of about 13 cm deep. In reality, the depths of peat burn scar varies tremendously from a fraction to tens of cm. Under the Tier 2 and Tier 3 inventories, the area and the depth of peat burn scar must be known. High vertical resolution maps (at least 5 cm resolution) demonstrating peat elevation prior to and after fire events will improve the activity data certainty. Apart from the high resolution, the remote sensing technologies should resolve tree canopy interference, and has to be cost effective so as not to bulge the transaction cost of carbon inventory.

4. Sustainable peat management

As explained in previous sections, in many cases, the management direction of development and conservation of peatland are contradictory. Therefore, tradeoff in sustainably managing peat soil leading to minimizing the degradation processes and optimizing the crop production must be implemented. There are at least four important approaches for this tradeoff:

a. Avoiding deforestation.
   In as much as possible, clearing of peat forest must be avoided. Developing of new agricultural areas should only be concentrated on degraded peatland [10]. The 3.8 Mha of degraded peatland [2] is large enough to keep the pace of agricultural development. Its conversion for production purpose will not only reduce the pressure of encroachment to forest, but also leading to no or minimam additional CO₂ emissions from the biomass loss and peat decomposition relative to peat forest conversion [7].

b. Minimizing water table depth.
   In general, the deeper the water table, the higher the rate of peat decomposition [17]. This is because of the thicker (the larger volume) of oxidized peat layer in most time of the year under the deeper water table. Therefore, water table depth needs to be adjusted as close to the peat soil surface as possible to a level that does not cause a significant loss of crop productivity. Technology development for economically competitive paludiculture system, i.e. production system under undrained condition, is needed to create disincentives for drained agricultural systems.

c. Controlling peat fire.
   There are enough country level regulations banning the use of fire in land management. Nevertheless, peatland is notorious as a fire subscriber during the dry season because of haze hazards on human health [24] and transportation as well as escalated greenhouse gases emissions. Therefore, enhancement of regulation enforcement is a must. In addition, improved preparedness of fire control system such as through improved forest fire brigade and improved community awareness and involvement in preventing forest fires are essential [25].

d. Regulatory and incentive measures
   Agricultural activities such as those for plantation and vegetable production becomes lucrative businesses entailing high opportunity cost of peatland conservation [7, 26]. For example, the net present value (NPV) from oil palm plantation (with assumed 25 year crop cycle and a 15% interest rate) ranged from USD 237 to 528 (ha yr)⁻¹ and opportunity costs for conserving peat forest from conversion to oil palm plantation ranged from USD 3.70 to 8.25 t⁻¹ CO₂e (Table 3). For smallholders, their small (<5ha) land area may be the only resort for livelihood. Unless some kind of incentive is provided, there is little possibility for them to conserve peat forest if it means losing the opportunity to generate income from peatland. For large plantations, there are regulations limiting the expansion of agriculture on peatland. New concessions will not be issued for the use of peatland for agriculture at least during the suspension period that will last until 2017. Considering the high opportunity of reducing emissions on land that have been entitled to plantations, incentives in terms of carbon credit and reforming the legal systems to allow land swap from the high to low C stock land should be explored.

Management techniques for improving soil fertility on the naturally low fertility peat soils and by regulating the water table are widely available. Besides the addition of macro nutrients N, P, K, Ca and Mg, micro nutrient fertilization, especially for B, Zn, Cu is essential. Water table should be regulated in the range ideal for crop production and at the same time causing minimal rate of decomposition and fire risk [6, 11].
The pressing need for agricultural expansion has led to the use of inherently infertile and environmentally crucial land resource of peatland. The current land uses are dominated by high economic value and high market demand crops that happen to be requiring drainage of this naturally wetland. Peatland is an important carbon and water storage and the loss of these functions due to drainage has become a national and global concern. However there are lack of certainty to support the inventory of carbon loss, especially of the activity data of peat fire and the emission factor of water table depth versus emission relationship. This strongly suggest regionalized research on these aspects. Technical, incentives and regulatory measures must be enhanced to make the best benefits of the use of peatland.

Furthermore, exploration of economically competitive crops under undrained system (paludiculture) should also be prioritized.

## References


