The perspective of oil palm production in swampland as a result of soil properties diversity: Review of survey results in Kalimantan and Sumatra

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Abstract. Currently, oil palm plantation has expanded into marginal lands, including swamp agroecosystems. Rapid development of oil palm plantation is due to increasing demand for raw materials of bioenergy. Utilization of swamplands for oil palm development is hindered by unfavorable physical, chemical, and soil fertility properties and vital environmental issues. However, many research demonstrate the potential and appropriate agronomic suitability for oil palm cultivation. This paper presents findings on surveys conducted on Kalimantan and Sumatra swamps. Land evaluation from six swampland sites showed that at the average, 36% of swamplands were categorized as moderately suitable (S2). Meanwhile, 37% of those were marginally suitable (S3), with the rest was not suitable (N). The evaluation indicated severe issues associated with unsuitable class (N), including shallow (<50 cm) pyrite, thick layer (>3 m) of peat and high level of inundation (>2 m) with a prolonged (3-6 months) overflow. In addition to these, acidity, peat maturity and nutrient status also serve as the limiting factors. Actual oil palm productivity in swamps remains low due to suboptimal cultivation technology and land and environmental management. It is, therefore, necessary to increase entrepreneurs and farmers’ capacity to improve management and cultivation systems. Land selection for site development should respect the following requirements: pyrite depth >100 cm, peat thickness >3 m with sapric maturity level, mixed peat and mineral soils, soil pH ranging from 5.0 to 6.0 and base saturation around 30%.

1. Introduction

Since the last ten years, oil palm plantation has expanded into swamp agroecosystem, despite its complex constraint. Swamp agroecosystem consists of coastal swamps, tidal swamps, freshwater swamps and peat. Of 4.7 M ha of oil palm development in Sumatra, 3.3 M are on mineral soils and 1.4 M are on peat soils. About 0.3 M ha is recorded on Kalimantan’s peat soils, out of a 2.9 M ha in total. During 2005-2010, the rate of oil palm development on peatlands reached 130,260 ha/year, almost doubled than previous records, i.e. 65,614 ha/year. This acceleration was much higher than similar expansion over mineral soils, about 383,103 ha/year from 229,876 ha/year [1].

Rapid development and expansion are due to increasing demand for bioenergy materials from palm oils. Hence, land use competition becomes inevitable. Expanding oil palm plantations eventually occupies swampy areas for new land developments, alongside with conversion from food crops [2]. In addition to unfavorable soil properties, utilization of swamplands might increase greenhouse gas (GHG) emissions, primarily from carbon dioxide (CO₂) which could cause global warming and impacts world climate change [3]. Despite this controversy, it is also necessary to understand the potential of
Swampland. About 10.87 M ha swamplands are suitable for oil palm development, out of 34.12 M ha existing swampland areas [4].

Oil palm plantation over swamp area is around 20-25% of its total (about 14.30 M ha), annually producing around 41.6 M tons crude palm oil (CPO) [5]. According to Sabiham [6] and Barus et al. [7], there were approximately 1.58 M ha oil palm plantations and 9.29 M ha non-oil palm plantations over Sumatran peatlands, with 16% (4.43 thousand ha) of the figure were in peat domes. Sabiham [8] estimated around 7.26 M ha plantations on peatlands, including 3.99 M ha in Sumatra, 2.9 M ha in Kalimantan, 292 thousand ha in Sulawesi, and 83 thousand ha in Papua.

This paper reviews the outcome of swampland surveys in several locations in Kalimantan and Sumatra, specifically used to develop oil palm plantations. In addition, this article presents future perspectives regarding constraints of land development.

2. Soil properties and land suitability for oil palm

Peatlands cover substantially large parts of Indonesian main islands, i.e. Sumatra (5.85 M ha), Kalimantan (4.54 M ha), Papua (3.01 M ha) and Sulawesi (0.03 M ha). Five largest provinces to host are Riau (3.57 M ha), Central Kalimantan (2.55 M ha), Papua (2.22 M ha), West Kalimantan (1.55 M ha), and South Sumatra (1.12 M ha) [9].

We surveyed swamplands in South Kalimantan (3 sites), East Kalimantan (1 site), West Kalimantan (1 site) and Nangro Aceh Darussalam (1 site), to describe the characteristics of swamp soil, covering physical, chemical, and soil fertility properties in the perspective of land suitability for the development of oil palm plantations.

2.1. Swampland characteristics

Soil properties are the primary consideration in agricultural development plans. Swamplands are mainly composed of three soil orders, namely (1) acid sulfate mineral soils (Entisols or Inceptisols) and (2) peat soils (Histosols). In general, swampland ecosystems are strongly influenced by water regimes, namely (1) tidal movements of river/seawater in tidal swamps typology; (2) inundation, both by height and duration in freshwater swampland typology; (3) thickness and maturity of the peat layer in the peatland typology; and (4) salinity levels in saline land typology [10, 11]. Land evaluation studies by Djaenudin et al. [12] and Furukawa [13] found that common agricultural failures, including plantations on swamps, were associated with (1) thick and raw peat layers; (2) shallow and oxidized pyrite; (3) high salinity due to seawater intrusion; or (4) a shallow layer of substrate in the form of quartz sand and/or pyrite.

Masganti et al. [14] put further details on the requirements for oil palm growth over mineral and peat soils, i.e. rainfall conditions (2,000-3,000 mm/year); the number of dry months (>1 month); altitude (0-200 m above sea level); area shape (flat-wavy), slope (<8%), amount of rock on the surface (<3%), adequate depth (>100 cm), drainage class (good-moderate), and texture (clay loam to sandy loam). Specifically for peatlands, they added the following properties: peat thickness < 3 m; sapric peat maturity, acidity level pH 3.5-4.5; pyrite depth > 100 cm; and subsoil substrate other than sand.

Prospective development sites indicated a shallow layer of pyrite, a thick and raw peat layer, and a bottom layer of quartz sand (Tables 1 and 2). Soil types, including hydrotopography and type of cover from each location, greatly varied, therefore, zoning a-third of development areas for conservation management zone is required.
Table 1. Soil types and their distribution over six oil palm plantations in Kalimantan and Sumatra

| Main Soil Types       | Survey Location (Regency, Province) | Tabalong, South Kalimantan | Tapin, South Kalimantan | Barito Kuala, South Kalimantan | Paser, East Kalimantan | Sintang, West Kalimantan | Nagan Raya, Aceh |
|-----------------------|------------------------------------|-----------------------------|-------------------------|-------------------------------|------------------------|--------------------------|------------------|
| Haplofibrist          | XXX                                | -                           | X                       | XX                            | -                      | XXX                      | XXX              |
| Haplohemist           | XXX                                | -                           | -                       | -                             | -                      | XXX                      | XX               |
| Haplosaprist          | -                                  | XXX                         | -                       | XXX                           | -                      | XXX                      | XX               |
| Sulfibrist            | -                                  | -                           | X                       | -                             | -                      | -                       | -                |
| Sulfaqvent            | -                                  | -                           | -                       | X                             | -                      | -                       | -                |
| Sulfihemist           | -                                  | -                           | -                       | X                             | -                      | -                       | -                |
| Sulfaquett            | -                                  | XX                          | XXX                     | -                             | -                      | -                       | -                |
| Sulfaquent            | -                                  | XXX                         | XX                      | -                             | -                      | -                       | X                |
| Endoaquent            | XX                                 | XXX                         | XXX                     | XX                            | -                      | -                       | -                |
| Endoaquett            | XXX                                | X                           | X                       | XX                            | -                      | -                       | -                |
| Psammaquent           | X                                  | -                           | X                       | X                             | X                      | -                       | -                |
| Dystrudept            | -                                  | -                           | -                       | -                             | X                      | -                       | -                |
| Hapludult             | -                                  | -                           | -                       | X                             | X                      | -                       | -                |

Description: - = not found, X = in a narrow area, XX = moderate, XXX = dominant
Source: processed from [15-19].

While soil acidity condition in freshwater swamp is generally better than in tidal swampland, our surveys did not reflect this common findings. Soil acidity in Table 2 showed that both typologies shared a similar soil pH. Soil acidity in swamps is highly dependent on land typology, overflow type, and soil type [15]. According to Noor [15], soil acidity on acid sulfate lands and moderate peat (thickness <50 cm) is higher, reaching pH 3.86 and 2.89 respectively. Meanwhile, actual acid sulfate lands and shallow to moderate peat (>50 cm thickness) have a pH of 4.30 and 3.66, respectively. Tidal swamps are often associated with a layer of pyrite at the bottom of the peat, so they can experience acidification when dried [11, 15]. In freshwater swamps (Tabalong, Tapin, Paser, and Nagan Raya Regency), peat was nearly ripe (hemic) and ripe (sapric). Meanwhile, peat in tidal swamp ecosystem (Barito Kuala and Sintang Regency) was mostly raw (fibric), with a few portion is found as sapric or hemic. Thick peat exposes raw peat materials on its top layer with reduced soil fertility [10]. Surveys found that there were clay mineral soils (Ultisols) and sandy soils (Entisols) associated. Clay minerals containing pyrite layers were found in tidal swamps at several sites with shallow depths.

As indicated in Table 2, N, P, and K level over tidal swamp is lower than those of freshwater swamp. Tidal swamp ecosystem recorded lower exchangeable bases (Ca, Mg, K, and Na) than observed on freshwater swamp peat. It was because freshwater swamp is often enriched by periodic flooding from the upstream. In contrast, tidal swamp undergoes decomposition and leaching more quickly through intensive tidal movements than freshwater swamp [11, 15]. Thickness and peat maturity determine chemical properties and fertility of the soil.
Table 2. Chemical properties and soil fertility of the six oil palm development sites in the swamps of Kalimantan and Sumatra

| No | Plantation Location                  | Layers | pH H₂O | pH KCl | DHL (mS cm⁻¹) | C-organic (%) | N (%) | P₂O₅ (mg100g⁻¹) | K₂O (mg100g⁻¹) | Al | H | CEC |
|----|-------------------------------------|--------|--------|--------|---------------|--------------|-------|----------------|----------------|----|---|-----|
| 1  | Paser, Kaltim (tidal swamp+freshwater swamp) | Top    | 4.68   | 3.86   | 0.18          | 13.20        | 0.41  | 37.22          | 160.10         | 2.98| 0.71 | 20.22 |
|    |                                     | Bottom | 4.98   | 4.04   | 0.11          | 4.34         | 0.23  | 20.64          | 20.07          | 2.20| 1.01 | 14.80 |
|    |                                     | Average| 4.87   | 3.98   | 0.13          | 7.66         | 0.30  | 26.86          | 50.08          | 2.49| 0.90 | 16.83 |
| 2  | Tapin, Kalsel (freshwater swamp)     | Top    | 4.08   | -      | 0.11          | 31.41        | -     | -              | -              | 5.43| 2.47 | 82.03 |
|    |                                     | Bottom | 4.02   | -      | 0.33          | 10.09        | -     | -              | -              | 5.72| 3.15 | 67.43 |
|    |                                     | Average| 4.01   | -      | 0.22          | 23.80        | 0.33  | -              | -              | 5.58| 2.80 | 76.40 |
| 3  | Barito Kuala, Kalsel (tidal swamp)   | Top    | 4.76   | 4.34   | 1.69          | 6.02         | 0.28  | 47.92          | 39.23          | 2.07| 0.87 | 12.97 |
|    |                                     | Bottom | 4.91   | 4.47   | 1.70          | 6.60         | 0.28  | 53.44          | 48.04          | 2.50| 0.41 | 11.35 |
|    |                                     | Average| 4.83   | 4.40   | 1.70          | 6.28         | 0.28  | 50.41          | 43.21          | 2.26| 0.66 | 12.24 |
| 4  | Tabalong, Kalsel (freshwater swamp)  | Top    | 4.44   | -      | 0.06          | 31.61        | 0.50  | 17.82          | 14.24          | -   | 67.31 |
|    |                                     | Bottom | 4.69   | -      | 0.05          | 26.30        | 0.38  | 16.59          | 10.26          | -   | 61.15 |
|    |                                     | Average| 4.57   | -      | 0.06          | 28.28        | 0.44  | 16.59          | 12.20          | -   | 62.51 |
| 5  | Sintang, Kalbar (tidal swamp+freshwater swamp) | Top    | 3.99   | 3.07   | -             | 29.89        | 0.51  | 17.82          | 14.24          | -   | 38.53 |
|    |                                     | Bottom | 4.03   | 3.28   | -             | 24.29        | 0.51  | 6.17           | 4.50           | -   | 35.36 |
|    |                                     | Average| 3.99   | 3.13   | -             | 27.93        | 0.55  | 9.29           | 6.96           | -   | 37.23 |
| 6  | Nagan Raya, Aceh (freshwater swamp)  | Top    | 4.53   | -      | 0.65          | 42.99        | 1.42  | 5.33           | 32.87          | -   | 95.97 |
|    |                                     | Bottom | 4.22   | -      | 0.36          | 43.91        | 1.59  | 5.99           | 20.21          | -   | 91.85 |
|    |                                     | Average| 4.39   | -      | 0.53          | 43.39        | 1.50  | 5.63           | 27.03          | -   | 94.29 |

Description: - = data not available
Source: processed from [16-21]

2.2. Land suitability criteria for oil palm

In the provisions of the Minister of Agriculture Regulation No. 14 Year 2009 concerning the Guidelines for Peatlands Utilization for Oil Palm Cultivation, PP 57 of 2016 in lieu of Governmental Regulation (PP) 71 Year 2014 concerning the Protection and Management of Peat Ecosystems, and Presidential Instruction No. 11 Year 2019 about the Postponing the Granting of New Permits and Improving Natural Forest Governance Primary and Peatlands (Moratorium on Forests and Peatlands), the criteria for land cultivation include: (1) peat thickness <3 m; (2) substratum other than quartz or pyrite sand. Pyrite layer is allowed if the depth is <50 cm; and (3) about 10% of minimum development area is used as a conservation management zone (protected areas). Condition of land degradation is based on the criteria of PP 150 Year 2000 concerning the Control of Soil Damage for Biomass Production, presented in Table 3.
Table 3. Wetland criteria, including degraded swamplands

| No. | Soil Properties                                      | Critical threshold                                      | Measurement method                  | Equipments                                    |
|-----|------------------------------------------------------|--------------------------------------------------------|-------------------------------------|-----------------------------------------------|
| 1   | Peat subsidence from the top of quartz sand          | • 35 cm/5 year for peat > 3 m                          | Direct measurement                  | Subsidence pegs                              |
|     |                                                      | • 10% /5 year for peat <3 m                           |                                     |                                               |
| 2   | Depth of pyrite layer from soil surface              | < 25 cm pH H₂O₂ ≤ 2.5                                  | Oxidation reaction and direct measurement | Plastic cup, H₂O₂, pH meter/pH stick scale 1/2-unit, roll meter |
|     |                                                      |                                                       |                                     |                                               |
| 3   | Depth of shallow groundwater                         | > 25 cm                                                | Direct measurement                  | Roll meter                                    |
| 4   | Redox (mV), for soil with pyrite                    | > -100                                                 | Electrical voltage                  | pH meter, platinum electrode                 |
| 5   | Redox (mV), for peat                                 | > 200                                                  | Electrical voltage                  | pH meter, platinum electrode                 |
| 6   | pH (H₂O) 1:2,5                                       | < 4.0; > 7.0                                          | Potentiometric electrical resistance | PH meter; pH stick                           |
| 7   | Electrical conductivity (EC)                         | > 4.0 mScm⁻¹                                          |                                     | EC meter                                      |
| 8   | Number of microbes                                  | < 10² CFU/gr soil                                     | Plating technique                  | Petri dish, colony counter                   |

○ For wetlands with no peat and pyrite depth >100 cm, provisions for groundwater depth and redox values do not apply.
○ Peat thickness, maturity, and depth of pyrite layer requirements do not apply if swamp has not been disturbed/is still in its original/natural condition/natural forest.
○ Source: PP No. 150 Year 2000

With aforementioned provisions and the criteria prepared by FAO [22] as the basis for determining land suitability as stated in the Technical Guideline for Land Evaluation for Agricultural Commodities [23], land suitability class for the sites can be obtained (Table 4).

Table 4. Land evaluation from six swamplands for oil palm plantation development in Kalimantan and Sumatra

| land suitability classes | Tabalong | Tapin | Barito Kuala | Paser | Sintang | Nagan Raya |
|-------------------------|----------|-------|--------------|-------|---------|------------|
|                         | Ha       | %     | Ha           | %     | Ha      | %          | Ha           | %     |
| S2                      | 2,425    | 24.0  | 9,880        | 56.7  | 4,983   | 55.3       | 715          | 37.7  | 3,209   | 16.0       | 5,493   | 36.0       |
| S3                      | 5,401    | 53.6  | 7,286        | 41.8  | 2,754   | 30.6       | 728          | 38.4  | 9,178   | 45.9       | 3,264   | 21.4       |
| N                       | 2,257    | 22.4  | 256          | 1.5   | 1,269   | 14.1       | 453          | 23.9  | 7,609   | 38.1       | 6,492   | 42.6       |
| Total                   | 10,083   | 100.0 | 17,427       | 100.0 | 9,006   | 100.0      | 1,896        | 100.0 | 19,996  | 100.0      | 15,249  | 100.0      |

Notes: S2 (moderately suitable), S3 (marginally suitable), N (not suitable)
Source: processed from [16-21]

The evaluation suggested that an average of 38% (range between 16% and 57%) was classified as moderately suitable category (S2), 39% (range between 21% and 54%) was classified as marginally class (S3) and 24% (range 1.5% - 42%) was categorized as not suitable class (N). This indicated that there were severe obstacles as a result of the inclusion of not suitable class (N), including a relatively
shallow depth of pyrite (<50 cm), a very thick layer of peat (>3 m), high inundation (>2 m) with a prolonged inundation reaching 3-6 months, and a thick surface layer of sand.

Tables 1, 2, and 4 emphasize that utilization and development of swampland for agriculture, including oil palm development, should consider the diversity of swampland sources, as well as their soil and environmental characteristics, to obtain optimal results. Restrictions on peatlands utilization for oil palm development are intended to improve existing management system to allow stable, sustainable, and environmentally sound production systems.

3. Oil palm development perspective in swamp

3.1. Soil and agronomic limiting factors
Soil and agronomic limiting factors in the development of oil palm in swamps are (1) soil physical properties including soil texture, soil maturity both mineral and peat, depth of pyrite layer, depth of solum, depth of water table or soil moisture content; (2) chemical properties and soil fertility including acidity, nutrient status, levels of toxic elements/compounds, and the number of microbes; and (3) selection of species or varieties adaptive to swamplands, plant resistance (varieties) to soil conditions and existing plant pests and diseases, high productivity and production age.

3.2. Oil palm productivity in swamplands
Productivity of oil palm in swamps is generally low. Oil palm plantations in Betung Krawo, South Sumatra yielded only about 10.86 -12.70 t FFB/ha. With a good swampland management, production could be achieved between 25-27 t FFB/ha and 19-25 t FFB/ha [24]. According to Juwanto [25], productivity of oil palm on sapric peatlands can reach 25.45 t FFB/ha, higher than hemic peat (23.20 t FFB/ha) and fibric peat (20.60 t FFB/ha). The success of increasing oil palm productivity is managing C-organic and soil pH. C-organic correlates to C/N ratio, N content, and CEC [26]. Table 2 shows that research sites had a moderate soil acidity and low nutrient status, requiring fertilizer and ameliorant inputs. Fertilization is vital for infertile soils because oil palm requires large amounts of nutrients compared to other crops (Figures 1 and 2).

Masganti and Susilawati [27] reported that oil palm productivity in peat swamplands can be increased by improving water management through installing overflow dams. These dams could improve yield by 5.9 t FFB/ha/year, from 116.6 t FFB/ha/year to 22.5 t FFB/ha/year. Application of ameliorant materials could increase yield by 5.77 t FFB/ha/year from 11.74 t FFB/ha/year. Meanwhile, complete fertilization could augment yield by 0.77 t/ha/month, from 2.08 t FFB/ha/month to 2.85 t FFB/ha/month.
Figure 1. Oil palm growth on freshwater peat soil in East Kalimantan (above); tidal mineral soil in South Kalimantan (bottom left); tidal peat soil in Central Kalimantan (bottom right) (photos by M. Noor/Balittra)

Figure 2. Oil palm growth in freshwater peat soils in West Kalimantan (left) and in Nagan Raya, Nangro Aceh Darussalam (right) (Photos by M.Noor/Balittra)
4. Conclusion and policy implications
Rapid development of oil palm plantations in swamps, especially peatlands, need to be well addressed. However, it requires appropriate technologies for water management and soil fertility and good agricultural practices to minimize the impact to the environment. Actual productivity of oil palm in swamps is still low because cultivation technology, land management, and the environment are not optimal. Hence, capacity of entrepreneurs and farmers needs to be improved in terms of crop management and cultivation systems. Selection of land development through a survey for the identification and characterization of development areas should regard optimal requirements for oil palm. These requirements include pyrite depth >100 cm, peat thickness >3 m with sapric maturity, mixed peat with mineral soil, soil pH ranging from 5.0 to 6.0, and base saturation around 30%.

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