Dynamic of groundwater table, peat subsidence and carbon emission impacted from deforestation in tropical peatland, Riau, Indonesia

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Abstract. Drainage canals have triggered peat subsidence and lowered groundwater table, enabling wildfires and peat degradation in Riau, Indonesia. This study examines the changes on groundwater table, peat subsidence rate, and carbon emission in response to deforestation and land cover changes. We established 31 study sites in some land cover types (i.e., oil palm plantation, acacia regrowth and shrub), with 124 monitoring shallow wells and 31 subsidence poles that were setup and have been monitored for 18 months. Groundwater table of all plots averaged -55 cm in Dosan Village, higher than that in Dayun Village (-66 cm). In accordance, peat had subsided in faster rate (8.4 cm year\(^{-1}\)) in Dayun Village than that in Dosan (3.3 cm year\(^{-1}\)). This average annual groundwater table has resulted in carbon emissions from peat decomposition up to 66 t CO\(_2\) eq ha\(^{-1}\) year\(^{-1}\). On the other hand, canal discharge of these sites ranged from 2 to 73 dm\(^3\) s\(^{-1}\), averaging 26 dm\(^3\) s\(^{-1}\). These results evidence that land uses converted from peat forest, and the dimension of canal control the decrease in groundwater table, the pace of peat subsidence, and rate of carbon emissions in tropical peatlands.

1. Introduction
Indonesia host about half of the tropical peatlands, which represent 3.5% of the 400 million ha global peatland area [1]. Tropical peatland ecosystems are among the richest ecosystem in C stocks on earth [2, 3], storing in Indonesia about 57 Pg [4]. The largest area of peatland in Indonesia is in Sumatera, with about 6.4 million ha, followed by the islands of Borneo (4.7 million ha) and Papua (3.7 million ha) [5, 6].

Deforestation and forest degradation have lurked this vital ecosystem for the last decades [7, 8], negatively affecting the structure of the ecosystem and lowering the capacity to supply products or services [9]. Previous estimates suggested that Indonesia’s forest loss rate is about 1,000 km\(^2\) year\(^{-1}\) to 5,000 km\(^2\) year\(^{-1}\) [10]. About three million ha of oil palm plantation and a million ha of abandoned peatlands had been developed in South East Asia’s peatlands in the last three decades [8]. This segregated the landscape into degraded forests, shrubs, and agricultural cover types in peatlands. Intact peat swamp forest has been lost so much (93%) from all peatland areas in main Indonesia’s islands, and the remaining forest mostly exists in Papua Island [8].

Competition among land uses for forestry and non-forestry sectors, have caused the conversion of natural peat swamp forests, including for paper and palm oil industries in Indonesia. The opening of peatland for plantation sector is commonly accompanied by a practice of drying the peatland to make it...
more amenable for agricultural purposes but had dampened its sustainability. This triggered peat subsidence and lowered groundwater table, then enabled peat degradation and wildfires [11]. Consequently, this tropical peat ecosystems shifted from carbon sequester to net carbon emitter that are prone to wildfire and unproductive [12, 13].

Within the last three decades, peatlands have been the major source of land for the development of oil palm and forestry plantation. At the same time, it has been the major source of regional problems such as fire, haze, and GHG emissions. As a fragile ecosystem, tropical peatland often forms a thick layer of undecomposed materials that will be prone to fires if it becomes dry.

Groundwater table in drained peatland is known to significantly affect GHG emission rates from peat decomposition. Carbon loss model has been developed as a function of groundwater table from plantation areas in peatlands [14, 15], their relationship in non-concession areas that have different drainage system and peat characteristics remains unclear. Moreover, few studies had investigated how land uses and hydro-topography may influence the groundwater table (GWT) within a peat dome context.

Previous studies reported that peat subsidence had been impacted much by long term groundwater table. Lower GWT leads to higher peat subsidence rates [16-18] and dictates on the rate of oxidation process, driving compaction and consolidation of peat layers [15, 18]. When a portion of peatlands are drained, the subsidence rate in the first five years after drainage is considerably higher than the following years due to compaction and consolidation [19]. This consolidation process decreases with time since drainage starts [20]. A knowledge gap exists in how the peat types (fibric, hemic and sapric) and GWT dynamic may influence the subsidence rates. Frequent measurements are needed to fill this gap, e.g. monthly measurement or more frequent measurement periods.

It is unclear how deforestation has impacted the peatland ecosystems in term of its groundwater table depth, peat subsidence and, ultimately, peat carbon emissions to the atmosphere. In this study we developed 31 study sites, 124 monitoring shallow wells, and 31 subsidence poles stratified across a range of land use types and peat depths, and monitored since early 2018. Previous studies on intact peat swamp forests (including from adjacent Zamrud National Park) were used as reference in assessing impact of deforestation.

This study aims to: a. Estimate the impact of land use change on water table, peat subsidence rate and carbon emission; b. Improve Emission Factor (EF) of each land use type based on the field measurement; and c. To understand land use characteristics that control changes in water table, peat subsidence rate and carbon emission.

2. Methods

2.1. Study area/research site

Total area of Siak District is about 855,609 ha, where the remaining natural forest areas in Siak is 159,048 ha (19%) (figure 1). Oil palm plantation and timber plantation are 165,324 ha and 205,730 ha, respectively.

Forest loss in these areas occurred mostly between 2000 to 2010 and were primarily converted into oil palm or timber (acacia) plantation. The main impacts of deforestation are degraded peatland and fires. Most of conversion of natural forest to plantation in peatland produce emission between 30 to 72 tCO2eq ha−1 year−1 [21], and this condition also become worst since degraded peatlands are prone to fire.

Dayun Sub-District (and Dayun Village) boundary is adjacent with Sungai Apit and also part of Kampar Peninsula Landscape and Zamrud NP. It takes about 1.5 hours from Pekanbaru to Dayun, passing through mostly oil palm plantations along the road. The total area of the sub-district is 137,352 ha, divided into forestry areas of about 70% (both natural and plantation forests) and non-forest areas, including oil palm plantation, shrubs and agriculture, about 30%. Oil palm plantation and shrubs were represented in our study area at Dayun Village, while the agriculture land are not included as they mostly located in mineral land.

Pusako Sub-District (and Dosan Village) is adjacent with Dayun Village areas. It takes about 2.5 hours from Pekanbaru to Pusako. The total area of the sub-district is 54,447 ha, where Dosan village composed of 10,028 ha. Total area of the district is non-natural forest areas, including acacia, oil palm
and rubber plantations, shrubs and agriculture areas. In this village, oil palm plantation, acacia plantation (regrowth) and shrubs were represented. Similar to that in Dayu Village, the limited area of agriculture land was not included in our study.

![Figure 1](image.png)

**Figure 1.** Land cover types in the study area dominated by oil palm (orange), acacia plantation (brown), shrubs (pink) and secondary swamp forest (green). White cross represents our study sites.

Age of oil palm plantations in both villages is similar (17 years old) and being the first planting. In Dosan, the plantation was mostly converted from degraded peat forests, and drained dominantly using small dimension canals that are about 2 m wide. In contrast, oil palm plantation in Dayun was developed from ex shrubs and has been drained by big dimension canal that is about 8 m wide. On the other hand, shrubs in both villages experienced peat fires in the past and influenced by canals with big dimension (8 m wide). Acacia plantation was only studied in Dosan Village and characterized by both small canals that are about 2 m wide each.

The study area belongs to tropical wet climate zone, showered by about 2,390 mm of annual rainfall ([https://id.climate-data.org/location/1062512](https://id.climate-data.org/location/1062512)). Local temperature averaged 26.9°C. The climate is classified as Af by the Köppen-Geiger system.

Siak is almost 58% covered by peatland ecosystems (figure 2). These peatlands are part of the Sungai Siak – Sungai Kampar peat hydrological unit (KHG) that covers Siak and Pelalawan Districts.

Most of the peatland in the area has been affected by selective logging concessions. The operational of new types of the concession had burned and drained the peatland and created big impact to the environment especially for carbon emission, peat fires and biodiversity loss. The peatlands can be
divided into developed zones, i.e., agriculture, oil palm plantation, acacia plantation, paddy field and settlement, around 183,245 ha), undeveloped zones (primary forests, secondary forests and swamps, around 190,462 ha), and degraded zones (bare ground and shrubs around 32,260). The study area represented peat dome across lowest reach near Siak River to the peak elevation, with peat maturity varied from fibric to sapric types.

Figure 2. Study site (white cross) on a peat dome (light brown to reddish color) in Siak Regency.

2.2. Groundwater table, peat subsidence, canal discharge measurements

Research has been implemented by measuring peatlands’ characteristics in various land cover types, including oil palm plantation (96 shallow wells; 24 subsidence poles), shrubs (20 shallow wells; 5 subsidence poles), and acacia regrowth (8 shallow wells; 2 subsidence poles) in Pusako (Dosan Village) and Dayun Districts (Dayun Village), Siak Regency (figure 3). Every sampling site was situated on the side of a secondary drainage canal. Measured characteristics on each site include peat depth, peat subsidence, water table, and canal discharge. Climate characteristics were measured using automatic weather system, to represent local condition.

Groundwater table was measured in each sampling site. Shallow wells were installed at the distances of 0 m, 10 m, 25 m, and 50 m distances from canal. Shallow well material (PVC pipe) cut in 2 m length with electric disc, and sharpened at one end. Each pipe should be drilled to make holes along the pipe, with a distance of 25 cm distance on four rows. Aluminum mesh used to cover the pipe, from the bottom to 20 cm before the top. The bottom of pipe was covered by a cap, which had been holed at its center.
This aluminum mesh and the cap will limit the peat materials from entering the pipe, when it has been installed in the soil. On measurement site, peat should be drilled with the eijkelkamp auger up to 2 m deep and the organic material taken out. Then the PVC pipe inserted into the hole, and left only the 0.2 m pipe aboveground (figure 4). Another cap, without hole, was placed at the top of pipe to avoid rain entering the shallow well.

![Figure 3](image)

**Figure 3.** Land cover types in peatlands, Siak Regency (Clockwise from the top left: natural forest, mixed agriculture, shrubs/ex-burned site, acacia regrowth, and oil palm plantation).

Groundwater table was measured relative to the peat surface, using the measurement stick [23]. First, measure the height of water table from the pipe end (B; figure 4). Then the height of the pipe from the ground should also be measured (A). GWT is the difference between B and A.

CO₂ emissions rate was estimated by using the carbon loss model as a function of GWT that was adapted from Carlson et al. [14], for oil palm plantation:

\[ CL = 5.4 + 0.21 \times GWT - 100 \times 3.67; \]

and Hooijer et al. [15] for acacia plantation and deforested peatland:

\[ CL = 21 - 69 \times GWT \text{ and } CL = 9 - 84 \times GWT; \]

where CL means total carbon loss (Mg CO₂eq ha⁻¹ year⁻¹) and GWT means groundwater table (m). The model was used because there are evidences that peat GWT significantly influence CO₂ emissions in plantations on drained tropical peatlands [14, 15].

Canal water discharge rate (m³ s⁻¹) was measured by float method [24]. The volume of a canal transect (m³) divided by the travel time of a float flowing through the transect (s). The volume of canal
transect was assessed by measuring the width and depth of water at both edges of a 5 m transect along canal.

![Diagram of groundwater measurement](image1.png)

**Figure 4.** Setting and components of measurement of the groundwater table in a shallow well.

Peat subsidence poles were installed at 10 m distance from canal edge, on 27 sites. They were made of iron re-bar (16 mm in diameter) and cut according to the peat depth. Peat depth should be measured using an eijkelkamp auger up to the mineral layer. Then, the re-bar (pole) inserted into the hole, and let 0.5 m left aboveground (figure 5).

![Diagram of peat subsidence pole](image2.png)

**Figure 5.** Peat subsidence pole setting within monitoring station.

Pole height from peat surface (T) should be measured once a month, using a metal measurement stick. Every subsidence pole should be measured at 12 different points, three points at every direction.
(north, south, east, west), in every measurement. A watertable equipment was used to ensure that all measurement done on a flat reference (figure 6). The baseline peat elevation relative to the top of the pole should be measured first (T0). The later (a month period) peat elevation should be measured again (T1). The difference of elevation (T1-T0) is the peat subsidence (positive value) or peat accretion (negative value).

Figure 6. Peat subsidence pole measurement points and their layout.

This study tested the difference on peat groundwater table and annual subsidence rate as impacted by deforestation. Characteristics in deforested areas (i.e., oil palm plantation, acacia regrowth and shrubs) measured in our study were compared to those reported from peat swamp forest [17, 25-27]. Shapiro-Wilk test used to test the normality of data distribution. Difference in mean groundwater table and annual subsidence rate among land cover types were tested using analysis of variance (ANOVA). Kruskal Wallis’ H test was used for non-normal data distribution. All these statistical tests carried out using the IBM SPSS statistics.

3. Results and discussion

3.1. Groundwater table and carbon emission

Average groundwater table of land cover type in both villages, i.e., oil palm plantation (-57 ± 5.7 cm), acacia regrowth (-68 ± 0.5 cm) and shrubs (-67 ± 10.7 cm), are significantly lower than that in intact peat swamp forest (-10 ± 0.3 cm; p <0.05; figure 7). The average groundwater table of all sites in both villages (-60.5 cm) indicates that the peatland has been degraded, having a much lower groundwater table than the average of annual water table in natural peat swamp forests (i.e. -10 cm), as reported by previous studies [25-27]. It also indicates that all the area is categorized as on ‘danger’ status of peat fires, according to the fire hazard status of Indonesian peatlands (BRG).

Groundwater table of sites in Dosan Village averaged -55 ± 2.1 cm (December 2017 to May 2019), higher than that in Dayun Village (-66 ± 2.6 cm; table 1). Groundwater table in Dayun was influenced by wider (8 m) and deeper canal (2 m) than that in Dosan Village (2 m wide and 1 m deep canal). Those wider and deeper canals in Dayun Village, constructed to facilitate bigger road and intensive activity of oil mining, forest plantation and oil palm plantation, had drained peat water storage faster than those smaller canals in Dosan.

In Dayun Village, the average water table in shrub areas (-68 ± 6.9 cm) was lower than that in the oil palm plantation (65 ± 2.8 cm). These two land cover types are influenced by similar dimension of canal, but have different history related to peat fire occurrence. Many areas of shrub had been burnt in 2015 and may form the hydrophobic layer aboveground. The layer may allow limited amount of water to infiltrate and reduce the water storage in shrubs.
In Dosan Village, the lowest mean water table was found near the acacia regrowth (-69 ± 4.6 cm) in contrast to that found in oil palm plantation (-51 ± 2.2 cm). Although both cover types had been influenced by small dimension of canal, acacia plantation areas had not been rewetted by canal blocks such as in the oil palm plantation.

![Figure 7. Groundwater table (cm) of various land use types and monthly rainfall rate (mm) in Dosan and Dayun Village from December 2017 until May 2019.](image)

Our average groundwater table reflects the CO$_2$ emission from peat decomposition, based on [14,15], as high as 64 and 55 t CO$_2$eq ha$^{-1}$ year$^{-1}$ in Dayun and Dosan Villages, respectively. The higher peat CO$_2$ emission rate in Dayun Village than that in Dosan Village indicates the influence of bigger canal dimension of Dayun Village on its lower water table.

| Village | Land use type | Number of shallow wells | Groundwater table (- cm) | CO$_2$ emission estimate [15] (Mg ha$^{-1}$ year$^{-1}$) |
|---------|---------------|-------------------------|--------------------------|-----------------------------------------------------|
| Dayun   | Oil Palm      | 64                      | 65 ± 2.8                 | 70                                                  |
|         | Shrubs        | 16                      | 68 ± 6.9                 | 66                                                  |
|         | All           | 80                      | 66 ± 2.6                 | 68                                                  |
|         | Acacia        | 8                       | 69 ± 4.6                 | 68                                                  |
|         | Oilpalm       | 32                      | 51 ± 2.2                 | 59                                                  |
|         | Shrubs        | 4                       | 63 ± 2.2                 | 62                                                  |
|         | All           | 44                      | 55 ± 2.1                 | 63                                                  |

The highest emission from potential peat decomposition occurred in the site of acacia regrowth in Dosan (68 t CO$_2$eq ha$^{-1}$ year$^{-1}$) and of oil palm plantation in Dayun Village (70 t CO$_2$eq ha$^{-1}$ year$^{-1}$). These land uses are characterized by canal bodies of bigger dimensions than those in oil palm plantation areas in Dosan Village, where the lowest peat CO$_2$ emission (59 t CO$_2$eq ha$^{-1}$ year$^{-1}$) was found.

Shrub areas in Dosan had CO$_2$ emissions of 64 t CO$_2$eq ha$^{-1}$ year$^{-1}$. While the calculated shrub’s CO$_2$ emission in Dayun (62 t CO$_2$eq ha$^{-1}$ year$^{-1}$) is three times higher than the default IPCC’s emission of
shrub (19 t CO₂eq ha⁻¹ year⁻¹). These sites are drained with 8 m wide canal next to the big road at the eastern part of Siak District.

The average value of acacia regrowth CO₂ emission (68 t CO₂eq ha⁻¹ year⁻¹) is slightly lower than the IPCC (2014) default of forest plantation, which is 73 t CO₂eq ha⁻¹ year⁻¹. Differences in emission rates between our research and IPCC default value may suggest that carbon emission from peat decomposition may vary and is site specific. In addition, variation in canal dimension and intensity as well as fire history may contribute to the gap. Furthermore, the difference also sourced from the different approach on the soil carbon emission measurement between the two.

3.2. Canal discharge
Secondary canal discharge ranged from 2 dm³ s⁻¹, near old oil palm plantation, to 73 dm³ s⁻¹, near cleared ex-burnt acacia that had been replanted with oil palm plantation. The discharge averages 26 dm³ s⁻¹.

Considering that annual rainfall is about 2,390 mm (https://id.climate-data.org/location/1062512), there are about 24,000 m³ ha⁻¹ of rain water would enter the peatlands in Siak annually. Discounting this with the amount of water loss through annual evapotranspiration, assuming in degraded forest and plantation dominated landscapes the number would be around 1,553 mm [28], the stored water in peat would be around 8,370 m³ ha⁻¹ per year. On the other hand, this study measured field (secondary)-canal discharge average value at 26 dm³ s⁻¹ that equals to about 0.8 million m³ of annual water drained from a canal. This means that a single canal may drain out all rain water dropped on and stored in almost one square km (97 ha) of surrounding peatlands in a year period. Additional measurement of primary-canal discharge would be needed to examine further the actual contribution of canal system to the water balance in degraded peatland ecosystems.

The information of canal discharge is essential in assessing the water balance, and thus the ground water table in peatlands. Despite of considerable studies on tropical peatland ecosystem, surprisingly there is a knowledge gap on the canal discharge and the number of canal outlets draining the water from peatlands.

3.3. Peat subsidence
In both villages, the mean annual peat subsidence rate of oil palm plantation (5.5 ± 0.7 cm) and shrubs (8.9 ± 3 cm) was significantly faster than the rate of logged-over peat swamp forest [17] (1.5 ± 0.5 cm; p <0.05). On the other hand, the annual subsidence rate was moderated in acacia regrowth being 3.5 ± 0.8 cm.

In Dosan Village, in average, peat had subsided for 3.3 cm annually (table 2). Peat annual subsidence rate ranges from 2.6 cm (oil palm plantation) to 3.9 cm (shrub). Shrub site was drained with bigger dimension of canal (8 m wide, 2 m depth) than those in oil palm plantation sites, and showed a relatively new burn scar.

In Dayun Village, peat had subsided at a much faster rate (8.4 cm per year) than that in Dosan (3.3 cm per year). This had been facilitated by more intensive canal network and bigger dimension of canal found in Dayun than in Dosan Village. Dayun Village territory had been managed intensively in order to facilitate oil mining, forest plantation and oil palm plantation activities. The annual subsidence rate varies from 6.5 cm in oil palm plantation to 10.3 cm in shrubs area. Shrubs area were burnt out in 2015, which had both swept away part of the peat and created impermeable layer on its surface and limit its water infiltration rate.

Over a 25 years period [15], it was reported that acacia plantation (subsidce rate at 5 cm year⁻¹) and oil palm plantation (subsidce rate at 5.4 cm year⁻¹) emit an average of annual carbon loss at about 90 t CO₂eq ha⁻¹year⁻¹ and 109 t CO₂eq ha⁻¹year⁻¹, respectively. Other recent study [29] suggested that acacia plantation may subside at 4.3 cm year⁻¹. Our results show lower subsidence rate for acacia and oil palm plantation in Dosan Village, than those previous reported values. This may indicates that there are differences in characteristics between these studies, such as canal dimension, management intensity and land use history. Our study focused on smallholder plantations and acacia regrowth, while the previous studies were located on business enterprise concessions.
Table 2. Annual mean peat subsidence rate (Mean ± SE; cm) on land use types in Dayun and Dosan Villages.

| Village | Land Use Type | Annual Subsidence (cm) |
|---------|--------------|------------------------|
| Dayun   | Oil Palm     | 6.5 ± 0.6              |
|         | Shrubs       | 10.3 ± 2.8             |
| Dosan   | Acacia       | 3.4 ± 0.8              |
|         | Oil Palm     | 2.6 ± 0.4              |
|         | Shrubs       | 3.9                    |

It should be noted that shrubs in Dayun Village show much higher rate of subsidence, compared to other land uses. This may be related to the fact that a lower groundwater table was found on this land cover type during the dry season (figure 7, above), thus accelerating compaction and oxidative peat decomposition. As shrub burnt out in 2015, their peat surface may have lower infiltration rate than other [30,31] and lowering the groundwater storage. To the best of our knowledge, this is the first reported value of subsidence rate on shrubs in tropical peatland. Overall, annual subsidence rate of all sample sites average 5.3 cm, much faster than the rate reported from logged-over forested peatlands [17] of up to 1.5 cm.

Our study currently has an imbalanced number of samples to represent land cover types, i.e. dominated by oil palm plantation compared to other types. This can affect the uncertainty of our results. However, our overall data are proportionally representing the local land cover types created through deforestation process, thus provide a reliable basis in assessing the impact of the deforestation.

4. Conclusions
This research suggests that deforestation and land cover changes have clear influences on peat degradation. We found that the peat annual groundwater table had been dropped to 63 cm, about 53 cm lower than that in intact peat swamp forests. This makes these valuable ecosystems more susceptible to fires during dry season, with severe implications for livelihoods, health, and global climate change. Moreover, intensive canal system within the plantations on peatlands had threatened the availability of water in the peatland ecosystems.

This study demonstrates that peat had subsided significantly during the measurement period (January 2018 to August 2019), almost four times faster than that found in logged-over peat forests. Large size and dimensions of drainage canals and peat fires have controlled a lower groundwater table, higher rate of peat subsidence and accelerated carbon emission rate.

Peat rehabilitation measures are needed in the plantations and shrubs areas. Our study evidences that blocking and back-filling of canals, as well as locating the effective position of the blockings will give the greatest increase on the water table condition, thus reducing the fire risks in and carbon emission from peatland ecosystems.

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