LETTER

Drainage canal impacts on smoke aerosol emissions for Indonesian peatland and non-peatland fires

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Abstract

Indonesia has experienced frequent fires due to the lowering of groundwater levels caused by drainage via extensive canal networks for agricultural development since the 1970s. However, the impact of canals on fire emissions is still poorly understood. Here we investigate canal impacts on smoke aerosol emissions for Indonesian peatland and non-peatland fires by quantifying the resulting changes of smoke aerosol emission coefficient (Ce) that represents total aerosol emissions released from per unit of fire radiative energy. First, we quantified the impacts of canal drainage and backfilling on water table depth (WTD) variations using field data and then expanded such impacts from field to regional scales by correlating field WTD to satellite terrestrial water storage (TWS) anomalies from Gravity Recovery and Climate Experiment. Second, we estimated Ce from fire radiative power and smoke-aerosol emission rates based on Moderate Resolution Imaging Spectroradiometer active fire and multi-angle implementation of atmospheric correction aerosol products. Finally, we evaluated the Ce variation with TWS anomalies. The results indicate: (a) Ce is larger in peatland fires than in non-peatland fires; (b) Ce increases significantly as TWS anomalies decrease for both peatland and non-peatland fires; and (c) Ce changes at nearly twice the rate in peatland for a given TWS anomaly range as in non-peatland. These phenomena likely result from the different fuel types and combustion phases prevalent under different moisture conditions. These findings support the Indonesian government’s recent peatland restoration policies and pave the way for improved estimation of tropical biomass burning emissions.

1. Introduction

Indonesia shares the largest portion (65%, 57.4 Gt) of tropical peat carbon (Page et al 2011). Undisturbed peat swamp forests rarely experience fire activity because the underlying peat is typically inundated with water under natural environmental conditions (Miettinen et al 2017). Since systematic peatland conversion to farmland and industrial plantations began in the 1970s, however, Indonesia has experienced frequent large fires linked to the lowering of water tables caused by drainage through extensive canal networks for agriculture development (Goldammer 2007, Hoscio et al 2011). Installation of drainage canals alters the natural peat dome and leads to significant declines of water table depths (WTDs) (Page et al 2004). Drained peat becomes susceptible to fires that increasingly burn downward into these organic
soils (Silvius et al. 2006). These fires, combined with compaction of the peatland peat, further alter the peatland hydrology (Hooijer et al. 2012). A vicious circle can ensue between dropping WTD and increasing prevalence of fires.

In recent decades, frequent Indonesian fires have emitted substantial carbon in the forms of trace gases (e.g. CO\(_2\), CO, and CH\(_4\)) and particulate matter (Wooster et al. 2018, Kiely et al. 2020, Lu et al. 2021). Several devastating peat fires have occurred during droughts associated with El Niño events of 1997, 2002, 2004, 2006, 2009, 2015, and 2019 (Han et al. 2017, Kiely et al. 2020, Susetyo et al. 2020), burning millions of hectares (Mha) across Indonesia (Kiely et al. 2020). In 1997 alone, fires released 0.81–2.57 Gt carbon into the atmosphere, potentially equating to 40% of global carbon emissions from fossil fuels (Page et al. 2002). In 2015, fires burned 2.6 Mha areas across Sumatra, Kalimantan, and Papua, causing terrible air pollution, US $16 billion in Indonesian economic losses (Glauber and Gunawan 2016), and more than 100,000 premature deaths from exposure to hazardous fire smoke (Koplitz et al. 2016). Degraded peatlands emit ~6.5 times as much CO\(_2\) (70% from fires, 30% from aerobic decomposition) as burning fossil fuels every year (Silvius et al. 2006, Parker et al. 2008). These peatland-related fire emissions have made Indonesia the world’s 3rd largest emitter of greenhouse gases in some years, behind only the United States and China, versus ranking 21st if peatland emissions were excluded (Silvius et al. 2006, Parker et al. 2008).

Destructive environmental, economic, and health impacts from multiple years of peatland fires and smoke emissions have incentivized the Indonesian government to mitigate the problems through peatland restoration (Page et al. 2002, Kiely et al. 2020). Recently, the Indonesian Peatland Restoration Agency (Badan Restorasi Gambut, BRG) has engaged in various mitigation efforts, primarily through canal blocking and backfilling, to restore 2.5 Mha of peatland ecosystems and protect them from burning (Dohong 2017). The Indonesian restoration program is arguably the largest global carbon-flux mitigation activity being undertaken. The premise is that both the number of fires and total emissions will decrease as water table levels are raised (Dohong 2017, Putra et al. 2018). Previous studies have shown that canal drainage increases fire frequency and burn depth (Konecny et al. 2016, Putra et al. 2018). However, the impacts of canal drainage and canal backfilling/blocking on fire emissions are poorly quantified.

Traditionally, fire emissions are estimated using bottom-up methods which require multiple inputs, including burned area, fuel loading, combustion completeness, and emission factors (Zhang et al. 2008, Van Der Werf et al. 2017). However, each input parameter propagates considerable uncertainties into final fire emission estimates (Zhang et al. 2008, Lu et al. 2017, Van Der Werf et al. 2017, Liu et al. 2020, Gale et al. 2021). For example, several widely used satellite-based burned area products show remarkable differences and accuracies of these products are highly uncertain due to dense smoke and frequent clouds in Indonesia (Vétrita et al. 2021). Recently, a top-down approach for estimating fire emissions directly using smoke aerosol emission coefficients (Ces) based on satellite fire radiative energy (i.e. the temporal integration of fire radiative power (FRP) that measures instantaneous fire-emitted energy) has been developed (Wang et al. 2006, Ichoku and Ellison 2014, Mota and Wooster 2018, Lu et al. 2019, Li et al. 2020). This approach bypasses the need to estimate combusted biomass amounts that is a major source of uncertainty in bottom-up approaches (Wiedinmyer et al. 2011, Van Der Werf et al. 2017).

Here, we estimate how canals impact water levels and then fire emissions in Indonesia. First, this study quantified the impacts of canal drainage and canal backfilling on water levels using field WTD data at a study site. Such impacts on water levels were subsequently expanded from field to regional scales by correlating field WTD data with satellite-observed terrestrial water storage (TWS) anomaly data from the Gravity Recovery and Climate Experiment (GRACE) over 2010–2019. Second, annual Ces values, to represent fire emissions, were calculated using a top-down approach based on Moderate Resolution Imaging Spectroradiometer (MODIS) active fire (AF) and multi-angle implementation of atmospheric correction (MAIAC) aerosol products during 2002 and 2019. Third, the impacts of water levels on regional fire emissions were evaluated by establishing relationships between TWS anomalies and Ces values for peatland and non-peatland fires separately for 2002–2019.

2. Study area and datasets

2.1. Study area

Sumatra (43%), Kalimantan (32%), and Papua (25%) contain nearly all Indonesian peatlands (figure 1(a)) (Wahyunto et al. 2014). These peatlands, particularly in Sumatra and Kalimantan, have experienced high deforestation rates and frequent fire events due to conversions from primary peat-swamp forests into agricultural areas since the 1970s (Page et al. 2002, Van Der Werf et al. 2008, Hoscio et al. 2011, Margono et al. 2014, Stibig et al. 2014). For example, the Ex-Mega Rice Project (MRP, 1995–1998) in Central Kalimantan converted ~1 Mha of peat-swamp forests into rice plantations that failed and were abandoned (Muhamad 2002). In this project, a massive network of drainage canals was established in peatlands (e.g. figure 1(b)), with a total length of 4500 km and depth of up to 10 m (Jainicke et al. 2011). The Ex-MRP area has burned frequently (up to 10 times)
(Konecny et al. 2016) and become the greatest contributor to area burned in Indonesia (MoEF 2020). During 2000–2012, 15.79 Mha forests were lost in Indonesia, 38% of which occurred in primary forests, with annual loss rates increasing significantly over the 13 year period (Margono et al. 2014).

Degraded peatlands have drawn national attention for restoration activities. The BRG restoration program is carried out through three approaches: rewetting of peatlands, revegetation, and revitalization of local livelihood (Dohong 2017). Rewetting drained peatlands through the construction of canal backfills and other techniques is the primary task of the peatland restoration project. Canal backfilling is a process of filling open drainage canals to make the canals shallow and sedimented and thus to reduce runoff and keep water retention capacity high in peatlands (Dohong 2017). Throughout 2016–2019, BRG constructed 143 canal backfills in the seven priority provinces (figure 1(a)). Across the canal-managed areas, we focused on the area in figure 1(b) not just because it was the only area that had both long-term systematic WTD measurements and backfilling activities, but because it was one of the severest areas affected by frequent fires in Indonesia. To investigate the impacts of canal drainage and canal backfilling on fire smoke aerosol emissions, we selected the Indonesian fire seasons from July to November during 2002–2019 as our study period (Giglio et al. 2013, Putra et al. 2018). The start year of 2002 is selected because both Aqua and GRACE observations are available from this year.

### 3. Methods

#### 3.1. Quantification of canal impacts on water levels

We quantified drainage canal impacts on water levels using field WTD data measured in a ∼1200 km² area that has experienced both extensive canal drainage during the Ex-MRP program and considerable canal backfilling as part of BRG activities (figure 1(b)). Specifically, the impacts of canal drainage were assessed by examining WTD variations with distance from canals, and the impacts of canal backfilling were estimated by comparing the WTD differences, near and far from canals, before and after backfilling.

Quantification of canal network impacts on water levels was expanded from field to regional scales by using satellite-based TWS anomalies as proxies of field-measured WTD. To this end, we evaluated inter-annual variations of GRACE TWS anomalies using WTD (2010–2019) measured at the field site (figure 1(b)). Because all field measurements were located in a single GRACE pixel within drained peatlands, we averaged all WTD values (inside and outside of canal backfilling areas) in October of each year and compared them with corresponding TWS anomalies. For these comparisons it is noteworthy that: (a) field data are investigated as a tool for expanding analysis of the canal effects from field to regional scales, and for evaluating the relationship between regional water levels and Ce values. MODIS AF, MAIAC aerosol optical depth (AOD), and wind dataset from the European Centre for Medium-Range Weather Forecasts Reanalysis version-5 (ERA5) are used to calculate Ce values. The peatland map from the Indonesian Ministry of Agriculture (MoA) is utilized to categorize observations into peatland and non-peatland classes. Detailed descriptions of these datasets are provided in the supplementary materials.

#### 2.2. Datasets

Datasets used in this study are listed in table 1. Field-measured WTD is used to quantify the impacts of canal drainage and backfilling on water level variations at the field scale. GRACE TWS anomaly

![Figure 1](https://example.com/figure1.png)

Figure 1. Study areas of Sumatra, Kalimantan, and Papua (light green). The Provinces and peatland areas with BRG activities are marked with grey hash and pink, respectively. The seven BRG provincial areas are (1) Riau, (2) Jambi, (3) South Sumatra, (4) West Kalimantan, (5) Central Kalimantan, (6) South Kalimantan, and (7) Papua provinces. In inset (b), red dots are the locations of field dipwells; straight blue lines represent canals; and black starred lines show the locations of backfilled canals from the Peatland Restoration Information and Monitoring System (PRIMS).
measurements only cover ~10% of the GRACE pixel; and (b) field data may not be measured on the exact day of the GRACE satellites overpass. Despite these limitations, this comparison is still necessary to verify the capability of TWS anomaly being a proxy of WTD for analyzing canal impacts on WTD and, in turn, on regional fire emissions.

3.2. Calculation of Ce values

Ce was derived from the linear regression between FRP and corresponding emission rates of smoke aerosols (Rsa) based on the algorithm developed by Ichoku and Kaufman (2005), Ichoku and Ellison (2014). In this algorithm, Rsa is determined using the mass of smoke aerosol emissions and the time it needs to emit such emissions. The mass of smoke aerosol emissions is calculated from the difference between total AOD in the downwind pixel and background AOD in the upwind pixel, pixel area, and mass extinction efficiency. The time to emit the emissions is computed from plume length and wind speed.

Note that several modifications have been made relative to Ichoku and Ellison (2014): (a) we used updated satellite data including duplication-corrected MODIS AF, 1 km MAIAC AOD, and hourly ERA5 wind vectors; (b) we assigned background AOD from the minimum value, instead of the mean value, of valid AOD values in the upwind region of fires. This was because aerosols in upwind pixels are more susceptible to neighboring fires at the spatial resolutions of MAIAC AOD (1 km) than the MODIS AOD (10 km) used by Ichoku and Kaufman (2005), Ichoku and Ellison (2014); (c) due to the close spatial resolution of MODIS fire and MAIAC AOD products, we defined plume length as the distance from the center of a 3 × 3 pixel window to the pixel edge in the wind direction, and calculated it based on pixel size and wind direction using trigonometric functions; and (d) annual Ce values were obtained based on daily summations of daytime FRP and corresponding rates of smoke aerosol emissions over a given region. Note, we combined Terra and Aqua data for linear regressions. Moreover, to ensure the high quality of Ce estimates, only qualified regression models (r² ≥ 0.5, p ≤ 0.01, and n ≥ 5) were used.

Since fire events mainly occurred in the dry years of 2002, 2004, 2006, 2009, 2015, and 2019 during our study period (Han et al 2017, Kiely et al 2020), we first estimated peatland and non-peatland Ce values separately during these six years across Sumatra, Kalimantan, and Papua, respectively. The dry years are associated with El Niño events that decrease precipitation, cause drought, and intensify fires in the study region (Han et al 2017, Susetyo et al 2020). Further, to study inter-annual variation of Ce values and associate them with water levels, we estimated yearly Ce (2002–2019) for peatland and non-peatland in three selected regions (figure 1 (a)). A single annual Ce value was calculated for peatland and non-peatland separately of each region so as to include sufficient samples of simultaneous satellite observations of fires and smoke for Ce derivation during each Indonesian fire season.

3.3. Evaluation of water level impacts on Ce variation

The regional-scale evaluation of water level impacts on Ce variation was substituted by GRACE TWS anomaly data due to the lack of regional WTD data. To coordinate with annual Ce values, GRACE TWS anomalies were pre-processed. First, TWS anomalies were extracted for corresponding locations and months of fire observations used to estimate Ce. Then, the extracted TWS anomalies were spatially and temporally averaged, yielding a single composite TWS anomaly for each fire season in each region (peatland and non-peatland separately), to be consistent with Ce values.

An exponential function characterized relationships between Ce values and TWS anomalies:

\[ y = ae^{bx} \]  

where \( x \) and \( y \) represent TWS anomaly and Ce; \( a \) is the \( y \)-intercept of the curve; and \( b \) denotes the continuous change rate of the curve. The exponential equation was applied for separate peatland and non-peatland analyses of each region. A general conclusion about the relationship between Ce values and TWS anomalies was also established by merging samples from the three regions for peatland and non-peatland separately.

4. Results

4.1. Impacts of canals on water levels

Figures 2(a) and (b) shows the impacts of canal drainage on October WTD measurements. Dipwells closer

| Dataset         | Source                  | Spatial resolution | Temporal resolution                  |
|-----------------|-------------------------|--------------------|--------------------------------------|
| WTD             | Field dipwells          | 50/100/200 m       | Monthly over 2010–2013 Twice yearly over 2014–2019 |
| TWS anomaly     | GRACE                   | 1°                 | Near-monthly (irregular)             |
| AF              | MODIS                   | 1 km               | Four times daily                     |
| AOD             | MAIAC                   | 1 km               | Twice daily                          |
| Wind vector     | ERA5                    | 0.25°              | Hourly                               |
| Peatland        | Indonesian MoA          | 1:250 000          | Constant                             |

Table 1. Descriptions of the datasets used in this study.
to canals had lower WTD values for almost all years (2010–2019). Within 50 m of canals, almost all WTD values were below −40 cm, a particularly dangerous indicator for fire risk (Putra et al 2018). Generally, WTD values increased with distance 50–200 m from canals, before becoming relatively constant afterward for dipwells out to 1100 m from canals. However, during the extreme 2015 El Niño event, WTD values (figure 2(a)) were as low as −112 cm and did not vary significantly with distance from canals because of the extensive drought conditions everywhere (figure S5 (available online at stacks.iop.org/ERL/16/095008/mmedia)) (Stockwell et al 2016, Jayaratne et al 2018, Wooster et al 2018). The uniformly low WTD was accompanied by widespread peat fires in 2015 that sped up initiation of the BRG project in 2016 (Dohong 2017).

The effectiveness of BRG’s canal backfilling projects is apparent in the reduced WTD differences between dipwells at 50 m and 200 m from canals before and after backfilling (figure 2(c)). Inside the backfilling area, WTD differences ranged from ∼15 to ∼25 cm before backfilling (2010–2014) and showed a noticeable decreasing trend once backfilling activities began (2016–2019) (figure 2(c)). In contrast, no obvious WTD trends exist outside of backfilling areas (figure 2(d)). During the 2015 El Niño, extreme drought effects dominated over canal drainage effects making WTD differences very low everywhere.

Regional impacts of canal networks were estimated using GRACE TWS anomaly data. Despite the noted disparities (section 3.1), TWS anomalies correlate significantly with field-based inter-annual variations of WTD (figure 3; $r^2 = 0.84$, $p < 0.001$). TWS anomaly and WTD data both show greatest and least values for 2010 and 2015, respectively. In addition, both have decreasing trends for the 2010–2015 and 2016–2019 intervals. The strong correlation between TWS anomaly and WTD justifies the use of TWS anomaly as a proxy for regional WTD. There are, however, some differences in water level trends over 2011–2012 between these two datasets. This may be related to heavy rainfall before and/or during the period of field WTD collection in 2011 (figure S5).

4.2 Peatland and non-peatland $C_e$ values

Figure 4 presents relationships between daytime total smoke aerosol emission rates ($R_{tsa}$) and daytime total FRP ($R_{FRP}$) in peatland and non-peatland areas of the three regions during fire seasons of six dry years (2002, 2004, 2006, 2009, 2015, and 2019), in which regression slopes provide estimated $C_e$ values. Specifically, the variables of $R_{tsa}$ and $R_{FRP}$ of the selected samples are significantly correlated in both peatland and non-peatland across all three regions ($r^2 > 0.83$, ...
Figure 3. The inter-annual variation of field WTD and GRACE TWS anomalies in October (2010–2019). Note that no field data are available for October 2013, and no GRACE data are available in 2017.

Figure 4. Scatterplots of daytime total smoke aerosol emission rate ($R_{tsa}$) against daytime total fire radiative power ($R_{FRP}$) derived from both Terra and Aqua MODIS during Indonesian fire seasons in the dry years of 2002, 2004, 2006, 2009, 2015, and 2019. 'n' is the number of scatter points. Colors correspond to the day of year when samples were observed. The slope of linear regression presents the estimated Ce, and the shaded area is the 95% confidence interval.

$p < 0.001$). Peatland Ce values are 12%–39% larger than non-peatland Ce for each given region, with the largest Ce difference in Papua (4.97 g MJ$^{-1}$), followed by Kalimantan (3.48 g MJ$^{-1}$) and then Sumatra (1.65 g MJ$^{-1}$). An example of the yearly Ce estimation in a typical dry year of 2006 is presented in figure S1.

4.3. Relationship between water levels and Ce

Regional-scale relationships between TWS anomalies and annual Ce values are used to quantify water level effects on fire emission rates. Figures S2–S4 show inter-annual variations of peatland and non-peatland Ce values and TWS anomalies of the three study
regions. The quantitative relationships between these two variables are presented in figure 5. As TWS anomalies shrink and then become increasingly negative, Ce values tend to grow larger in most cases. More rapid rates of Ce change and greater values exist in peatlands than non-peatlands for negative TWS anomalies. Greater rates exist in peatlands (Sumatra: 11%; Kalimantan: 11%; and Papua: 4%) than non-peatlands (Sumatra: 7%; Kalimantan: 6%; and Papua: 0%), with best-fit models (equation (1)) showing flatter responses in the less degraded Papua region. Merged results (figures 5(g) and (h)) further confirm the significant positive relationship between Ce values and negative TWS anomalies for peatland (9%, \( p < 0.001 \)) and non-peatland (5%, \( p < 0.01 \)).

5. Discussions

5.1. Impacts of canals on water levels

Field-measured WTD shows that canal drainage regularly reduces water levels with impacts out to at least 200 m (figures 2(a) and (b)). Observed WTD decreases attributable to canals were as high as 25 cm in this degraded landscape, hence, affecting significantly the whole of Indonesia where extensive canal networks were established in peatlands (Dadap et al 2021). Despite large inter-annual variance of water levels, the pattern of greater WTD impacts with increasing proximity to canals was consistent, though the degree of variation was smaller during extremely dry years (i.e. 2015) when WTD was greatly lowered everywhere. Drainage canals lead to persistently lower WTD during dry seasons that convert not only surface vegetation but underlying peat soils into flammable fuels (Goldstein et al 2020). It is noteworthy that peat soils are rarely affected by fires previously (Miettinen et al 2017), but nowadays are subjected to frequent fires that burn more deeply into the peat near canals (Konecny et al 2016, Putra et al 2018).

Pre-existing water level differences between locations inside and outside backfilling areas, prior to backfilling, are most evident in 2015 (figures 2(a) and (b)). The two regions have somewhat different disturbance histories (Vetrita and Cochrane 2019) with areas inside backfilling operations including the last remnant natural forests while outside backfilling areas including much more bare soils due to fires (Vetrita and Cochrane 2021). As such, dipwells are distributed across different land cover types, including forest, exposed soil, shrub and fern, as well as having differences in WTD measurement times/dates in October (Goldstein et al 2020). Regardless of these differences, only areas within the BRG backfilling areas have shown progressive improvement in water levels.

Since 2016, canal backfilling activities have progressed gradually within Indonesia’s degraded peatlands despite resistance by local farmers since the canals are used to access and irrigate their agricultural lands as well as transport their products (e.g. oil palm) (Giesen and Sari 2018). Although more research will be needed to quantify the benefits of backfilling and restoration and determine if degraded peatlands can...
be successfully rewetted and restored, BRG mitigation activities have demonstrably increased nearby water levels in subsequent years (figure 2). Differences between WTD at 30 m and 200 m from canals decreased after BRG initiated canal backfills (2016–2019) (figure 2(c)). WTD near canals has become increasingly similar to water levels farther away as more normal hydrology was re-established. By 2019, WTD differences with distance were near zero, much lower than that outside backfilling areas.

To quantify canal impacts on water levels at regional scales, we used satellite TWS as a proxy for regional WTD (figure 3). Vegetation covers had little impact on the TWS-WTD relationships since the monthly dynamics of TWS and WTD were highly correlated and synchronous over both areas within and outside fire-prone regions in Kalimantan during 2002–2014 (Han et al. 2017). The robustness of TWS has been widely investigated for improving simulations of WTD in land surface models (Strassberg et al. 2007, Lo et al. 2010, Girotto et al. 2016, Seyoum and Milewski 2016, Stampoulis et al. 2019). Thus, relationships between TWS and Ce values at regional scales hold promise for adequately reflecting the impacts of canal-related water level changes on fire emissions.

5.2. Peatland and non-peatland Ce values
In dry years, Ce values are generally larger for peatland fires than non-peatland fires (figure 4), likely due to the following reasons. First, when WTD falls well below the peat surface, fires in peatlands include both surface vegetation and peat soil fires, whereas non-peatland fires only include surface vegetation fires. Second, smoldering peat fires have a very low combustion efficiency due to insufficient oxygen for completed oxidation, yielding the release of much denser concentrations of particulate matter than flaming vegetation fires (Chand et al. 2005, Ichoku and Kaufman 2005, Reid et al. 2005, Shi et al. 2018, Lu et al. 2019). Third, the carbon content of tropical peat soils (∼61%) is much higher than that of vegetation (∼45%) (Wooster et al. 2018), and organic carbon is the primary component of particulate matter emissions from combustion (Jayarathe et al. 2018). In wet years, however, Ce differences between peatland and non-peatland fires are not significant (figures S2–S4), since peat soils are either too wet to burn or only provide a minor contribution to fuels (Heil and Goldammer 2001, Chand et al. 2005, Lu et al. 2019). Therefore, whenever peat is not involved in combustion, peatland and non-peatland fires are relatively similar, burning only surface vegetation.

Another finding is that the Ce difference between peatland and non-peatland is greatest in Papua, reduced in Kalimantan, and least in Sumatra (figure 4). This is likely related to settlement and land use patterns. Development in peatlands of Sumatra has been substantial since the 1970s, versus the 1990s in Kalimantan, and the 2010s in Papua. Due to the earlier settlement and social development in Sumatra, human activities (e.g. agriculture development, rural and urban expansion, logging) would possibly lead to more burning on easily accessible shallow peatland (<0.5 m) that has been excluded from the MoA peatland map and categorized into the non-peatland class (Goldammer 2007, Cochrane 2009, Hoscio et al. 2011, Margono et al. 2014).

5.3. Impacts of canals on fire emissions
This study investigated drainage canal impacts on fire emissions indirectly using satellite-based TWS at regional scales. The exceedingly labor-intensive and time-consuming efforts to measure field WTD, preclude development of widespread and continuously monitored networks of sampling sites. We made use of WTD from several hundred dipwells within ∼1200 km² of degraded peatland in Kalimantan (figure 1(b)). However, since the data were from a single location, we were not able to establish a direct relationship between fire smoke emissions and WTD for Indonesian peatlands and non-peatlands. Therefore, we used satellite-observed TWS as a proxy of WTD at regional scales because TWS anomalies were significantly correlated with WTD (figure 3; r² = 0.84, p < 0.001). Thus, we hypothesized that relating TWS anomalies to regional fire emissions could approximate the impacts of drainage-canal-caused changes in WTD on fire emissions. Future work investigating direct relationships between fire emissions and drainage-canal-caused WTD would be an improvement but such work relies highly on the availability of sufficient field measurements.

Magnitudes of Ce change in concert with TWS anomalies but the rates of change differ between peatland and non-peatland areas because of the additional fuel types (peat soils) and combustion phases (smoldering vs. flaming) prevalent under different moisture conditions in peatlands (Lu et al. 2019, Goldstein et al. 2020, Nguyen and Wooster 2020). In wet years, high TWS values are associated with higher water tables in the peat soils and greater water availability for various live plants, making both potential fuel sources more difficult to burn. Since small-diameter, low-density fuels (e.g. grass and savanna, leaves and twigs) dry more quickly, they become much easier to combust than large-diameter fuels (e.g. tree trunk and branch) and peat soils in the absence of extended drought (Belcher 2013). Flaming combustion dominates in small-diameter fuels and these fuels typically have much lower Ce values than either large-diameter fuels or peat soils (Chand et al. 2005, Ichoku and Ellison 2014, Lu et al. 2019, Nguyen and Wooster 2020). On the other hand, high moisture affects combustion phases by reducing biomass combustion efficiency. This leads to more smoldering and less...
flaming combustion, hence, higher Ce values per unit mass of combustion because much denser particulate matter is emitted from smoldering combustion than flaming combustion (Rogge et al 1998, Simoneit 2002). However, low combustion efficiency caused by high moisture does not lead to Ce rising continuously because wet fuels do not combust above condition-dependent moisture contents. Effectively, increasing moisture reduces fuel availability to finer and finer fuels, reducing the mass of fuel available to burn, and hence Ce, to a greater degree than low combustion efficiency can increase it. Ce values are typically low in wet years (figure 5).

Conversely, in dry years, the relationship between Ce and larger magnitude TWS anomalies likely results from the increasing amounts and rates of fuel consumption, since more potential fuels become available for combustion under drier conditions (Cochrane 2009, Goldstein et al 2020). During dry years when TWS anomaly values are very low (highly anomalous), water levels drop and peat soils dry to greater depths, moisture contents of both above-and near-surface belowground fuels are reduced. This increases risks of large-diameter fuels and peat soils becoming involved during fires. During drier years, Ce increases together with combustion of large-diameter fuels because they have higher carbon contents and smolder much more than small-diameter fuels (Heil and Goldammer 2001) under the same moisture conditions (Mota and Wooster 2018, Lu et al 2019, Nguyen and Wooster 2020). This is the most probable reason for observations of increasing Ce under low TWS conditions in both peatland and non-peatland areas. In peatlands, environmental conditions allow the underlying peat to burn to even greater depths as dry periods continue, with maximum observed depth up to 85 cm (Page et al 2002, Konecny et al 2016, Simpson et al 2016). Ce values for peat soils are larger than for vegetation (section 5.1) and contribute to peatland fire emissions during dry years. This additional fuel source helps explain why Ce values increase much faster in peatland than in non-peatland as TWS decreases (figure 5).

The exponential relationship between Ce and TWS anomalies does not behave well in Papua, although it is significant in both Sumatra and Kalimantan. This is because Ce estimates are more uncertain in Papua due to the limited numbers of fires (e.g. 2006; figure S1) compared to Sumatra and Kalimantan. Besides, peatland distribution and associated fires are more scattered in Papua than in Sumatra and Kalimantan (figure 1). Peatland map accuracy may be lower in Papua where development has only recently begun. However, if the two largest outlying Ce values in Papua non-peatland are removed, a clear decreasing trend of Ce for increasing TWS anomalies emerges (figure 5(f)) but more data are necessary to be confident of appropriate Ce values in this region.

5.4. Potential uncertainties in Ce estimation and TWS anomaly

Although the negative relationship between Ce values and TWS anomalies is significant, it is not a perfect exponential function and may be influenced by uncertainties in both variables. Ce estimation has several inherent uncertainties. First, plume heights of individual smoke plumes are likely different. However, we used a fixed plume height (750 m), indicated by wind pressure level, due to challenges to obtain accurate plume heights for each and every smoke plume. Second, background AOD values may have been affected by smoke from fires in neighboring pixels. We minimized the effects of potential neighboring fires by deriving the background AOD values from the minimum of valid AOD retrievals in regions upwind of focal fires. Third, while expedient, associating instantaneous FRP observations with corresponding smoke plumes is not ideal since FRP values may change during the period used for calculating the smoke aerosol emission rate (Ichoku and Ellison 2014). However, this issue has been minimized in this study by using finer spatial resolution MAIAC AOD (1 km) and averaging calculations from numerous fires. Finally, FRP is another parameter that may propagate uncertainties to Ce estimates because FRP tends to be underestimated in the presence of exceedingly dense smoke (Giglio et al 2016, Kumar et al 2020).

Similarly, although the GRACE TWS anomaly is a good indicator of both below- and above-ground fuel moisture, using a single mean TWS anomaly value for each year in each region may not correspond well to moisture conditions of all fuels being used to derive Ce values (Tapley et al 2004, Sadeghi et al 2020). Using mean TWS anomalies values from smaller areas (province or pixel) could reduce uncertainties related to spatial variation of TWS anomalies, but the number of fire samples, within smaller areas, during any given year would likely be insufficient for building the regressions to calculate Ce. We tried unsuccessfully to use high spatio-temporal moisture
products from the Soil Moisture and Ocean Salinity and Soil Moisture Active Passive missions to better understand fuel moisture dynamics. However, these sensor responses saturate over much of the tropics and have limited canopy penetration capabilities (Njoku and Entekhabi 1996, Gao et al 2020).

6. Conclusion

To mitigate destructive environmental effects caused by smoke aerosol emissions from extensive peat fires, the Indonesian government has initiated canal backfilling and blocking activities across millions of hectares of degraded peatlands to raise water table levels and reduce burning associated with extensive canal drainage for agricultural development. In this paper, for the first time, we investigated the impacts of both canal drainage and canal backfilling on the fire smoke aerosol Ce that is critical for estimating biomass-burning emissions. Specifically, this research (a) studied the impacts of canal drainage and backfilling on water levels using both field- and satellite-measured data; (b) estimated annual Ce values for tropical peatland and non-peatland fires using MODIS AF, MAIAC aerosol, and ERA5 wind products; and (c) assessed the relationship between regional water levels, represented as TWS anomalies, and Ce values during the period from 2002 to 2019. Results show that canal drainage causes water levels to decline within 200 meters, while canal backfilling is helpful in raising water levels and restoring more natural hydrology conditions. Ce values of peatland fires are generally higher than those of non-peatland fires in dry years. In addition, a negative relationship exists between water levels and Ce for both peatland and non-peatland. Moreover, the Ce value decays much faster for peatland fires than non-peatland fires as water levels increase. Through the above findings, we conclude that lower water levels caused by canal drainage lead to higher Ce values, whereas canal backfilling produces higher water levels and lower Ce values. Ce in peatlands is more sensitive than non-peatland to canal drainage because the underlying peat soils become fuels for smoldering fires if water levels are reduced too much, dramatically changing the amounts of aerosol emissions. The Indonesian government is currently implementing large-scale peatland restoration activities which hold promise for reducing both the incidence and emissions from fires, and these efforts should be supported and furthered to successfully rewet the many peatland areas with heavily degraded conditions resulting from long-term extensive drainage.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

Belcher C M College of Life and Environmental Sciences, University of Exeter 2013 Fire Phenomena and the Earth System 1 Belcher C M (Chichester: John Wiley & Sons) 352 (https://books.google.com/books?hl=en&dr=aid=G2RaPl1hhJIC&oi=fnd&pg=PT11&q=Fire+-+Phenomena+and+the+Earth+System:+An+Interdisciplinary+Guide+to+Fire+Science&ots=gVzsCM6hxR-8sig=ghDVwXQhGwmtF-1hnmNmlg3Q1s#v=onepage&q=Fire%20Phenomena%20and%20the%20Earth%20System%3A%20An%20Interdisciplinary%20Guide%20to%20Fire%20Science&f=false)
Chand D, Schmid O, Gwaze P, Parmar R S, Helas G, Zeromskiene K, Wiedensohler A, Massling A and Andreae M O 2005 Laboratory measurements of smoke optical properties from the burning of Indonesian peat and other types of biomass Geophys. Res. Lett. 32 112819
Cochrane M 2009 Tropical Fire Ecology: Climate Change, Land Use and Ecosystem Dynamics (Heidelberg: Springer)
Dadap N C, Hoyt A M, Cobb A R, Oner D, Kozinski M, Fua P V, Rao K, Harvey C F and Konings A G 2021 Drainage canals in Southeast Asian peatlands increase carbon emissions AGU Adv. 2 e2020AV00321
Dohong A Peatland Restoration Agency Republic of Indonesia 2017 Implementing peatland restoration in Indonesia: technical policies, interventions and recent progress The 2nd Partners Meeting of Global Peatlands Initiative (GPI) Int. Peat Society (IPS) 50th Anniversary Jubilee Symp. May 2017 Jakarta, Indonesia (Netherlands) (https://doi.org/10.13140/RG.2.2.13576.67849)
Gale M G, Cary G J, Van Dijk A J M and Yebra M 2021 Forest fire fuel through the lens of remote sensing: review of approaches, challenges and future directions in the remote sensing of biotic determinants of fire behaviour Remote Sens. Environ. 255 112282
Gao I, Sadeghi M and Ebtehaj A 2020 Microwave retrievals of soil moisture and vegetation optical depth with improved
resolution using a combined constrained inversion algorithm: application for SMAP satellite Remote Sens. Environ. 239 111662

Giesen W and Sari E N N Berbak Green Prosperity Partnership 2018 Tropical Peatland Restoration Report: The Indonesian Case Contract No. 2015/Grant/010 Millennium Challenge Account Indonesia

Giglio L, Randerson J T and Werf G R 2013 Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4) J. Geophys. Res.: Biogeosci. 118 317–28

Giglio L, Schroeder W and Justice C O 2016 The collection 6 MODIS active fire detection algorithm and fire products Remote Sens. Environ. 178 31–41

Girotto M, De Lannoy G J, Reichle R H and Rodell M 2016 Assimilation of gridded terrestrial water storage observations from GRACE into a land surface model Water Resour. Res. 52 4164–83

Glauber A and Gunawan I 2016 The cost of fire: an economic analysis of Indonesia’s 2015 fire crisis (The World Bank) (available at: http://pubdocs.worldbank.org/en/643781465443250600/Indonesia-forest-fire-notes.pdf) (Accessed 27 August 2021)

Goldammer J G 2007 History of equatorial vegetation fires and fire research in Southeast Asia before the 1997–98 episode: a reconstruction of creeping environmental changes Mitig. Adapt. Strateg. Glob. Change 12 13–32

Goldstein J E, Graham L, Ansori S, Vetrita Y, Thomas A, Girotto M, De Lannoy G J, Reichle R H and Rodell M 2016 The collection 6 MODIS active fire detection algorithm and fire products Remote Sens. Environ. 206 45–62

Goldstein J E, Graham L, Ansori S, Vetrita Y, Thomas A, Applegate G, Yadva A P, Saharjo B H and Cochrane M A 2020 Beyond slash-and-burn: the roles of human activities, altered hydrology and fuels in peat fires in Central Kalimantan, Indonesia Sinagap. Trop. Geogr. 41 190–208

Han J, Tangdamrongsub N, Hwang C and Abidin H Z 2017 Intensified water storage loss by biomass burning in Kalimantan: detection by GRACE J. Geophys. Res.: Solid Earth 122 2409–30

Heil A and Goldammer J 2001 Smoke-haze pollution: a review of the 1997 episode in Southeast Asia Reg. Environ. Change 2 24–57

Hooijer A, Page S, Jauhiainen J, Lee W, Lu X, Idris A and Muhamad M Z and Rieley J O 2002 Management of tropical peatlands Biogeosciences 9 1053–71

Hoscio A, Page S E, Tansey K J and Rieley J O 2011 Effect of repeated fires on land-cover change on peatland in southern Central Kalimantan, Indonesia, from 1973 to 2005 Int. J. Wildland Fire 20 578–88

Ichoku C and Ellison L 2014 Global top-down smoke-aerosol emissions estimation using satellite fire radiative power measurements Atmos. Chem. Phys. 14 6643–67

Ichoku C and Kaufman Y J 2005 A method to derive smoke emission rates from MODIS fire radiative energy measurements IEEE Trans. Geosci. Remote Sens. 43 2636–49

Jaenicke J, Enghgart S and Siegert F 2011 Monitoring the effect of restoration measures in Indonesian peatlands by radar satellite imagery J. Environ. Manage. 92 630–8

Jayarathne T et al 2018 Chemical characterization of fine particulate matter emitted by peat fires in central Kalimantan, Indonesia, during the 2015 El Niño Atmos. Chem. Phys. 18 2585–600

Kiely L et al 2020 Air quality and health impacts of vegetation and peat fires in Equatorial Asia during 2004–2015 Environ. Res. Lett. 15 094054

Konecny K, Ballhorn U, Navratil P, Jubesinski J, Page S E, Tansey K, Hooijer A, Vernimmen R and Siegert F 2016 Variable carbon losses from recurrent fires in drained tropical peatlands Glob. Change Biol. 22 1469–80

Klopitz S N et al 2016 Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure Environ. Res. Lett. 11 094023

Kumar S S, Hult J, Picotte J and Peterson B 2020 Potential underestimation of satellite fire radiative power retrievals over gas flares and wildland fires Remote Sens. 12 238

Li F, Zhang X, Kondragunta S and Lu X 2020 An evaluation of advanced baseline imager fire radiative power based wildfire emissions using carbon monoxide observed by the tropospheric monitoring instrument across the conterminous United States Environ. Res. Lett. 15 094049

Liu T, Mickley L J, Marlier M E, DeFries R S, Khan M F, Latif M T and Karambelas A 2020 Diagnosing spatial biases and uncertainties in global fire emissions inventories: Indonesia as regional case study Remote Sens. Environ. 237 111557

Lo M H, Famiglietti J S, Yeh P F and Syed T 2010 Improving parameter estimation and water table depth simulation in a land surface model using GRACE water storage and estimated base flow data Water Resour. Res. 46 W05517

Lu X, Zhang X, Li F and Cochrane M A 2019 Investigating smoke aerosol emission coefficients using MODIS active fire and aerosol products—a case study in the CONUS and Indonesia J. Geophys. Res.: Biogeosci. 124 1413–29

Lu X, Zhang X, Li F, Cochrane M A and Ciren P 2021 Detection of fire smoke plumes based on aerosol scattering using VIIRS data over global fire-prone regions Remote Sens. 13 196

Lu X, Zheng G, Miller C and Alvarado E 2017 Combining multi-source remotely sensed data and a process-based model for forest aboveground biomass updating Sensors 17 2062

Margono B A, Potapov P V, Turubanova S, Stolle F and Hansen M C 2014 Primary forest cover loss in Indonesia over 2000–2012 Nat. Clim. Change 4 730–5

Miettinen J, Shi C and Liew S C 2017 Fire distribution in Peninsular Malaysia, Sumatra and Borneo in 2015 with special emphasis on peatland fires Environ. Manage. 60 747–57

MoEF 2020 Rekapitulasi Luas Kebakaran Hutan Dan Lahan (Ha) per Provinsi Di Indonesia Tahun 2015–2020 (Jakarta: Sipongi, Karhutta Sistem)

Mota B and Wooster M J 2018 A new top-down approach for directly estimating biomass burning emissions and fuel consumption rates and totals from geostationary satellite fire radiative power (FRP) Remote Sens. Environ. 206 45–62

Muhammad M Z and Rieley J O 2002 Management of tropical peatlands in Indonesia: mega reclamation project in Central Kalimantan (Indonesia) Int. Symp. Tropical Peatlands (Jakarta, Indonesia, 22–23 August 2002) (BPPT)

Nguyen H M and Wooster M J 2020 Advances in the estimation of high Spatio-temporal resolution pan-African top-down biomass burning emissions made using geostationary fire radiative power (FRP) and MAIAC aerosol optical depth (AODs) Remote Sens. Environ. 240 111571

Njoku E G and Entekhabi D 1996 Passive microwave remote sensing of soil moisture J. Hydrol. 184 101–29

Page S E, Rieley J O and Banks C J 2011 Global and regional importance of the tropical peatland carbon pool Glob. Chang. Biol. 17 798–818

Page S E, Siegert F, Rieley J O, Boehm H-D V, Jaya A and Limin S 2002 The amount of carbon released from peat and forest fires in Indonesia during 1997 Nature 420 61–65

Page S E, Wüst R, Weiss D, Rieley J O, Shotyk W and Limin S H 2004 A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics J. Quat. Sci. 19 625–35

Parker L, Bloydgett J E and Director D A 2008 Greenhouse Gas Emissions: Perspectives on the Top 20 Emitters and Developed versus Developing Nations (Washington, DC: Congressional Research Service)

Putra E I, Cochrane M A, Vetrita Y, Graham L and Saharjo B H 2018 Determining critical groundwater level to prevent degraded peatland from severe peat fire IOP Conf. Ser.: Earth Environ. Sci. 149 012007

Reid J, Koppmann R, Eck T and Eleuterio D 2005 A review of biomass burning emissions part II: intensive physical
properties of biomass burning particles Atmos. Chem. Phys. 5 799–825
Rogge W F, Hildemann L M, Mazurek M A, Cass G R and Simonet B R 1998 Sources of fine organic aerosol. 9. Pine, oak, and synthetic log combustion in residential fireplaces Environ. Sci. Technol. 32 13–22
Sadeghi M, Gao L, Ebtehaj A, Wigneron J-P, Crow W T, Reager J T and Warrick A W 2020 Retrieving global surface soil moisture from GRACE satellite gravity data J. Hydrol. 584 124717
Seoyma M and Milewski A M 2016 Monitoring and comparison of terrestrial water storage changes in the northern high plains using GRACE and in-situ based integrated hydrologic model estimates Adv. Water Resour. 94 31–44
Shi Y R et al 2018 Characterizing the 2013 Indonesia fire event using modified MODIS aerosol retrievals Atmos. Chem. Phys. Discuss. 19 259–74
Silvius M, Hooijer A, Kaat A and Van de Bund H Wetlands International and Delft Hydraulics 2006 Peatland degradation fuels climate change No. D-1390 Wetlands International
Simoneit B R 2002 Biomass burning—a review of organic tracers for smoke from incomplete combustion Appl. Geochem. 17 129–62
Simpson J E, Wooster M J, Smith T E, Trivedi M, Vernimmen R R, Dedi R, Shakti M and Dinata Y 2016 Tropical peatland burn depth and combustion heterogeneity assessed using UAV photogrammetry and airborne LiDAR Remote Sens. 8 1000
Stampoulis D et al 2019 Model-data fusion of hydrologic simulations and GRACE terrestrial water storage observations to estimate changes in water table depth Adv. Water Resour. 128 13–27
Stibig H-J, Achaied F, Carboni S, Raïi R and Miettinen J 2014 Change in tropical forest cover of Southeast Asia from 1990 to 2010 Biogeosciences 11 247–58
Stockwell C E et al 2016 Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño Atmos. Chem. Phys. 16 11711–32
Strassberg G, Scanlon B R and Rodell M 2007 Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA) Geophys. Res. Lett. 34 L14402
Susetyo K E, Kusin K, Nina Y, Jagatu Y, Kawasaki M and Naito D Research Institute for Humanity and Nature 2020 2019

Peatland and Forest Fires in Central Kalimantan, Indonesia (Newsletter of Tropical Peatland Society Project) 8 (https://chikyu.repo.nii.ac.jp?action=repository_action_common_download&item_id=3818&item_no=1&attribute_ation_in_equatorial_Aid=22&file_no=1)
Tapley B D, Bettadpur S, Watkins M and Riegl C 2004 The gravity recovery and climate experiment: mission overview and early results Geophys. Res. Lett. 31 L09607
Van Der Werf G R et al 2008 Climate regulation of fire emissions and deforestation in equatorial Asia Proc. Natl Acad. Sci. 105 20305–9
Van Der Werf G R et al 2017 Global fire emissions estimates during 1997–2016 Earth Syst. Sci. Data 9 697–720
Vetrina Y and Cochrane M A 2019 Annual burned area from Landsat, Mawas, Central Kalimantan, Indonesia, 1997–2015 ORNL DAAC (Oak Ridge, TN) (https://doi.org/10.3334/ORNLDAAC/1708)
Vetrina Y and Cochrane M A 2021 Land use and land cover maps from Landsat, Mawas, Central Kalimantan, Indonesia, 1994–2019 ORNL DAAC (Oak Ridge, TN) (https://doi.org/10.3334/ORNLDAAC/1838)
Vetrina Y, Cochrane M A, Priyatna M, Sukowati K A and Khomarudin M R 2021 Evaluating accuracy of four MODIS-derived burned area products for tropical peatland and non-peatland fires Environ. Res. Lett. 16 035015
Wahyunto K N, Ritung S and Sulaiman Y 2014 Indonesian peatland map: method, certainty, and uses Proc. Lokakarya Kajian Dan Sebaran Gambut Di Indonesia August Jakarta pp 81–96
Wang J, Christopher S A, Nair U, Reid J S, Prins E M, Szykman J and Hand J L 2006 Mesoscale modeling of Central American smoke transport to the United States: 1. ‘Top-down’ assessment of emission strength and diurnal variation impacts J. Geophys. Res.: Atmos. 111 D05S17
Wiedinmyer C, Akagi S, Yokelson R J, Emmons L, Al-Saadi J, Orlando I J and Soja A J 2011 The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning Geosci. Model Dev. 4 625
Wooster M J et al 2018 New tropical peatland gas and particulate emissions factors indicate 2015 Indonesian fires released far more particulate matter (but less methane) than current inventories imply Remote Sens. 10 495
Zhang X, Kondragunta S, Schmidt C and Kogan F 2008 Near real time monitoring of biomass burning particulate emissions (PM2.5) across contiguous United States using multiple satellite instruments Atmos. Environ. 42 6959–72