Running head: Linking soil respiration and remotely sensed changes in water storage

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Linking soil respiration and water table depth in tropical peatlands with remotely sensed changes in water storage from the Gravity Recovery and Climate Experiment

Abstract

CO_2 emissions from peatlands in Southeast Asia are contributing substantially to global anthropogenic emissions to the atmosphere. Peatland emissions associated with land-use change and fires are closely related to changes in the water table level. Remote sensing is a powerful tool that is potentially useful for estimating peat CO_2 emissions over large spatial and temporal scales. We related ground measurements of total soil respiration and water table depth collected over 19 months in an Indonesian peatland to remotely sensed GRACE Terrestrial Water Storage Anomaly (TWSA) data. GRACE TWSA can be used to predict changes in water storage on land relative to a time-mean baseline. We combined ground observations from undrained forest and drained smallholder oil palm plantations on peat in Central Kalimantan to produce a representation of the peatland landscape in one 0.5º x 0.5º GRACE grid cell. In both ecosystem types, total soil respiration increased with increasing water table depth. Across the landscape grid, monthly changes in water table depth were significantly related to fluctuations in GRACE TWSA. GRACE TWSA explained 75% of variation in total soil respiration measured on the ground. By facilitating regular sampling across broad spatial scales that captures essential variation in a major driver of soil respiration, our approach could improve information available

to decision makers to monitor changes in water table depth and peat CO_2 emissions. Testing over larger regions is needed to operationalize this exploratory approach.

Key words: Indonesia, land-use, oil palm, greenhouse gas emissions, climate change

1. Introduction

Over the past several decades the area of tropical peat swamp forest converted to other uses has increased substantially. Oil palm expansion is a major driver of peatland conversion, accounting for 73% of industrial plantations on peat in Peninsular Malaysia, Sumatra, and Borneo, while pulp wood plantations account for the remaining area under industrial management (Miettinen et al. 2016). Smallholdings are equally important as industrial plantations, covering 22% of peatlands in insular Southeast Asia versus 27% for industrial plantations (Miettinen et al. 2016). Available estimates indicate that CO_2 emissions from converted peatlands in Southeast Asia contribute substantially to global anthropogenic emissions to the atmosphere (Harris et al. 2012; Miettinen et al. 2017). Peatland drainage and conversion increase CO_2 emissions as a consequence of decreased organic matter inputs and increased rates of decomposition of organic peat soils (Hergoualc'h & Verchot, 2014). Fires used for clearing lands and fertilization of nutrient-poor peat soils also constitute a major source of emissions (Gaveau et al. 2014; Miettinen et al. 2017).

To accurately estimate peat CO_2 emissions and to understand how they may change in the future, frequent measurements over months, seasons, and years are needed, as are measurements that span the entire sequence of land-use change. In addition to understanding the impacts of land-use change on emissions, we must assess how CO_2 emissions in tropical peatlands respond to climate change. The frequency and severity of El Niño events is projected to increase in the future (Cai et al. 2014) and may influence emissions from both converted and forested tropical peatlands. Studying seasonal and interannual changes in temperature and moisture is essential to understand microbial responses to land-use and climate changes, and can provide insight on peat emissions of CO_2. Remote sensing can be a powerful tool for predicting spatial and temporal variation in environmental conditions influencing peat C storage and loss.

Water table depth and soil moisture are critical environmental parameters affecting soil C storage and loss in tropical peat ecosystems (Hirano et al. 2007). Water table depth, determined by rainfall, evapotranspiration, and discharge, influences soil moisture throughout the soil column, and controls to some extent soil respiration across tropical peatlands (Hergoualc'h & Verchot 2014). NASA Gravity Recovery and Climate Experiment (GRACE) data provide spaceborne observations of monthly changes in the Earth's gravity field. Changes in gravity measured by GRACE over land are caused by mass fluctuations attributed to changes in water storage by terrestrial ecosystems over time. GRACE Terrestrial Water Storage Anomaly (TWSA) data can be used to predict changes in water storage on land relative to a time-mean baseline. GRACE may provide a new tool for predicting spatio-temporal variations in water table depth and soil moisture and support the monitoring of variables contributing to peat CO_2 losses, in particular soil respiration. GRACE data have been used to estimate depletion of ground water in aquifers around the world (Rodell et al. 2009, Famiglietti et al. 2011, Voss et al. 2013) but have never been tested for assessing changes in water storage in tropical peatlands. Application of GRACE to assess trace gas fluxes from soils have largely been limited to studies on methane (Bloom et al. 2010; Bloom et al. 2012).

In this study we use GRACE TWSA data to predict changes in total respiration and water table depth in peat soils. Our objective was to develop a new method for linking soil respiration – a process that is difficult and expensive to measure in the field over time and space – and water table depth, to readily available, spatially extensive, satellite-based estimates of changes in soil water storage. Therefore, we tested for potentially useful relationships among soil respiration, our parameter of interest, and water table depth, a physical driver of soil respiration in tropical peatlands. Then we tested how variations in soil respiration and water table depth on a broader landscape scale can be inferred from GRACE TWSA (Figure 1).

If soil respiration is related to soil moisture regime, and if water table depth is related to TWSA, then TWSA could be used to predict total soil respiration in tropical peatlands. Since soil respiration is a key component of the peat C budget (Hergoualc'h & Verchot 2014), successful operationalization and application of our remote sensing approach at large spatial scales could improve understanding of the influence of seasonal and interannual variation in water storage on the C cycle.

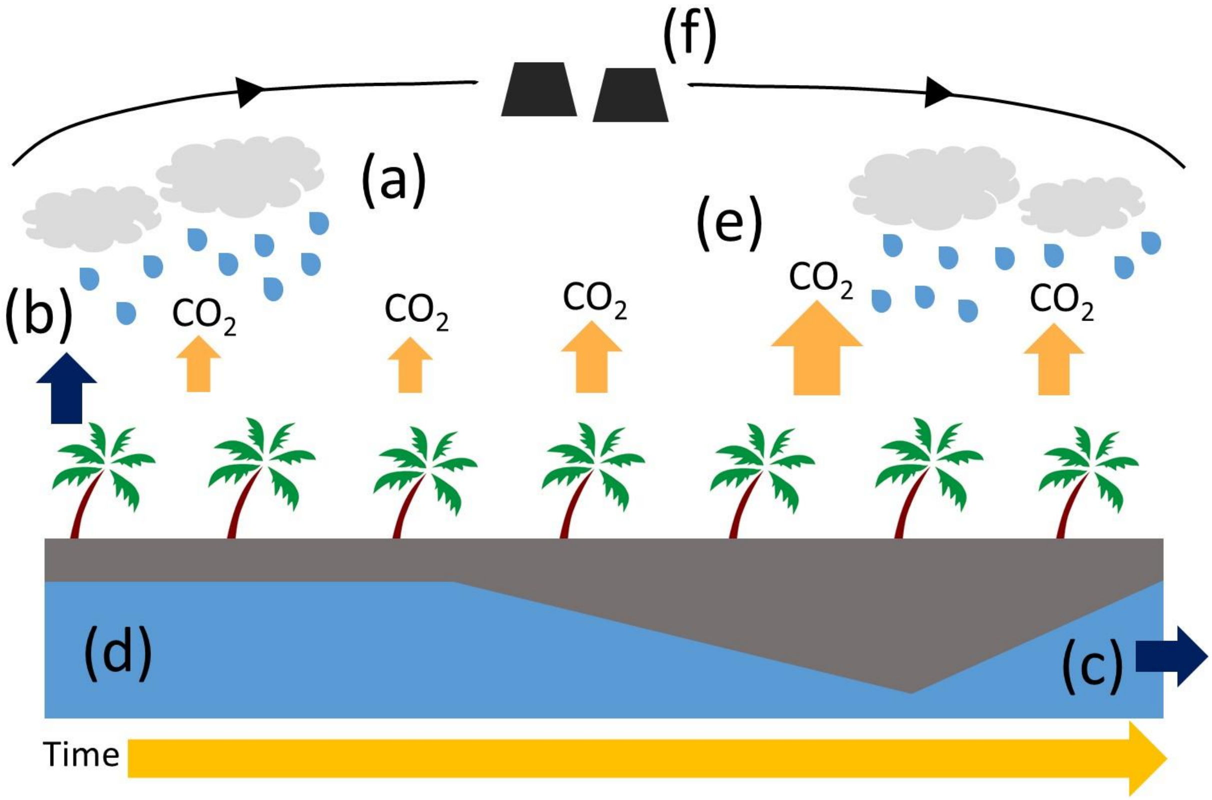


Figure 1. Conceptual model of links among total soil respiration, water table depth, GRACE TWSA and climate drivers in an Indonesian peatland. Precipitation (a), evapotranspiration (b), and discharge (c) influence water table depth (d). Water table depth increases under conditions of reduced precipitation during dry periods, and total soil respiration increases (e). GRACE TWSA (f) indicates monthly changes in soil water storage ultimately driven by variation in precipitation, evapotranspiration, and discharge.

2. Materials and methods

2.1 Site description

We collected ground measurements at permanent plots in peat forest and smallholder oil palm plantations in Central Kalimantan Province, approximately 50 km from the city of Pangkalan Bun, in and around Tanjung Puting National Park (-2.82806, 111.813, Figure 2a). The climate of the region is humid tropical, with little variation in temperature throughout the year and high annual rainfall. We used weather observations from Iskandar airport in Pangkalan Bun during 2004-2013 to describe climate at the study area. Mean annual temperature in Pangkalan Bun is 27.4^{o}C. Mean annual rainfall is 2058 mm and September is typically the driest month (85 mm).

Three plots were established in forest, and three in oil palm plantations, for a total of six plots. The plots were located 1-10 km apart, representing a range of peat depths, land use histories and vegetation ages (Table 1). All plots fell within a roughly 10 km x 10 km area in one GRACE grid cell, 0.5° x 0.5° or 55 km x 55 km (Figure 2b). Forest plots were situated at varying distances from river's edge and thus differed in peat depth. Two of the plots (K-FOR-2, K-FOR-3) were mature forest whereas the plot closest to the river (K-FOR-1) was a 30 year old secondary forest, likely formerly used as an agroforestry garden (Novita 2016). Oil palm plantations were planted in 2007 (K-OP-2007), 2009 (K-OP-2009), and 2011 (K-OP-2011). Oil palm plots underwent multiple fires.

Table 1. Characteristics of the sample plots in Central Kalimantan, Indonesia. (after Swails et al. 2017)

Code	Landuse	Location		Clearance Year	Plantation Age	Fires	Distance to River	Peat Depth
K-FOR-1	Forest	-2.82360	111.813	pre 1982	-	Multiple	0.5 km	27 cm
K-FOR-2	Forest	-2.82220	111.807	-	-	-	1 km	155 cm
K-FOR-3	Forest	-2.83080	111.802	-	-	-	2 km	290 cm
K-OP-2011	Oil palm	-2.82310	111.810	1989	4 year	Multiple	3.5 km	20 cm
K-OP-2009	Oil palm	-2.82170	111.803	2005	6 year	Multiple	3.5 km	47 cm
K-OP-2007	Oil palm	-2.82060	111.801	2005	8 year	Multiple	3.5 km	47 cm

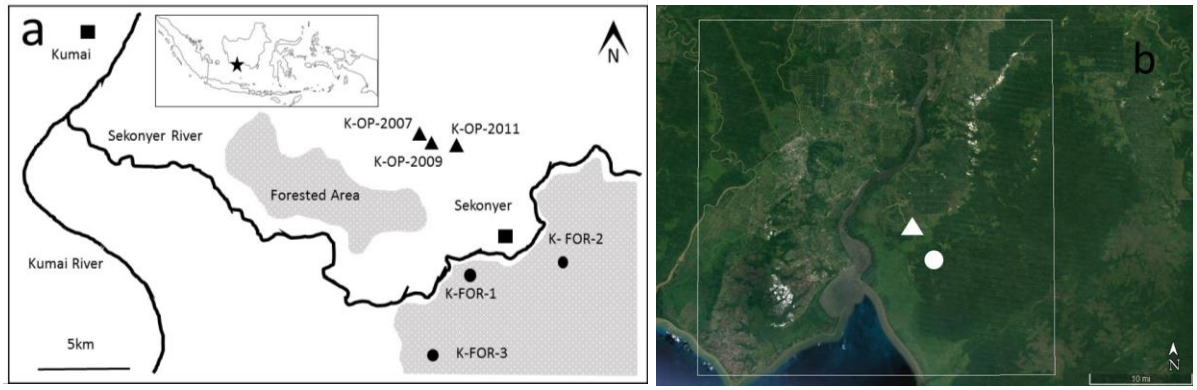


Figure 2. Research sites and sampling design. Location of the three plots in the undrained forest site and three plots in the nearby drained smallholder oil palm site (a) in Central Kalimantan, Indonesia (inset, a). Oil palm (triangle) and forest (circle) sampling sites were located in an approximately 10km by 10km area within the 0.5^{o} GRACE grid cell (b).

2.2 Monthly ground measurements

We collected measurements of total soil respiration and water table depth from plots once each month from January 2014 through June 2015 and again in September 2015. Plots were measured on consecutive days between the hours of 0800 and 1200 usually during the last week of the month. We measured water table depth concomitantly with CO_2 measurements. Daily precipitation data for the area were obtained from Iskander Airport in Pangkalan Bun. Our measurements covered one year with normal precipitation (2014) and one El Niño year (2015).

Our ground sampling approach was designed to account for spatial heterogeneity in soil respiration and environmental conditions while capturing temporal heterogeneity. Sixteen months before the beginning of this study, we inserted sets of two PVC collars to 5 cm depth at six locations per plot. In forest plots, we installed one collar on a hummock and one collar in the adjacent hollow at locations roughly 10 meters apart. In oil palm plots, we installed one collar at the base of a palm (near) and one collar at mid-distance between two adjacent rows of palm (far), at locations 7-9 meters apart (the distance between palms determined by the planting density, Swails et al. 2017). Total soil respiration was measured by the dynamic closed chamber method (Pumpanen et al. 2009) with a portable infrared gas analyzer/EGM-4 (Environmental Gas Monitor) connected to a Soil Respiration Chamber (SRC-1) (PP System, Amesbury, USA) placed on the permanent PVC collar. Water table depth was measured in a dipwell permanently installed next to each CO_2 collar. The dipwells were perforated PVC pipe (2.5 cm diameter) inserted to 2 m depth below the peat surface.

With the goal of creating a single monthly value of soil respiration and water table depth against which to compare remotely sensed data, we combined data in a way appropriate to the scale of the measurements. First, we calculated plot-level weighted averages of total soil respiration and water table depth measurements. The weighting was based on the spatial extent of conditions within the plot (hummock/hollow and near/far). In forest plots, we measured the length of hummocks and hollows along two perpendicular 50 m transects and divided the total length of hummocks by the total length of hollows to calculate the ratio of hummock to hollow area in each forest plot. In oil palm plots, we assume that measurements at collars near palms are representative of the area within a 2 m radius of the base of the palms. This is the zone where smallholders apply fertilizers and root density (Comeau et al. 2016; Khalid et al. 1999) and activity (Nelson et al. 2006) are usually highest. In forest plots, the ratios of hummock to hollow area were 48:52 (K-FOR-1), 52:48 (K-FOR-2), and 63:37 (K-FOR-3). In oil palm plots, the ratios of the area within a 2 m radius of palms (near) to the area outside of this radius (far) were 25:75 (OP-2011), 27:73 (OP-2009), and 37:63 (OP-2007). For each plot, we multiplied the mean value of hummock/near measurements by the hummock/near ratio, and the mean value of hollow/far measurement by the hollow/far ratio. Then, we summed the two numbers to yield a single value for each plot. To calculate mean monthly values, we pooled the weighted averages from each plot in each month to yield a single value for each land use (three plots, n=3 per land use). Detailed soil respiration rates for each plot are reported elsewhere (Swails et al. in preparation).

Finally, we combined data from the two land uses to estimate a single value of soil respiration and water table depth for comparison with GRACE TWSA and precipitation. We multiplied the mean respiration rate by the proportional coverage of the two land uses in our 0.5° x 0.5° GRACE grid cell. We estimated the proportional coverage of oil palm and forest by overlaying a 0.05° x 0.05° grid on the GRACE cell boundaries in Google Earth (Figure 2b). The proportional coverage of forest (60%) and oil palm (30%) in each of the .05° x .05° cells was determined by visual inspection. We inspected each of the 100 cells individually, and tallied the coverage by land use in each cell. The actual factors used in weighting (forest, 2/3 and oil palm, 1/3) spread the residual effect of the area in water, urban areas, or other crops (10%) proportionally across the two land uses. We weighted data for water table depth in the same manner to generate a single landscape-scale value representative of the 0.5° x 0.5° GRACE grid cell. We related these weighted average monthly values for the landscape—derived from measurements in oil palm and forest—to GRACE TWSA and precipitation.

2.3 GRACE data acquisition

We extracted GRACE TWSA values for our study site from one 0.5° x 0.5° grid cell (-2.75000 111.750, Figure 2b) in JPL-RL05 GRACE monthly mass grids (Watkins et al. 2015; Wiese 2015). JPL-RL05 uses a-priori constraints in space and time to estimate global, monthly gravity fields in terms of equal area 3-degree spherical cap mass concentration functions. A Coastal Resolution Improvement (CRI) filter is applied in post-processing to separate land and ocean portions of mass. The mass grids, updated monthly, provide surface mass changes relative to a baseline average over January 2004 to December 2009 with a spatial sampling of 0.5° (approximately 55 km at the equator). After oceanic and atmospheric effects are removed, monthly and interannual variations in Earth's gravity field are mostly accounted for by changes in terrestrial water storage. The vertical extent of these changes can be considered as a thin layer of water concentrated at the Earth's surface, measured in units of centimeters equivalent water thickness. Scaled uncertainty estimates are also provided on a 0.5° global grid in the JPL-RL05 product.

About one month of satellite measurements are required to generate the GRACE monthly mass change data, although occasionally, values represent less than a month of observations. Nevertheless, the temporal resolution of GRACE TWSA is fixed at one month. The mass changes reported for a given month were usually estimated as the average of measurements collected from day 16 of the previous month to day 16 of the present month. We matched these data with the observations of soil respiration and water table depth closest in time, most often taken at the end of the month, within a week or two of the GRACE value determined by integrating over the last half of the previous month and the first half of the current month.

Rather than the January 2004 – December 2009 baseline, we used a January 2014 – September 2015 baseline to match the time of our study. To calculate TWSA relative to 2014 – 2015, we calculated an average of TWSA values over our study period relative to the Jan 2004 – Dec 2009 baseline, and subtracted that value from the TWSA value for each month. TWSA data were not available for the months of February, July, and December 2014, and June 2015 due to satellite battery management.

2.4 Calculations and statistical analysis

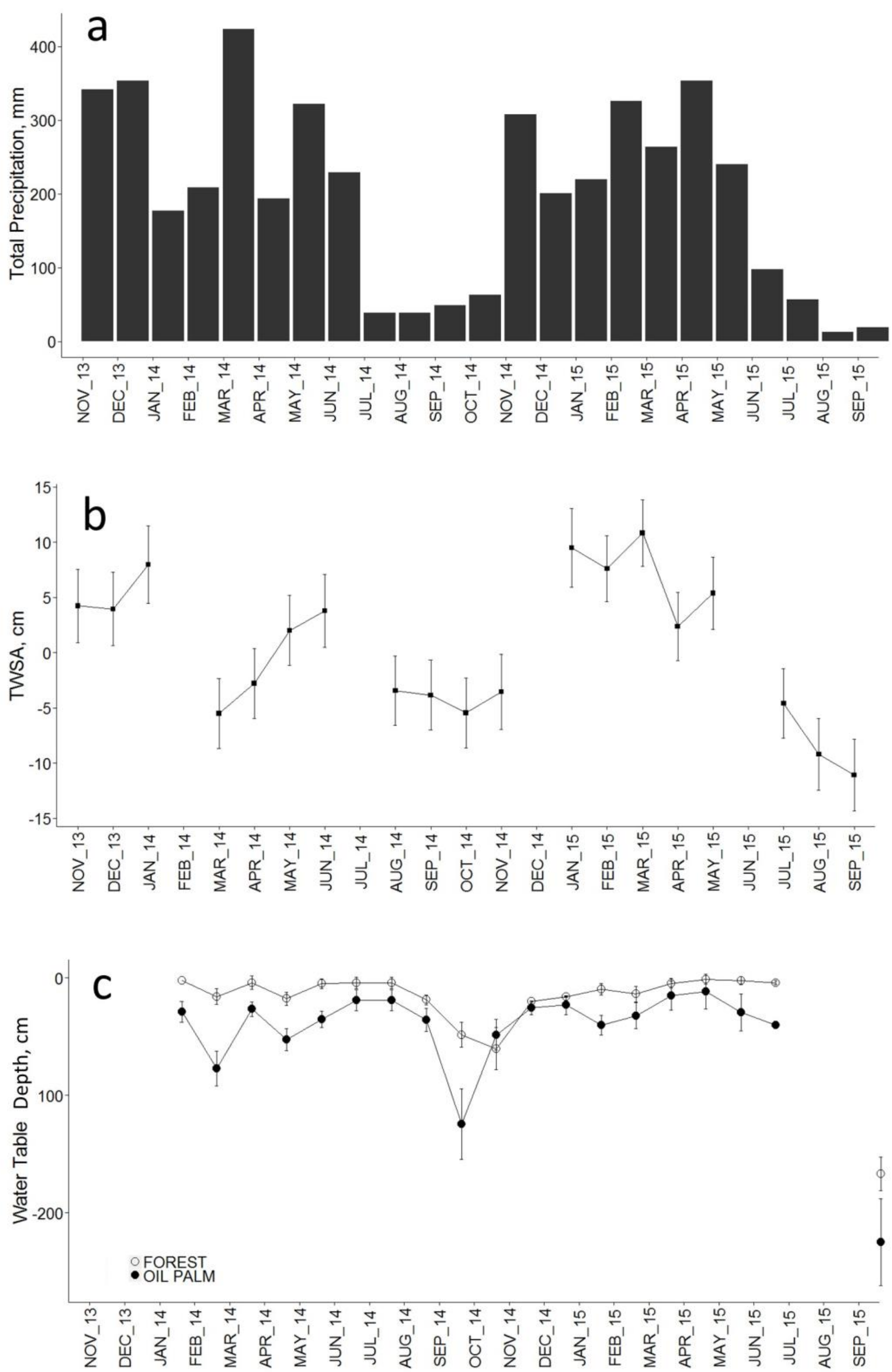
All statistical analyses were completed using R (v 3.2.5). We used ordinary least squares (OLS) linear regression to test for relationships among total soil respiration, water table depth, GRACE TWSA, and monthly precipitation calculated as cumulative rainfall over the 30 days prior to sampling. To test for a relationship between soil respiration and water table depth in forest and oil palm, we related mean monthly soil respiration to water table depth in each land-use (n=19). Finally, we related weighted average water table depth and weighted average soil respiration to GRACE TWSA (n=16 for both regressions). We also related mean monthly water table depth and soil respiration in forest and oil palm as well as weighted average water depth and soil respiration to monthly precipitation. At 0.033, the ratio of area represented by the dependent variable (roughly 10 km x 10 km covered by ground measurement plots = 100 km^2) to the area represented by the independent variable (roughly 55 km x 55 km for a 0.5º x 0.5º GRACE grid cell at the equator= 3,025 km^2) is small but not unprecedented. For example, Spruce et al. (2011) validate a 250 m x 250 m MODIS product using 30 m x 30 m Landsat scenes, for a dependent:independent area ratio of 0.014. There are many additional highly cited examples in the literature where Landsat is used as reference data for assessing a MODIS product (see for example Chen et al. 2005; Vina et al. 2008; Painter et al. 2009).

We used data transformation as necessary to adequately model the functional form of dependent variables, e.g. we added 12 to GRACE TWSA to eliminate negative values to model the relationship between combined total soil respiration and GRACE TWSA as a logarithmic function. To assess the normality assumption of OLS regression we used normality probability plots with a 95% confidence envelope produced using a parametric bootstrap. Durbin-Watson test was used to test for autocorrelation. To test for heteroscedasticity we used a score test of the hypothesis of constant error variance against the alternative that the error variance changes with the level of the fitted values. We identified outliers for examination using Bonferroni adjusted p-value for the largest absolute studentized residual. Data points with high leverage were identified using the hat statistic p/n, where p is the number of parameters estimated and n is the sample size. We examined observations with hat values greater than 3 times the average hat value. We used Cook's D to identify influential observation.

3. Results

3.1 Variation in total soil respiration, water table depth, TWSA, and rainfall

Precipitation, TWSA, water table depth, and total soil respiration showed clear seasonal variation in both oil palm and forest sites. Monthly precipitation was ≤ 100 mm during the months of July – October 2014 and June – September 2015. Precipitation reached a maximum of 424 mm in the month of March 2014 (Figure 3a) and a minimum in August 2015 (13 mm). Monthly TWSA ranged from 10.8 cm in March 2015 to -11.1 cm in September 2015 (Figure 3b), with considerable interseasonal variation (Figure 4). In both forest and oil palm, the water table was highest in April 2015 (-2.3 ± 3.5 cm and -13.7 ± 3.8 cm, respectively) and lowest in September 2015 (-167.9 ± 6.5 cm and -227.3 ± 9.0 cm, respectively). Total soil respiration was lowest in April 2014 in the forest (0.36 ± 0.04 g CO_2 m^{-2} hr^{-1}) and April 2015 in the plantations (0.54 ± 0.07 g CO_2 m^{-2} hr^{-1}). It was highest in September 2015 at the beginning of the most intense El Niño Southern Oscillation event in recent history, in both forest (1.54 ± 0.23 g CO_2 m^{-2} hr^{-1}) and oil palm (1.07 ± 0.14 g CO_2 m^{-2} hr^{-1}).


a
Total Precipitation, mm
0
100
200
300
400
NOV_13
DEC_13
JAN_14
FEB_14
MAR_14
APR_14
MAY_14
JUN_14
JUL_14
AUG_14
SEP_14
OCT_14
NOV_14
DEC_14
JAN_15
FEB_15
MAR_15
APR_15
MAY_15
JUN_15
JUL_15
AUG_15
SEP_15
b
TWSA, cm
15
10
5
0
-5
-10
-15
c
Water Table Depth, cm
0
100
-200
FOREST
OIL PALM

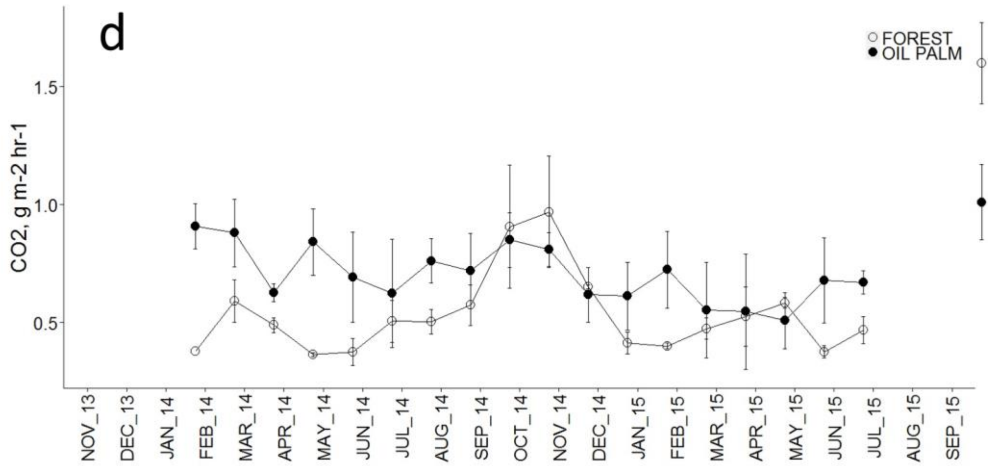


Figure 3. Monthly precipitation (a), GRACE TWSA (b), mean water table depth (c) and mean total soil respiration in forest (solid circle) and oil palm (open circle) plots (d). Values in (b) represent the change in remotely sensed water storage at the sampling sites in centimeters liquid water equivalent. Error bars in (b) represent the scaled uncertainty associated with the 3° mascon estimate (Weise et al. 2016). Error bars in (c) and (d) represent standard error of the mean (n=3).

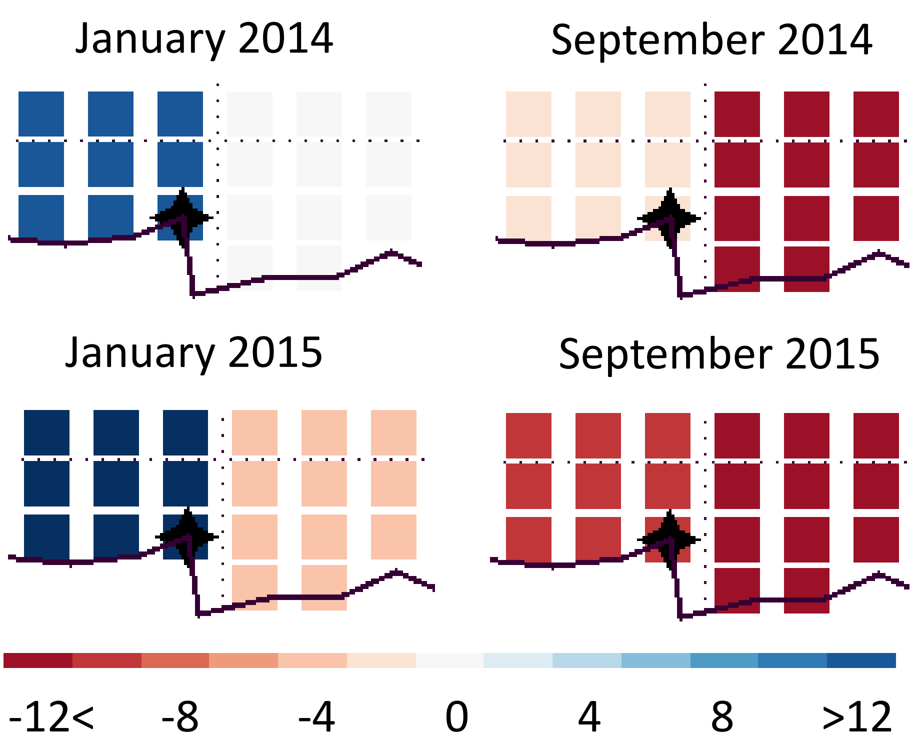


Figure 4. Gridded GRACE TWSA across southern Central Kalimantan, Indonesia during wet months (precipitation > 100 mm) in January 2014 and 2015 and dry months (precipitation ≤ 100 mm) in September 2014 and 2015. September 2015 was the beginning of a very intense El Niño Southern Oscillation across Indonesia. Colors represent the change in water thickness (units = cm liquid water equivalent) relative to January 2004 to December 2009 average baseline. The grid cell covering our study site is marked with a star. Dotted lines indicate -2 latitude and 112 longitude.

3.2 Relationships among total soil respiration, water table depth, and TWSA

Total soil respiration increased with the natural log of concurrently measured water table depth in both forest (Figure 5a) and oil palm (Figure 5b). As the water table dropped further below the soil surface, soil respiration increased, in both oil palm and forest. The strong effect of ENSO-induced drying and associated drop in the water table are evident in data from September 2015. Extremely low rainfall during the two preceding months led to low water table levels in forest and oil palm in September 2015 during the El Niño event. The data point corresponding to measurements collected in September 2015 in forest plots (water table of -167.9 cm, soil respiration of 1.54 g m^{-2} hr^{-1}) was an outlier (Bonferroni adjusted p=0.03) with marginally significant influence on the relationship between water table depth and soil respiration in forest (Cook's D=2.5).

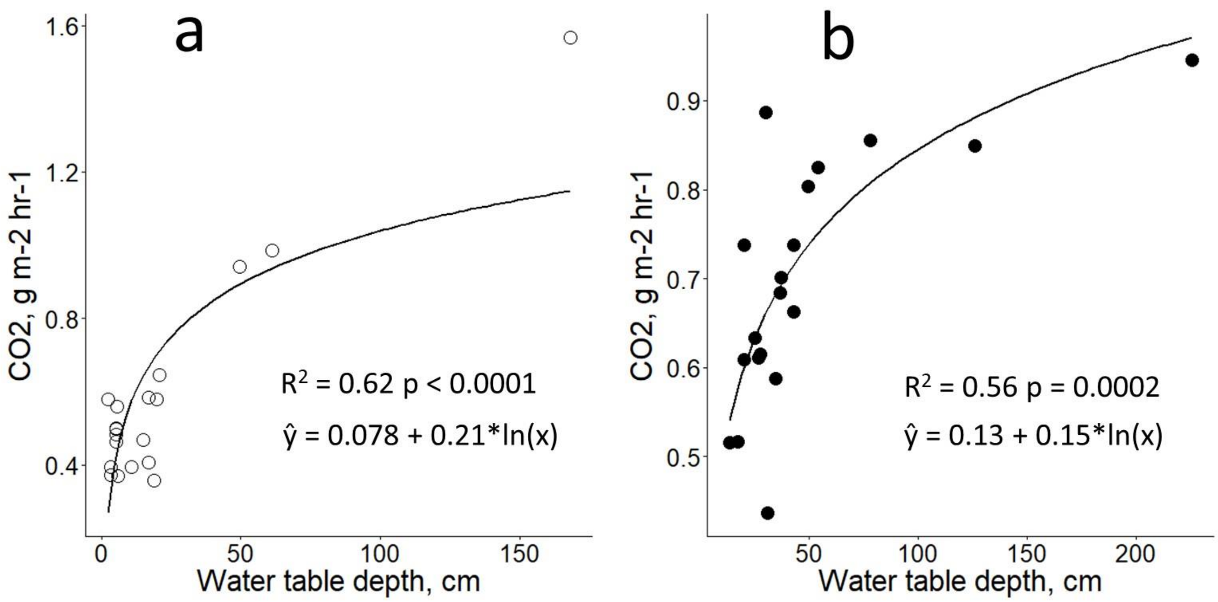


Figure 5. Mean total soil respiration as a function of mean water table depth (presented as a positive difference from the surface) in forest (a) and oil palm (b) from January 2014 through September 2015 (n = 19 months).

The relationships between TWSA and water table depth, and between TWSA and soil respiration, were also logarithmic in the independent variable. As water level approached the surface TWSA increased (Figure 6a). Total soil respiration declined with increasing TWSA (Figure 6b).

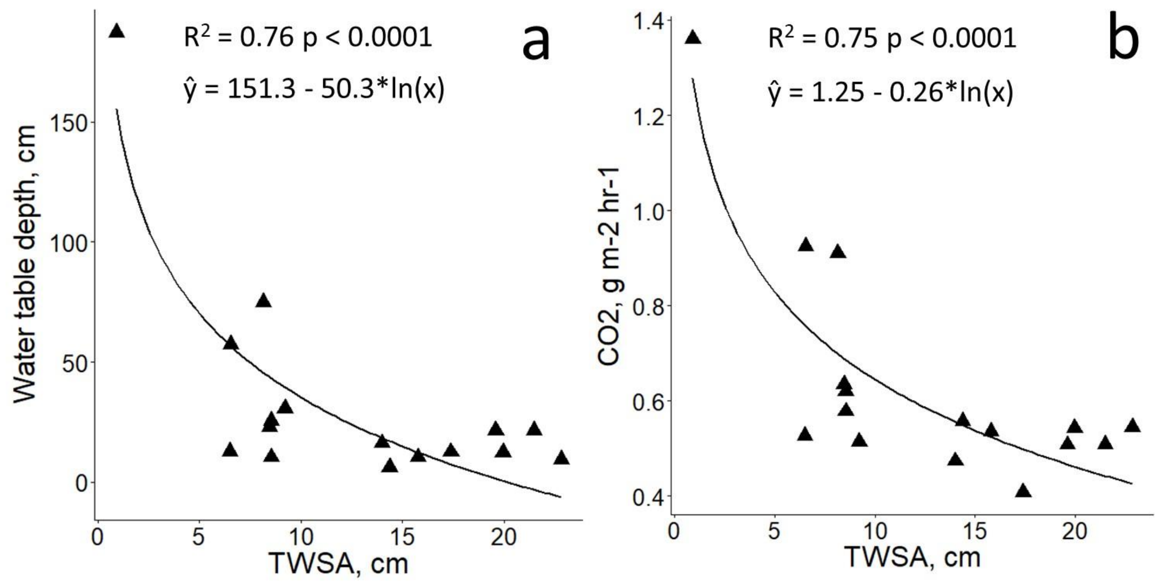


Figure 6. Weighted average water table depth (presented as a positive difference from the surface) (a) and weighted average soil respiration (b) as a function of GRACE TWSA from January 2014 through September 2015 (n = 16 months). Note that TWSA is presented as anomaly values plus 12, to eliminate negative TWSA values. Smaller TWSA values indicate lower soil water storage (deeper water table) and larger values indicate higher soil water storage (shallow water table).

3.3 Precipitation as a predictor variable of soil respiration and water table depth

Precipitation explained variation in water table depth and soil respiration in forest and oil palm, as well as variation in the weighted average water table depth and soil respiration values. Water table depth decreased with increasing cumulative precipitation over the 30 days prior to sampling in forest (Figure 7a) and oil palm (Figure 7b), but precipitation explained more variation in water table in forest (R^2 = 0.75) than oil palm (R^2 = 0.66). Soil respiration also decreased with increasing precipitation in both forest (Figure 7c) and oil palm (Figure 7d). Precipitation explained over two times more variation in soil respiration in forest ($R^2 = 0.73$) than oil palm ($R^2 = 0.31$).

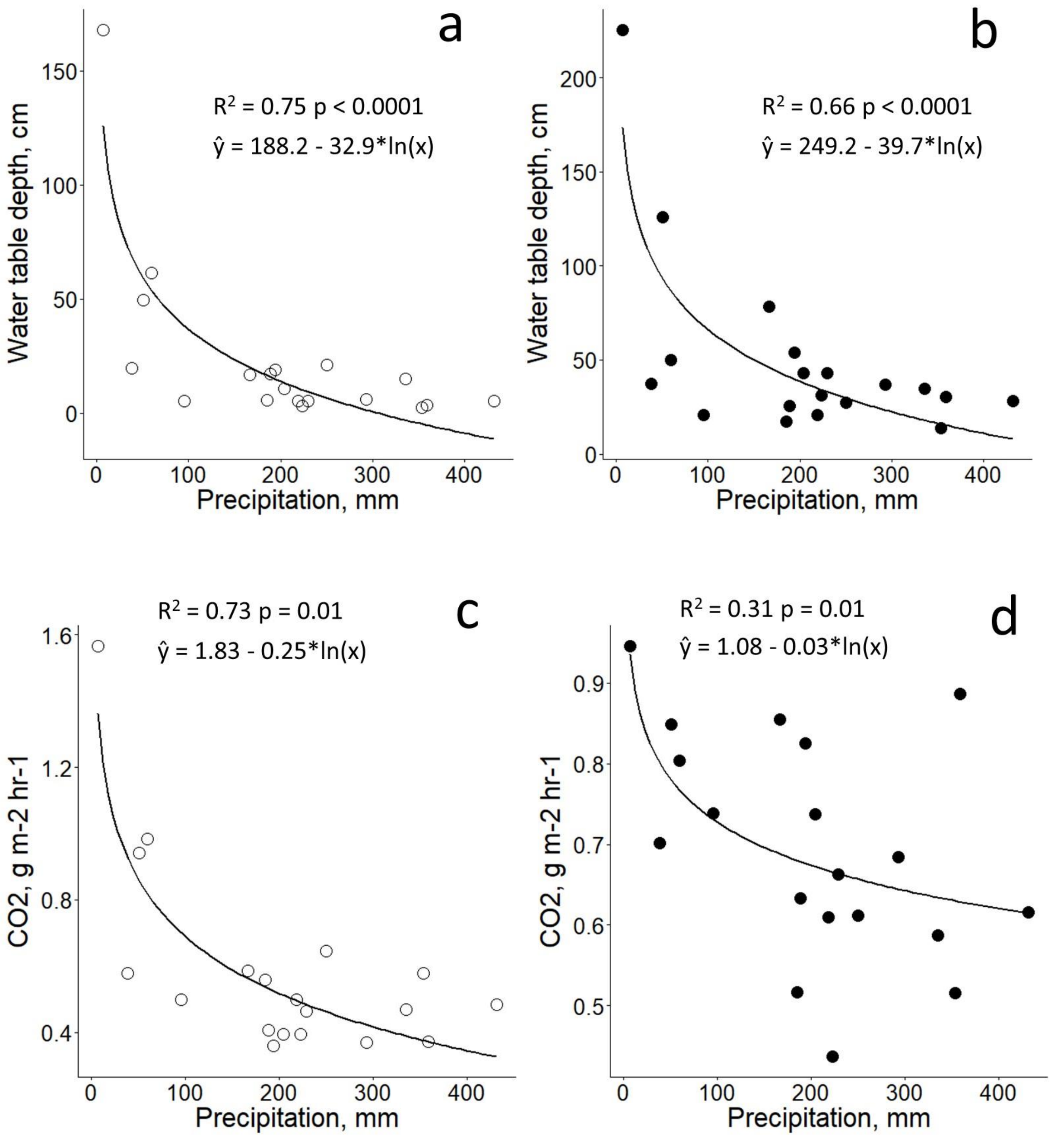


Figure 7. Mean water table depth (presented as a positive difference from the surface) (a and b) and soil respiration (c and d) as a function of cumulative precipitation during the 30 days prior to

the sampling date in forest (a and c) and oil palm (b and d) from January 2014 through September 2015 (n = 19 months).

Precipitation explained 74% and 76% of variation in weighted average water table depth (Figure 8a) and soil respiration (Figure 8b) respectively.

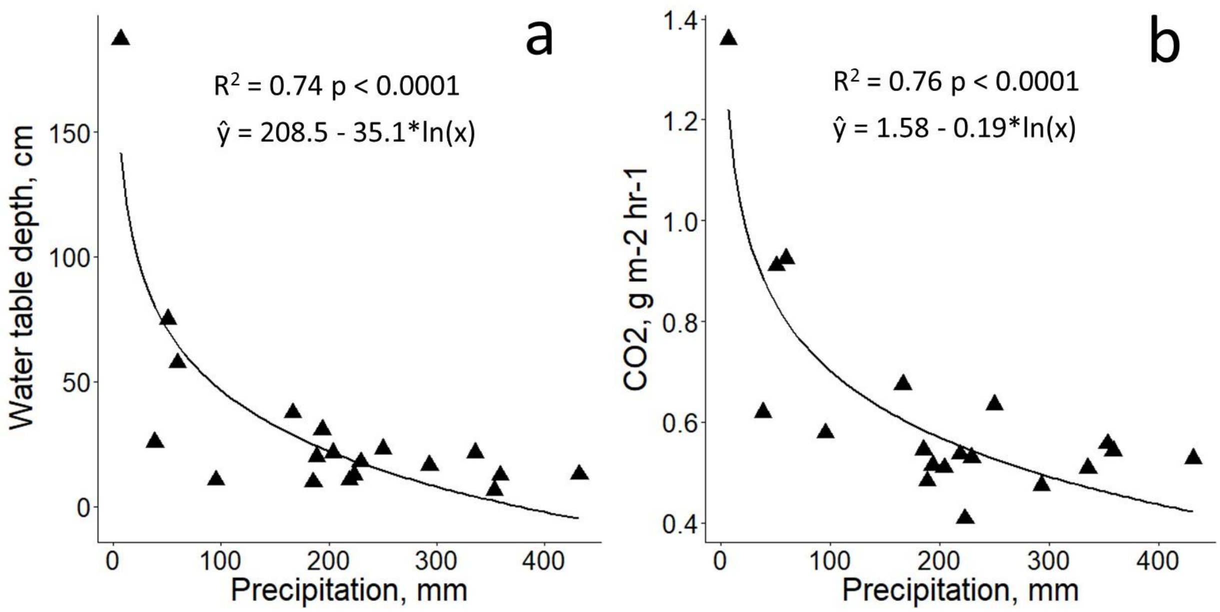


Figure 8. Weighted average water table depth (presented as a positive difference from the surface) (a) and weighted average soil respiration (b) as a function of cumulative precipitation during the 30 days prior to sampling from January 2014 through September 2015 (n = 16 months).

4. Discussion

4.1 Linking total soil respiration and water table depth to GRACE observations

GRACE TWSA was well in phase with precipitation and water table depth (Figure 3). Water table depth, influenced by precipitation (Hirano et al. 2007), is a reasonably good predictor of total soil respiration in our test site (Figure 5 and Swails et al. in preparation), and other tropical peatlands sites (Hirano et al. 2009; Jauhiainen et al. 2008). However, at larger spatial scales, the relationship between peat soil respiration and water table depth loses strength (Hergoualc'h and Verchot 2014). Additional work is needed to investigate other proxies and develop new approaches allowing broader scale evaluations of total soil respiration. Soil moisture is another critical variable influencing soil respiration and particularly important in drained peatlands (Marwanto and Agus 2014; Comeau et al. 2016; Hergoualc'h et al. 2017). Because GRACE TWSA tracks soil water storage, which includes water table depth and soil moisture, GRACE data could be a useful tool to assess soil respiration, an important C flux from tropical peat soils. GRACE TWSA data as a tool for monitoring water table depth might also serve as a fire-alert system. Indeed, we found a significant relationship between total soil respiration and water table depth (Figure 5), between water table depth and GRACE TWSA (Figure 6a), and between total soil respiration and GRACE TWSA (Figure 6b) in our test site. GRACE TWSA was sensitive to extreme dry down during the 2015 El Niño event associated with increased water table depth and higher soil respiration in forest and oil palm. The most negative GRACE TWSA value was associated with the lowest water table depth and highest soil respiration measurements in September 2015. Broad scale monitoring of water table depth and soil respiration concomitantly in peatlands would also benefit peat restoration efforts.

Understanding the hydrological processes driving variation in soil water storage is important for interpreting relationships among precipitation, GRACE TWSA, and water storage in tropical peatlands. GRACE TWSA is related to changes in water storage, which is a function of precipitation, but also evapotranspiration and discharge, which were not accounted for in our study. Relating total soil respiration to water table depth on the ground to GRACE TWSA is constrained by many factors. For example, TWSA reported for March 2014 was strongly negative. Despite extremely high rainfall in the latter half of March 2014, because the period followed two relatively dry months, TWSA remained negative for April, and it did not become positive again until May 2014. These data indicate that ground water reservoirs required several months of rainfall to recharge after the relatively dry conditions in January and February 2014. Careful consideration of antecedent conditions (wet to dry versus dry to wet transitions) and time lags is necessary for determining a predictive relationship between soil respiration, hydroclimatic drivers on the ground, and GRACE TWSA.

Another constraint on estimating relationships among critical hydroclimatic parameters and soil respiration is the dearth of meteorological data. The precipitation recorded at Iskander Airport in Pangkalan Bun may not have been representative of the climatic conditions represented in the GRACE grid cell, which covers an area of approximately 3,025 km^2. The spatial resolution of the current product, at 0.5°, is fairly coarse. Finally, missing days in the data record due to instrument issues may have influenced the accuracy of TWSA observations. Estimation of a good gravity field solution requires accumulation of satellite-to-satellite tracking data for about one month, and there were many days missing from the record. Beginning in 2011 the GRACE mission has shut down battery power for consecutive weeks approximately every six weeks to extend satellite lifetime. The anticipated GRACE follow-on mission will extend the GRACE time series with minimal data gaps while significantly improving on the accuracy and spatial resolution of the original mission (Fletchner et al. 2014).

4.2 A new way to assess a critical CO_2 flux from tropical peatlands

Smaller TWSA, indicating drier conditions, was associated with greater landscape-scale soil respiration in our test site, one GRACE grid cell, comprised of roughly 1/3 oil palm and 2/3 intact peat swamp forest (Figure 6b). Using relationships among precipitation, GRACE TWSA, and total soil respiration, soil water storage, an important driver of respiration in tropical peat soils, could be related to seasonal and interannual climatic variation. This method of assessing soil water status with GRACE TWSA would better characterize spatial and temporal variability in total soil respiration in tropical peatlands compared to some other potential approaches using satellites. For example, the Soil Moisture Active Passive (SMAP) mission L4-C product for monitoring terrestrial ecosystem – atmosphere CO_2 exchange using L-band microwave observations of soil moisture achieves 9 km resolution (Jones et al. 2016) compared to 0.5 degree resolution with GRACE JPL-RL05. However, SMAP, while useful for assessing soil moisture status in other parts of the world (Piepmeier et al. 2017), cannot be used in densely vegetated tropical peatlands. GRACE is uniquely appropriate for application in tropical peatlands in that it is able to "see through" dense vegetation, unlike SMAP. Additionally, soil respiration in tropical peatlands depends on water table depth in addition to soil moisture. Therefore GRACE TWSA, as an integrated measure of groundwater and soil moisture, is particularly useful. Satellite based rainfall data such as the Global Precipitation Mission (GPM) can be used in the tropics to model soil water storage, and achieves higher spatial resolution than GRACE (e.g. 10 km x 10 km for GPM). However satellite based rainfall products may underestimate rainfall in Southeast Asia during dry months (Vernimmen et al. 2012). Furthermore, rainfall remains one step removed from soil water status which is the ultimate determinant of soil respiration.

The strength of relationships between the weighted average water table depth and soil respiration and precipitation are similar to those of relationships between water table depth and soil respiration and TWSA. This indicates that in our study area, precipitation was an equally good predictor as TWSA for assessing landscape soil respiration and water table depth variation. Notwithstanding, in oil palm where water table level is controlled by drainage, precipitation was not a good predictor of soil respiration (Figure 7d). GRACE TWSA could therefore be useful for predicting soil respiration in landscapes dominated by oil palm on peat. Further testing of this application across larger spatial scales is needed, with additional ground measurements properly designed to systematically test results presented here before they may be generalized. This case study represents an early exploration of the potential of GRACE TWSA as a tool for assessing total soil respiration and soil moisture regime. It should lead to further investigation of how GRACE data can be used in a broader land-use change and climatic change context.

Several issues complicate the application of GRACE data for assessment of CO_2 emissions from tropical peatlands. Total soil respiration includes both heterotrophic and autotrophic contributions, but only heterotrophic respiration is directly linked to peat decomposition. The literature indicates that anywhere from 50-90% of the flux is likely due to heterotrophic respiration (Comeau et al. 2016, Hergoualc'h et al. 2017). Furthermore, peat C storage or loss results from the balance of C entering the peat – litterfall, root mortality, and exudates, and C leaving the peat – heterotrophic respiration, dissolved organic carbon, methane, and fire, if any. Also, GRACE data are coarse, and grid level TWSA represents the contribution of changes in water storage in both undrained peat forest and drained oil palm. As we have done here, using land cover data, GRACE grid level data could be weighted to represent coverage by forest and oil palm to better predict soil respiration and water table depth with TWSA observations. Finally, total soil respiration within a specific land use in tropical peatlands responds to multiple factors in addition to soil water storage, such as temperature, soil organic matter quality, and nutrients. For instance, higher peat substrate quality in forest than oil palm may have contributed to the stronger response of soil respiration to increased water table depth in forest than oil palm during the El Niño event in September 2015 (Swails et al. 2017).

Ultimately, a multi-factor model could be developed linking remotely sensed measures with ground measurements for large scale assessments of soil respiration in tropical peatlands. More work is needed to operationalize the application of GRACE TWSA for assessing CO_2 emissions from tropical peatlands. Additional ground measurements of soil respiration and physical drivers are needed to increase the spatial extent of *in-situ* observations and scale the relationship with coarse resolution GRACE data. The current sample size is very small and the plot locations do not represent any randomized selection. While a small, non-randomized sample is adequate for this exploratory study, for rigorous inference, a well-defined probability sampling design would be necessary. Next, characterization of error and uncertainty of annual emissions estimates at various scales from the plot to the plantation, district, province, and island is needed. This will enable the identification of an optimal sampling strategy for monitoring CO_2 emissions from peat using limited ground based measurements and remotely sensed data. Additional work is needed to account for other critical C fluxes. However GRACE data shows great promise for providing an alternative approach for understanding the role of tropical peatlands in the global C cycle and the combined influence of land-use change and climate variability on peat C emissions. With further development and systematic testing of results presented here, this new application could provide useful information to decision makers to monitor changes in water table depth and peat CO_2 emissions in remote and inaccessible areas with limited measurements on the ground.

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