Title

Effect of groundwater level fluctuation on soil respiration rate of tropical peatland in Central Kalimantan, Indonesia

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ABSTRACT

Soil respiration (SR) rate was measured at the burned land (BL), the cropland (CL), the forest land (FL) and the grassland (GL) of a tropical peatland in Central Kalimantan, Indonesia from 2002 to 2011 for the purpose of analysis with a relation to the drying and rewetting. The SR rate was fitted with groundwater level (GWL) to the equation of $\log(\mathrm{SR}) = \alpha - \beta \times \mathrm{GWL}$ using hierarchical Bayesian analysis where α and β were regression coefficients classified by GWL changing directions (drying, rewetting and fluctuating), water-filled pore space (WFPS) ranges in topsoil (low 0–0.54, intermediate 0.54–0.75 and high 0.75–1 m^3 m^{-3}), and land uses (BL, CL, FL and GL). SR rate (Mean ± SD, mg C m^{-2} h^{-1}) was the significantly largest in the CL (333 ± 178) followed by GL (259 ± 151), FL (127 ± 69) and lastly BL (100 ± 90). In the CL, the significantly larger SR rate was found in the rewetting period than in the drying period in the high WFPS range. Also, the significantly steeper slope (β) in the rewetting period was obtained in the high WFPS range than in the drying period. These results suggested that the rewetting of peatland enhanced the SR rate rapidly in the CL, and that the further rise of GWL decreased the SR rate. In contrast, the SR rate in the rewetting period was significantly smaller than in the drying period in the BL in the high WFPS range, because the BL in the high WFPS range was flooded in most cases. The SR rate in the rewetting period was not significantly different from the drying period in the FL and GL. All of β were significant in the high WFPS range in all land uses, but not in the low–intermediate WFPS ranges, suggesting that GWL was not controlling factor of the SR rate when the GWL was deep due to the disconnection of capillary force under dry conditions. According to the results of correlation analysis of the α and β, the α was significantly correlated with relative humidity, soil temperature and soil pH, suggesting that the α was enhanced by dry condition, high soil temperature and neutralization of soil acidity, respectively. The β was significantly correlated with exchangeable Na^+ and Mg^{2+} in the soil, but the reason was not clear. In conclusion, SR rate was enhanced by rising GWL with rewetting in the CL in the high WFPS ranges as well as by deepening GWL.

KEY WORDS: Rewetting, Soil respiration rate, Groundwater level, Tropical peatland, Hierarchical Bayesian analysis

1. INTRODUCTION

Peatlands occupy a small area (3% of global terrestrial area) but have disproportionately high soil carbon (C) stocks (525 Gt C), which constitute about 25 % of terrestrial C in 0–1 m (Maltby and Immirzi 1993). The total area of tropical peatlands is estimated at 39–65 Mha, which is about 11% of the global peatland area (Page *et al.* 2011). The tropical peatlands C stock is estimated to be 81.7–91.9 Gt C, or roughly 19% of total C stocks in global peatlands (Page *et al.* 2011). Most tropical peatlands are distributed in Southeast Asia, particularly in Indonesia.

Soil respiration (SR) is defined as a sum of organic matter decomposition and root respiration. Generally speaking, SR is mainly controlled by soil temperature (Lloyd and Taylor 1994), soil moisture (Davidson *et al.* 1998; Xu and Qi 2001), and soil physicochemical properties (Lee and Joes 2003; Arai *et al.* 2014; Li *et al.* 2015). Land use influences SR rate directly by the difference of root respiration rate due to the different vegetation type, and also influences soil temperature, soil moisture and soil physicochemical properties, which result in affecting the SR rate indirectly (Wagai *et al.* 1998; Raich and Tufekciogul 2000; Inubushi *et al.* 2003). In peatland ecosystems, it is reported that groundwater level (GWL) is important to control SR (Kim and Verma 1992; Glenn *et al.* 1993; Silvola *et al.* 1996) instead of soil water content, because groundwater level is an important source of soil water as well as precipitation in peatland ecosystems. Especially in tropical peatlands, researchers generally agree that land use affects GWL, and that both land use and GWL influence SR (Melling *et al*. 2005; Furukawa *et al*. 2005; Couwenberg *et al*. 2010; Jauhiainen *et al*. 2012) other than soil temperature because of the small variation of soil temperature in tropical area (Davidson *et al*. 2000; Jauhiainen *et al*. 2008). Also, the effect of soil physicochemical properties on SR rate in tropical peatland has not been understood well.

However, this knowledge in tropical peatland is mainly based on annual cumulative SR and annual mean GWL, and the knowledge at the process level is still limited. It is reported that SR rate in tropical peatland is successfully explained by GWL when GWL is near surface (Jauhiainen *et al*. 2008; Hirano *et al*. 2009). On the other hand, SR rate could not be linearly explained by GWL due to the large variability of SR rate when peatland is drained well and when GWL is deep, which makes bell-shaped relationship in appearance between SR rate and GWL (Kim and Verma 1992; Jauhiainen *et al*. 2008).

Soil-drying effect is also important in peatland, which enhance organic matter decomposition by rewetting of soil after dryness (Birch 1958). The soil-drying effect is a phenomenon whereby labile organic matter, derived from dead microbes due to the excess dryness of soil, is quickly decomposed soon after its rewetting (Marumoto *et al*. 1977; van Gestel *et al*. 1993). This effect might be one of the main causes of the large variability of SR rate because the rewetting occurs frequently by the temporal rise in GWL. The soil-drying effect is commonly observed in mineral soils (Kessavalou *et al*. 1998; Borken *et al*. 2003; Yanai *et al*. 2007; Unger *et al*. 2012), and the rewetting of boreal and temperate peatlands enhance organic matter decomposition temporarily (Goldhammer and Blodau, 2008; Fenner and Freeman, 2011). However, soil-drying effect has not been reported in tropical peatland yet.

Hierarchical Bayesian analysis is useful to evaluate the uncertainties of model parameter and objective variable (Clark *et al*. 2005; Nishina *et al*. 2009). Linear regression estimates intercept and slope in a model as a single value, respectively, and calculates the objective variable from the regression model as a single value, which is called as point estimation. On the other hand, hierarchical Bayesian analysis evaluates the uncertainty of each model parameter, and calculates the probability distribution of the objective variable from the model (Clark *et al*. 2005), which is called as interval estimation. Therefore, hierarchical Bayesian analysis is useful to analyze the data with large variability, such as gas flux from soil (Cable *et al*. 2010; Kim *et al*. 2014; Li *et al*. 2014).

The objectives of this study were to develop a model to estimate SR rate with GWL at the process level by the consideration of soil-drying effect, soil moisture, and land uses in tropical peatlands. Also, we investigated the environmental factors including soil physicochemical properties that control the intercept and the slope of the relationship between SR rate and GWL.

2. MATERIALS AND METHODS

2.1. Site description

The study site was located in Palangka Raya, Central Kalimantan, Indonesia (Fig. 1). Mean annual temperature and precipitation are 26.3°C and 2235 mm, respectively (Hirano *et al*. 2007). Organic matter has been accumulated around 3–6 m in this region (Table 1) from around 26,000 years before (Page *et al*. 2004), and the soil type is classified as Typic Haplofibrist in USDA Soil Taxonomy (Soil Survey Staff 2014). The major soil properties were described in Table 1.

There were four burned land (BL) plots. BL1 (2°20’31”S, 114°02’16”E) and BL2

(2°19’23”S, 114°00’59”E) plots were set up in 2002 (Takakai *et al*. 2006), and BL3 (2°18’40”S, 114°03’59”E) and BL4 (2°19’19”S, 114°03’28”E) were set up in 2008. Those plots received peat fires in 1997, 2002 and 2009, and had several centimeters of black charcoal. The main vegetation in the BL plots was *pakis* (*Stenochlaena palustris*) and sub-vegetation included *tumih* (*Combretocarpus rotundatus*) and *hawuk* (*Pteris* sp.). The BL in Central Kalimantan suffers from peat fire in almost every year (Tansey *et al.* 2008), and the BL plots suffered peat fire in September–November 2009 at least one time. However, the main vegetation before and after the peat fire did not change from *pakis*, because it is a pioneer plant for peat fire so that *pakis* could grow up fast after the peat fire.

The cropland (CL) plots (2°17’00”S, 114°00’39”E) were set up in 2002 in Kalampangan village opened in 1981 (Takakai *et al*. 2006). The farming system in the village consisted of three to four upland crop cultivation a year. Maize (*Zea mays* L.) was the main crop in CL1 and CL3 plots. CL2 plot cultivated various crops: spinach (*Spinacia oleracea* L.), cassava (*Manihot esculenta* Crantz.), eggplant (*Solanum melongena* L.), red pepper (*Capsicum annuum* L.), peanut (*Arachis hypogaea* L.) and papaya (*Carica papaya* L.). Chemical fertilizer (TN 16%, P_2O_5 16%, K_2O 16%) was applied before planting, and urea, ash and manure were additionally applied 1 month after planting. Total N application rate was shown in Table 2.

There were three forest land (FL) plots. FL1 (2°20’41”S, 114°02’14”E), FL2 (2°19’35”S, 113°54’15”E) and FL3 (2°19’00”S, 113°54’29”E) were set up in 2002 (Takakai *et al*. 2006). FL1 was located 8 km from the Kahayan River. FL3 was located at the edge of the Sebangau River, 0.7 km away from FL2. FL1 was closed to BL1, and affected by drainage, while FL2 and FL3 were in natural forest that was not affected by drainage. Vegetation in these plots consisted of deciduous trees such as *Tetramerista* *glabra*, *Calophyllum* sp., *Shorea* sp., *Combretocarpus rotundatus*, *Palaquium* sp., *Buchanania sessilifolia*, *Syzygium* sp., *Dactylocladus stenostachys*, *Dyera costulata*, *Ilex cymosa*, *Tristaniopsis obovata* and *Dyospyros* sp. (Tuah *et al*. 2003). The FL was the original land use in our study site, and the other land uses were converted from the FL by peat fires (Page *et al*. 2002) or land reclamations (Limin *et al*. 2007).

The grassland (GL) plot (2°17’00”S, 114°00’39”E) was set up in 2002 (Takakai *et al*. 2006), neighbored the CL plots in Kalampangan village. Vegetation in the GL plot was turfgrass, and was managed for livestock without any fertilizer applications until 2009.

Rainy and dry months from 2002 to 2011 in the study site were judged based on the frequency of peat fires of ATSR World Fire Atlas (Arino *et al*. 2011). The month having monthly peat fire counts more than 1 % of the annual peat fire counts was defined as dry month (Putra 2010; Table 3), and month other than dry month was defined as rainy month.

2.2. Measurement of soil respiration and environmental factors

Measurement was conducted basically once or twice a month from 2002 to 2011 except the BL in 2004–2009 and the FL in 2006–2009, in which the measurement was conducted in February (rainy season) and September (dry season). The measurement in BL2 was finished in 2008.

Soil respiration (SR) rate was measured by a closed chamber method using white colored stainless cylinders, 25 cm in height and 18.5–21.0 cm in diameter. The same methods of gas sampling, gas analysis and calculation were used as described by Toma *et al*. (2011). Three chamber bases (18.2 cm in diameter) were installed in each plot. The chamber closing time was 6 min; gas samples were taken from each chamber before and after the closing, and stored into Tedlar® bags (GL Sciences Inc., Tokyo, Japan). The air temperature (T_a; °C) and relative humidity (%) were measured at the time of gas sampling. The concentration of CO_2 in these samples was analyzed within 10 hours of sampling with the infrared CO_2 analyzer (ZFP-9, Fuji Electric Systems, Tokyo, Japan). SR rate (mg C m^{-2} h^{-1}) was calculated by the following equation:

$$SR = \rho \frac{\Delta c}{\Delta t} \frac{V}{S_b} \frac{273.15}{273.15 + T_a} \frac{12.0}{44.0} \quad \text{Eq. 1}$$

where ρ is the CO_2 gas density (1.977 kg m^{-3}), Δc is the difference of CO_2 concentration in a chamber during the close of a chamber (10^{-6}×m^3 m^{-3}), Δt is the time to close the chamber (0.1 h), V is the volume of the chamber (m^3), S_b is the area of the chamber base (m^2), and 12.0 and 44.0 are the molecular weights of C and CO_2, respectively.

Soil temperature from a top 4 cm depth (T_s; °C) was measured with three replications at each chamber. Volumetric water content of soil from a top 6 cm depth (m^3 m^{-3}) was measured by amplitude domain reflectometry (ADR, ML2 Theta Probe Delta-Y Devices, Cambridge, UK). Groundwater level (GWL; m) was measured by a polyvinylchloride pipe, 4 cm in diameter, installed up to the mineral soil horizon at each plot, and the GWL was measured at the time of SR measurement. Positive value of GWL represents flooding conditions.

To define GWL changing directions (drying, rewetting and fluctuating period), the difference in the GWL between the sampling dates, ΔGWL (m $month^{-1}$), was defined in each plot as follows:

$$\Delta GWL(t) = \frac{GWL(t) - GWL(t-1)}{date(t) - date(t-1)} \times 30 \quad \Delta GWL(1) = 0 \quad \text{Eq. 2}$$

where t is the index of the sampling date in each plot. Our sampling interval was basically 1 month, but it changed in plots and dates. Therefore, the ΔGWL is standardized by 30 days in Eq. 2. The positive ΔGWL indicates the rise in the GWL from the previous sampling. The definition of drying, rewetting and fluctuating periods are shown in Table 4. Drying period was defined as GWL deepening period, which satisfied that $\Delta GWL(t) < 0$ and $\Delta GWL(t-1) < 0$. Rewetting period was defined as GWL rising period, which satisfied that $\Delta GWL(t) > 0$ and $\Delta GWL(t-1) > 0$. To incorporate a sharp change in the GWL between two subsequent sampling events into the drying and the rewetting period, the sampling date with $|\Delta GWL(t)| > IQR_{\Delta GWL}$ was also defined as the drying and rewetting period where $|\Delta GWL(t)|$ was absolute value of $\Delta GWL(t)$, and $IQR_{\Delta GWL}$ was the interquartile range (the difference between third and first quartiles, positive value) of the ΔGWL in the whole dataset. Fluctuating period was defined as GWL fluctuating period that was neither drying nor rewetting period.

2.3. Measurement of physicochemical properties of soil

Composite soil samples were taken from a top 10 cm soil depth at the time of SR rate measurement. They were air-dried and sieved by 2 mm sieve. Soil pH was measured using 1:20 air-dried soil and deionized water mixture with a glass electrode pH meter (pH meter F-22, Horiba, Kyoto, Japan) according to Takakai *et al*. (2006). The ratio of 1:20 corresponds to the ratio of 1:4 of fresh soil and deionized water, because mean soil moisture content of the fresh soil was 355%. Total carbon content, total nitrogen content, cation exchange capacity (CEC), exchangeable cations (Na, K, Mg and Ca), NH_4-N and NO_3-N contents were analyzed with the procedures used by Takakai *et al*. (2006). Water-soluble organic carbon (WSOC) was measured as total organic carbon in the soil extracted by water (1:20). Microbial biomass carbon (MBC) was measured by a fumigation-extraction method (Joergensen *et al.* 1996). The concentration of total organic carbon of WSOC and MBC was analyzed by TOC analyzer (TOC-5000A, Shimadzu, Kyoto, Japan).

Soil core of 100 mL was also sampled from top 0–10 cm depth in each plot. Bulk density and porosity were measured using the soil core samples. The porosity was measured using soil core of 100 mL by digital soil volume analyzer (DIK-1150, Daiki-Rika, Saitama, Japan). The porosity was used to convert the volumetric water content to water-filled pore space (WFPS), which represented the proportion of volumetric water content to porosity. The WFPS was divided into three ranges (low, intermediate and high WFPS) by the first and third quartiles of WFPS in the whole dataset to represent the dryness of surface soil moisture.

2.4. Statistical analyses

First of all, SR rate data was log-transformed because they did not follow a normal distribution according to the Shapiro test ($P < 0.001$), and they were well fitted by log normal distribution (Fig. 2).

The one-way ANOVA and the Tukey HSD test was carried out for the log SR rate, T_s, GWL and WFPS to compare among plots. The one-way ANOVA and the Tukey HSD test was carried out for log SR rate to compare among GWL changing directions. The two-way ANOVA and Tukey HSD test was carried out for log SR rate to compare among GWL changing directions and WFPS ranges in each land use.

The multiple regression analysis of the log SR rate with GWL, WFPS and T_s were performed with the whole dataset. However, accuracies of these regressions were quite small. Therefore, the SR rate was fitted by the GWL using hierarchical Bayesian analysis as below:

$$SR_{ijkl} \sim \mathrm{LogNormal}(\alpha_{jkl} - \beta_{jkl} GWL_{ijkl}, \sigma_y^2) \quad \text{Eq. 3}$$

where α_{jkl} and β_{jkl} are the parameters that are different among GWL changing directions, WFPS ranges, and land uses; σ_y is the scale parameter. The exp(α) represents the SR rate at the GWL = 0 m. The GWL changing directions have 3 levels (j = 1 as drying, 2 as rewetting, and 3 as fluctuating), the WFPS ranges have 3 levels (k = 1 as low, 2 as intermediate, and 3 as high WFPS range), and the land uses have 4 levels (l = 1 as BL, 2 as CL, 3 as FL, and 4 as GL), respectively. The positive β shows the increase in SR rate with deepening GWL. The intercept (α_{jkl}) and the slope (β_{jkl}) are estimated by the following equations:

$$\alpha_{jkl} \sim \mathrm{Normal}\left(\mu_\alpha + \gamma_{\alpha j} + \delta_{\alpha k} + \lambda_{\alpha l}, \sigma_\alpha^2\right) \quad \text{Eq. 4}$$

$$\beta_{jkl} \sim \mathrm{Normal}\left(\mu_\beta + \gamma_{\beta j} + \delta_{\beta k} + \lambda_{\beta l}, \sigma_\beta^2\right) \quad \text{Eq. 5}$$

where μ_α and μ_β are the grand mean of α and β in the whole dataset including all GWL changing directions, WFPS ranges and land uses; σ_α and σ_β are the standard deviation of α and β, respectively. $\gamma_{\alpha j}$, $\gamma_{\beta j}$, $\delta_{\alpha k}$, $\delta_{\beta k}$, $\lambda_{\alpha l}$ and $\lambda_{\beta l}$ are constrained by zero-sum binding condition that was analogy with analysis of variance (Qian and Shen 2007).

To avoid the arbitrary selection of prior distributions, relatively flat prior distributions, called as the weakly informative prior distributions, were selected for the parameters above. Half-Cauchy distribution (Gelman 2006) was applied for $\gamma_{\alpha j}$, $\gamma_{\beta j}$, $\delta_{\alpha k}$, $\delta_{\beta k}$, $\lambda_{\alpha l}$, $\lambda_{\beta l}$, σ_y, σ_α and σ_β, and normal distribution was applied for μ_α and μ_β. The posterior distribution was calculated by the Hamiltonian Monte Carlo method (Hoffman and Gelman 2014) implemented by RStan (Stan Development Team 2015; version 2.6.0). The iteration was 10,000 including 5,000 warm-up periods, and the number of chains was 4. The convergence diagnostics were carried out by the Gelman-Rubin method (Gelman and Rubin 1992). To compare models, R^2, RMSE, AIC/2n (Akaike 1987) and WAIC (Watanabe 2010) were calculated for each model. Larger R^2, smaller RMSE, smaller AIC/2n and smaller WAIC indicate better model. The significance of each regression was evaluated by the correlation of the observed log SR rate with the predictive mean of the regressed log SR rate.

95% credible interval (CI) of the α and β was defined as the interval of the posterior distribution between 2.5%tile and 97.5%tile of the α and β, respectively. We defined the significance of a regression coefficient (α and β) as the 95% CI did not include 0. Also, we defined the significant difference of two regression coefficients was defined that the 95% CIs were not overlapped each other.

The significant α and β were selected only, and the Pearson's correlation analysis was performed to investigate the controlling factors of the α and β by the environmental factors including the soil physicochemical properties. According to the results of Shapiro-Wilk normality test, both α and β did not significantly violate the normality.

All the statistical calculations were carried out by R software (R Development Core Team 2015; version 3.1.3).

3. RESULTS

3.1. Soil physicochemical properties

Table 1 shows the soil physicochemical properties in the study plots. Peat thickness varied from 3.1 m (the CL and GL) to 6.5 m (BL1 and BL2). Bulk density was larger in the CL and GL, which reflected in the smaller porosity in these land uses. Soil pH was higher in the CL, which resulted from higher exchangeable Ca content due to the application of ash. Higher NH_4 content in the FL might be caused by larger N supply by litter and larger N mineralization, and higher NO_3 content in the CL might be caused by larger nitrification.

3.2. Soil temperature, groundwater level, and water-filled pore space

There was no clear seasonal and inter annual variation in T_s. Soil temperature T_s was significantly higher in the CL and GL than in the BF and FL, and that in the FL was the lowest (Table 5).

Groundwater level (GWL) was significantly deeper in the CL and GL than in the BL and FL (Table 5). There was a tendency of deeper GWL at higher T_s. However, the

GWL was more fluctuated than T_s. The GWL varied from −1.96 m (in GL on September 28, 2006) to 0.80 m (in BL1 on March 28, 2003) in the whole dataset (Fig. 3). There were clear negative peaks of the GWL in 2006 and 2009 of El Niño years, although in 2004 of El Niño year such negative peaks could not be found due to the lack of data (Fig. 3).

Water-filled pore space (WFPS) varied from 0.04 m^3 m^{-3} (in BL1 on September 27, 2002) to 1.0 m^3 m^{-3} (in BL1–4, FL2 and FL3 during flooding) in the whole dataset (Fig. 4). According to the first and the third quartiles of WFPS, the WFPS range (low, intermediate and high) was defined as follows: the low WFPS range as $0 < \text{WFPS} < 0.54$, the intermediate WFPS range as $0.54 < \text{WFPS} < 0.75$, and the high WFPS range as $0.75 < \text{WFPS} < 1$. More than half of the WFPS values in the BL were in the high WFPS range, and those in the CL and GL were in the intermediate WFPS range. In the FL, most WFPS values in FL1 were in the low WFPS range due to drainage, while those in FL2 and FL3 were in the higher WFPS range.

There was a significant correlation between the WFPS and the GWL, and the slope of the WFPS to the GWL was steeper in the BL and FL than in the CL and GL (Fig. 5). This indicates that the WFPS change with the GWL change was more in the BL and FL than the CL and GL.

3.3. Soil respiration rate

SR rate varied from 3 mg C m^{-2} h^{-1} (in BL3 on April 20, 2010) to 1242 mg C m^{-2} h^{-1} (in CL2 on January 27, 2006) in the whole dataset (Fig. 6). The SR rate in the BL plots did not change significantly before and after the peat fire in 2009, and therefore we did not consider the effect of peat fires on the SR rate in the BL. The SR rate was significantly different among plots ($P < 0.001$), and the largest SR rates were observed in CL1–3 (Table 5). The SR rate was not significantly different within the same land use except FL1 (Table 5). Therefore, one-way ANOVA and the Tukey HSD test were performed for the SR rate to compare among land uses. The largest SR rate was obtained in CL, and the smallest SR rates were obtained in BL and FL ($P < 0.001$, Table 6).

Next, two-way ANOVA and the Tukey HSD test were performed for the SR rate to compare among GWL changing directions and WFPS ranges in each land use. Compared among GWL changing directions, the SR rate in the CL was significantly higher during the rewetting period than during the drying period in the high WFPS range, but not in the low–intermediate WFPS ranges (Table 6). However, in contrast, the SR rate in the BL was significantly lower during the rewetting period than during the drying period in the low WFPS range, but not in the intermediate–high WFPS ranges (Table 6). In the whole WFPS ranges, the SR rate in the CL was significantly higher in the rewetting period than in the drying and fluctuating periods (Table 6). In contrast, the SR rate in the BL was significantly smaller in the rewetting period than in the drying period in the whole WFPS ranges (Table 6).

Compared among different WFPS ranges, the significantly higher SR rates in the low WFPS range than in the high WFPS range were obtained in the drying period in BL, in the rewetting period in FL and in the fluctuating period in FL (Table 6). In the whole periods of GWL changing directions, the significantly lower SR rates were obtained in the high WFPS range than in low WFPS range in BL and FL, but not in CL (Table 6). The SR rate was not different significantly in any cases in the GL (Table 6).

3.4. The relationship between soil respiration rate and groundwater level

The relationships between SR rate and GWL in each GWL changing direction, WFPS range and land use were shown in Fig. 7. The peak in the SR rate mainly appeared between −0.8 and −0.4 m of the GWL.

Linear regression analyses were carried out for the log-transformed SR rate by GWL, WFPS and T_s (Table 7). However, the accuracies of these regressions were low especially with WFPS (Table 7). Next, dataset was divided by the combination of GWL changing directions (3 levels), The WFPS ranges (3 levels) and land uses (4 levels), and the linear regressions between the log-transformed SR rate and GWL were applied for each sub-dataset (3×3×4 = 36 sub-datasets). However, the significant relationships were obtained from only four sub-datasets (P < 0.05). Therefore, hierarchical Bayesian analysis was applied.

The SR rate was regressed by the GWL significantly using hierarchical Bayesian analysis, and the accuracy of the regression of hierarchical Bayesian analysis was improved from the log-transformed linear regression (Table 7). The results of hierarchical Bayesian analysis showed all the intercepts (α) were significant (Table 8). The α varied from 3.97 to 5.72, which indicated that the SR rate at GWL = 0 m varied from 53 to 306 mg C m^{-2} h^{-1}. The α was significantly larger in the CL, followed by GL, FL and lastly BL (Table 8). The α in each land use was significantly smaller in the high WFPS range than in the low–intermediate WFPS ranges except GL in the drying period (Table 8). All slopes (β) values in the high WFPS range were significant, but not in the low–intermediate WFPS ranges (Table 9). The significant β varied from 0.26 to 1.21. In the whole GWL changing directions in the high WFPS range, the steepest β was obtained in the FL, and the flattest β was obtained in the CL and GL (Table 9). The β in the high WFPS range was significantly steeper in the rewetting period than in the fluctuating period in BL, CL and FL, and was significantly steeper than in the drying period in BL and CL, respectively (Table 9).

A correlation analysis was performed for the significant intercept (α) and slope (β)

with environmental factors including the soil physicochemical properties (Table 10). The α was significantly correlated with relative humidity, T_s, peat depth, bulk density, pH, total C and N, WSOC, CEC, exchangeable Na^+ and Ca^{2+}, NH_4^+ and NO_3^- contents in the soil (Table 10). The β was significantly correlated with exchangeable Na^+ and Mg^{2+} in the soil.

4. DISCUSSIONS

4.1. Effect of rewetting and drying on soil respiration

Hierarchical Bayesian regression succeeded in explaining SR rate by GWL more than log-transformed linear regression due to the consideration of GWL changing directions, WFPS ranges and land uses (Table 7). Therefore, we will discuss about the characteristics of the SR rates in tropical peatland and their controlling factors based on the results from hierarchical Bayesian analysis.

The largest SR rate was observed in the CL (Table 6). In our study, the mean WFPS in the CL was in the intermediate WFPS range as 0.54–0.75 m^3 m^{-3} (Table 5), which is well known as an optimum soil water condition for aerobic mineralization (Linn and Doran 1984). This optimum WFPS might contribute the largest SR rate in the CL. N fertilization might also promote the SR rate in the CL. Several studies reported the promotion of peat decomposition by N fertilization in tropical peatland (Jauhiainen *et al.* 2014; Comeau *et al.* 2016). These studies support our result.

The increase of SR rate with deepening GWL in tropical peatland has been reported (Couwenberg *et al.* 2010). Here, we tried to show that the rising GWL with rewetting also enhance SR rate as well as deepening GWL. The larger SR rate was found in the rewetting period than in the drying period in the high WFPS range in the CL (Table 6), in which the mean GWL was deeper than −0.6 m (Table 5). Also, the β

(the slope of the log SR rate to GWL) in the CL were larger during the rewetting period than during the drying and fluctuating periods in the high WFPS range (Table 9). These results suggest that the SR rate in the CL during the rewetting period is strongly enhanced by "soil-drying effect" (Birch 1958), and is also rapidly decreased by further rise in GWL inducing anaerobic condition (Couwenberg *et al*. 2010). The enhancement of SR rate by rewetting is common in mineral soils, which is generally caused by decomposition of labile organic matter derived from dead microbes and by modification of organic matter during dry periods (Birch 1958; Marumoto *et al*. 1977; van Gestel *et al*. 1993). The enhancement of SR rate by rewetting is also reported in field studies (Borken 1999; Cable *et al.* 2008). Borken (1999) reported that the increase of SR rate in a temperate forest mineral soil was larger during rewetting period than during drying period. This soil-drying effect might also contribute the largest SR rate in the CL.

All slopes (β) in the high WFPS range were significant, but the β in the low–intermediate WFPS ranges were significant only in some cases (Table 9). This suggests that GWL may not control SR rate in the low WFPS ranges. As well known, the controlling factors of SR rate are mainly temperature and moisture. In the case of tropics, as temperature is always high enough, usually soil moisture become major controlling factor for the SR rate (Davidson *et al*. 2000; Jauhiainen *et al*. 2008), and the WFPS in the topsoil was controlled by the GWL with the capillary force (Chen and Hu 2004; Kalpan and Muñoz-Carperna 2011). However, continuity of capillary pores in the subsoil with well-developed macropore system is poor (Beven and German 1982; Mooney 2003). Tropical peat soil is generated from coarse woody materials, and develops macropore systems very well in the subsoil especially in natural forest. Discontinuity of capillary pores disturbs the control of WFPS in the topsoil by GWL. It is likely to occur the discontinuity of capillary pores when the GWL is deep enough, and therefore in such conditions, the WFPS in the topsoil cannot be controlled by the GWL. Since CO_2 is mainly produced in the topsoil (Fierer *et al.* 2003, Kusa *et al.* 2010), SR rate is affected by the WFPS in the topsoil, and the WFPS is controlled by the GWL when there is continuity of capillary pores. However, when the WFPS in the topsoil is not controlled by the GWL due to the deep GWL, SR rate cannot be controlled by the GWL. This may be a reason why the slopes β in the low WFPS range were not significant. Hirano *et al*. (2009) measured SR rate in a natural tropical peat swamp forest in Central Kalimantan, and reported a significant linear relationship between the daily mean SR rate and the GWL when the GWL was shallower than −0.2 m, while there was no significant relationship when the GWL was deeper than −0.2 m. These results may be induced by the disconnection of capillary water in tropical peat soil.

The effect of macropore system on drainage was seen more strong in the BL and FL than in the CL and GL, because the slope of the relationship between WFPS and GWL was steeper in the BL and FL than in the CL and GL (Fig. 5), that is, the WFPS was increased more rapidly with rising GWL in the BL and FL than in the CL and GL. This may lead to rapid decrease of the SR rate with the further rise in the GWL. In fact, the slope β was steeper in the BL and FL than in the CL (Table 9). Also, the SR rate in the whole WFPS range was significantly lower during the rewetting period than during the drying period in the BL (Table 6), which was opposite result from the CL. Therefore, the effect of macropore system on drainage might be a reason why the effect of rewetting on SR rate was negative in the BL, or was not found in the FL. The GL soils kept the GWL deep, and the WFPS seldom reached the high WFPS range, which might be a reason why the effect of rewetting on SR rate was not found in the GL. In contrast, the mean WFPS in the CL was in the intermediate WFPS, and the WFPS in the CL often reached the high WFPS range, which might result in the positive effect of the rewetting on SR rate.

4.2. Controlling factors for the intercept and the slope

The α and β were significantly correlated with the environmental factors including the soil physicochemical properties (Table 10). The significantly positive correlation of the α with T_s might result from the enhancement of the SR rate by the higher soil temperature. The significantly negative correlation of the α with the relative humidity might result from the enhancement of root respiration under dry conditions. Nepstad *et al*. (1994) reported that large amount of total C was allocated into belowground for root growth to obtain water from deeper soil profile in dry season in the eastern half of Amazon Basin. This promotion of root growth under dry conditions might enhance root respiration (Nicolas *et al*. 1985, Liu *et al*. 2004). The similar result of the enhancement of root respiration in low relative humidity was also obtained in natural forest on Malaysian tropical peatland (Melling *et al*. 2005).

The significant correlation of the α with peat thickness, bulk density, pH, total C and N contents, CEC and exchangeable Ca^{2+} content might result from land use change from the FL to the CL and GL by reclamation of peatland. The reclamation of peatland for agricultural uses requires drainage, and it has been reported that the reclamation and drainage of peatland decreases peat thickness, increases bulk density, decreases total C and N contents, and decreases CEC (Ramchunder *et al.* 2009). Therefore, the significant correlations with these soil physicochemical properties might reflect that the SR rate was enhanced by the reclamation and drainage in the CL and GL. Also, farmers in this area generally apply ash every cropping, which resulted in high content of exchangeable Ca^{2+} in the CL (Table 1), and could have increased soil pH in the CL from the other land uses. The neutralization of soil acidity promotes microbial activity that leads to the enhancement of organic matter decomposition (Murakami *et al*. 2005). Therefore, the application of ash in the CL could be one of the causes of large SR rate in our study.

The significantly negative correlation of the α with NH_4^+, and the significantly positive correlation with NO_3^- might reflect the enhancement of SR rate in land uses under the dry conditions. The dry conditions promote nitrification as well as SR rate, which result in the lower soil NH_4^+ content and the higher soil NO_3^- content. Therefore, the promotion of nitrification under dry conditions might be a reason of the significant correlations of the α with NH_4^+ and NO_3^- contents.

The slope (β) was significantly correlated with exchangeable Na^+ and Mg^{2+}, but not with the other exchangeable cations and the total exchangeable cations (Table 10). However, the relationship between SR rate and the exchangeable Na^+ and Mg^{2+} were not understood. Also, the contents of the exchangeable Na^+ and Mg^{2+} were less than the exchangeable K^+ and Ca^{2+} in most plots, respectively (Table 1). Therefore, it was not clear why the significant correlations of the β with the exchangeable Na^+ and Mg^{2+} were obtained.

5. CONCLUSIONS

The SR rate was the largest in the CL, and the smallest in the BL and FL. In the CL, the rewetting of the soil significantly enhanced SR rate in the high WFPS range due to the soil-drying effect, while the further rise in GWL rapidly repressed SR rate by anaerobic condition. In contrast, the rewetting of the soil significantly decreased SR rate in the high WFPS range in the BL compared to the drying of the soil, and the effect of rewetting could not be found in the FL and GL.

The SR rate was significantly regressed by the GWL mainly in the high WFPS range using hierarchical Bayesian analysis. The intercept (α) of regression equation for the SR rate to the GWL was promoted by the high temperature, the dry conditions, and the neutralization of soil pH, but the slope (β) was not well explained.

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FIGURE LEGENDS

Fig. 1. Study sites in Central Kalimantan, Indonesia. Four land uses: burned land (BL1, BL2, BL3 and BL4), cropland (CL1, CL2 and CL3), forest (FL1, FL2 and FL3) and grassland (GL) were selected for the study. Map image: Google Earth, Digital Globe. 2°26’19.47” S and 113°56’15.05” E, taken on April 10, 2013, retrieved on April 14, 2014

Fig. 2. Histogram of soil respiration (SR) rate in each land use. SR rate followed log-normal distribution with N as the number of data, μ as location parameter and σ as scale parameter.

Fig. 3. Observed groundwater level (GWL) in our study sites from 2002 to 2011. Grey bars represent the dry month defined by peat fire occurrences in Central Kalimantan. Measurement sites are cropland (CL1, CL2 and CL3), grassland (GL), burned land (BL1, BL2, BL3 and BL4) and forest (FL1, FL2 and FL3). Negative value shows belowground.

Fig. 4. Observed water-filled pore space (WFPS) in our study sites from 2002 to 2011. Grey bars represent the dry month defined by peat fire occurrences in Central Kalimantan. Measurement sites are cropland (CL1, CL2 and CL3), grassland (GL), burned land (BL1, BL2, BL3 and BL4) and forest (FL1, FL2 and FL3).

Fig. 5. Relationship between water-filled pore space (WFPS) and groundwater level (GWL) in each land use. Two dashed horizontal lines represent the first and third

quartiles of WFPS in the whole dataset (0.54 and 0.75 $m^3 m^{-3}$, respectively), and low, intermediate and high WFPS are defined from the lines.

Fig. 6. Observed soil respiration (SR) rate in our study sites from 2002 to 2011. Grey bars represent the dry month defined by peat fire occurrences in Central Kalimantan. Measurement sites are cropland (CL1, CL2 and CL3), grassland (GL), burned land (BL1, BL2, BL3 and BL4) and forest (FL1, FL2 and FL3).

Fig. 7. The relationship between soil respiration (SR) rate and groundwater level (GWL) in each GWL changing directions (drying, rewetting and fluctuating), water-filled pore space (WFPS) range (low, intermediate and high) and land use (burned land, cropland, forest land and grassland). The grey regions represent the 95% credible interval of posterior predictive distribution calculated by hierarchical Bayesian analysis.

Tables

Table 1

The major soil physicochemical properties in this study sites in the surface 10 cm depth in tropical peatland in Central Kalimantan, Indonesia.

Plot	Peat thickness	Bulk density	pH (H_2O)	Total C	MBC	WSOC	Total N	CEC	Exchangeable cations				Base sat.	NH_4^+	NO_3^-
									Na^+	K^+	Mg^{2+}	Ca^{2+}			
	m	Mg m^{-3}		g kg^{-1}				cmol$_C$ kg^{-1}					%	mg N kg^{-1}	
BL1	6.5	0.22	3.7	634	0.45	0.41	12.4	206	0.16	0.42	1.20	1.04	1.4	98.7	31.8
BL2	6.5	0.22	4.1	649	0.10	0.26	12.5	149	0.07	0.04	0.12	0.19	0.3	32.1	16.0
BL3	2.9	0.13	3.7	644	0.41	0.56	11.9	213	0.15	0.42	2.94	3.43	3.3	80.5	62.8
BL4	3.8	0.13	3.8	628	0.37	0.76	12.6	213	0.15	0.30	2.50	2.72	2.7	161.8	22.8
CL1	3.1	0.38	4.6	393	0.13	0.24	12.5	98	0.13	0.46	1.16	6.94	8.9	45.1	276.3
CL2	3.1	0.38	4.4	553	0.28	0.31	13.5	162	0.18	0.83	2.95	8.98	8.0	47.4	150.2
CL3	3.1	0.42	5.0	533	0.08	0.35	11.4	181	0.19	0.38	4.79	9.18	8.0	84.5	144.5
FL1	3.7	0.13	3.7	544	0.19	0.97	17.6	209	0.20	0.43	1.62	0.83	1.5	490.6	71.2
FL2	4.2	0.12	4.1	560	1.17	0.95	19.2	248	0.94	0.74	1.73	1.70	2.1	481.9	28.7
FL3	4.2	0.12	3.9	549	0.60	0.96	18.0	213	0.54	0.62	2.71	1.18	2.4	396.0	57.0
GL	3.1	0.33	4.0	469	0.92	0.34	11.0	191	0.15	0.87	3.39	3.54	4.2	77.4	82.7

MBC: microbial biomass carbon

WSOC: water-soluble organic carbon

Table 2

Application rate of N fertilizer in each crop in CL1, CL2 and CL3.

Plot	Year	Main crop	N fertilizer application	
			$year^{-1}$	$kg\ N\ ha^{-1}\ year^{-1}$
CL1	2002–2011	Corn	3–4	665–1638
CL2	2002–2005	Egg plant	4	773–800
	2006–2008	Grass	0–1	0–84
	2009	Peanut and spinach	9	608
	2010	Red pepper	3	78
	2011	Papaya	4	37
CL3	2002–2011	Corn	3–4	785–1278

Data from 2002–2004 were cited from Takakai *et al.* (2006), and data from 2005–2006 were cited from Toma *et al.* (2011).

Table 3

Annual fire counts in Central Kalimantan and the length of the dry month (Arino *et al.* 2012). Dry month is defined as the month in which monthly fire counts are more than 1% of annual fire counts. Because there were almost no fires in Central Kalimantan in 2008 and 2010, there was no dry month in these years.

Year	Annual fire counts	Dry month length	Relative humidity in dry months (%)
2002	2366	123 days (July – Oct.)	73.6 ± 7.2
2003	433	184 days (Mar., May – Sep.)	69.9 ± 5.8
2004	887	92 days (Aug. – Oct.)	72.7 ± 8.1
2005	163	153 days (Mar., June – Sep.)	69.0 ± 7.8
2006	2221	122 days (Aug. – Nov.)	57.1 ± 8.1
2007	35	184 days (Jan., June – Oct.)	68.3 ± 10.4
2008	5	0 days	
2009	720	123 days (July – Oct.)	54.9 ± 13.3
2010	0	0 days	
2011	95	153 days (June – Oct.)	70.1 ± 14.1

Table 4

Classification of GWL changing direction. ΔGWL is a rate of change of groundwater level (GWL), and $\mathrm{IQR}_{\Delta \mathrm{GWL}}$ is an inter-quartile range of ΔGWL, respectively. Positive ΔGWL shows a rise in GWL.

GWL changing direction	Cases
Drying	$\Delta\mathrm{GWL}(t) < 0$ & $\Delta\mathrm{GWL}(t-1) < 0$; *or*
	$\Delta\mathrm{GWL}(t) < -\mathrm{IQR}_{\Delta \mathrm{GWL}}$
Rewetting	$\Delta\mathrm{GWL}(t) > 0$ & $\Delta\mathrm{GWL}(t-1) > 0$; *or*
	$\Delta\mathrm{GWL}(t) > \mathrm{IQR}_{\Delta \mathrm{GWL}}$
Fluctuating	The other cases

Table 5

The number of data (N), soil respiration (SR) rate, soil temperature (T_s), groundwater level (GWL), and water-filled pore space (WFPS) in each plot in tropical peatland in Central Kalimantan, Indonesia. All values show Mean ± SD. The values with the same letters are not significantly different ($P < 0.05$). Positive GWL shows flooding. BL1−BL4 belong to burned land, CL1−CL3 belong to cropland, FL1−FL3 belong to forest land, and GL belong to grassland, respectively.

Plot	N	SR (mg C m^{-2} h^{-1})		T_s (°C)		GWL (m)		WFPS (m^3 m^{-3})	
BL1	58	99 ± 69	d	30.4 ± 1.8	bc	−0.16 ± 0.25	a	0.80 ± 0.26	abc
BL2	26	72 ± 33	d	30.5 ± 1.5	abc	−0.56 ± 0.31	bc	0.62 ± 0.19	ef
BL3	31	116 ± 143	d	29.7 ± 1.5	cd	−0.06 ± 0.28	a	0.88 ± 0.19	a
BL4	33	111 ± 89	d	28.7 ± 1.6	de	−0.08 ± 0.24	a	0.86 ± 0.23	ab
CL1	141	351 ± 185	a	31.1 ± 1.8	ab	−0.70 ± 0.28	c	0.64 ± 0.10	ef
CL2	140	316 ± 173	ab	30.8 ± 2.3	bc	−0.93 ± 0.26	d	0.61 ± 0.10	f
CL3	141	330 ± 175	a	31.6 ± 1.9	a	−0.66 ± 0.23	c	0.69 ± 0.12	de
FL1	68	167 ± 67	c	27.6 ± 1.2	ef	−0.45 ± 0.29	b	0.42 ± 0.12	g
FL2	46	94 ± 58	d	26.8 ± 1.4	f	−0.15 ± 0.27	a	0.70 ± 0.27	cde
FL3	48	103 ± 50	d	26.9 ± 0.7	f	−0.18 ± 0.19	a	0.75 ± 0.26	bcd
GL	144	259 ± 151	b	31.4 ± 2.1	ab	−1.08 ± 0.29	e	0.59 ± 0.12	f
All	876	243 ± 176		30.3 ± 2.4		−0.63 ± 0.42		0.65 ± 0.19	

Table 6

Soil respiration (SR) rate in each GWL changing direction, WFPS range and land use. All the values show Mean ± SD (*N*). The values with the same small and capital alphabetical letters are not significantly different (*P* < 0.05) for a given land use. The values with the same Greek letters are not significantly different (*P* < 0.05) among land uses.

WFPS range	GWL changing direction	SR rate (mg C m^{-2} h^{-1})							
		Burned land (BL)		Cropland (CL)		Forest land (FL)		Grassland (GL)	
Low	Drying	220 ± 206 (8)	a	315 ± 172 (24)	b	144 ± 69 (25)	a	216 ± 84 (20)	a
	Rewetting	82 ± 44 (3)	b	276 ± 156 (7)	b	155 ± 55 (25)	a	240 ± 145 (5)	a
	Fluctuating	139 ± 90 (14)	ab	285 ± 160 (19)	b	147 ± 66 (51)	a	236 ± 90 (18)	a
Intermediate	Drying	147 ± 133 (10)	ab	320 ± 159 (91)	ab	177 ± 32 (2)	a	249 ± 118 (24)	a
	Rewetting	80 ± 22 (7)	b	365 ± 194 (88)	ab	112 ± 6 (2)	ab	268 ± 184 (28)	a
	Fluctuating	101 ± 77 (19)	b	319 ± 171 (122)	b	160 ± 60 (8)	a	297 ± 202 (37)	a
High	Drying	86 ± 50 (15)	b	259 ± 153 (15)	b	90 ± 78 (8)	ab	183 (1)	
	Rewetting	61 ± 40 (24)	b	430 ± 220 (31)	a	60 ± 24 (13)	b	269 ± 120 (6)	a
	Fluctuating	87 ± 71 (48)	b	322 ± 169 (25)	ab	81 ± 56 (28)	b	255 ± 80 (5)	a
Whole	Drying	137 ± 135 (33)	A	312 ± 161 (130)	B	134 ± 73 (35)	A	233 ± 103 (45)	A
	Rewetting	67 ± 38 (34)	B	376 ± 200 (126)	A	122 ± 64 (40)	A	264 ± 168 (39)	A
	Fluctuating	100 ± 77 (81)	AB	315 ± 169 (166)	B	127 ± 70 (87)	A	275 ± 169 (60)	A
Low	Whole	158 ± 138 (25)	A	298 ± 163 (50)	A	148 ± 64 (101)	A	228 ± 93 (43)	A
Intermediate		110 ± 91 (36)	AB	333 ± 175 (301)	A	154 ± 53 (12)	A	277 ± 177 (89)	A
High		80 ± 61 (87)	B	356 ± 200 (71)	A	77 ± 54 (49)	B	256 ± 97 (12)	A
Whole	Whole	100 ± 90 (148)	γ	333 ± 178 (422)	α	127 ± 69 (162)	γ	259 ± 151 (144)	β

Table 7

Model comparison of soil respiration (SR, mg C m^{-2} h^{-1}) by groundwater level (GWL, m) using log-transformed linear regression and hierarchical Bayesian analysis (N = 876). Larger R^2, smaller RMSE, smaller AIC/2N and smaller WAIC indicate better model.

Log-transformed linear regression analysis	P	R^2	RMSE	AIC/2N
Log(SR) = 4.59 – 0.98 × GWL	< 0.001	0.247	179.7	6.541
Log(SR) = 6.05 – 1.29 × WFPS	< 0.001	0.086	188.1	6.578
Log(SR) = 2.01 + 0.11 × T_s	< 0.001	0.095	179.0	6.533
Log(SR) = 3.44 – 0.88 × GWL + 0.040 × T_s	< 0.001	0.258	178.6	6.558
Hierarchical Bayesian analysis by Log(SR) ~ GWL	P	R^2	RMSE	WAIC
Full model	< 0.001	0.528	143.4	6.096
Without GWL changing directions	< 0.001	0.516	146.2	6.100
Without WFPS ranges	< 0.001	0.495	145.9	6.121
Without land uses	< 0.001	0.390	167.2	6.214

Table 8

Posterior distributions of intercept (α) in log(SR rate) = $\alpha - \beta \times$ GWL fitted by hierarchical Bayesian analysis. All the values show Mean ± SD (N). The significant α are shown only ($P < 0.05$). The values with the same small and capital alphabetical letters are not significantly different ($P < 0.05$) for a given land use. The values with the same Greek letters are not significantly different ($P < 0.05$) among land uses.

WFPS range	GWL changing direction	Intercept (α, log [mg C m^{-2} h^{-1}])							
		Burned land (BL)		Cropland (CL)		Forest land (FL)		Grassland (GL)	
Low	Drying	4.64 ± 0.18 (8)	b	5.64 ± 0.20 (24)	a	4.71 ± 0.13 (25)	a	5.38 ± 0.26 (20)	ab
	Rewetting	4.57 ± 0.19 (3)	ab	5.64 ± 0.21 (7)	ab	4.79 ± 0.12 (25)	a	5.40 ± 0.25 (5)	ab
	Fluctuating	4.69 ± 0.16 (14)	a	5.71 ± 0.19 (19)	a	4.80 ± 0.11 (51)	a	5.49 ± 0.24 (18)	a
Intermediate	Drying	4.50 ± 0.15 (10)	b	5.54 ± 0.14 (91)	b	4.63 ± 0.19 (2)	a	5.30 ± 0.24 (24)	ab
	Rewetting	4.45 ± 0.15 (7)	b	5.62 ± 0.12 (88)	a	4.62 ± 0.18 (2)	a	5.26 ± 0.22 (28)	bc
	Fluctuating	4.49 ± 0.13 (19)	b	5.64 ± 0.12 (122)	a	4.74 ± 0.16 (8)	a	5.43 ± 0.23 (37)	ab
High	Drying	4.07 ± 0.12 (15)	c	5.02 ± 0.18 (15)	c	4.08 ± 0.14 (8)	b	4.80 ± 0.26 (1)	abcd
	Rewetting	4.01 ± 0.10 (24)	c	5.30 ± 0.15 (31)	d	4.10 ± 0.12 (13)	b	4.81 ± 0.25 (6)	d
	Fluctuating	4.08 ± 0.08 (48)	c	5.21 ± 0.15 (25)	d	4.14 ± 0.10 (28)	b	4.90 ± 0.25 (5)	cd
Whole	Drying	4.40 ± 0.29 (33)	A	5.40 ± 0.32 (130)	B	4.48 ± 0.32 (35)	A	5.16 ± 0.36 (45)	A
	Rewetting	4.35 ± 0.28 (34)	A	5.52 ± 0.22 (126)	A	4.50 ± 0.33 (40)	A	5.16 ± 0.35 (39)	A
	Fluctuating	4.42 ± 0.29 (81)	A	5.52 ± 0.27 (166)	A	4.56 ± 0.32 (87)	A	5.27 ± 0.36 (60)	A
Low	Whole	4.63 ± 0.18 (25)	A	5.66 ± 0.20 (50)	A	4.77 ± 0.13 (101)	A	5.42 ± 0.26 (43)	A
Intermediate		4.48 ± 0.15 (36)	B	5.60 ± 0.13 (301)	B	4.66 ± 0.18 (12)	B	5.33 ± 0.24 (89)	A
High		4.05 ± 0.10 (87)	C	5.18 ± 0.20 (71)	C	4.11 ± 0.12 (49)	C	4.84 ± 0.26 (12)	B
Whole	Whole	4.38 ± 0.30 (148)	δ	5.48 ± 0.27 (422)	α	4.53 ± 0.33 (162)	γ	5.21 ± 0.37 (144)	β

Table 9

Posterior distributions of slope (β) in log(SR rate) = $\alpha - \beta \times$ GWL fitted by hierarchical Bayesian analysis. All the values show Mean ± SD (N). The significant β are shown only ($P < 0.05$). Since all the significant β were obtained only in high WFPS range, the multiple comparison among land uses were carried out only in high WFPS range (last row). The values with the same small alphabetical letters are not significantly different ($P < 0.05$) for a given land use. The values with the same Greek letters are not significantly different ($P < 0.05$) among land uses.

WFPS range	GWL changing direction	Slope (β, m^{-1})			
		Burned land (BL)	Cropland (CL)	Forest land (FL)	Grassland (GL)
Low	Drying				
	Rewetting			0.41 ± 0.23 (25) a	
	Fluctuating				
Intermediate	Drying				
	Rewetting	0.39 ± 0.23 (7) a	0.26 ± 0.17 (88) a	0.54 ± 0.25 (2) ab	
	Fluctuating				
High	Drying	0.97 ± 0.24 (15) b	0.77 ± 0.23 (15) b	1.11 ± 0.26 (8) bc	0.76 ± 0.28 (1) a
	Rewetting	1.08 ± 0.23 (24) c	0.97 ± 0.26 (31) c	1.21 ± 0.25 (13) c	0.86 ± 0.28 (6) a
	Fluctuating	0.87 ± 0.23 (48) b	0.71 ± 0.23 (25) b	1.01 ± 0.24 (28) b	0.65 ± 0.27 (5) a
High	Whole	0.94 ± 0.23 (87) β	0.83 ± 0.24 (71) α	1.07 ± 0.25 (49) γ	0.76 ± 0.27 (12) αβ

Table 10

Result of regression analysis of intercept (α) and slope (β) of the relationship between log soil respiration and groundwater level with environmental factors. All the values show Pearson's correlation coefficient. Since the significant α and β are selected only, the number of data (n) of α and β are 36 and 16, respectively.

Environmental factors	α (N = 36)		β (N = 16)	
Relative humidity	−0.608	***	0.466	
T_s	0.626	***	−0.318	
Peat thickness	−0.832	***	0.234	
Bulk density	0.838	***	−0.329	
pH (H_2O)	0.581	***	−0.043	
Total C	−0.760	***	0.176	
MBC	−0.057		0.122	
WSOC	−0.490	**	−0.112	
MBC:WSOC ratio	0.298		−0.033	
Total N	−0.429	**	0.296	
C:N ratio	−0.119		−0.158	
CEC	−0.692	***	0.319	
Exchangeable Na^+	−0.378	*	0.587	*
Exchangeable K^+	0.053		0.381	
Exchangeable Mg^{2+}	−0.003		0.633	*
Exchangeable Ca^{2+}	0.375	*	0.191	
Total exchangeable cations	0.242		0.442	
Base saturation	0.387		0.296	
NH_4^+	−0.533	***	0.158	
NO_3^-	0.463	**	0.135	

* P value < 0.05

** P value < 0.01

*** P value < 0.001

MBC: microbial biomass carbon

WSOC: water-soluble organic carbon

Figures

Figure 1

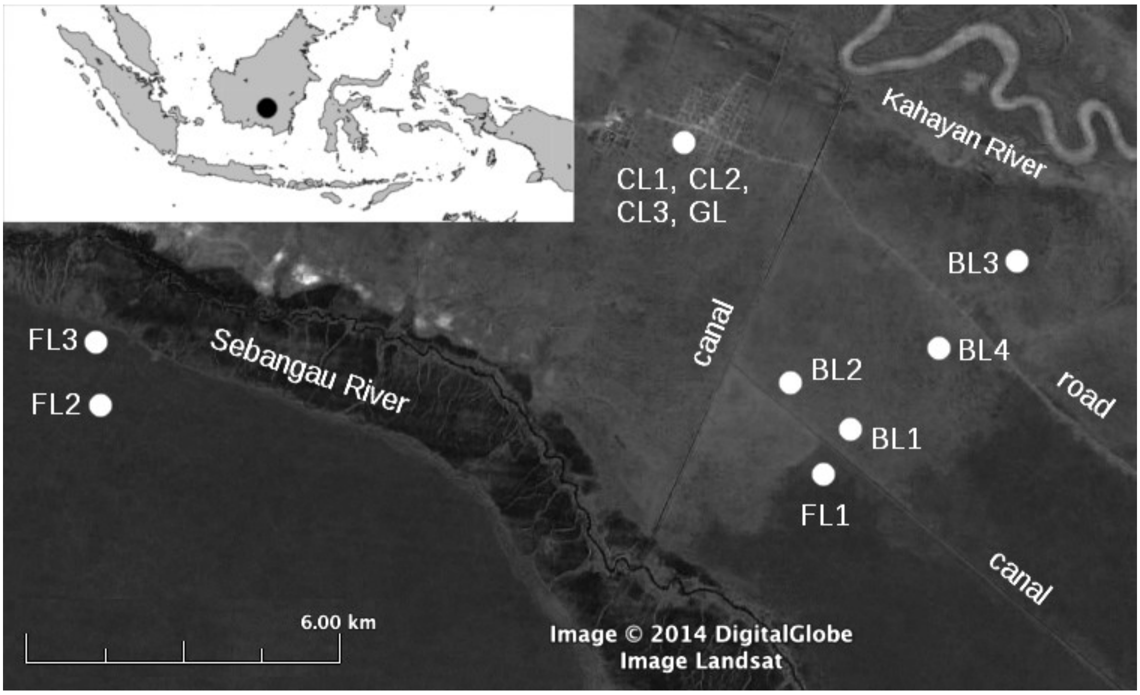
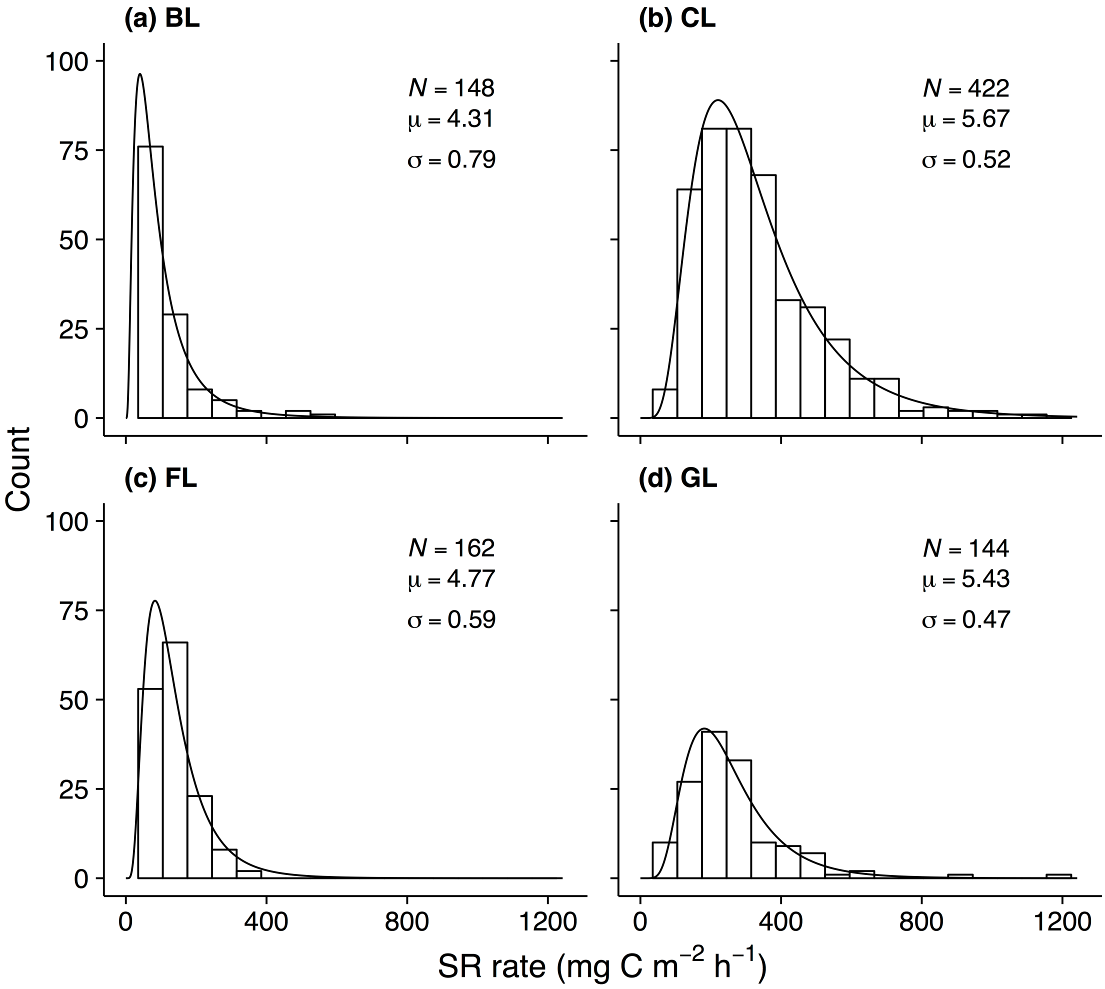
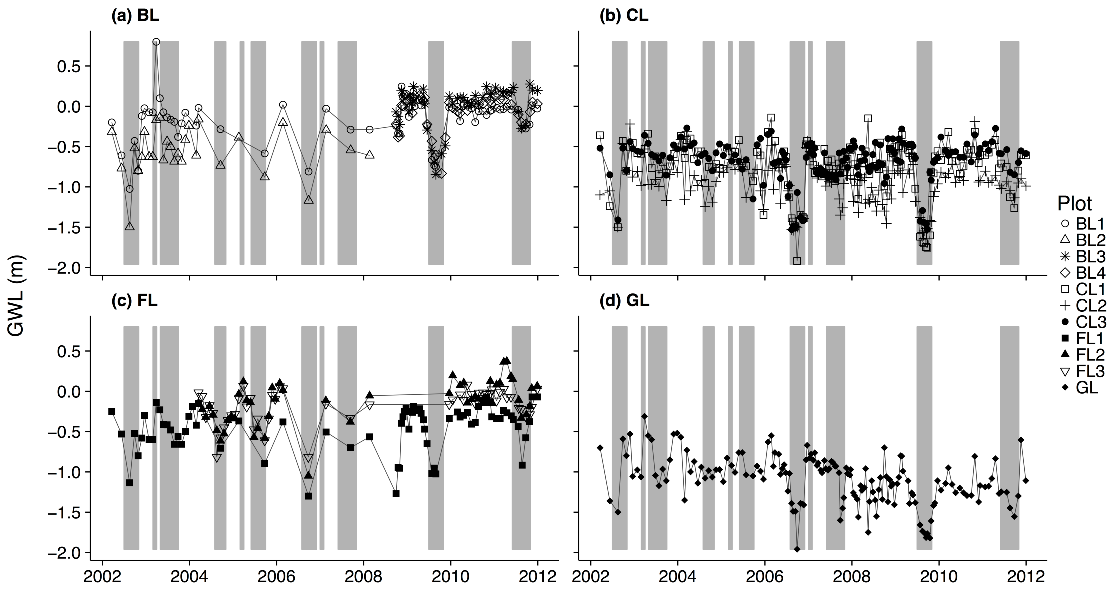


Figure 2



(a) BL
N = 148
μ = 4.31
σ = 0.79
(b) CL
N = 422
μ = 5.67
σ = 0.52
(c) FL
N = 162
μ = 4.77
σ = 0.59
(d) GL
N = 144
μ = 5.43
σ = 0.47
Count
100
75
50
25
0
0
400
800
1200
SR rate (mg C m−2 h−1)

Figure 3



(a) BL
(b) CL
(c) FL
(d) GL
GWL (m)
0.5
0.0
−0.5
−1.0
−1.5
−2.0
2002
2004
2006
2008
2010
2012
Plot
BL1
BL2
BL3
BL4
CL1
CL2
CL3
FL1
FL2
FL3
GL

Figure 4

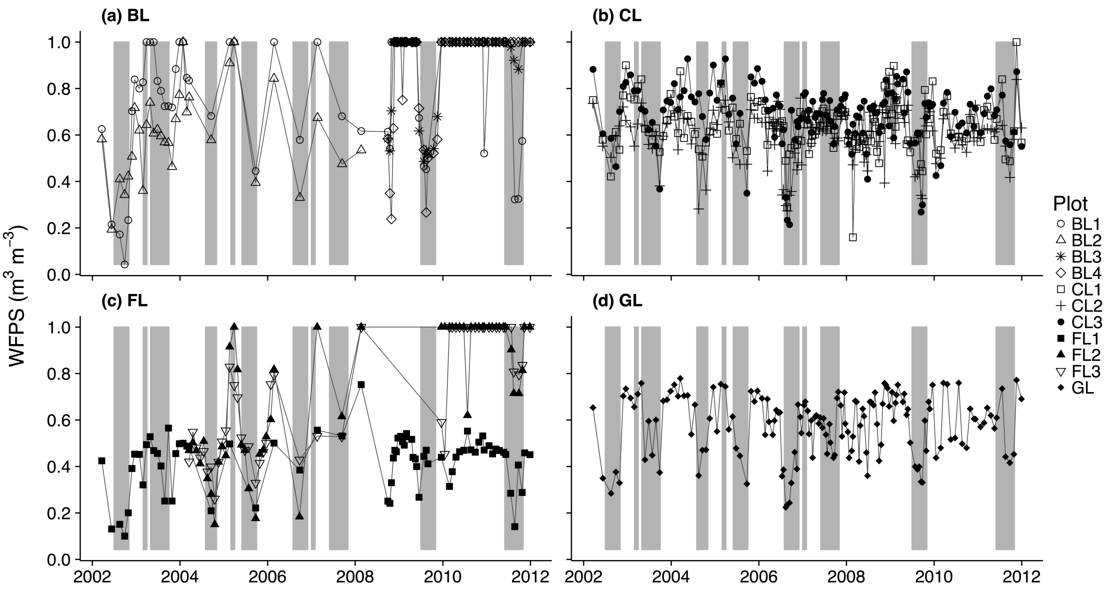
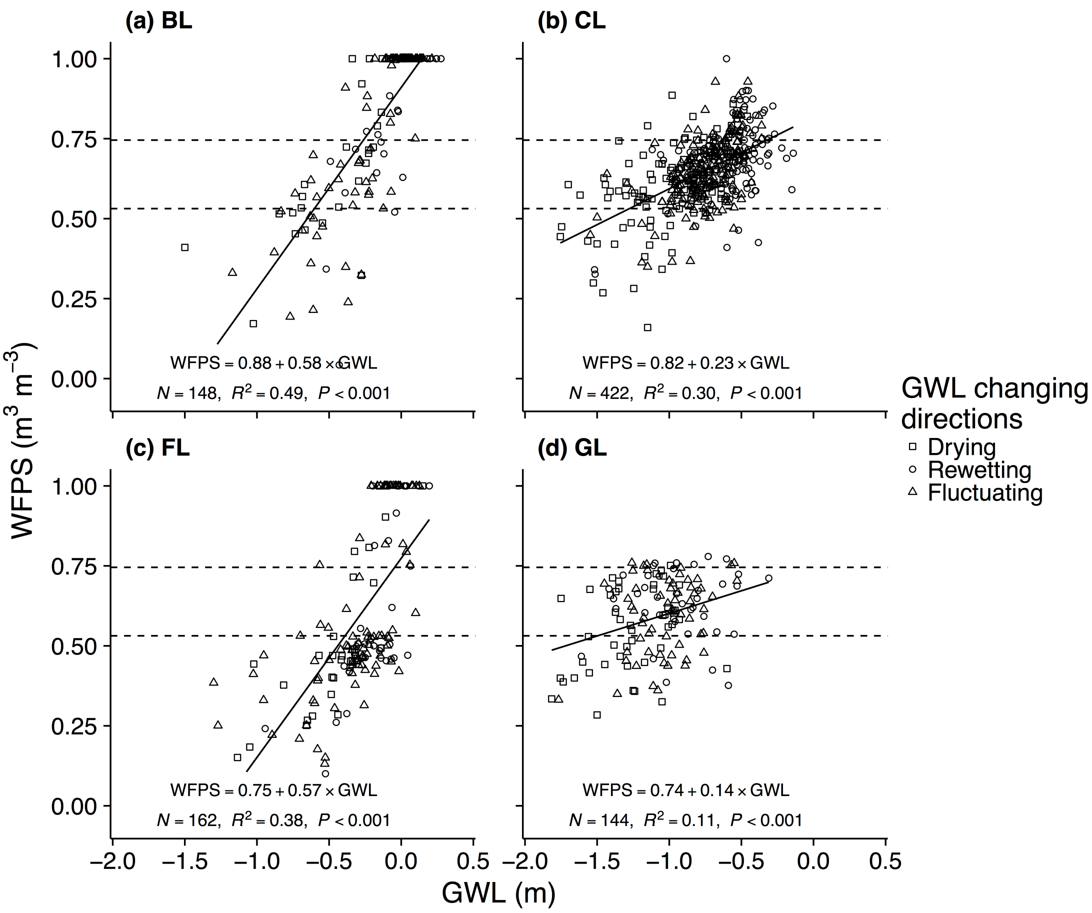
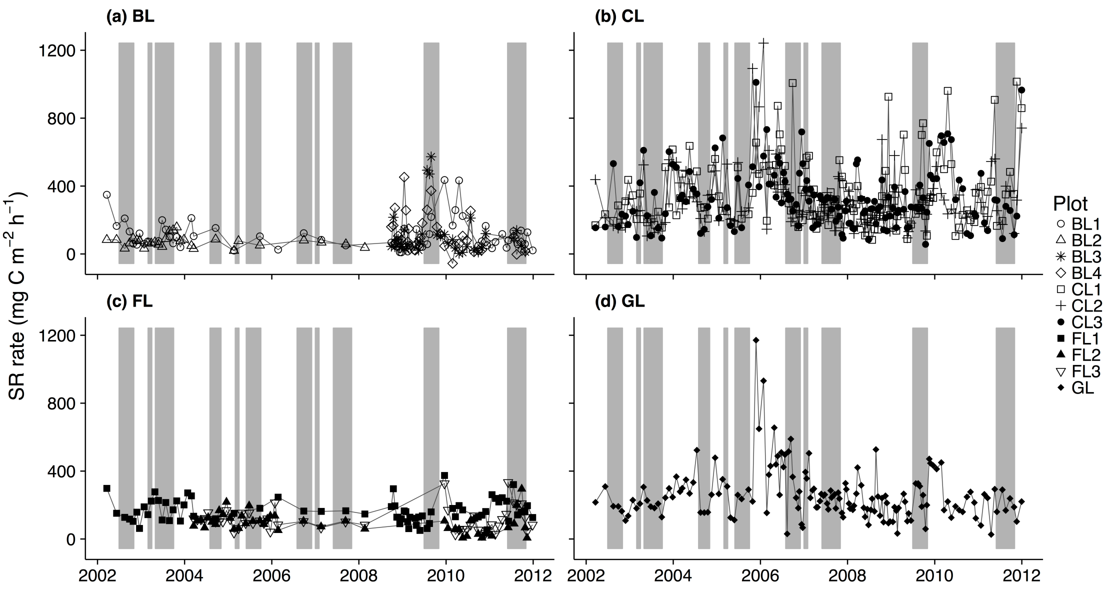

(a) BL
(b) CL
(c) FL
(d) GL
WFPS (m^3 m^{-3})
0.0
0.2
0.4
0.6
0.8
1.0
2002
2004
2006
2008
2010
2012
Plot
BL1
BL2
BL3
BL4
CL1
CL2
CL3
FL1
FL2
FL3
GL

Figure 5



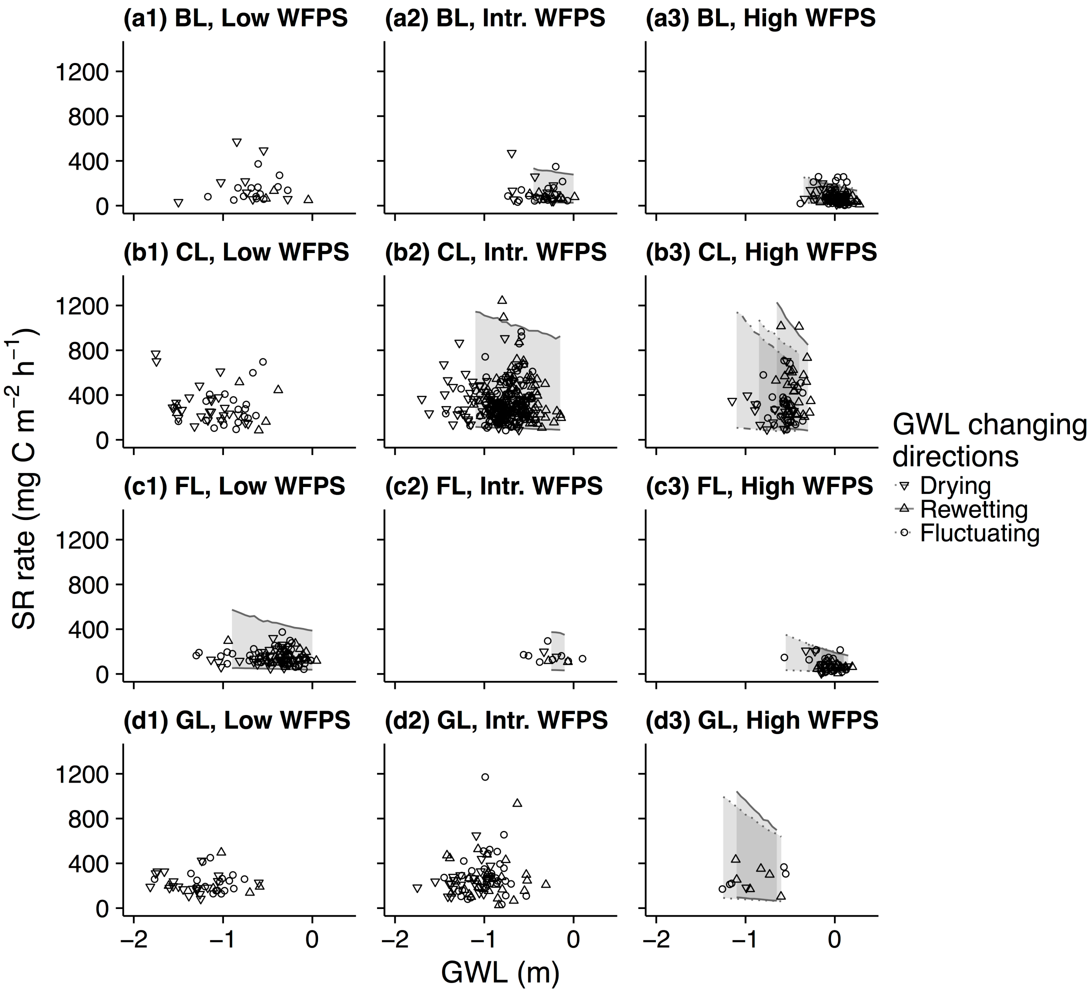
(a) BL
(b) CL
(c) FL
(d) GL
WFPS (m^3 m^{-3})
GWL (m)
WFPS = 0.88 + 0.58 × GWL
N = 148, R^2 = 0.49, P < 0.001
WFPS = 0.82 + 0.23 × GWL
N = 422, R^2 = 0.30, P < 0.001
WFPS = 0.75 + 0.57 × GWL
N = 162, R^2 = 0.38, P < 0.001
WFPS = 0.74 + 0.14 × GWL
N = 144, R^2 = 0.11, P < 0.001
GWL changing directions
Drying
Rewetting
Fluctuating
1.00
0.75
0.50
0.25
0.00
−2.0
−1.5
−1.0
−0.5
0.0
0.5

Figure 6



(a) BL
(b) CL
(c) FL
(d) GL
SR rate (mg C m^{-2} h^{-1})
0
400
800
1200
2002
2004
2006
2008
2010
2012
Plot
BL1
BL2
BL3
BL4
CL1
CL2
CL3
FL1
FL2
FL3
GL

Figure 7


(a1) BL, Low WFPS
(a2) BL, Intr. WFPS
(a3) BL, High WFPS
(b1) CL, Low WFPS
(b2) CL, Intr. WFPS
(b3) CL, High WFPS
(c1) FL, Low WFPS
(c2) FL, Intr. WFPS
(c3) FL, High WFPS
(d1) GL, Low WFPS
(d2) GL, Intr. WFPS
(d3) GL, High WFPS
SR rate (mg C m^{-2} h^{-1})
0
400
800
1200
GWL (m)
−2
−1
0
GWL changing directions
Drying
Rewetting
Fluctuating