https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Comprehensive increase in CO_2 release by drying-rewetting cycles among Japanese forests and pastureland soils and exploring predictors of increasing magnitude

Yuri Suzuki[1,2], Syuntaro Hiradate[3], Jun Koarashi[4], Mariko Atarashi-Andoh[4], Takumi Yomogida[4], Yuki Kanda[1], and Hirohiko Nagano[5]

[1]Faculty of Agriculture, Niigata University, Niigata 950-2181, Japan
[2]Graduate School of Environmental Science, Niigata University, Niigata 950-2181, Japan
[3]Graduate school of Agriculture, Kyushu University, Fukuoka 819-0395, Japan
[4]Nuclear Science and Engineering Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
[5]Institute of Science and Technology, Niigata University, Niigata 950-2181, Japan

Correspondence: Hirohiko Nagano (hnagano@agr.niigata-u.ac.jp)

Abstract. It is still difficult to precisely quantify and predict the effects of drying-rewetting cycles (DWCs) on soil carbon dioxide (CO_2) release due to the paucity of studies using constant moisture conditions equivalent to the mean water content during DWC incubation. The present study was performed to evaluate overall trends in the effects of DWCs on CO_2 release and to explore environmental and soil predictors for variations in the effect size in 10 Japanese forests and pastureland soils variously affected by volcanic ash during their pedogenesis. Over an 84-day incubation period including three DWCs, CO_2 release was 1.3- to 3.7-fold greater than under continuous constant moisture conditions ($p < 0.05$) with the same mean water content as in the DWC incubations. Analysis of the relations between this increasing magnitude of CO_2 release by DWCs (IF_{CO2}) and various environmental and soil properties revealed significant positive correlations between IF_{CO2} and soil organometal complex contents ($p < 0.05$), especially pyrophosphate extractable aluminum (Alp) content ($r = 0.74$). Molar ratios of soil total carbon (C) and pyrophosphate-extractable C (Cp) to Alp contents and soil carbon content-specific CO_2 release rate under continuous constant moisture conditions (qCO_2_soc) were also correlated with IF_{CO2} ($p < 0.05$). The covariations among Alp, total C, and Cp to Alp molar ratios and qCO_2_soc suggested Alp as the primary predictor of IF_{CO2}. Whereas soil microbial biomass C and nitrogen (N) levels were significantly lower in DWCs than under continuous constant moisture conditions, there was no significant relation between the microbial biomass decrease and IF_{CO2}. The present study showed a comprehensive increase in soil CO_2 release by DWC in Japanese forests and pastureland soils, suggesting that Alp is a predictor of the effect size likely due to vulnerability of organo-Al complexes to DWC.

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

1 Introduction

There is accumulating evidence of climate change-induced alterations in global water cycling (IPCC, 2021; Allan et al., 2020; Dai, 2012; Donat et al., 2016; Pfleiderer et al., 2019). Of the consequent water regime changes, decreasing precipitation frequency (e.g., number of rainy days) and increasing intensity (e.g., number of heavy rainy days) are becoming more frequent (Dai, 2012; Donat et al., 2016), although decadal trends in annual precipitation levels are not significant over global scales (IPCC, 2021). For example, the annual number of precipitation days in Japan has decreased by 15% during the past 120 years, whereas the annual number of heavy precipitation days (more than 100 mm in a day) has increased by 26% (Ministry of Education, Science, and Technology (MEXT) and Japanese Meteorological Agency (JMA), 2020). There is a non-significant trend in annual precipitation level during the same period (MEXT and JAM, 2020). This changing pattern in precipitation is often observed in the temperate region of the northern hemisphere (IPCC, 2021) and is related to increased fluctuation of soil water environments, especially DWCs, and consequent alterations in ecosystem functions (Borken and Matzner, 2009; Jin et al., 2023; Zhang et al., 2020, 2023).

Carbon dioxide (CO_2) release from soil is an ecosystem process that is sensitive to DWCs (Birch, 1958; Borken and Matzner, 2009; Lee et al., 2002; Nagano et al., 2019; Unger et al., 2010, 2012; Zhang et al., 2020, 2023) and has substantial feedback potential to the ongoing climate change due to its magnitude reaching as much as seven times greater than anthropogenic CO_2 emission on a global scale (Bond-Lamberty and Thomson, 2010; Friedlingstein et al., 2020). The effects of DWCs on soil CO_2 release were first shown by Birch (1958) as the marked increase in soil organic matter (SOM) decomposition and CO_2 release after the rapid rewetting of dried soil, and has since been the subject of intensive investigation (Borken and Matzner, 2009; Kpemoua et al., 2023; Lee et al., 2002, 2004; Miller et al., 2005; Nagano et al., 2019; Unger et al., 2010, 2012; Xiang et al., 2008), including meta-analyses (Kim et al., 2012; Jin et al., 2023; Zhang et al., 2020). However, it is still difficult to precisely quantify and predict the effects of DWCs on soil CO_2 release.

The significant uncertainties in the effects of DWCs on soil CO_2 release include the inconsistent trends and sizes of effects likely due to the paucity of studies using constant moisture conditions equivalent to the mean water content during DWC incubation (Kpemoua et al., 2023; Zhang et al., 2020, 2023). According to a meta-analysis by Zhang et al. (2020) using 208 data from 34 sites in 29 reports, the effects of DWCs vary according to soil and water contents in continuous constant moisture conditions. Especially, changes in CO_2 release rate associated with DWCs ranged from -4% to +19% with an average of +4% in comparison with the medium level of constant moisture content equivalent to the mean water content during DWC incubation, whereas only 9 of 38 data representing CO_2 release rates for conditions of constant moisture were measured (Zhang et al., 2020). Another 29 data were calculated from the CO_2 release rates at the upper and lower ends of the range of constant moisture content, corresponding to the maximum and minimum water contents of DWC treatment, respectively (Zhang et al., 2020). In the experiment using three Alfisols from Chinese long-term experimental field studies, Zhang et al. (2023) showed similar or somewhat lower CO_2 release in the DWC compared with the constant moisture conditions with the same mean water content for the DWC incubation. Using two Luvisols from French long-term field experiment sites, Kpemoua et al. (2023) also showed similar features of changes in CO_2 release associated with DWCs, indicating the need for further comparison of CO_2 release

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

between DWCs and constant moisture conditions with the same mean water content. In contrast to these studies, Nagano et al. (2019) found a 49% increase in CO_2 release rate associated with DWCs in an Andisol collected from a Japanese forest, and this increase was more than double that of another non-volcanic ash soil from the same forest. Therefore, there are substantial variations in trends of effects of DWCs in comparison with constant moisture conditions with the same mean water content during incubation, and knowledge gaps remain about environmental and soil predictors for variations in effect sizes.

The present study was performed to evaluate overall trends in the effect of DWCs on soil CO_2 release and to explore the predictors of variations in its effect size in 10 Japanese forests and pastureland soils. These soils were variously affected by volcanic ash during their pedogenesis, and therefore include several Andisols, which are known to have a high SOM storage capacity (Morisada et al., 2004), likely due to the protection of SOM from microbial decomposition by enrichment of reactive minerals and metals in these soils (Asano and Wagai, 2014; Imaya et al., 2007; Shirato et al., 2004). Reactive minerals and metals that contribute to the protection of SOM are iron (Fe) and aluminum (Al), constituting short-range-order minerals and organometal complexes (Asano and Wagai, 2014; Rasmussen et al., 2018; Shirato et al., 2004; Wagai et al., 2018). Although global coverage of Andisols is about 1% (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009), determination of the responses of carbon cycling in Andisols to DWCs will help in understanding the responses of non-volcanic ash soils, where reactive minerals and metals are also essential in high soil carbon stocks (Rasmussen et al., 2018; Hall and Thompson, 2022) and may be sensitive to climate and land use management, including water regime (Georgiou et al., 2022; Kramer and Chadwick, 2018).

2 Materials and methods

2.1 Site description and soil sampling

We collected 10 soil samples from depths of 0–5 cm or 0–10 cm in six forests and a pastureland located in Niigata (six soils from four forests), Ibaraki (two soils from a forest) (Nagano et al., 2019), and Oita (two soils from a forest and a pastureland) (Wijesinghe et al., 2021) prefectures in Japan. Figure 1 and Table 1 present the locations and site characteristics, i.e., elevation, mean annual temperature (MAT), mean annual precipitation (MAP), potential evapotranspiration (PET), and net primary production (NPP). Briefly, all of the investigated sites have a humid temperate climate with MAT of 9.1–10.8°C and MAP of 1474–2930 mm. All of the forests are dominated by beech (*Fagus crenata* and *Fagus japonica*) and oak (*Quercus serrata*), except for Oita forest which is a deciduous/evergreen mixed forest dominated by Siebold's maple (*Acer sieboldianum*), Japanese snowbell (*Styrax japonicus*), and Japanese holly (*Ilex crenata*). The pastureland in Oita is dominated by Japanese lawn grass (*Zoysia japonica*), dwarf fountain grass (*Pennisetum alopecuroides*), cranesbill (*Geranium thunbergii*), white clover (*Trifolium repens*), and Indian strawberry (*Potentilla indica*).

Soil sampling was conducted in the snow-free season (April to October) of 2021. We also collected soil samples from layers below the target depth (i.e., 0–5 cm or 0–10 cm depth) down to 50 cm as the maximum depth to examine whether the soil could be classified as Andisol. According to the USDA Soil Taxonomy criteria (Soil Survey Staff, 2022), soils with 60% or more of the thickness containing more than 20 mg of acid oxalate-extractable Al (Alo) plus 1/2 Fe (Feo) per 1 g soil within a depth of 0–60 cm are classified as Andisols. According to these criteria, 4 of the 10 soils were Andisols (one each from Niigata

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

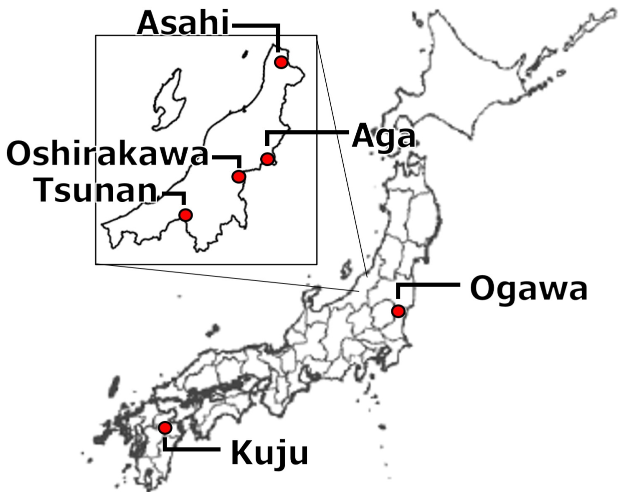

Figure 1. Locations of Japanese forests and pastureland where investigated soils were collected.

Table 1. Environmental properties of Japanese forests and pastureland where investigated soils were collected[a)]

Prefecture	Soil	Latitude °N	Longitude °E	Elevation m	MAT °C	MAP mm	Annual PET mm	MAP-PET mm	Annual NPP $g\ C\ m^{-2}$
Niigata	Aga1, Aga2	37.55	139.51	474	10.6	1714	747	967	633
	Tsunan1, Tsunan2	37.04	138.60	716	10.8	1899	795	1104	628
	Asahi1	38.38	139.70	655	9.2	1887	697	1190	605
	Oshirakawa1	37.35	139.16	627	9.1	1963	668	1295	563
Ibaraki	Ogawa13, Ogawa 14	36.93	140.59	643	10.7	1474	764	710	785
Oita	Kuju_pasture, Kuju_forest	33.06	131.23	841	10.8	2930	786	2144	819

[a)] MAT, MAP, and PET were obtained as averages for 1981–2020 in a global data set of climate and climatic water balance (i.e., TerraClimate) by Abatzoglou et al. (2018). NPP data were obtained as averages for 2001–2020 in the global distribution of NPP estimated from MODIS observation products (i.e., MOD17A3HGF) by Running and Zhao. (2021). MAT, mean annual temperature; MAP, mean annual precipitation; PET, potential evapotranspiration; NPP, net primary production.

and Ibaraki, and two from Oita) with non-allophanic properties determined by a high ratio of pyrophosphate-extractable Al (Alp) content to Alo content (Alp/Alo > 0.5; Soil Survey Staff (2022); Fig. S1). Collected soil samples were transferred to the laboratory and stored at 4°C before further analysis. Before analysis, soils were gently passed through a 4-mm sieve to remove gravel and plant tissue. Fine roots in the sieved samples were removed with tweezers.

2.2 Soil analysis

The soil properties analyzed were pH(H_2O), electrical conductivity, water content, water-holding capacity (WHC), total carbon (C) and nitrogen (N) contents, and selectively dissolved Al and Fe contents (Tables 2 and 3). The pH(H_2O) was measured in soil and water mixtures consisting of 1 g of soil and 2.5 mL of water. For measurement of electrical conductivity, 5 mL of water was added to 1 g of soil. Water content was measured by determining the difference in soil weight before and after drying at 105°C for 24 h. WHC was measured as the difference in soil weight before and after water saturation. Soil total C and N contents were measured for air-dried and well-ground soil samples using an elemental analyzer (vario PYRO cube; Elementar, Manchester, UK). Selectively dissolved metals such as reactive Al and Fe were measured according to the procedure described previously Nagano et al. (2023). The contents of Al and Fe extractable with 2.0 M acid ammonium oxalate (i.e., Alo and Feo, respectively) were measured as contents of organometal complexes and short-range-order minerals, while Al and Fe extractable with 0.1 M sodium pyrophosphate solution (i.e., Alp and Fep, respectively) were measured as contents of organometal complexes (Asano and Wagai, 2014; Takahashi and Dahlgren, 2016; Wagai et al., 2018). The difference between acid oxalate- and pyrophosphate-extractable metals (i.e., Alo-p and Feo-p) represented the contents of short-range-order minerals (Courchesne and Turmel, 2008). Contents of Al and Fe in the solution were measured with an inductively coupled plasma–optical emission spectrometer (ICP-OES) (5110; Agilent Technologies, Santa Clara, CA, USA). Carbon concentrations in pyrophosphate-extracted solution (Cp) were also measured with a total organic carbon (TOC) analyzer (TOC-L; Shimadzu, Kyoto, Japan).

For the soils after incubation (see Section 2.3), soil microbial biomass C and N were measured by the chloroform fumigation-extraction method (Vance et al., 1987). Organic C and total N concentrations in 0.5 M potassium sulfate solution used for extraction of fumigated and nonfumigated soils were measured using another TOC analyzer (TOC-L; Shimadzu) equipped with a total nitrogen (TN) unit (TNM-L, Shimadzu).

2.3 Incubation experiment and soil CO_2 release rate measurement

Soils were incubated aerobically at 20°C for 84 days including three DWCs (i.e., 28 days per cycle). Simultaneously, soils were incubated in the same manner but without DWCs, during which water content of the soils was maintained at a constant level equivalent to the mean water content for the DWC treatment (Fig. 2). A pre-incubation was conducted at the constant water content for 7 days prior to the 84-day incubation. A post-incubation was also conducted at the constant water content for 28 days after the 84-day incubation to evaluate the remaining effect of DWCs on soil CO_2 release.

Mason jars (1.0 L volume; Ball, Buffalo, NY, USA) with lids equipped with tube fitting systems for gas sample collection (Koarashi et al., 2012; Nagano et al., 2019) were used as incubation jars. Small vials (300 mL, SM sample glass vial; Sansyo, Tokyo, Japan) containing 5.31–10.63 g of soil sample depending on water content were placed in Mason jars. For each DWC, Day 1 to Day 8 and Day 18 to Day 25 were drying stages (Fig. 2), during which the soils were incubated with silica gel (20 g jar^{-1}), which lowered the water content to < 5% WHC by Day 8. Day 8 to Day 13, Day 13 to Day 18, and Day 25 to Day 29 were the driest, wettest, and moderately wet stages, respectively, and CO_2 release rates in these three stages were measured using a gas chromatograph equipped with a thermal conductivity detector (GC-14B; Shimadzu). The CO_2 release rates were also measured in the pre- and post-incubation periods. At the beginning of the wettest stage, soils were rapidly rewetted with distilled water to double the soil water content from the initial status of DWC incubation. For CO_2 release rate measurements, at the start of each stage, the headspace of the incubation jar was flushed with CO_2-free air for 15 min at a rate of 0.5 L min^{-1} and the jar was closed. At the end of each stage, 15 mL of gas sample was collected from the jar using a 20-mL plastic syringe

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Table 2. Soil properties of 10 Japanese forests and pastureland soils collected from depths of 0–5 or 0–10 cm

Soil	Soil type[a]	pH(H_2O)	EC $\mu S\ cm^{-1}$	Water content g water g^{-1} soil	WHC g water g^{-1} soil	Total C %	Total N %	Total C/N
Aga1	Inceptisols or Entisols	4.36	23	0.77	0.80	8.8	0.56	15.7
Aga2	Inceptisols or Entisols	4.39	27	1.07	1.12	14.3	0.79	18.2
Tsunan1	Inceptisols (Brown forest soils)	4.72	17	0.78	1.06	8.8	0.63	19.8
Tsunan2	Inceptisols (Brown forest soils)	4.08	39	1.06	1.32	14.3	0.98	15.6
Asahi1	Inceptisols (Brown forest soils)	4.07	39	1.70	2.14	23.7	1.41	16.9
Oshirakawa1	Andisols	4.66	24	1.07	1.26	15.1	0.76	19.8
Ogawa13	Inceptisols (Brown forest soils)	5.29	18	0.46	1.00	6.8	0.31	22.2
Ogawa14	Andisols	5.30	27	1.14	1.68	16.1	0.86	18.6
Kuju_pasture	Andisols	5.35	133	1.32	1.43	21.8	1.37	15.9
Kuju_forest	Andisols	3.80	168	1.49	1.58	22.3	1.18	18.9

[a] Andisols were determined according to the USDA Soil Taxonomy criteria (Soil Survey Staff, 2022) based on acid oxalate-extractable Al plus 1/2 Fe contents (see text for details). All Andisols were non-allophanic. Other soil types were determined using a Japanese soil digital map, i.e., Japan Soil Inventory NARO (2023).

(Terumo, Kyoto, Japan) and stored in a pre-evacuated 5-mL glass vial (SVG-5; Nichiden Rika, Osaka, Japan). Then, the CO_2 release rate was determined from the increase in CO_2 concentration during this period. After gas sampling, the jars were flushed with CO_2-free air and closed for the next incubation stage. Incubations with the constant water content were conducted as controls, where the CO_2 release rates were measured for Day 1 to Day 13 and Day 13 to Day 29. Soil water contents during the incubation were measured periodically and maintained by adding water to ensure the same mean water content between the two treatments. All incubations were conducted with three replicates for each treatment and soil.

2.4 Data processing and statistical analysis

The CO_2 release rates were compared between the DWC and constant water content treatments. For the DWC treatment, the CO_2 release rates in the drying stages (i.e., Day 1 to Day 8 and Day 18 to Day 25) could not be measured and therefore had to be estimated to evaluate the mean CO_2 release rates for the individual cycle and total of three cycles. The rates in the drying stages were estimated as the mean values of the CO_2 release rates measured before and after the period of interest, in the same manner as described previously (Nagano et al., 2019). Then, the effect size of the DWCs on CO_2 release (defined here as the

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Table 3. Selectively dissolved minerals and associated carbon contents in soils

Soil	Acid oxalate-extractable metals			Pyrophosphate-extractable metals			Acid oxalate – Pyrophosphate			Alp/Alo	Pyrophosphate-extractable C
	Al	Fe	Al+0.5Fe	Al	Fe	Al+0.5Fe	Al	Fe	Al+0.5Fe		
	mg g^{-1} dry soil			mg g^{-1} dry soil			mg g^{-1} dry soil				mg g^{-1} dry soil
Aga1	3.3	7.9	7.2	2.8	5.0	5.3	0.5	2.8	2.0	0.84	21.0
Aga2	6.9	10.6	12.2	6.8	10.5	12.0	0.1	0.2	0.2	0.98	42.9
Tsunan1	8.9	13.8	15.8	8.5	11.3	14.2	0.4	2.5	1.6	0.96	39.9
Tsunan2	6.9	8.5	11.1	7.1	7.2	10.6	-0.2	1.4	0.5	1.03	47.4
Asahi1	4.8	10.2	9.9	4.7	9.2	9.3	0.1	1.0	0.6	0.98	45.4
Oshirakawa1	9.5	12.4	15.7	9.1	11.0	14.6	0.4	1.4	1.2	0.95	43.0
Ogawa13	9.2	8.7	13.5	6.9	6.5	10.2	2.3	2.2	3.4	0.75	19.4
Ogawa14	24.9	16.6	33.2	23.2	12.7	29.6	1.6	3.9	3.6	0.93	59.1
Kuju_pasture	22.0	20.3	32.2	19.0	14.1	26.0	3.1	6.3	6.2	0.86	96.7
Kuju_forest	19.5	19.1	29.0	19.0	16.2	27.1	0.4	2.9	2.0	0.98	109.8

increase factor, IF_{CO2}) was quantified as the ratio of CO_2 release rate under the DWC condition to that under the constant water content condition (Nagano et al., 2019; Zhang et al., 2020). Here, doubling of CO_2 release by DWC resulted in IF_{CO2} of 2, while halving resulted in IF_{CO2} of 0.5.

The pairwise *t* test was applied to examine the statistical significance of differences in CO_2 release rates between the DWC and constant water content treatments with adjustment of site-by-site variations in the metrics. Differences in soil microbial biomass C and N between the two treatments were also evaluated with the pairwise *t* test. To explore predictors explaining the variation in IF_{CO2} among soils, relations between IF_{CO2} and environmental and soil properties were visualized on scatter plots and evaluated by linear correlation analysis. All statistical analyses were conducted with R 4.1.1 (R Core Team, 2021), and $p < 0.05$ was taken to indicate statistical significance.

3 Results

3.1 Quantifying the effect of DWCs on soil CO_2 release

The CO_2 release rates under DWC conditions showed large fluctuations for all soils along with fluctuations in soil water content (Fig. 3). The CO_2 release rates in the driest stages (3.5%–18.2% of WHC depending on the soil) were 3.0–41.5 μg C g^{-1} dry soil day^{-1}. In contrast, CO_2 release rates in the wettest stages (90.8%–201.1% of WHC) reached 18.8–194.1 μg C g^{-1} dry soil day^{-1}. In the moderately wet stages, CO_2 release rates were 8.4–63.9 μg C g^{-1} dry soil day^{-1}. For the constant water content

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

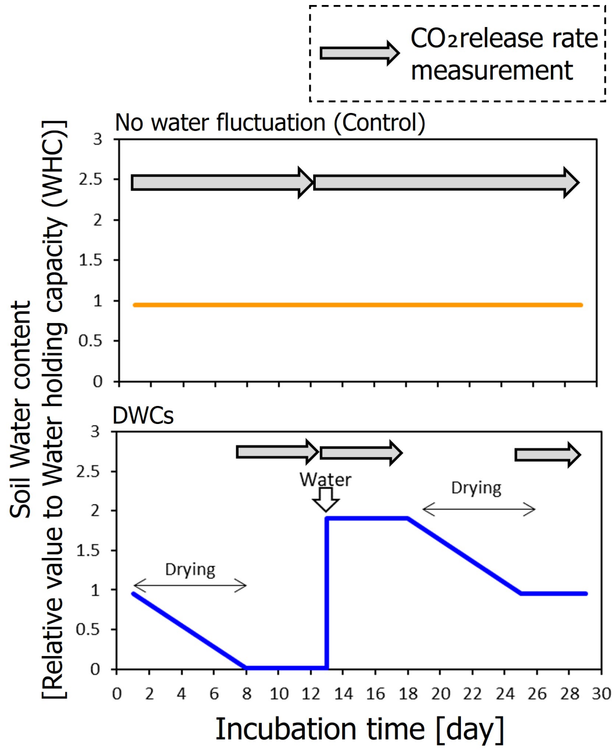

Figure 2. Schematic time courses of soil moisture during incubation with constant moisture content (upper panel) and DWCs (bottom panel) with measurement period of CO_2 release rate.

treatment, CO_2 release rates observed for each soil showed little fluctuation during incubation although the rates varied from 7.3 to 69.9 μg C g^{-1} dry soil day^{-1} depending on the soil.

For all soils, the observed large fluctuations in CO_2 release under DWC treatment resulted in a greater CO_2 release rate than under constant water content treatment, although the IF_{CO2} values varied among the soils (Fig. 4). At the wettest stage in the first DWC, the CO_2 release rates increased by 47.2–127.7 μg C g^{-1} dry soil day^{-1} compared with those under the constant water content conditions, resulting in IF_{CO2} values of 2.9–12.2. For the whole of the first cycle (i.e., the first 28 days), the CO_2 release rates increased by 15.4–43.4 μg C g^{-1} dry soil day^{-1} under the DWCs compared with the constant water content conditions, resulting in IF_{CO2} values of 1.6–5.2. For the whole incubation period (84 days) including three DWCs, IF_{CO2} values were 1.3–3.7, with an increase in CO_2 release rate by 7.4–23.8 μg C g^{-1} dry soil day^{-1} by DWCs. These increases in CO_2 release by DWCs were observed in all cycles during the 84-day incubation period, whereas no increase was observed in the 28-day post-incubation period after the three DWCs (Fig. S2). Taking these results into consideration, we focused on the IF_{CO2} values obtained for the whole incubation period including three DWCs.

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

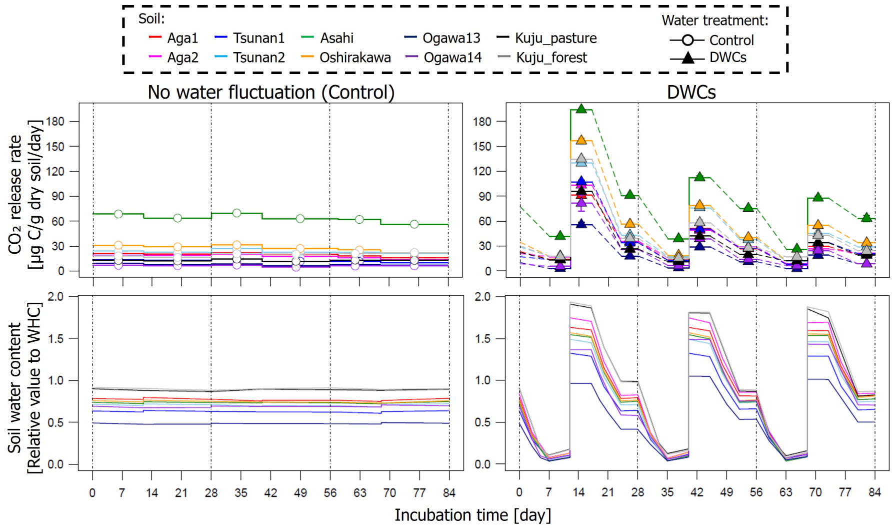

Figure 3. Time courses of soil CO_2 release rates (upper panels) and water contents (bottom panels) during 84-day incubation under constant water content and three DWC conditions.

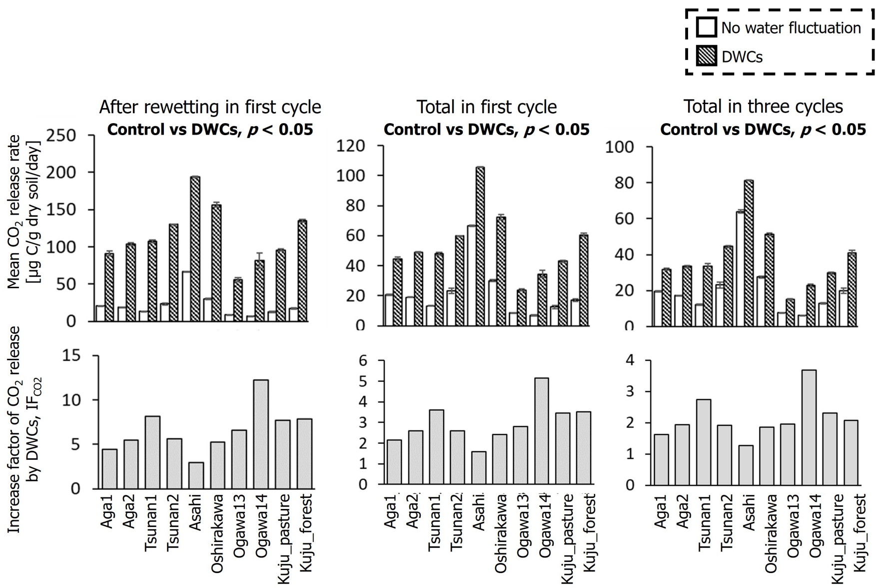

Figure 4. Comparisons of mean CO_2 release rates after rewetting in the first cycle, the whole of the first cycle, and for the total of three cycles between DWC and constant water content conditions (upper panels), and the factor of increase in CO_2 release by DWCs (IF_{CO2}) for individual periods (bottom panels). Statistically significant differences ($p < 0.05$, pairwise t test) in CO_2 release rate between the two treatments are presented.

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

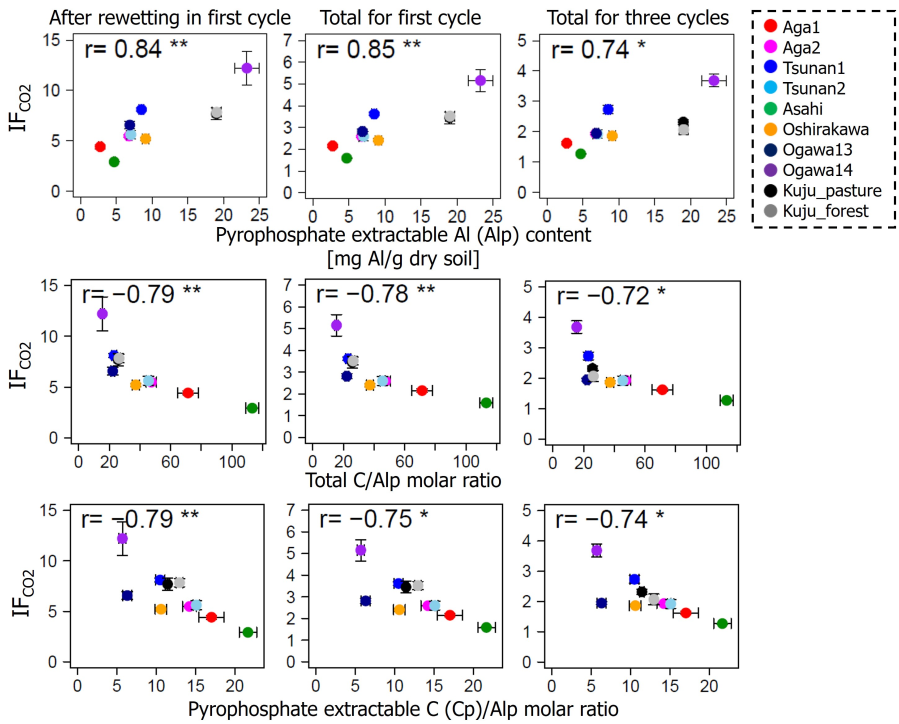

Figure 5. Relations between IF$_{CO2}$ and soil pyrophosphate-extractable Al (Alp) content (upper panels), total C to Alp molar ratio (middle panels), and pyrophosphate-extractable C (Cp) to Alp molar ratio (bottom panels). Significant correlation coefficients at p < 0.01 and p < 0.05 are indicated with single (*) and double asterisks (**), respectively.

3.2 Exploring predictors of the effect sizes on the increase in CO_2 release

Among the environmental and soil physiochemical properties, reactive mineral and metal contents (i.e., Alo+0.5Feo, Alo, Feo, Alp+0.5Fep, and Alp) in soil, other than Fep, Alo-p+0.5Feo-p, Alo-p, and Feo-p, showed significant positive correlations with IF$_{CO2}$ ($p < 0.05$; Table 4). In particular, Alp content appeared to be a key predictor of the variation in IF$_{CO2}$ among the soils, given that Alp accounted for most (73%–99%) of Alo (Table 3) and showed a higher correlation coefficient than Feo (Table 4). Scatterplots for Alp content and IF$_{CO2}$ values are presented in Fig. 5. In addition, the molar ratios of soil total C and Cp contents to Alp contents showed significant negative correlations to IF$_{CO2}$ ($p < 0.05$; Table 4, Fig. 5).

Among the additional soil properties related to soil microbial activity and abundance, the soil C content-specific CO_2 release rate under constant moisture conditions (defined as the CO_2 release rate per unit of C in soil, qCO_2_soc, in μg CO^2-C mg^{-1} soil-C day^{-1}) showed significant negative correlations with IF$_{CO2}$ values in all incubation stages ($p < 0.01$; Table 5, Fig. 6). Microbial biomass N also showed significant negative correlations with IF$_{CO2}$ values after rewetting in the first cycle and in the whole of the first cycle ($p < 0.05$) but not in the whole incubation period including three cycles ($p = 0.12$).

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Table 4. Pearson's correlation coefficients between IF_{CO2} and environmental and soil properties

Environmental or soil property	After rewetting in first cycle	Total in first cycle	Total in three cycles
Elevation	0.36	0.37	0.22
MAT	0.54	0.55	0.46
MAP	0.05	0.08	-0.11
MAP-PET	0.01	0.04	-0.14
Water content at sampling	-0.11	-0.07	-0.15
WHC	0.06	0.08	0.04
pH(H_2O)	0.54	0.51	0.57
Electronic conductivity	0.19	0.21	-0.01
Total C	-0.03	0.01	-0.11
Total N	-0.07	-0.03	-0.12
C/N ratio	0.27	0.23	0.22
Alo+0.5Feo	**0.81****	**0.82****	**0.70***
Alo	**0.84****	**0.85****	**0.73***
Feo	**0.64***	**0.66***	0.53
Alp+0.5Fep	**0.81****	**0.82****	**0.70***
Alp	**0.84****	**0.85****	**0.74***
Fep	0.55	0.58	0.54
Alo-p+0.5Feo-p	0.46	0.43	0.37
Alo-p	0.56	0.57	0.48
Feo-p	0.55	0.55	0.46
Total C/Alp molar ratio	**-0.79****	**-0.78****	**-0.72***
Cp	0.39	0.42	0.23
Cp/Alp molar ratio	**-0.79****	**-0.75***	**-0.74***

There were also considerable relations among Alp contents, total C/Alp molar ratio, and qCO_2_soc (Fig. 7). Soil Alp content and total C/Alp molar ratio showed a trend toward a positive correlation, although the p value was 0.06. The qCO_2_soc showed a positive correlation with total C/Alp molar ratio and negative correlation with Alp content at $p < 0.01$. The Cp/Alp molar ratio also showed similar covariations with these variables, showing a strongly positive correlation with total C/Alp molar ratio ($r = 0.90$, $p < 0.01$; Fig. S3).

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Table 5. Pearson's correlation coefficients between IF_{CO2} and soil microbial properties

Soil microbial property	After rewetting in first cycle	Total in first cycle	Total in three cycles
Total C content-specific CO_2 release rate under no water fluctuation, qCO_2_soc	**-0.87***	**-0.86****	**-0.77***
K_2SO_4 extractable C	-0.25	-0.21	-0.33
K_2SO_4 extractable N	-0.63	-0.60	-0.55
K_2SO_4 extractable C/N	0.15	0.18	-0.01
Microbial biomass C	-0.62	-0.61	-0.48
Microbial biomass N	**-0.67***	**-0.66***	-0.52
Microbial biomass C/N	0.47	0.48	-0.31

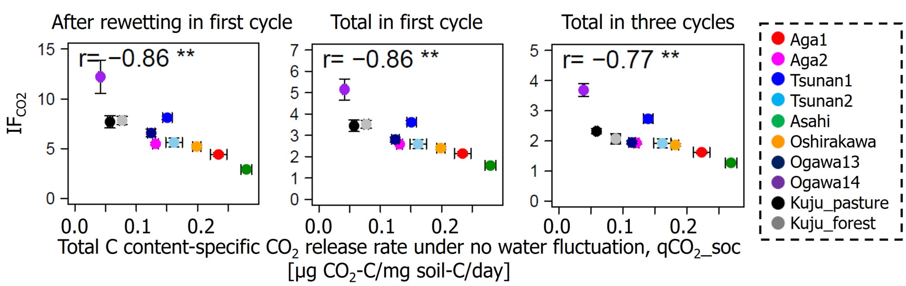

Figure 6. Relations between IF_{CO2} and total C content-specific CO_2 release rate under constant moisture content (qCO_2_soc). Significant correlation coefficients at $p < 0.01$ and $p < 0.05$ are indicated with single (*) and double asterisks (**), respectively.

It should be noted that both microbial biomass C and N were significantly lower in soils incubated under DWC conditions than constant water content conditions ($p < 0.05$; Fig. 8). Microbial biomass C under DWC conditions was lower by $\geq 20.2\%$ than those under constant water content conditions. Microbial biomass N under DWC conditions was $\geq 12.6\%$ lower than under constant water content conditions. Nevertheless, there were no significant correlations between the differences in microbial biomass and the value of IF_{CO2} ($p \geq 0.15$; Fig. 9).

4 Discussion

An increase in CO_2 release due to DWCs was consistently observed across 10 forest and pastureland soils in Japan (Figs. 3 and 4). The comprehensive increases in CO_2 release by DWCs were different from the findings of a recent meta-analysis of studies showing no significant increases in CO_2 release under DWCs compared with constant water content with an equivalent

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

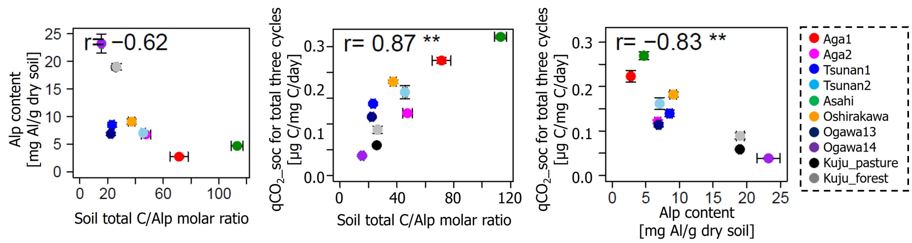

Figure 7. Relations among soil Alp contents, total C/Alp molar ratio, and qCO_2_soc. Significant correlation coefficients at $p < 0.01$ and $p < 0.05$ are indicated with single (*) and double asterisks (**), respectively.

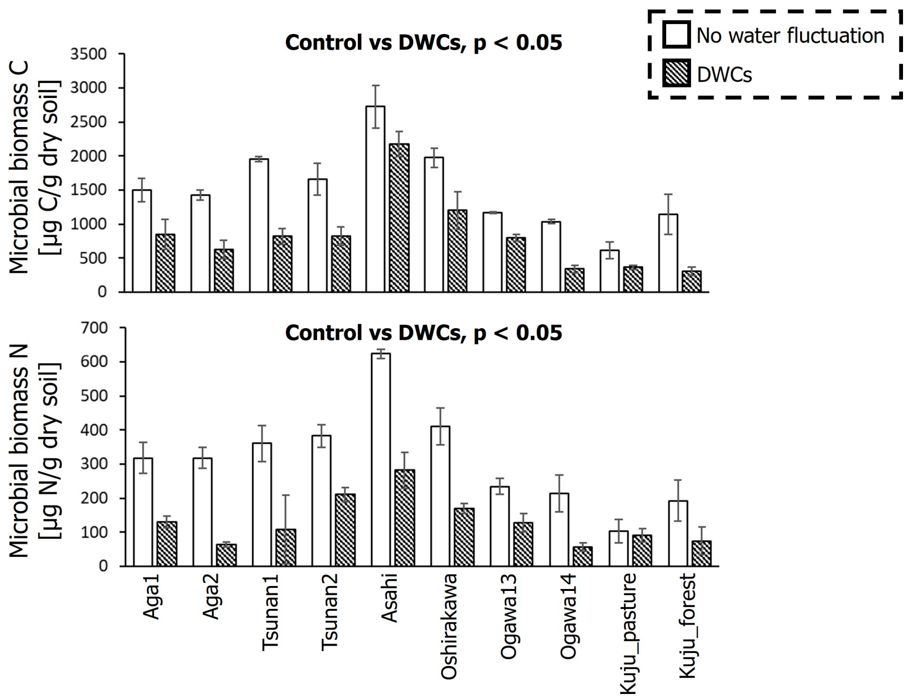

Figure 8. Comparisons of microbial biomass C (upper panel) and N (bottom panel) after incubation between DWC and constant water content conditions. Significant differences ($p < 0.05$ by pairwise t test) in microbial biomass between two treatments are presented.

mean water content during the period of interest (Zhang et al., 2020). Furthermore, our observations quantified the increase in CO_2 release due to three DWCs as IF_{CO2} values of 1.3–3.7. The observed effect size of DWCs on the CO_2 release from soils was large given that even a 20% increase in CO_2 release from the world's soils can exceed the annual CO_2 emission from anthropogenic processes (Friedlingstein et al., 2020). Especially, the importance of Alp for variations in IF_{CO2} (Table 4, Fig. 5; discussed below) indicated the vulnerability of Andisols covering about 1% of global land area (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009). In addition to Andisols, Spodic horizons in Podzols are often abundant in Alp (Ferro-Vázquez et al., 2020;

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

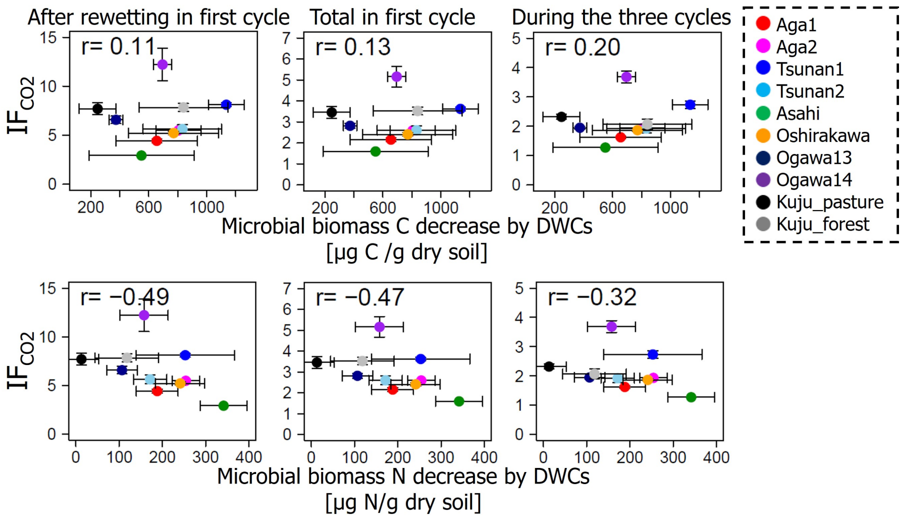

Figure 9. Relations between IF_{CO2} and microbial biomass C or N decrease by DWCs. There were no statistically significant correlations (p > 0.05).

Mokma, 1983). Therefore, Alp-rich soils cover approximately 5% of the global land area (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009). As these Alp-rich soils sometimes store much greater amounts of C than other soils (Asano and Wagai, 2014; Imaya et al., 2007; Morisada et al., 2004; Shirato et al., 2004), the vulnerability of SOM protection by Alp offers significant insight for quantifying feedback of terrestrial C cycling to climate change.

A significant positive correlation was found between IF_{CO2} and soil Alp content by analyzing the relations between IF_{CO2} and fundamental soil properties (Table 4, Fig. 5). Here, soil Alp content was different between non-volcanic ash soils in previous meta-analyses (Zhang et al., 2020; Jin et al., 2023) and the present study in Japanese forest and pastureland soils. Of the organometal complexes measured as pyrophosphate-extractable metals, Fep is known to be sensitive to DWCs, especially in seasonally flooded forests and wetlands, likely due to their vulnerability to redox potential changes caused by alterations to the water regime (Lacroix et al., 2019; Chen et al., 2017, 2018; Chen and Thompson, 2018). Less is known about the vulnerability of Alp to DWCs. However, soil Alp content may be affected by DWCs through changes in soil acidity. A previous field survey conducted in Japanese forest and arable soils by Takahashi et al. (2006) showed that liming of non-allophanic Andisols increased soil pH and decreased Alp content. Miyazawa et al. (2013) verified this behavior by a laboratory incubation experiment for Andisols. Although we did not monitor pH during incubation in the present study, increases in pH after DWCs have been widely observed in upland agricultural (Wang et al., 2020; Meng et al., 2020), seasonally submerged paddy, and wetland soils (Majumdar et al., 2023). Therefore, the acidity mitigation by DWCs would destroy the organo-Al complexes, and increase microbially available C through the release of C protected by the organo-Al complexes or other soil elements, such as macro- and microaggregates, which are tightly bonded by organo-Al complexes and thus physically protect organic C from microbial decomposition (Asano and Wagai, 2014; Takahashi and Dahlgren, 2016; Wagai et al., 2018).

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Covariations among soil Alp contents, total C/Alp molar ratio, and qCO_2_soc (Fig. 7) also support the state of soil Alp content as the primary predictor of variations in IF_{CO2}. Negative correlations of soil Alp contents with both total C/Alp molar ratio and qCO_2_soc suggested that more Alp to total C (i.e., high total C/Alp values) strengthens binding between Alp and organic matter, resulting in resistance of organic matter to microbial decomposition under constant water conditions (i.e., low qCO_2_soc values). These features among reactive Al and SOM dynamics would result in positive correlations of qCO_2_soc and total C/Alp molar ratio with IF_{CO2} (Table 5, Figs. 5 and 6). However, such ability of Alp-rich soils to protect SOM from microbial decomposition likely does not persist under conditions of increased water fluctuations associated with DWCs, as suggested above.

We also found substantially lower microbial biomass in soils subjected to DWCs than constant water content conditions (Fig. 8), suggesting a decrease in microbial biomass through the destruction of microbial cells by DWCs (Kaiser et al., 2015; Marumoto et al., 1977, 1982; Marumoto, 1984; Nagano et al., 2023; Unger et al., 2010, 2012). The destruction of microbial cells is expected to release soluble organic matter available for microbes that have survived the DWC and to cause a marked increase in CO_2 release after rewetting (Marumoto et al., 1977, 1982; Marumoto, 1984; Nagano et al., 2019; Unger et al., 2010, 2012). Nevertheless, the contribution of microbially derived substances to the increase in CO_2 release remained unclear in the present study because of the lack of a significant correlation between IF_{CO2} and the decrease in microbial biomass (Fig. 9). There was also no significant correlation between the decrease in microbial biomass and the increase in CO_2 release due to DWCs (Fig. S3), whereas the decrease in microbial biomass C (246–1134 μg C g^{-1} dry soil) was within the amount of increase in CO_2 release (620–1999 μg C g^{-1} dry soil 84 $days^{-1}$). Furthermore, such changes in microbial biomass likely affect the microbial community structure and have the potential to alter the dynamics of other greenhouse gases (e.g., methane and nitrous oxide), which are driven by specific microbes and are also known to be sensitive to DWCs (Kim et al., 2012; Jin et al., 2023).

5 Conclusions

The present study provides significant insights into the precise quantification of the effects of DWCs on soil CO_2 release on regional and global scales. A comprehensive increase in CO_2 release by DWCs (i.e., 1.3–3.7-fold greater than CO_2 release under constant water conditions) was observed in Japanese forest and pastureland soils. These magnitudes of increase in CO_2 release were strongly correlated with soil Alp content, total C/Alp molar ratio, and total C content-specific CO_2 release rate under constant water conditions (i.e., qCO_2_soc), suggesting the vulnerability of SOM protection by organo-Al complexes against DWCs. A decrease in microbial biomass by DWCs was also suggested, whereas their relation with the increase in CO_2 release remains to be determined in future studies.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Author contributions. YS and HN established the basic research design, conducted all data analyses, including software preparation, validation, and visualization, and wrote the original manuscript. SH, MA-A, JK, and HN conducted soil sampling. YS, SH, MA-A, JK, and HN contributed to the detailed research design, soil analysis, data validation, interpretation of the results, and editing of the manuscript. TY and YK provided essential support in analysis of soil properties and data. All authors contributed to editing the article and approved the submitted version.

Competing interests. The authors declare that they have no known competing financial interests or personal relations that could have appeared to influence the work reported in this paper.

Acknowledgements. This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI (grant numbers 21H02231, 21H05313, 22H05717). The authors thank Prof. Kouki Hikosaka and Dr. Hirofumi Kajino of Tohoku University for providing the vegetation information on the Oita forest site. Ms. Ayako Tamaki and Mr. Masahiro Otaki at Niigata University supported sample preparation and analysis during the experiment and text editing in preparing the manuscript. Dr. Rei Shibata at Niigata University and Dr. Masami Tsukahara, Mr. Kosuke Ito, and Mr. Tatsuki Tanaka at Niigata Prefectural Forest Research Institute helped in site selection and soil sampling in Niigata Prefecture, Japan. Prof. Naoki Harada, Dr. Kazuki Suzuki, and Dr. Asiloglu Rasit of Niigata University and Dr. Hiroyuki Sase and Dr. Rieko Urakawa of Asia Center for Air Pollution Research (ACAP) provided valuable preliminary discussion in writing the manuscript. The authors also thank Ms. Misuzu Kaminaga, Ms. Kikuko Yoshigaki, Ms. Makiko Ishihara, and Ms. Kazumi Matsumura at JAEA for support with laboratory work.

References

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., and Hegewisch, K. C.: TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015, Scientific Data, 5, 170 191, https://doi.org/10.1038/sdata.2017.191, 2018.

Allan, R. P., Barlow, M., Byrne, M. P., Cherchi, A., Douville, H., Fowler, H. J., Gan, T. Y., Pendergrass, A. G., Rosenfeld, D., Swann, A. L., Wilcox, L. J., and Zolina, O.: Advances in understanding large-scale responses of the water cycle to climate change, Annals of the New York Academy of Sciences, 1472, 49–75, https://doi.org/10.1111/NYAS.14337, 2020.

Asano, M. and Wagai, R.: Evidence of aggregate hierarchy at micro- to submicron scales in an allophanic Andisol, Geoderma, 216, 62–74, https://doi.org/10.1016/j.geoderma.2013.10.005, 2014.

Birch, H. F.: The effect of soil drying on humus decomposition and nitrogen availability, Plant and Soil, 10, 9–31, https://doi.org/10.1007/BF01343734, 1958.

Bond-Lamberty, B. and Thomson, A.: Temperature-associated increases in the global soil respiration record, Nature, 464, 579–582, https://doi.org/10.1038/nature08930, 2010.

Borken, W. and Matzner, E.: Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils, Global Change Biology, 15, 808–824, https://doi.org/10.1111/j.1365-2486.2008.01681.x, 2009.

Chen, C. and Thompson, A.: Ferrous Iron Oxidation under Varying pO2 Levels: The Effect of Fe(III)/Al(III) Oxide Minerals and Organic Matter, Environmental Science and Technology, 52, 597–606, https://doi.org/10.1021/acs.est.7b05102, 2018.

Chen, C., Kukkadapu, R. K., Lazareva, O., and Sparks, D. L.: Solid-Phase Fe Speciation along the Vertical Redox Gradients in Floodplains using XAS and Mössbauer Spectroscopies, Environmental Science and Technology, 51, 7903–7912, https://doi.org/10.1021/acs.est.7b00700, 2017.

Chen, C., Meile, C., Wilmoth, J., Barcellos, D., and Thompson, A.: Influence of pO2 on Iron Redox Cycling and Anaerobic Organic Carbon Mineralization in a Humid Tropical Forest Soil, Environmental Science and Technology, 52, 7709–7719, https://doi.org/10.1021/acs.est.8b01368, 2018.

Courchesne, F. and Turmel, M.-C.: Extractable Al, Fe, Mn, and Si, in: Soil Sampling and Methods of Analysis, edited by Carter, M. and Gregorich, E., chap. 26, pp. 307–316, CRC Press, second edi edn., ISBN 978-0-8493-3586-0, 2008.

Dai, A.: Increasing drought under global warming in observations and models, Nature Climate Change 2012 3:1, 3, 52–58, https://doi.org/10.1038/nclimate1633, 2012.

Donat, M. G., Lowry, A. L., Alexander, L. V., O'Gorman, P. A., and Maher, N.: More extreme precipitation in the world's dry and wet regions, Nature Climate Change 2016 6:5, 6, 508–513, https://doi.org/10.1038/nclimate2941, 2016.

FAO/IIASA/ISRIC/ISS-CAS/JRC: Harmonized World Soil Database (version 1.1), FAO, Italy and IIASA, Laxenburg, Austria, 2009.

Ferro-Vázquez, C., Nóvoa-Muñoz, J. C., Klaminder, J., Gómez-Armesto, A., and Martínez-Cortizas, A.: Comparing podzolization under different bioclimatic conditions, Geoderma, 377, 114 581, https://doi.org/10.1016/J.GEODERMA.2020.114581, 2020.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneth, A., Arora, V., Bates, N. R., Becker, M., Benoit-Cattin, A., Bittig, H. C., Bopp, L., Bultan, S., Chandra, N., Chevallier, F., Chini, L. P., Evans, W., Florentie, L., Forster, P. M., Gasser, T., Gehlen, M., Gilfillan, D., Gkritzalis, T., Gregor, L., Gruber, N., Harris, I., Hartung, K., Haverd, V., Houghton, R. A., Ilyina, T., Jain, A. K., Joetzjer, E., Kadono, K., Kato, E., Kitidis, V., Korsbakken, J. I., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Liu, Z., Lombardozzi, D., Marland, G., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T.,

https://doi.org/10.5194/egusphere-2024-419
Preprint. Discussion started: 9 April 2024

Palmer, P. I., Pierrot, D., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Smith, A. J. P., Sutton, A. J., Tanhua, T., Tans, P. P., Tian, H., Tilbrook, B., van der Werf, G., Vuichard, N., Walker, A. P., Wanninkhof, R., Watson, A. J., Willis, D., Wiltshire, A. J., Yuan, W., Yue, X., and Zaehle, S.: Global Carbon Budget 2020, Earth System Science Data, 12, 3269–3340, https://doi.org/10.5194/essd-12-3269-2020, 2020.

Georgiou, K., Jackson, R. B., Vindušková, O., Abramoff, R. Z., Ahlström, A., Feng, W., Harden, J. W., Pellegrini, A. F., Polley, H. W., Soong, J. L., Riley, W. J., and Torn, M. S.: Global stocks and capacity of mineral-associated soil organic carbon, Nature Communications 2022 13:1, 13, 1–12, https://doi.org/10.1038/s41467-022-31540-9, 2022.

Hall, S. J. and Thompson, A.: What do relationships between extractable metals and soil organic carbon concentrations mean?, Soil Science Society of America Journal, 86, 195–208, https://doi.org/10.1002/saj2.20343, 2022.

Imaya, A., Inagaki, Y., Tanaka, N., and Ohta, S.: Free oxides and short-range ordered mineral properties of brown forest soils developed from different parent materials in the submontane zone of the Kanto and Chubu districts, Japan, Soil Science and Plant Nutrition, 53, 621–633, https://doi.org/10.1111/j.1747-0765.2007.00175.x, 2007.

IPCC: Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the IPCC Sixth Assessment Report, Cambridge University Press, United Kingdom and New York, https://doi.org/10.1017/9781009157896, 2021.

Jin, X., Wu, F., Wu, Q., Heděnec, P., Peng, Y., Wang, Z., and Yue, K.: Effects of drying-rewetting cycles on the fluxes of soil greenhouse gases, Heliyon, 9, e12 984, https://doi.org/10.1016/j.heliyon.2023.e12984, 2023.

Kaiser, M., Kleber, M., and Berhe, A. A.: How air-drying and rewetting modify soil organic matter characteristics: An assessment to improve data interpretation and inference, Soil Biology and Biochemistry, 80, 324–340, https://doi.org/10.1016/j.soilbio.2014.10.018, 2015.

Kim, D.-G., Vargas, R., Bond-Lamberty, B., and Turetsky, M. R.: Effects of soil rewetting and thawing on soil gas fluxes: a review of current literature and suggestions for future research, Biogeosciences, 9, 2459–2483, https://doi.org/10.5194/bg-9-2459-2012, 2012.

Koarashi, J., Hockaday, W. C., Masiello, C. A., and Trumbore, S. E.: Dynamics of decadally cycling carbon in subsurface soils, Journal of Geophysical Research: Biogeosciences, 117, 1–13, https://doi.org/10.1029/2012JG002034, 2012.

Kpemoua, T. P., Barré, P., Houot, S., and Claire, C.: Accurate evaluation of the Birch effect requires continuous CO2 measurements and relevant controls, Soil Biology and Biochemistry, 180, 109 007, https://doi.org/10.1016/J.SOILBIO.2023.109007, 2023.

Kramer, M. G. and Chadwick, O. A.: Climate-driven thresholds in reactive mineral retention of soil carbon at the global scale, Nature Climate Change, 8, 1104–1108, https://doi.org/10.1038/s41558-018-0341-4, 2018.

Lacroix, R. E., Tfaily, M. M., McCreight, M., Jones, M. E., Spokas, L., and Keiluweit, M.: Shifting mineral and redox controls on carbon cycling in seasonally flooded mineral soils, Biogeosciences, 16, 2573–2589, https://doi.org/10.5194/BG-16-2573-2019, 2019.

Lee, M.-s., Nakane, K., Nakatsubo, T., Mo, W.-h., and Koizumi, H.: Effects of rainfall events on soil CO2 flux in a cool temperate deciduous broad-leaved forest, Ecological Research, 17, 401–409, https://doi.org/10.1046/j.1440-1703.2002.00498.x, 2002.

Lee, X., Wu, H. J., Sigler, J., Oishi, C., and Siccama, T.: Rapid and transient response of soil respiration to rain, Global Change Biology, 10, 1017–1026, https://doi.org/10.1111/j.1365-2486.2004.00787.x, 2004.

Majumdar, A., Dubey, P. K., Giri, B., Moulick, D., Srivastava, A. K., Roychowdhury, T., Bose, S., and Jaiswal, M. K.: Combined effects of dry-wet irrigation, redox changes and microbial diversity on soil nutrient bioavailability in the rice field, Soil and Tillage Research, 232, 105 752, https://doi.org/10.1016/J.STILL.2023.105752, 2023.

Marumoto, T.: Mineralization of C and N from microbial biomass in paddy soil, Plant and Soil, 76, 165–173, https://doi.org/10.1007/BF02205577, 1984.

Marumoto, T., Kai, H., Yoshida, T., and Harada, T.: Drying effect on mineralizations of microbial cells and their cell walls in soil and contribution of microbial cell walls as a source of decomposable soil organic matter due to drying, Soil Science and Plant Nutrition, 23, 9–19, https://doi.org/10.1080/00380768.1977.10433017, 1977.

Marumoto, T., Anderson, J., and Domsch, K.: Decomposition of 14C- and 15N-labelled microbial cells in soil, Soil Biology and Biochemistry, 14, 461–467, https://doi.org/10.1016/0038-0717(82)90105-5, 1982.

Meng, Z., Huang, S., Xu, T., Deng, Y., Lin, Z., and Wang, X.: Transport and transformation of Cd between biochar and soil under combined dry-wet and freeze-thaw aging, Environmental Pollution, 263, 114 449, https://doi.org/10.1016/J.ENVPOL.2020.114449, 2020.

MEXT and JAM: Climate Change in Japan: Report on Assessment of Observed/Projected Climate Changes Relating to the Atmosphere, Land and Oceans., Tech. rep., Ministry of Education, Culture, Sports, Science and Technology; Japan Meteorological Agency, https://www.data.jma.go.jp/cpdinfo/ccj/index.html, 2020.

Miller, A. E., Schimel, J. P., Meixner, T., Sickman, J. O., and Melack, J. M.: Episodic rewetting enhances carbon and nitrogen release from chaparral soils, Soil Biology and Biochemistry, 37, 2195–2204, https://doi.org/10.1016/j.soilbio.2005.03.021, 2005.

Miyazawa, M., Takahashi, T., Sato, T., Kanno, H., and Nanzyo, M.: Factors controlling accumulation and decomposition of organic carbon in humus horizons of Andosols, Biology and Fertility of Soils, 49, 929–938, https://doi.org/10.1007/s00374-013-0792-8, 2013.

Mokma, D. L.: New Chemical Criteria for Defining the Spodic Horizon, Soil Science Society of America Journal, 47, 972–976, https://doi.org/10.2136/SSSAJ1983.03615995004700050026X, 1983.

Morisada, K., Ono, K., and Kanomata, H.: Organic carbon stock in forest soils in Japan, Geoderma, 119, 21–32, https://doi.org/10.1016/S0016-7061(03)00220-9, 2004.

Nagano, H., Atarashi-Andoh, M., and Koarashi, J.: Effect of dry-wet cycles on carbon dioxide release from two different volcanic ash soils in a Japanese temperate forest, Soil Science and Plant Nutrition, 65, 525–533, https://doi.org/10.1080/00380768.2019.1649976, 2019.

Nagano, H., Atarashi-Andoh, M., Tanaka, S., Yomogida, T., Kozai, N., and Koarashi, J.: Stable C and N isotope abundances in water-extractable organic matter from air-dried soils as potential indices of microbially utilized organic matter, Frontiers in Forests and Global Change, 6, 1228 053, https://doi.org/https://doi.org/10.3389/ffgc.2023.1228053, 2023.

NARO: Japan Soil Inventory, https://soil-inventory.rad.naro.go.jp/index.html, 2023.

Pfleiderer, P., Schleussner, C.-F., Kornhuber, K., and Coumou, D.: Summer weather becomes more persistent in a 2 °C world, Nature Climate Change, pp. 1–6, https://doi.org/10.1038/s41558-019-0555-0, 2019.

R Core Team: R: A Language and Environment for Statistical Computing, https://www.r-project.org/, 2021.

Rasmussen, C., Heckman, K., Wieder, W. R., Keiluweit, M., Lawrence, C. R., Berhe, A. A., Blankinship, J. C., Crow, S. E., Druhan, J. L., Hicks Pries, C. E., Marin-Spiotta, E., Plante, A. F., Schädel, C., Schimel, J. P., Sierra, C. A., Thompson, A., and Wagai, R.: Beyond clay: towards an improved set of variables for predicting soil organic matter content, Biogeochemistry, https://doi.org/10.1007/s10533-018-0424-3, 2018.

Running, S. and Zhao., M.: MODIS/Terra Net Primary Production Gap-Filled Yearly L4 Global 500m SIN Grid V061., https://doi.org/10.5067/MODIS/MOD17A3HGF.061, 2021.

Shirato, Y., Hakamata, T., and Taniyama, I.: Modified rothamsted carbon model for andosols and its validation: changing humus decomposition rate constant with pyrophosphate-extractable Al, Soil Science and Plant Nutrition, 50, 149–158, https://doi.org/10.1080/00380768.2004.10408463, 2004.

Soil Survey Staff: Keys to Soil Taxonomy, USDA-Natural Resources Conservation Service, 13th editi edn., https://www.nrcs.usda.gov/resources/guides-and-instructions/keys-to-soil-taxonomy#keys, 2022.

Takahashi, T. and Dahlgren, R. A.: Nature, properties and function of aluminum-humus complexes in volcanic soils, Geoderma, 263, 110–121, https://doi.org/10.1016/j.geoderma.2015.08.032, 2016.

Takahashi, T., Ikeda, Y., Fujita, K., and Nanzyo, M.: Effect of liming on organically complexed aluminum of nonallophanic Andosols from northeastern Japan, Geoderma, 130, 26–34, https://linkinghub.elsevier.com/retrieve/pii/S0016706105000108, 2006.

Unger, S., Máguas, C., Pereira, J. S., David, T. S., and Werner, C.: The influence of precipitation pulses on soil respiration - Assessing the " Birch effect" by stable carbon isotopes, Soil Biology and Biochemistry, 42, 1800–1810, https://doi.org/10.1016/j.soilbio.2010.06.019, 2010.

Unger, S., Máguas, C., Pereira, J. S., David, T. S., and Werner, C.: Interpreting post-drought rewetting effects on soil and ecosystem carbon dynamics in a Mediterranean oak savannah, Agricultural and Forest Meteorology, 154-155, 9–18, https://doi.org/10.1016/j.agrformet.2011.10.007, 2012.

Vance, E. D., Brookes, P. C., and Jenkinson, D. S.: An extraction method for measuring soil microbial biomass C, Soil Biology and Biochemistry, 19, 703–707, https://doi.org/10.1016/0038-0717(87)90052-6, 1987.

Wagai, R., Kajiura, M., Uchida, M., and Asano, M.: Distinctive Roles of Two Aggregate Binding Agents in Allophanic Andisols: Young Carbon and Poorly-Crystalline Metal Phases with Old Carbon, Soil Systems, 2, 29, https://doi.org/10.3390/soilsystems2020029, 2018.

Wang, D., Felice, M. L., and Scow, K. M.: Impacts and interactions of biochar and biosolids on agricultural soil microbial communities during dry and wet-dry cycles, Applied Soil Ecology, 152, 103 570, https://doi.org/10.1016/J.APSOIL.2020.103570, 2020.

Wijesinghe, J. N., Asaoka, H., Mori, Y., and Hiradate, S.: Depth profile of plant nutrients and acidity in a non-allophanic Andosol as affected by a half-century of fertilization, Soil Science and Plant Nutrition, pp. 1–12, https://doi.org/10.1080/00380768.2021.1887711, 2021.

Xiang, S. R., Doyle, A., Holden, P. A., and Schimel, J. P.: Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface California grassland soils, Soil Biology and Biochemistry, 40, 2281–2289, https://doi.org/10.1016/j.soilbio.2008.05.004, 2008.

Zhang, S., Yu, Z., Lin, J., and Zhu, B.: Responses of soil carbon decomposition to drying-rewetting cycles: A meta-analysis, Geoderma, 361, 114 069, https://doi.org/10.1016/j.geoderma.2019.114069, 2020.

Zhang, S., Lin, J., Wang, P., and Zhu, B.: The direct and legacy effects of drying-rewetting cycles on active and relatively resistant soil carbon decomposition, Land Degradation & Development, 34, 2124–2135, https://doi.org/10.1002/ldr.4594, 2023.