communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-022-00590-8 OPEN

A globally robust relationship between water table decline, subsidence rate, and carbon release from peatlands

Lei Ma[1,2], Gaofeng Zhu[3], Bolong Chen[1], Kun Zhang[4,5], Shuli Niu[2,6,7], Jinsong Wang[2,6], Phillipe Ciais[8] & Hongchao Zuo[1✉]

Peatland ecosystems are globally important carbon stores. Disturbances, such as drainage and climate drying, act to lower peatland water table depths, consequently enhancing soil carbon release and subsidence rates. Here, we conduct a global meta-analysis to quantify the relationship among water table depth, carbon release and subsidence. We find that the water table decline stimulated heterotrophic, rather than autotrophic, soil respiration, which was associated with an increase in subsidence rate. This relationship held across different climate zones and land uses. We find that 81% of the total annual soil respiration for all drained peatlands was attributable to tropical peatlands drained for agriculture and forestry and temperate peatlands drained for agriculture. Globally, we estimate that, drained peatlands release 645 Mt C yr^{-1} (401–1025 Mt C yr^{-1}) through soil respiration, equivalent to approximately 5% of global annual anthropogenic carbon emissions. Our findings highlight the importance of conserving pristine peatlands to help mitigate climate change.

[1] College of Atmospheric Sciences, Lanzhou University, No. 222 Tian-shui South Road, Lanzhou 730000, PR China. [2] Sichuan Zoige Alpine Wetland Ecosystem National Observation and Research Station, Southwest Minzu University, No.16, South 4th Section First Ring Road, Chengdu 610041, PR China. [3] College of Earth and Environmental Sciences, Lanzhou University, No. 222 Tian-shui South Road, Lanzhou 730000, PR China. [4] Department of Mathematics, The University of Hong Kong, Hong Kong, PR China. [5] School of Biological Sciences, The University of Hong Kong, Hong Kong, PR China. [6] Key Laboratory of Ecosystem Network Observation and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China. [7] School of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, PR China. [8] Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France. ✉email: zuohch@lzu.edu.cn

Pristine peatlands—i.e., peatlands (where peat soil has at least 30% dry organic matter and a peat depth generally exceeding 40 cm[1]) that have thus far not been directly impacted by anthropogenic activities, such as draining for agriculture or forestry land uses[2]—are among the most valuable ecosystems on Earth[1]. These ecosystems are critical for preserving global biodiversity, providing safe drinking water, minimizing flood risk, sequestering carbon (C) and mitigating climate change[3,4]. Although peatlands cover only ~2.84% of the Earth's land surface[5], they store 500–700 Gt (1 Gt = 10^3 Mt) of soil C[1], which contributes 21–47% of the global soil C storage (1500–2400 Gt C) and is equivalent to more than 50% of the C in the atmosphere (860 Gt C)[6]. Therefore, peatlands are recognized as critically important and long-term C sinks to support the Climate Action Sustainable Development Goal of the United Nations[7,8]. However, peatlands worldwide are vulnerable to drainage and climate drying, which can substantially lower their water table (WT) level[3,8,9] and consequently stimulate soil respiration (SR) and cause widespread peat subsidence (PS)[10–12]. SR, the second largest C flux between terrestrial ecosystems and the atmosphere after net ecosystem production[13], is the major pathway for releasing CO_2 through the soil surface due to microbial decomposition of organic matter and litter (heterotrophic respiration: HR) and due to belowground vegetation respiration (autotrophic respiration: AR)[14,15]. SR plays a vital role in regulating atmospheric CO_2 concentrations and climate warming[13,15] and is mainly regulated by WT levels in peatlands[10,11,16].

Drainage was the most important driver of WT decline and global pristine peatland shrinkage in the past century[17,18]. Almost 50% of the total European pristine peatland area (0.53×10^6 km^2) has been lost since the 20th century due to drainage[3,19]. Approximately 11–13% of global pristine peatlands were lost[18,20] due to drainage for agriculture[21,22], forestry[23,24], grassland expansion (to support livestock grazing[25,26] and herbage production[27,28]) and peat extraction[29,30]. Furthermore, future climate drying is predicted to be widespread in the mid-latitudes and subtropics and has already impacted European peatlands[8,31], potentially causing further drops in WT levels and impacting the SR and its components, HR and AR, of pristine peatlands[32,33].

The drawdown of WT due to drainage and climate drying directly exposes the anoxic peat layer to oxygen and thus causes significantly higher SR from drained peatlands than from pristine peatlands[10,11]. Previous meta-studies exclusively reported significant decreases in the net ecosystem production of pristine peatlands due to global WT decline[3,4,8,20], however, the responses of SR in pristine peatlands to global WT decline remain unknown. Furthermore, in situ measurements showed that large uncertainties existed in the responses of SR to WT decline, with increases[28,29], decreases[25,34] or no changes[35,36] all observed. To date, the global patterns and controls in the responses of SR to WT decline in pristine peatlands remain largely unclear. Additionally, although it is well known that SR comprises HR and AR[14,15], another open question is whether the changes in SR due to global WT decline were contributed by the changes in HR or AR or both, which remains elusive. Disentangling the relative contributions of HR and AR to SR is crucial for understanding soil C dynamics because the former decomposes C that may have accumulated over millennia in the soil, whereas the latter represents the respiration of C recently assimilated by plants[37,38]. Consequently, the lack of clarity on this issue further limits the understanding of peatland soil C biogeochemistry, as HR is used to appropriately evaluate peat C decomposition and the PS rate (R_{ps}) owing to peat C oxidation[12,39]. WT decline has caused high R_{ps}, which severely threatens the utilization of agriculturally drained peatlands if peat C is depleted due to oxidation[11,12]. The R_{ps} is triggered by a combination of processes, such as physical compaction by heavy equipment or livestock trampling and shrinkage through the contraction of organic fibers when drying, consolidation by loss of water from pores in the peat, and oxidation due to the breakdown of peat C[10–12]. Therefore, disentangling the R_{ps} from oxidation (i.e., HR) is crucial for the sustainable management of drained peatland, decelerating peat C loss, and mitigating soil CO_2 release. However, the patterns of R_{ps} by oxidation and associated total annual soil heterotrophic CO_2 emissions from global drained peatlands are far from clear, underscoring the urgent need for assessments of the impacts of WT decline to inform conservation guidelines for pristine peatlands and sustainable land-use policies for drained peatlands, as well as to reduce soil C losses for climate change mitigation.

Here, we report on a global meta-analysis of the impacts of WT decline (due to drainage and climate drying) on SR and its components, HR and AR, and their controls, as well as on R_{ps} due to oxidation from global pristine peatlands (Figs. 1–8, Table 1, Supplementary Figs. 1–14 and Table 1). The in situ SR observations (measured by the chamber method) in our study covered most peatlands globally except for tropical swamps in Central Africa and South America (Fig. 1a and Supplementary Fig. 1). In total, 386 paired (i.e., pristine *vs*. drained) observations (250 SR, 101 HR, and 35 AR) were collected from 63 different publications of studies conducted globally (Fig. 1b). Most observations targeted only one of the three efflux components. Only 35 paired observations measured SR, HR, and AR simultaneously (Supplementary Fig. 3). In addition, 485 R_{ps} values and 485 proportions of peat oxidation to R_{ps} (Supplementary Fig. 9), estimated using the empirical models developed in our study (Fig. 5), were used to map the global patterns of R_{ps} due to oxidation and associated soil HR rates from global drained peatlands (Fig. 6). Our study aims to 1) reveal the responses of SR and its components, HR and AR, in pristine peatlands to the global WT decline; 2) clarify the influencing factors for the responses of SR and its components in pristine peatlands to the global WT decline; and 3) estimate the total annual SR and HR due to the drainage of previously pristine peatlands worldwide. We hypothesize that the net increases in SR were mainly due to the net increases in HR rather than in AR, as the declining WT in pristine peatlands directly exposes the anoxic peat layer to oxygen and consequently promotes peat C oxidation. We also hypothesize that drained peatlands are global hotspots for SR, as peatlands store immense amounts of soil C in terrestrial ecosystems[1]. Consistent with the hypotheses, we found that WT decline significantly stimulated SR from global pristine peatlands mainly through HR rather than AR, and resulted in widespread PS across global drained peatlands. Tropical pristine peatlands drained for agriculture and forestry functioned as the largest SR emitters, while boreal pristine peatlands drained for forestry served as the lowest emitters, mainly due to the significantly higher R_{ps} in tropical peatlands drained for agriculture and forestry. The total annual SR from global drained peatlands contributed 4.6% (3.0–7.3%) to the global total annual anthropogenic CO_2 emissions. Our study calls for conserving pristine peatlands and restoring degraded peatlands to reduce peat C loss and mitigate climate change while lowering PS to achieve multiple Sustainable Development Goals (e.g., combat climate change, halt and reverse land degradation and halt biodiversity loss) of the United Nations.

Results

Changes in SR and its components, HR and AR, due to water table decline. The meta-data were slightly right-skewed for the impacts of WT decline on SR and HR (Fig. 1b). Overall, WT decline significantly increased SR by 35% ($n = 250$) and increased HR by 44% ($n = 101$) but had no significant effect on AR (30%,

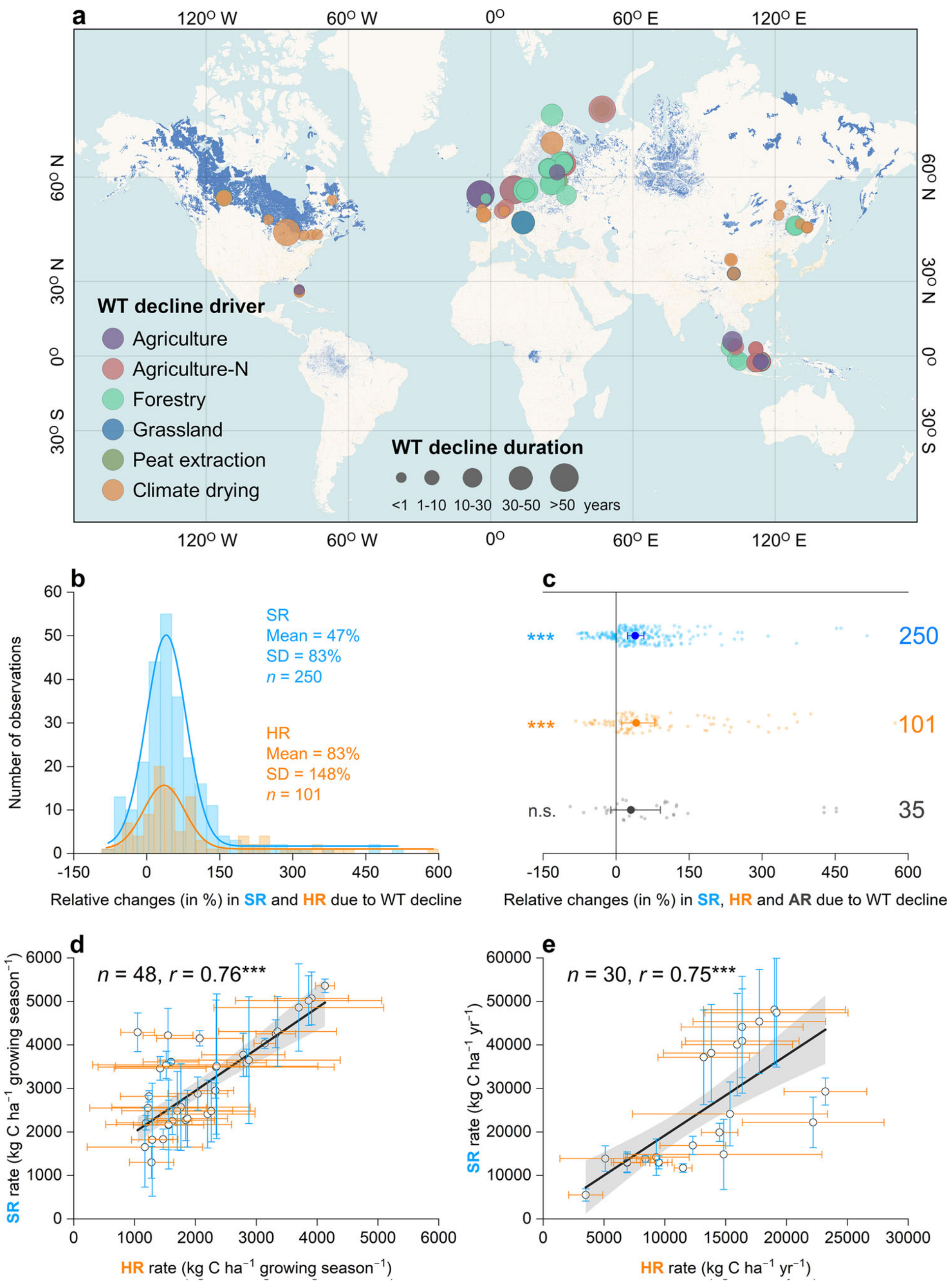

Fig. 1 Relative changes in soil respiration (SR) and its components, heterotrophic respiration (HR) and autotrophic respiration (AR), due to water table (WT) decline in global pristine peatlands. **a** Distribution of the in situ observations. **b** Frequency distributions of the relative changes in SR and HR due to WT decline (AR was not shown due to the scarcity of data points ($n = 35$)). **c** Relative changes in SR, HR, and AR due to WT decline. **d** Pearson correlation of the growing season HR and SR rates in pristine and drained boreal peatlands. **e** Pearson correlation of the annual HR and SR rates in pristine and drained tropical peatlands. No data were observed in pristine and drained temperate peatlands. Each data point for WT decline impacts on in situ SR and its components were classified on the basis of the driver of WT decline and duration of WT decline in **a**. The gray-blue regions in **a** indicate the global distributions of peatlands derived from PEATMAT[5]. The larger solid circles and horizontal bars in **c** denote the weighted means of relative changes and their 95% confidence intervals. The smaller circles and numbers in **c** indicate individual relative changes due to WT decline and the number of data points, respectively. The open circles and bars in **d**, **e** show the means and standard deviations for individual data points. The asterisks *, **, *** indicate significance at the levels of $p < 0.05$, 0.01 and 0.001, respectively, and n.s. indicates no significance (for details, see Meta-analysis in Methods).

$n = 35$) (Fig. 1c). This result was also supported by a separate meta-analysis of incubation observations that measured the SR from peat soil samples under WT decline ($n = 21$, Supplementary Fig. 2). The simultaneous measurements from 35 paired SR, HR and AR observations were further analyzed, and a similar trend of a significant decline in WT corresponding to significant increases in SR and HR while having no significant effect on AR was observed (Supplementary Fig. 3). Additionally, significant positive linear correlations (Pearson correlation coefficients of 0.76 and 0.75, respectively) were observed for the growing season or annual SR and HR rates in boreal and tropical pristine and drained peatlands (Fig. 1d, e), reflecting the similar dynamics of these two effluxes in response to WT decline. Recent annual measurements also revealed strong linear correlation between SR

Table 1 Estimated peat subsidence rate (R_{ps}) due to oxidation and associated soil C release from global drained peatlands.

	Boreal			Temperate			Tropical		
Variable	Agriculture	Forestry	Grassland	Agriculture	Forestry	Grassland	Agriculture	Forestry	Grassland
SOC (g kg^{-1})	473(452–495)[a]			315(269–362)[b]			483(437–524)[a]		
BD (g cm^{-3})	0.11(0.08–0.15)[b]			0.17(0.12–0.22)[a]			0.16(0.13–0.22)[a]		
R_{ps} due to oxidation (cm yr^{-1})	0.74 (0.69– 0.79)[c]	0.14(0.13–0.15)[f]	0.65(0.64–0.67)[cd]	0.82(0.74–0.90)[b]	0.19(0.18–0.20)[e]	0.60(0.57–0.63)[d]	1.95(1.89–2.02)[a]	1.89(1.83–1.96)[a]	1.89(1.87–1.90)[a]
HR rate due to oxidation (kg C ha^{-1} yr^{-1})	3992(2626–5812)[b]	729(484–1054)[c]	3515(2428–4905)[b]	4319(2400–7082)[b]	991(565–1593)[c]	3149(1841–4927)[b]	15975(10,967–23,685)[a]	15492(10,646–22,926)[a]	15408(10,865–22,264)[a]
Drained area (×10^3 km^2)	54(37–72)	58(55–61)	13(4–22)	73(37–109)	53(43–63)	42(26–58)	95(94–96)	91(72–109)	20(1–39)
Contribution to total area (%)	10.9(7.4–14.3)	11.6(11.0–12.1)	2.6(0.8–4.4)	14.6(7.4–22.0)	10.6(8.5–12.7)	8.5(5.2–11.8)	19.0(18.7–19.4)	18.2(14.6–21.8)	4.0(0.1–7.7)
Total HR due to oxidation (Mt C yr^{-1})	22(10–42)	4(3–6)	5(1–11)	32(9–77)	5(2–10)	13(5–29)	152(103–228)	140(77–250)	31(1–87)
Contribution to total HR (%)	5.4(4.6– 5.7)	1.0(0.9–1.3)	1.1(0.5–1.5)	7.8(4.2–10.4)	1.3(1.1–1.4)	3.3(2.3–3.9)	37.7(30.8–49.0)	34.8(33.8–36.6)	7.6(0.4– 11.7)
Contribution of HR to SR (%)	66(59–72)			66(59–72)[g]			62(52–72)		
Total SR (Mt C yr^{-1})	33(16–58)	6(4–9)	7(2–5)	48(15–108)	8(4–14)	20(8–40)	246(200–345)	227(149–315)	49(1–120)
Contribution to total SR (%)	5.1(4.1– 5.7)	1.0(0.9–1.1)	1.1(0.4–1.5)	7.4(3.8–10.5)	1.2(1.0–1.4)	3.1(2.0– 3.9)	38.2(30.7–49.9)	35.2(33.7–37.3)	7.7(0.4–11.7)

The data are expressed as means with 95% confidence intervals and were calculated by bootstrap resampling with 10,000 iterations. The R_{ps} due to oxidation was estimated according to the R_{ps} and proportion of R_{ps} attributed to oxidation (%) (for details, see Methods). SOC, BD, and drained peatland area and the contribution of HR to SR were compiled from previous publications (for details, see Methods and Supplementary Data B). Note that SOC and BD measurements were obtained from pristine peatlands at a depth of 0–30 cm. The different lowercase letters within the same row indicate significant differences in means among climate zones and land uses at the level of $p < 0.05$ according to Kruskal–Wallis test and pairwise comparisons. For a more detailed explanation of the estimation processes, see the "Methods".

SOC soil organic C, *BD* bulk density, *HR* heterotrophic respiration, *SR* soil respiration.

[g]Indicates that boreal data were used, as no observations were available for the temperate climate zone.

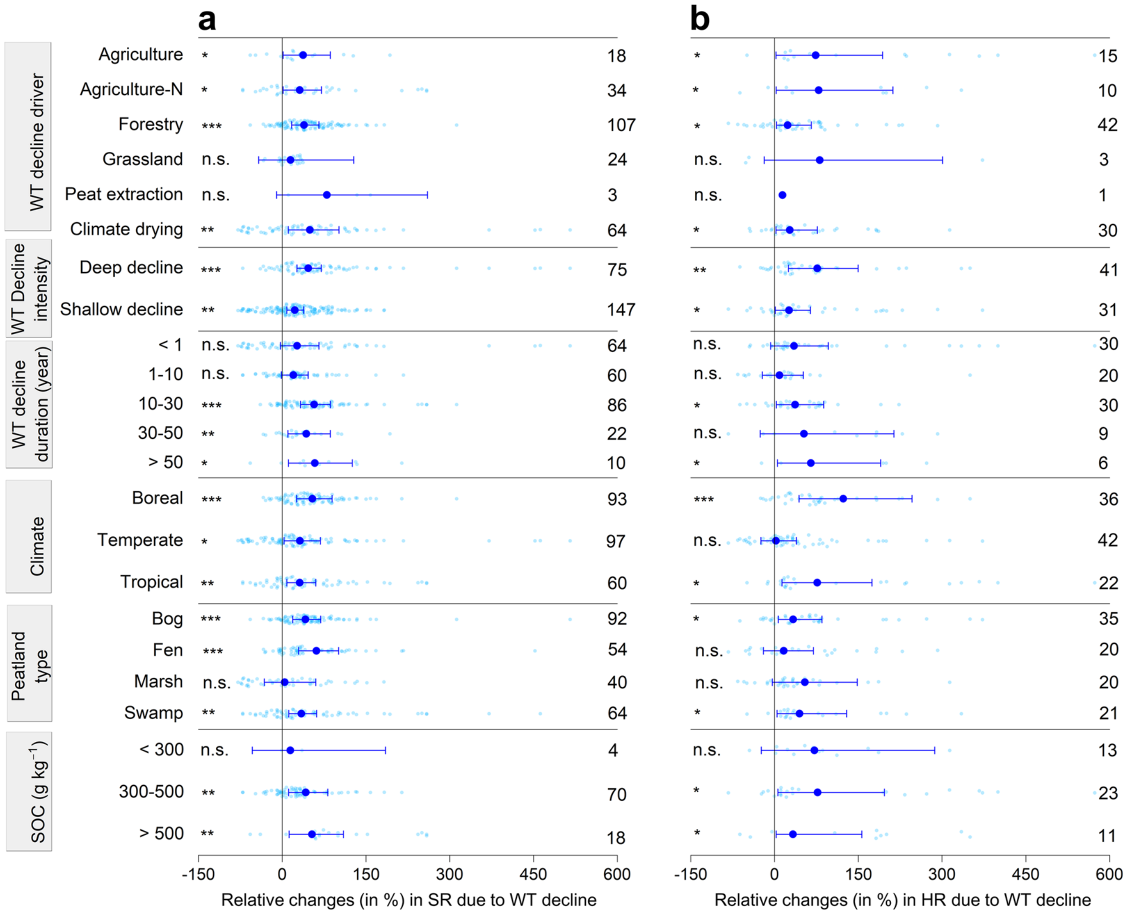

Fig. 2 Relative changes in soil respiration (SR) and heterotrophic respiration (HR) under different conditions due to water table (WT) decline in pristine peatlands. a Relative changes in SR due to WT decline. **b** Relative changes in HR due to WT decline (AR was not shown due to the scarcity of data points ($n = 35$)). The larger solid circles and horizontal bars denote the weighted means of relative changes and their 95% confidence intervals. The smaller circles and the numbers indicate individual relative changes due to WT decline and numbers of data points, respectively. The asterisks *, **, *** indicate significance at the levels of $p < 0.05$, 0.01 and 0.001, respectively, and n.s. indicates no significance (for details, see Meta-analysis in Methods). Net water table declines greater and less than 30 cm are defined as deep and shallow declines, respectively, according to ref. 42.

and HR from temperate to boreal pristine and drained peatlands[40]. These results collectively indicated that increases in SR from global pristine peatlands under WT decline were mainly due to HR rather than AR.

Subgroup analysis for SR and HR (which had larger sample sizes than AR) (Fig. 2a, b and Supplementary Fig. 4) also supported the finding that WT decline significantly stimulated SR mainly through HR rather than AR (Fig. 1c). Among the drivers of WT decline, significant increases in SR and HR were observed in all land-use types except for grassland and peat extraction, including agriculture (36%, $n = 18$; 78%, $n = 15$), agriculture-N (agricultural land use with nitrogen application, 32%, $n = 34$; 82%, $n = 10$), forestry (39%, $n = 107$; 24%, $n = 42$) and climate-induced drying of pristine peatlands (49%, $n = 644$; 27%, $n = 30$). With regard to the impact of the magnitude of the WT decline, a stronger decline (>30 cm) resulted in significantly higher SR (46%, $n = 75$) and HR (78%, $n = 41$) than a weaker decline (≤30 cm; 22%, $n = 147$ for SR; 26%, $n = 31$ for HR), showing that a much lower WT (Supplementary Fig. 5) stimulates more peat oxidation[41,42]. Considering the duration of WT decline, significant increases in SR and HR were observed when the period since WT decline implementation was longer than 10 years; otherwise, no significant stimulation effects were observed, particularly when the duration of WT decline was less than 1 year.

In terms of climate zone, the effect of WT decline on increasing SR was significantly higher in boreal areas (54%, $n = 93$) than in temperate (32%, $n = 97$) or tropical (31%, $n = 60$) areas. A similar trend was observed for HR, but this effect was much larger, particularly for boreal (123%, $n = 36$) and tropical areas (77%, $n = 22$), highlighting that climate regime functioned as a key mediator of the WT decline effects on SR and HR. We also observed that the impacts of WT decline on SR and HR from pristine peatlands relied upon peatland type and the SOC concentration of the pristine peatlands (Fig. 2a, b). Specifically, WT decline significantly increased SR and HR from bogs, fens and swamps, while it did not have a significant influence on SR from marshes. Significant stimulations of SR and HR were found in pristine peatlands with SOC contents ≥300 g kg^{-1}.

Changes in environmental variables due to water table decline. Overall, WT decline significantly decreased SWC (−29%, $n = 56$) and SOC concentration (0–30 cm, −10%, $n = 88$) while increasing E_h (242 mV, $n = 15$), T_s (4%, $n = 88$), BD (79%, $n = 101$), and concentrations of soil NO_3^- (325%, $n = 44$), MBN (17%, $n = 4$) and DTP (311%, $n = 3$) (Fig. 3). The decreases in SWC were significantly related to decreases in WTD (Supplementary Fig. 6). WT decline did not exert significant effects on the concentrations of SOC in deeper soil layers (30–100 cm: 11%, $n = 22$), TN (0–30:

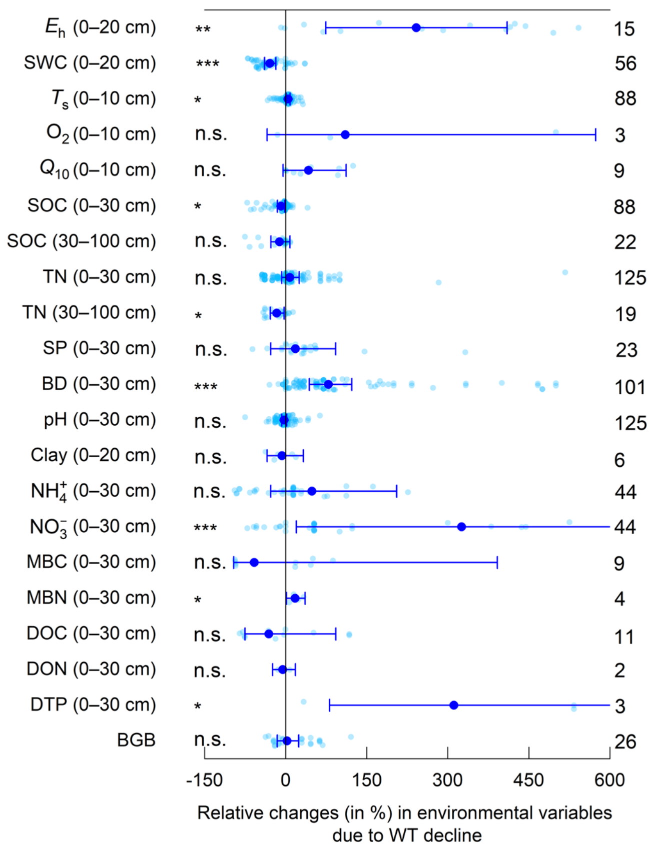

Fig. 3 Relative changes in environmental variables due to water table (WT) decline in pristine peatlands. E_h (soil redox potential), SWC (soil water content), T_s (soil temperature), O_2 (oxygen), Q_{10} (temperature sensitivity coefficient), SOC (soil organic carbon concentration), TN (total nitrogen concentration), SP (soil phosphorus concentration), BD (soil bulk density), pH, clay content, NH_4^+ (soil ammonium concentration), soil NO_3^- (soil nitrate concentration), MBC (microbial biomass carbon), MBN (microbial biomass nitrogen), DOC (dissolved organic carbon), DON (dissolved organic nitrogen), DTP (dissolved organic phosphorus) and BGB (belowground root biomass). The larger solid circles and horizontal bars denote the weighted means of relative changes and their 95% confidence intervals. The smaller circles and numbers indicate individual relative changes due to WT decline and the number of data points, respectively. The asterisks *, **, *** indicate significance at the levels of $p < 0.05$, 0.01 and 0.001, respectively, and n.s. indicates no significance (for details, see Meta-analysis in Methods). E_h was denoted as the net change (treatment − control, in mV) due to WT decline (for details, see Meta-analysis in Methods).

7%, $n = 125$; 30–100 cm: −17%, $n = 19$), SP (18%, $n = 23$), soil NH_4^+ (48%, $n = 44$), MBC (−58%, $n = 9$) and DOC (−31%, $n = 11$) (Fig. 3). In addition, WT decline did not significantly affect the coefficient of temperature sensitivity (Q_{10}, 42%, $n = 9$), soil pH (−3%, $n = 125$) or BGB (2%, $n = 26$) (Fig. 3).

Controls of the changes in SR and HR due to water table decline. Across the study sites, the increases in SR significantly linearly increased with the peat depth ($p = 0.03$) and SOC content of pristine peatlands ($p < 0.001$) due to WT decline (Fig. 4a, b). In addition, greater increases in SR were significantly correlated with greater decreases in WTD ($p < 0.001$), greater decreases in SWC ($p = 0.02$) and greater decreases in DOC contents ($p = 0.02$) (Fig. 4d, e). The changes in SR were not correlated with the drainage durations (Fig. 4c) and were not controlled by meteorological conditions such as the mean annual air temperature and precipitation (Supplementary Fig. 7).

As there were fewer observations for HR, we only observed that the increases in HR due to WT decline were controlled by the SOC content of pristine peatlands ($p = 0.08$), changes in WTD ($p = 0.03$) and changes in MBC ($p = 0.03$) (Supplementary Fig. 8).

Peat subsidence and associated soil C emissions due to drainage. Drainage of pristine peatlands worldwide has led to widespread PS[10–12]. Our synthetic results showed that the R_{ps} varied greatly, from 0.04 to 20.10 cm yr^{-1}, across different drainage drivers (i.e., land uses) and climate zones, with significant and negative exponential trends associated with the number of years after drainage (Fig. 5a, b). It is well known that R_{ps} is triggered by a combination of processes such as physical densification (e.g., consolidation by dehydration of the peat, compaction associated with trampling due to livestock grazing or farm machinery, and shrinkage through the contraction of organic fibers when drying) and oxidation due to the breakdown of peat organic matter[10]. Therefore, the proportion of peat oxidation should be extracted from the total R_{ps} to accurately estimate the actual HR from drained peatlands[12]. Our synthetic results showed that the proportion of oxidation to R_{ps} (P_o) ranged from 2% to 95% across different climate zones and land uses, with significant and positive logarithmic trends associated with the number of years since drainage (Fig. 5c, d), consistent with previous observations across drained temperate and boreal peatlands[12,41].

Using the established equations between the R_{ps} and drainage duration and P_o and drainage duration (Fig. 5a–d) as well as the globally synthesized drainage duration measurements ($n = 485$) categorized by climate zone and land use (Supplementary Fig. 9a, see also Eqs. (6–11) in Methods), we estimated the spatial patterns of the R_{ps} due to oxidation across global drained peatlands (Fig. 6a). On average, the R_{ps} due to oxidation of drained peatlands varied greatly across climate zones and land uses, where the R_{ps} due to oxidation was significantly higher in the drained tropical peatlands under different land uses (1.89–1.95 cm yr^{-1}) than in temperate or boreal peatlands (0.14–0.82 cm yr^{-1}, Table 1 and Supplementary Fig. 10c). The R_{ps} due to oxidation exhibited significant differences among different land uses following the decreasing order of agriculture>grassland>forestry in both drained boreal and temperate peatlands. Two other important variables, SOC concentration and soil bulk density (BD), in pristine peatlands, together with the R_{ps} due to oxidation, were used for calculating soil HR rates[11] and showed large spatial variations worldwide (Fig. 6b, c). Overall, the SOC concentrations of pristine peatlands were significantly higher for tropical areas (mean with 95% CI, 483 (437–524) g kg^{-1}, the same below) and boreal areas (473 (452–495) g kg^{-1}) than for temperate areas (315 (269–362) g kg^{-1}) (Table 1 and Supplementary Fig. 10a). Soil BD was significantly higher in the temperate (0.17 (0.13–0.22) g cm^{-3}) and tropical pristine peatlands (0.16 (0.13–0.22) g cm^{-3}) than in the boreal pristine peatlands (0.11 (0.08–0.15) g cm^{-3}) (Table 1 and Supplementary Fig. 10b). According to Eqs. (12, 13) (see Methods), on an areal basis, soil HR rates were lowest in forestry-drained boreal peatlands (729 (484–1054) kg C ha^{-1} yr^{-1}), followed by forestry-drained temperate peatlands (991 (565–1593) kg C ha^{-1} yr^{-1}), grassland-drained temperate (3149 (1841–4927) kg C ha^{-1} yr^{-1}), boreal peatlands (3515 (2428–4905) kg C ha^{-1} yr^{-1}), and agriculture-drained boreal (3992 (2626–5812) kg C ha^{-1} yr^{-1}) and temperate peatlands (4319 (2400–7082) kg C ha^{-1} yr^{-1}), and highest in drained tropical peatlands under different land uses (15,408 (10,865–22,264) to 15,975 (10,967–23,685) kg C ha^{-1} yr^{-1}) (Table 1 and Fig. 6d).

To test the reliability of our estimated HR rates, we collected 36 annual HR rates from global drained peatlands. We extracted

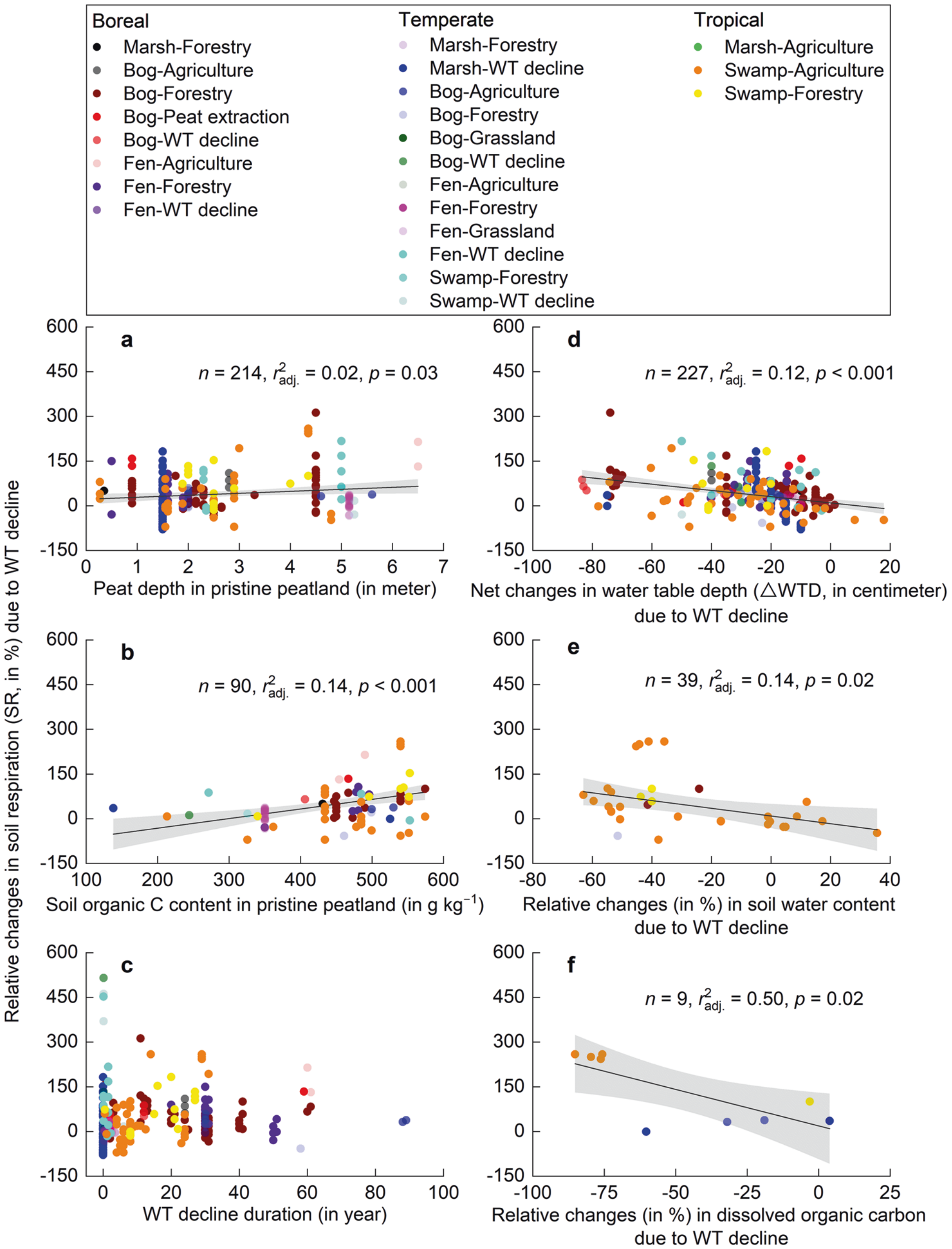

Fig. 4 Relationships between the relative changes in soil respiration (SR) and environmental variables due to WT decline. Relationships between the relative changes in SR and the **a** peat depth of pristine peatlands, **b** soil organic C concentration of pristine peatlands, **c** WT decline duration, **d** net changes in water table depth, **e** relative changes in soil water content and **f** relative changes in dissolved organic carbon concentration due to WT decline. The gray area indicates the 95% confidence interval for the fitted regression curve. We note that the SR observations were classified based on the climate, peatland type, and driver of WT decline (i.e., land use).

drainage duration, climate zone, and land use information from these studies and then estimated the annual HR rates by using previously established Eqs. (6–13) (see Methods). We observed a significant linear trend between the estimated and in situ measured annual HR rates across different climate zones and land uses (Fig. 7). This finding suggested that the estimation methods used in our study could be applied for estimating HR rates from regional to global drained peatlands.

Taking HR rates due to peat oxidation and drained peatland areas together (categorized by climate zone and land use, see Methods), the estimated total annual mean soil HR values were 22 (95% CI: 10–42), 4 (3–6), 5 (1–11), 32 (9–77), 5 (2–10), 13 (5–29), 152 (103–228), 140 (77–250) and 31 (1–87) Mt C yr^{-1} for agriculture-, forestry- and grassland-drained peatlands in boreal, temperate and tropical climate zones, respectively, with contributions of approximately 5.4 (4.6–5.7), 1.0 (0.9–1.3), 1.1 (0.5–1.5), 7.8 (4.2–10.4), 1.3 (1.1–1.4), 3.3 (2.3–3.9), 37.7 (30.8–49.0), 34.8 (33.8–36.6), and 7.6 (0.4–11.7)% to global total annual soil HR (404 (210–740) Mt C yr^{-1}, total drained area 499 × 10^3 km^2) due to subsidence of drained peatlands (Table 1).

Using 35 simultaneously measured sets of SR, HR, and AR observations across pristine and drained peatlands, we observed that there were no significant differences in the relative contributions of HR to SR between the drained tropical (62%) and boreal (66%) peatlands (Table 1 and Supplementary Fig. 11b). After combining the area-weighted total HR due to drainage and

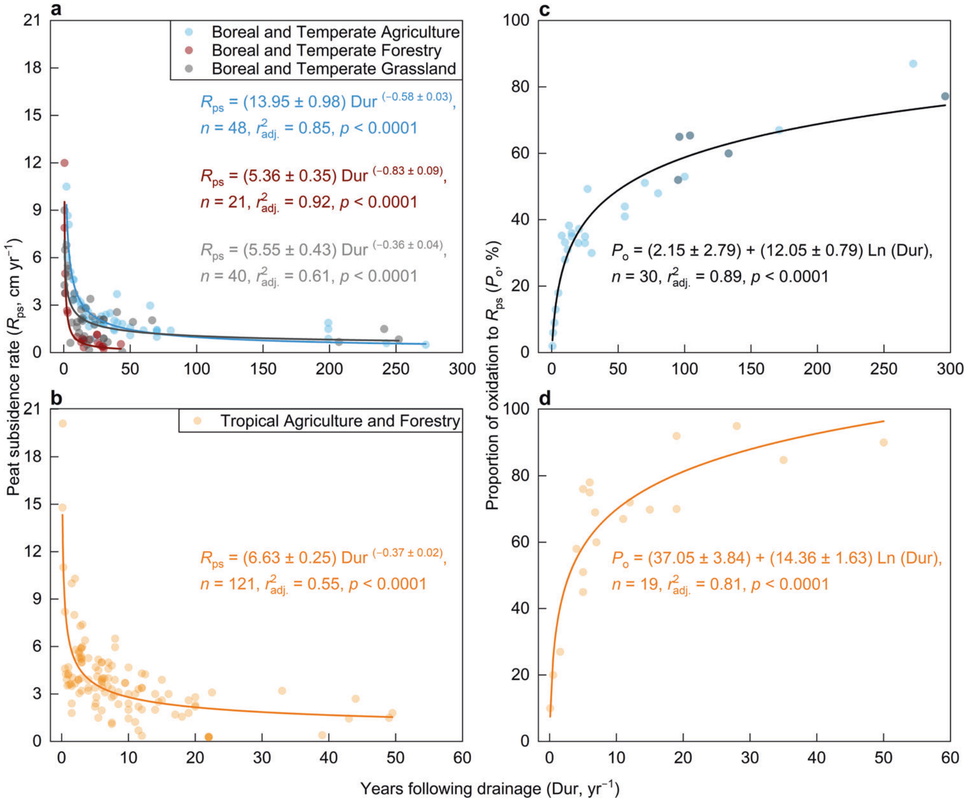

Fig. 5 Drainage duration controls peat subsidence rate (R_{ps}) and the proportion of peat oxidation to R_{ps} (P_o). a, **b** Relationships of R_{ps} with drainage duration (i.e., years since drainage) for drained peatlands across different climate zones and land uses. **c**, **d** Proportion of subsidence attributed to peat oxidation (P_o) with drainage duration for drained peatlands across different climate zones and land uses. The fitted regression curves and their 95% confidence intervals are shown. The same P_o was used for drained boreal and temperate peatlands under different land use due to a lack of sufficient observations. Similarly, the same P_o was used for drained tropical peatlands under different land uses.

the bootstrapped relative contribution of HR to SR in the different climate zones and land-use types (see Methods), the estimated total SR emissions from global drained peatlands were 645 (95% CI: 401–1025) Mt C yr^{-1} (Table 1) or 640 (95% CI: 428–953) Mt C yr^{-1} (Supplementary Table 1).

Discussion

Underlying mechanisms controlling SR and its components from global pristine peatlands due to water table decline. Our meta-analysis results demonstrated that WT decline due to drainage and climate-induced drying significantly promoted SR from global pristine peatlands, mainly through HR rather than AR (Fig. 8), resulting in positive feedback to climate warming. Recent studies also found that drainage significantly stimulated SR primarily through HR rather than AR from tropical pristine peatlands[12,39]. The significant net decrease in the WTD (overall weighted mean: −25 cm with 95% CI: −29 to −21 cm) enhanced soil aerobic conditions and increased soil redox potentials (Fig. 8 and Supplementary Fig. 5), consequently stimulating soil microbial activity and accelerating peat organic matter decomposition[36,43]. Similar improvements in soil aerobic conditions and soil redox potentials and consequently stimulations of HR from pristine peatlands due to WT decline were reported[44,45]. Our meta-regression analysis also showed significant linear increases in SR and HR with decreases in WTD (Fig. 4d and Supplementary Fig. 8b). This finding was further supported by the significant increases in SR and HR with higher pristine peatland SOC concentrations (Fig. 4b and Supplementary Fig. 10a) and with significant decreases in dissolved organic carbon and microbial biomass carbon contents (Fig. 4f and Supplementary Fig. 8c). Peat organic C functioned as the substrate for microbial decomposition[11,33,46], with a consequence that the higher substrates were provided for microbial decomposition given the higher SOC concentrations in peatlands[11,47]. Meanwhile, easily decomposable peat organic C, such as DOC and MBC, was preferentially lost due to WT decline[48,49]. Moreover, the lowered WT significantly decreased the soil water content and increased the soil temperature (Figs. 3 and 8), further stimulating the activities of soil enzymes and microbes in decomposing soil organic matter[50,51], resulting in significant reductions in the topsoil (0–30 cm) SOC concentrations of pristine peatlands, as observed in our study (Fig. 3). This finding was verified by the observed significant linear increase in SR with decreasing soil water content (Fig. 4e). In addition, the decreased WT did not result in a change in belowground root biomass (Figs. 3 and 8) and thus did not exert a significant influence on AR, as roots are the main source of AR[15,33]. This explanation was consistent with recent findings that drainage exhibited non-significant impacts on AR across boreal to tropical pristine peatlands[39,52].

Although WT decline significantly promoted SR and HR from pristine peatlands, the magnitudes of the relative changes were also regulated by factors such as the driver and intensity of WT decline, climate zone, and peatland type. Decreases in WT due to agriculture were more extensive than those due to other land uses because the much lower WT could provide more soil aerations for crop growth[53], dropping to more than two meters belowground (Supplementary Figs. 5 and 12) and thus promoting SR and in particular, HR (Fig. 2). This promotion trend was much more obvious in boreal and tropical peatlands (such as bogs, fens, swamps) than in temperate peatlands (such as marshes), as boreal

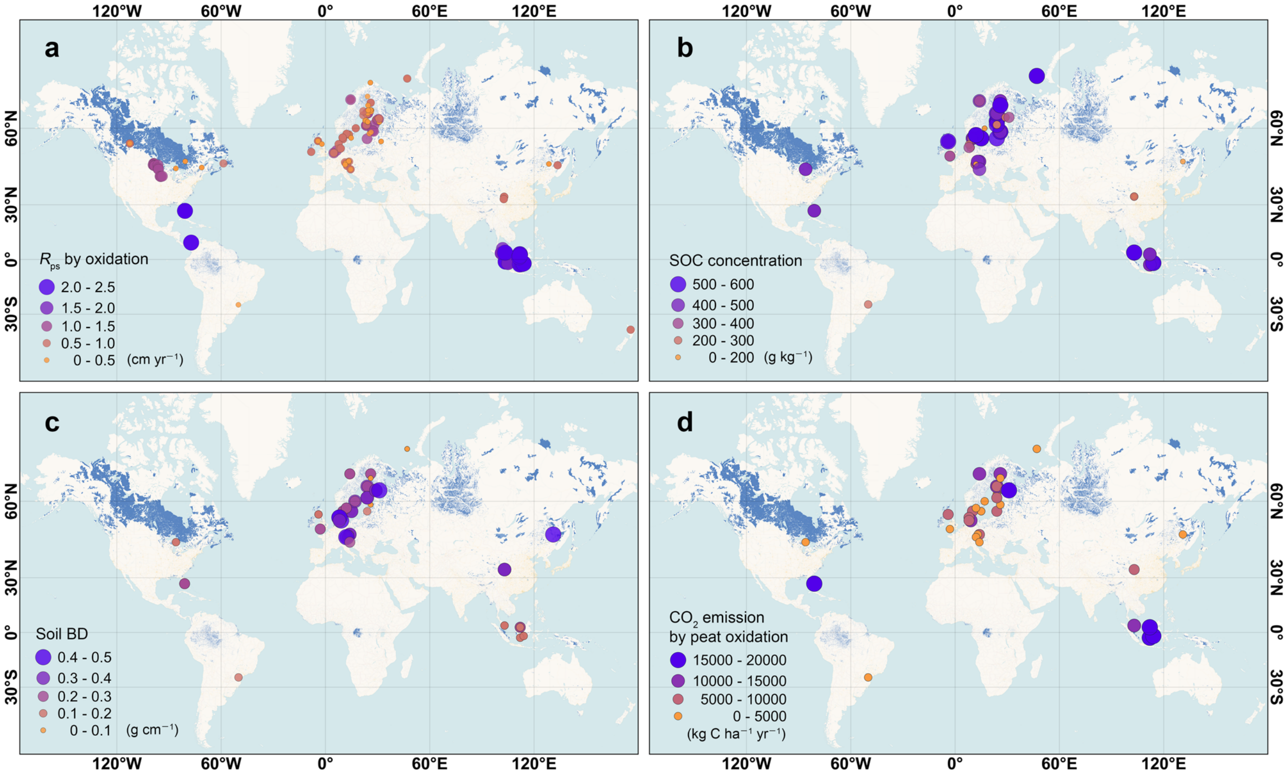

Fig. 6 Peat subsidence rate (R_{ps}) (cm yr^{-1}) due to oxidation and associated soil heterotrophic CO_2 emissions. Spatial variations in the **a** estimated R_{ps} due to oxidation of drained peatlands, **b** soil organic carbon (SOC) concentration (g kg^{-1}) of pristine peatlands, **c** soil bulk density (BD, g cm^{-3}) of pristine peatlands, and **d** estimated soil heterotrophic CO_2 emissions due to peat oxidation (kg C ha^{-1} yr^{-1}) among global drained peatlands. For the calculation processes of R_{ps} and HR, see the Methods. The gray-blue regions indicate the global distributions of peatlands derived from PEATMAT[5].

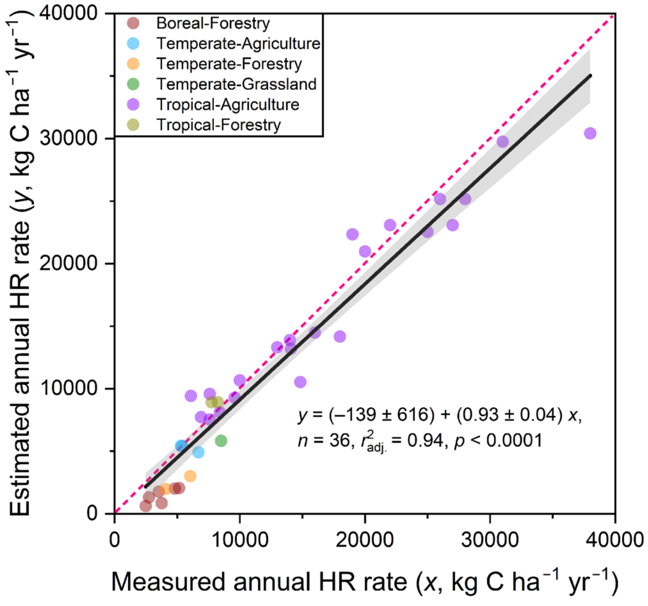

Fig. 7 Linear correlation between the estimated and measured annual soil heterotrophic respiration (HR) rates across climate zones and land uses for drained peatlands. The measured annual HR was synthesized from previous publications. The predicted annual HR was obtained using Eqs. (6–13) in the Methods. The climate zone, land use, and drainage duration information were directly extracted from these publications, which simultaneously reported the measured annual HR. For details related to the estimation of annual HR, see Eqs. (6–13) in the Methods.

and tropical peatlands exhibited significantly higher peat SOC concentrations and peat depths than temperate peatlands (Supplementary Figs. 10a and 13a, b). This result was further verified by the finding that WT declines with larger magnitudes stimulated higher emissions from SR, particularly from HR in pristine peatlands with higher SOC concentrations, than WT declines with smaller magnitudes (Fig. 2 and Supplementary Fig. 13). Moreover, agricultural tillage practices that loosen soils further stimulated peat organic matter decomposition[16,28]. The WT decreases associated with grasslands showed nonsignificant effects on SR and HR, probably because management practices such as grazing and harvesting, which cause trampling, decreased soil porosity and consequently inhibited SR and HR[54,55], thus counteracting the stimulatory effects of WT decline on SR and HR. Additionally, consumption by grazing animals and biomass harvesting reduced litter input[28] and inhibited microbial growth and activity[56] and further reduced soil substrates for microbes[34,53]. Only three sites with peat extraction were involved in our meta-analysis; thus, there are large uncertainties in the results associated with this land-use type, and more research is warranted. The significant increases in SR and HR associated with WT declines due to climate-induced drying suggested that climate change has already impacted C cycles in peatlands[4,8,31]. Our study suggests that climate change mitigation actions, as well as minimizing human disturbances, are crucial for the conservation of pristine peatlands and reductions in soil CO_2 release[7,11,16].

Net emissions of SR and HR from global pristine peatlands due to drainage. Drainage promoted peat organic matter decomposition, as observed by significant increases in HR in our study, and consequently, peat oxidation was considered the overriding contributor to the widespread PS in the drained peatlands[10,11,57].

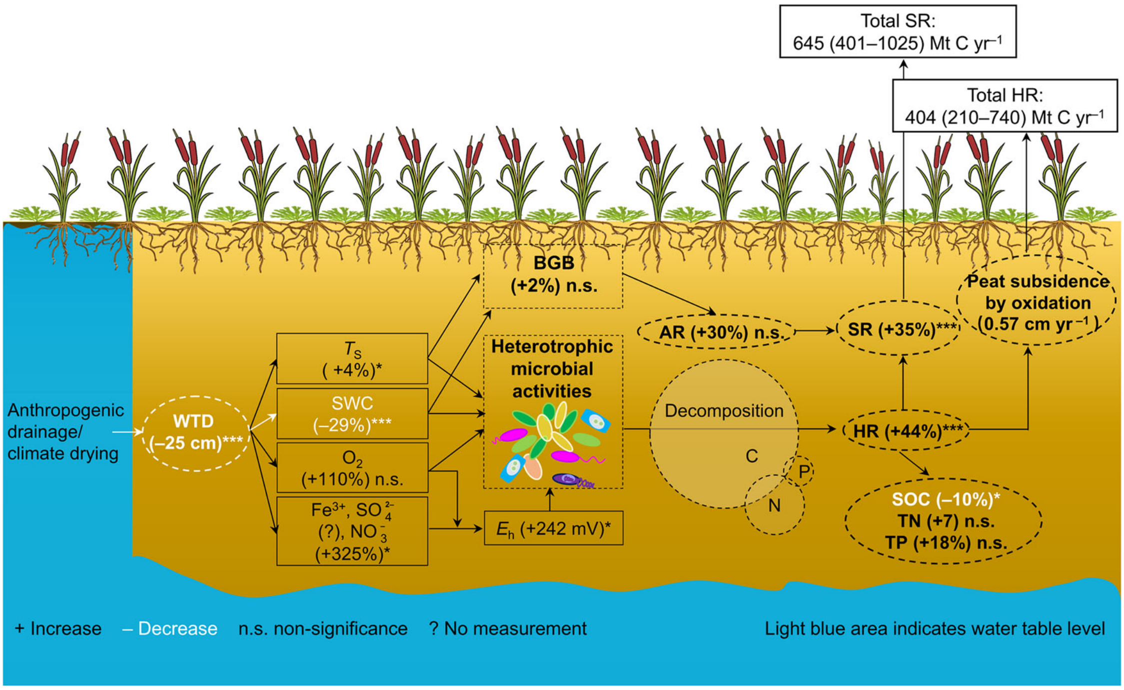

Fig. 8 Conceptual model describing the effects of WT decline on soil carbon emissions and peat subsidence from global pristine peatlands. SR (soil respiration), HR (heterotrophic respiration), AR (autotrophic respiration), WTD (water table depth), T_s (soil temperature), SWC (soil water content), O_2 (soil oxygen content), Fe^{3+} (soil trivalent iron concentration), SO_4^{2-} (soil sulfate concentration), NO_3^- (soil nitrate concentration), E_h (soil redox potential), BGB (belowground biomass), SOC (soil organic carbon concentration), TN (total nitrogen concentration) and SP (soil phosphorus concentration). The asterisks *, **, *** indicate significance at the levels of $p < 0.05$, 0.01 and 0.001, respectively, and n.s. indicates no significance (for details, see Meta-analysis in Methods). The total SR and HR are presented as the means with 95% confidence intervals (for estimation details, see Methods).

The highest R_{ps} due to oxidation was observed in the agriculture-drained tropical peatlands, followed by forestry- and grassland-drained tropical peatlands, and the lowest R_{ps} due to oxidation was observed in the forestry-drained boreal peatlands (Table 1). The warm and humid conditions in tropical regions make them more favorable to peat oxidation when pristine peatlands are drained for agriculture, grassland, or forestry uses than pristine peatlands in temperate and boreal cold environments[12,58]. This finding demonstrated that the R_{ps} due to oxidation was largely dependent on climate zones and land uses, and therefore, these factors should be considered simultaneously when using this parameter for estimating soil HR from global drained peatlands.

In this study, the estimated total annual soil HR in global drained peatlands was 404 Mt C yr^{-1} (95% CI: 210–740 Mt C yr^{-1}) (Table 1). Additionally, after aggregating the R_{ps} due to oxidation in the boreal and temperate drained peatlands under each land use (see Methods, Supplementary Fig. 14), the estimated total annual soil HR in global drained peatlands was 400 Mt C yr^{-1} (95% CI: 226–688 Mt C yr^{-1}) (Supplementary Table 1). The results of these estimates were very similar, indicating that our estimates were robust. Nonetheless, our results suggested that peat oxidation due to drainage was a large source for soil HR, consistent with previous estimates from global drained peatlands (520 Mt C yr^{-1}, area 509×10^3 km^2, ref. [18], 355. Mt C yr^{-1}, area 460×10^3 km^2, ref. [19]).

Previous studies[18,19] estimated only global HR due to drainage, with the consequence that the global SR due to drainage remained unknown. Our study revealed that drained peatlands were global hotspots for SR, with emissions of 645 (95% CI: 401–1025) Mt C yr^{-1} (i.e., 2.36 (1.47–3.76) Gt CO_2 yr^{-1}) (Table 1) or 640 (95% CI: 428–953) Mt C yr^{-1} (i.e., 2.35 (1.57–3.49) Gt CO_2 yr^{-1}) (Supplementary Table 1). These estimates are equivalent to ~14% (8.7–22%) of the total annual CO_2 emissions from all land use changes and contributed 4.6% (3.0–7.3%) to global annual anthropogenic CO_2 emissions (i.e., total emissions from land use change and fossil fuel burning) from 2010 to 2019[6]. Considering the range of the remaining cumulative CO_2 emissions (920–1980 Gt CO_2-eq. (including methane and nitrous oxide)) associated with limiting warming to 1.5 °C (compared to the preindustrial era) by the end of this century[59], our study calls for conserving pristine peatlands and restoring drained peatlands (by rewetting) to reduce peat carbon losses. The potential for enhancing methane emissions through rewetting does not negate the climate change mitigation potential of rewetting degraded peatlands[3,8,20].

Our study also showed that agriculture- and forestry-drained tropical peatlands and agriculture-drained temperate peatlands were the top three emitters of SR, occupying half of global drained peatlands while accounting for ~81% (75–91%) of the total annual SR from global drained peatlands, suggesting that these drained peatlands should be given priority for restoration to reduce peat C loss and mitigate SR effluxes.

Limitations and the way forward. Our meta-analysis included only 35 paired simultaneous measurements of SR, HR, and AR from global pristine and drained peatlands; moreover, these measurements were mainly performed in tropical and boreal peatlands. This limitation probably resulted in some uncertainties in our results showing that decreases in WT due to drainage and climate-induced drying significantly promoted pristine peatland SR, mainly through HR rather than AR, and consequently caused widespread peat subsidence. Performing more simultaneous measurements of soil SR, HR and AR will be beneficial for more reliably assessing the impacts of WT decline on pristine peatland soil carbon effluxes and their feedback to climate change. Additionally, in our study, we were unable to obtain empirical models of R_{ps} or R_{ps} due to oxidation with drainage duration for drained boreal or temperate peatlands, respectively, as we currently lack sufficient measurements for these climate zones. Accordingly, we used two methods (i.e., climate was categorized into boreal, temperate, and tropical or boreal+temperate and tropical types) to constrain the uncertainties in the estimated annual SR and HR from global drained peatlands. Similar results were obtained from these two methods, and these results were in the ranges of the previous two estimates from global drained peatlands. Nevertheless, more observations of these variables should be conducted to support more reliable estimates of the annual SR and HR from drained peatlands. Finally, we did not estimate the annual SR and HR from peatlands affected by peat extraction and climate-induced drying, as the extent of the impact (e.g., the net decreases in WTD, impacted areas and their distributions) remains unknown, underscoring the necessity of considering these potentially important sources of changes in future studies.

Conclusions

Our meta-analysis revealed that water table decline due to drainage and climate-induced drying resulted in significant increases in soil respiration from pristine peatlands, mainly through heterotrophic respiration rather than autotrophic respiration, and consequently intensified positive climate-carbon feedback and induced widespread global peat subsidence. Considerable amounts of peat organic matter were lost in the form of soil CO_2 emissions from global drained peatlands, contributing almost 14% of the total annual anthropogenic CO_2 emissions from all land use changes or 4.6% of the total annual anthropogenic CO_2 emissions from fossil fuel burning combined with land use changes. Therefore, urgent measures, such as conserving global pristine peatlands and restoring degraded peatlands particularly agriculture- and forestry-drained tropical peatlands and agriculture-drained temperate peatlands, are crucial for reducing peat carbon loss and mitigating soil CO_2 emissions.

Methods

Systematic review. We searched relevant publications through Web of Science (all databases), Google Scholar, and the China National Knowledge Infrastructure Database between 1945 and March 2021 with the following combinations of keywords: (drain* OR lower* water table OR standing water depth OR ground water table level drawdown OR decline OR drought OR dry*) with (peatland* OR mire* OR fen OR bog OR swamp OR marsh*) with (soil respiration OR heterotrophic respiration OR microbial respiration OR soil CO_2 OR soil carbon decompos* OR soil carbon minerali* or peat subsidence). Using these search terms, we initially identified 2120 different publications. To reliably evaluate WT decline impacts on SR and peat subsidence-associated soil CO_2 emissions, the following further criteria were applied:

1) Only paired studies with pristine peatland (i.e., undrained, near-natural peatland without direct drainage history) as a control and pristine peatland with direct WT decline (due to drainage and land use or climate-induced drying) as a treatment were included by carefully checking the descriptions of field conditions from the publications. For the pristine peatlands, we included the peatland only if the peat soil had at least 30% dry organic matter, a peat depth of >40 cm[1], and did not have any direct drainage history[2]. We acknowledge that few, if any, untouched and completely pristine peatlands currently exist, particularly in Europe.

2) WT decline in peatlands referred to only the WT depth lowered by drainage or climate-induced drying and/or additional management practices related to C or N input (e.g., manure/N fertilizers); treatments in which WT decline was combined with manipulated warming, elevated CO_2, N deposition, etc., were excluded, while individual treatments (i.e., peatlands affected by WT decline without additional warming, elevated CO_2, N deposition treatments, etc.) were included, as the primary objective of this study was to evaluate the responses of peatland C decomposition to WT decline.

3) Each individual study included SR or at least one of its components (HR and AR), and the measurement intervals were at least monthly. The in situ measurements of SR or its components (HR and AR) covered at least the growing or nongrowing season in temperate/boreal climate zones and the whole wet or dry season in (sub)tropical climate zones.

4) Both in situ and soil core/microcosm/mesocosm measurements of SR or its components (HR and AR) were included. SR and its components were exclusively measured using the chamber method. The results of the latter group were used to test the results of the former.

Finally, 386 paired in situ and 21 paired soil core incubation measurements of SR or its components (HR and AR) were extracted from 63 in situ studies and 9 soil core studies, respectively (see Supplementary Data A). Furthermore, to estimate HR emissions from global drained peatlands, the in situ measured paired peat subsidence rate (R_{ps}, cm yr^{-1}) and drainage duration (i.e., years since first drainage) and the proportion of peat subsidence rate attributed to oxidation (P_o, %) and drainage duration, as well as the soil (0–30 cm) organic C and bulk density in pristine peatlands, were extracted from peer-reviewed publications. In drained boreal and temperate peatlands, most studies measured the total subsidence (in meter) during a certain drainage period, therefore the average R_{ps} was calculated as the ratio of total subsidence and drainage years. It was assumed that the R_{ps} was faster at the beginning and lower at the end of drainage duration, so the average subsidence rate is the rate for the middle year of the drainage duration[41]. The remaining studies directly showed the in situ measured R_{ps} at the ith year of drainage. A similar procedure was applied for the P_o in the ith year of drainage. In sum, 230 paired R_{ps}–drainage duration observations and 49 paired P_o–drainage duration observations, as well as 76 SOC and 63 BD in pristine peatlands, were taken from 80, 25, 58, and 44 studies, respectively (see Supplementary Data B).

Data compilation. To systematically evaluate the impacts of WT decline on SR in pristine peatlands and clarify the underlying mechanisms, we obtained data related to SR and its components (HR and AR) together with environmental variables such as the mean annual temperature [MAT], mean annual precipitation [MAP], peat depth [PD], WT depth [WTD], soil water content [SWC], soil temperature [T_s], soil redox potential [E_h], soil air oxygen level [O_2], soil bulk density [BD], soil pH [pH], soil organic carbon [SOC], soil total nitrogen [TN], soil total phosphorus [TP], soil ammonium [NH_4^+], soil nitrate [NO_3^-], soil dissolved organic carbon [DOC], microbial biomass carbon [MBC], microbial biomass nitrogen [MBN], dissolved total phosphorus [DTP], belowground biomass [BGB], iron [Fe^{3+}, Fe^{2+}] and sulfate [SO_4^{2-}] when possible. If available, other important information, such as geographic location (latitude, longitude), climate and WT decline driver and duration, intensity, peatland type, R_{ps}, P_o, nutrient type, inundated condition, microtopography, and plant functional types, was recorded. For WT decline intensity, net WT declines greater and less than 30 cm were defined as deep and shallow declines, respectively, according to the IPCC wetland report[42]. The abovementioned information about pristine peatlands and peatlands affected by WT decline is compiled in Supplementary Data A and B.

We subsequently extracted the mean ($\bar{X}$), standard deviation (SD) and replicates (n) from different publications. If studies reported standard error (SE) rather than SD, then SD was calculated by SE $\sqrt{n}$. If studies reported only the median, maximum, minimum, and 25th and 75th percentiles, then the mean and SD were estimated following the mathematical equations recommended by ref. [60]. If neither SD nor SE was reported, then the missing SD was estimated by multiplying the reported mean by the average coefficient of variation (CV) obtained from the remaining observations, resulting in both the mean and SD being reported[61]. The data were either obtained directly from tables and texts or extracted by digitizing graphs using Getdata Graph Digitizer software (version 2.26, Russia).

The final database consisted of 250 paired SR, 101 paired HR and 35 paired AR in situ observations. Only 35 paired observations simultaneously reported SR, HR, and AR. Twenty-one paired SR soil core incubation measurements were also collected to test the results of the in situ measurements. The dataset mainly originated from Europe, North America, and Southeast Asia, and most studies (>70%) were conducted in temperate and boreal peatlands in the Northern Hemisphere (Fig. 1a). Moreover, 230 paired R_{ps}–drainage duration observations and 49 paired P_o–drainage duration observations (Fig. 5a, b) and an additional 485 drainage year (Supplementary Fig. 9) observations classified by climate zone (i.e., boreal, temperate and tropical) and land use (i.e., agriculture, forestry, and grassland) were collected. A total of 76 SOC and 63 BD measurements from pristine peatlands categorized by climate zone (i.e., boreal, temperate, and tropical) were extracted to estimate R_{ps} by oxidation and associated soil HR from global pristine peatlands due to drainage activities (Supplementary Fig. 10 and Supplementary Data B). In this study, we were unable to estimate climate drying-induced net CO_2 emissions through soil HR, as the areas of pristine peatlands affected by climate drying currently remain unknown.

Meta-analysis. To assess the relative changes in SR and its components (HR and AR), as well as environmental variables (e.g., SOC, BD, T_s, etc.) due to WT decline, the log-transformed response ratio (RR) was used:[62]

$$\ln(\mathrm{RR}) = \ln(X_t/X_c) \tag{1}$$

The results are presented as the percent change (($e^{\ln\mathrm{RR}}$ − 1) × 100). The variance (v) of RR was estimated using the following equation:

$$v = \frac{\mathrm{SD}_t^2}{n_t X_t^2} + \frac{\mathrm{SD}_c^2}{n_c X_c^2} \tag{2}$$

where X_t and X_c indicate the means of the treatment and control, SD_t and SD_c

indicate the SDs of the treatment and control and n_t and n_c indicate the numbers of replicates in the treatment and control, respectively.

However, in our study, approximately 60% of the WTD and E_h observations for the peatlands in pristine condition (control) and affected by WT decline (treatment) showed opposite signs; e.g., the pristine peatlands generally exhibited positive WTDs (higher than the peat surface) and negative E_h values, while those affected by WT decline exhibited negative WTDs (lower than the peat surface) and positive E_h values. Since it is impossible to calculate the logarithm of negative values, we introduced a new study index (net changes) for these two variables in our meta-analysis according to ref. [63]:

$$D = X_t - X_c \tag{3}$$

where X_t and X_c indicate the paired annual mean WTD and E_h for the treatment and control, respectively, and D indicates the difference between the treatment and control.

The SD and variance (v) of D were estimated using the following equation:

$$SD = \sqrt{\frac{(n_c - 1)\,SD_c^2 + (n_t - 1)\,SD_t^2}{n_c + n_t - 2}} \tag{4}$$

$$v = \frac{SD_t^2}{n_t} + \frac{SD_c^2}{n_c} \tag{5}$$

where SD_t and SD_c indicate the SD of the treatment and control and n_t and n_c indicate the number of replicates for the treatment and control, respectively.

The weighted mean RR or D was calculated by individual RR or D with bias-corrected 95% confidence intervals (CIs) using the rma.mv function in the metafor package in R software (R core team, 2019)[64], in which the variable "study" was regarded as a random effect to account for the dependence of observations derived from the same study. The impact of WT decline on a response variable was considered significant if the 95% CI did not overlap 0[65]. Differences between subgroups (e.g., WT decline driver, climate zone, drainage duration) were considered significant if the 95% CIs did not overlap each other[65]. The frequency distribution of RR was calculated to test variability among individual studies using the Gaussian function (i.e., normal distribution)[66].

Estimation of peat subsidence rate by oxidation and associated HR rate. Drainage has induced widespread peat subsidence and associated large CO_2 release through soil HR and consequently reduced the sustainable utilization of drained peatlands and contributed to global warming[11,12]. In this study, we estimated the spatial patterns of R_{ps} by oxidation and associated soil HR from global drained peatlands. Using the 230 paired R_{ps} and drainage duration observations synthesized in this study, we first constructed empirical models between R_{ps} and drainage duration for drained peatlands categorized by climate zone (boreal, temperate and tropical climate) and land use (i.e., agriculture, forestry and grassland) (Fig. 5a, b). The values of R_{ps} for certain groups classified by climate zone and land use could be estimated by using the corresponding empirical models established in this study and reported drainage durations that were extracted from the literature. The empirical models categorized by climate zone and land use are listed below (Fig. 5a, b):

$$R_{ps}\text{-Bor-Tem-Agr} = 13.95\,\mathrm{Dur}^{-0.58},\ n = 48,\ R^2_{adj.} = 0.85,\ p < 0.0001 \tag{6}$$

$$R_{ps}\text{-Bor-Tem-For} = 5.36\,\mathrm{Dur}^{-0.83},\ n = 21,\ R^2_{adj.} = 0.92,\ p < 0.0001 \tag{7}$$

$$R_{ps}\text{-Bor-Tem-Gra} = 5.55\,\mathrm{Dur}^{-0.36},\ n = 40,\ R^2_{adj.} = 0.61,\ p < 0.0001 \tag{8}$$

$$R_{ps}\text{-Tro-Agr-For-Gra} = 6.63\,\mathrm{Dur}^{-0.37},\ n = 121,\ R^2_{adj.} = 0.55,\ p < 0.0001 \tag{9}$$

where R_{ps} indicates the peat subsidence rate (cm yr^{-1}), Dur is the drainage duration, and the numbers indicate coefficients for the established empirical models. Bor, Tem, and Tro indicate boreal, temperate, and tropical climate zones, respectively. Agr, For, and Gra represent agriculture, forestry, and grassland land uses, respectively. We note that it was not possible to further distinguish these models between boreal and temperate climate zones and among agriculture, forestry, or grassland land use in tropical climates, as there is currently a lack of sufficient measurements, which warrants more research.

However, the R_{ps} is triggered by a combination of processes such as physical compaction by heavy equipment or livestock trampling and shrinkage through contraction of organic fibers when drying, consolidation by loss of water from pores in the peat and oxidation owing to the breakdown of peat organic matter[10–12]. Therefore, to reliably estimate the soil HR rate from R_{ps} due to oxidation, the proportion of R_{ps} attributed to oxidation (P_o, in %) should be considered[12]. Using the 49 paired P_o and drainage duration observations synthesized in this study, we then constructed empirical models between P_o and drainage duration for drained peatlands that were also categorized by climate zone (boreal, temperate, and tropical climate) and land use (agriculture, forestry, and grassland) (Fig. 5c, d). Similarly, the P_o values of certain groups classified by climate zone and land use could be estimated by using the corresponding empirical models established in this study and reported drainage durations that were extracted from the literature. The empirical models categorized by climate zone and land use are shown below (Fig. 5c, d):

$$P_o\text{-Tem-Bor-Agr-For-Gra} = 12.05\,\mathrm{Ln(Dur)} + 2.15,\ n = 30,\ R^2_{adj.} = 0.89,\ p < 0.0001 \tag{10}$$

$$P_o\text{-Tro-Agr-For-Gra} = 14.36\,\mathrm{Ln(Dur)} + 37.05,\ n = 19,\ R^2_{adj.} = 0.81,\ p < 0.0001 \tag{11}$$

where P_o indicates the proportion of R_{ps} attributable to oxidation, Dur is the drainage duration, and the numbers indicate coefficients for the established empirical models. The abbreviations Bor, Tem, Tro, Agr, For, and Gra have been described previously. We note that the different land uses shared the same models across temperate and boreal climates and tropical climate due to a lack of sufficient global observations. This will also induce some uncertainties in our analysis.

Furthermore, the soil HR (F_{HR}, Mt C yr^{-1}) due to peat oxidation induced by drainage was estimated using the following equation according to ref. [11]:

$$F_{HR} = \sum R_{ps,i,j} \times P_{o,i,j} \times SOC_i \times BD_i \times A_{i,j} \tag{12}$$

where SOC (g kg^{-1}) and BD (g cm^{-3}) indicate the soil (0–30 cm) organic C concentration and bulk density of pristine peatlands, respectively; A ($\times 10^3$ km^2) indicates the drained peatland area; i indicates the climate zone (boreal, temperate or tropical); j indicates the land use (agriculture, forestry or grassland); and R_{ps} (cm yr^{-1}) and P_o (%) are described in Eqs. (6–11). Datasets of the SOC concentration and BD and R_{ps} due to oxidation were systematically reviewed and bootstrapped and categorized by climate zones and land uses (see Supplementary Fig. 10 and Supplementary Data B). Regarding the large uncertainties for areas of drained peatlands, we combined two previously published datasets (72, 61, 22, 37, 43, 26, 94, 109, and 39 × 10^3 km^2 by ref. [18], and 37, 55, 4, 109, 63, 58, 96, 72, and 1 × 10^3 km^2 by ref. [20]. for agriculture-, forestry- and grassland-drained peatlands in boreal, temperate and tropical climate zones, respectively) and obtained their mean values with 95% CIs (for details, see bootstrapping procedure in Data analysis). Uncertainties (i.e., 95% CI) in total HR (δF_{HR}) were propagated according to the Gaussian random error propagation principle as follows:

$$\delta F_{HR} = \sqrt{\sum \sqrt{\begin{array}{l}(\delta R_{ps,i,j})^2 \times (P_{o,i,j} \times SOC_i \times BD_i \times A_{i,j})^2 + \\ (\delta P_{o,i,j})^2 \times (R_{ps,i,j} \times SOC_i \times BD_i \times A_{i,j})^2 + \\ (\delta SOC_i)^2 \times (R_{ps,i,j} \times P_{o,i,j} \times BD_i \times A_{i,j})^2 + \\ (\delta BD_i)^2 \times (R_{ps,i,j} \times P_{o,i,j} \times SOC_i \times A_{i,j})^2 + \\ (\delta A_{i,j})^2 \times (R_{ps,i,j} \times P_{o,i,j} \times SOC_i \times BD_i)^2\end{array}}} \tag{13}$$

where δF_{HR}, δR_{ps}, δP_o, δSOC, δBD, and δA indicate the 95% CIs of total soil HR, R_{ps}, P_o, SOC, and BD and drained peatland area, respectively, and i and j indicate the climate zone (boreal, temperate, tropical) and land use (agriculture, forestry, or grassland), respectively.

To further estimate the total SR (F_{SR}, Mt C yr^{-1}) and its uncertainty (δF_{SR}) from global drained peatlands, the following equations were used:

$$F_{SR} = \sum \frac{F_{HR,i,j}}{C_{HR,i,j}} \tag{14}$$

$$\delta F_{SR} = \sqrt{\sum \sqrt{\left(\frac{1}{C_{HR,i,j}}\right)^2 \times \delta F^2_{HR,i,j} + \left(-\frac{F_{HR,i,j}}{C^2_{HR,i,j}}\right)^2 \times \delta C^2_{HR,i,j}}} \tag{15}$$

where C_{HR} (%) indicates the mean relative contribution of HR to SR from simultaneously measured SR, HR, and AR from our meta-analysis (see Supplementary Fig. 11 and Supplementary Data A) and i and j indicate the climate zone (boreal, temperate, tropical) and land use (agriculture, forestry, or grassland), respectively. F_{HR} and δF_{HR} are given in Eqs. (12, 13). We note that the C_{HR} could be classified only by climate zone, as there is a lack of sufficient measurements of land use; that is, the different land uses under the same climate shared the same C_{HR} value, which may induce uncertainties in estimating the total SR from global drained peatlands.

Regarding the abovementioned lack of sufficient measurements for distinguishing between boreal and temperate drained peatlands, we also used another method to estimate the annual total HR and SR from global drained peatlands. Specifically, we obtained the mean values of R_{ps} by oxidation across boreal and temperate drained peatlands for each land use (i.e., climate zones were classified as boreal+temperate or tropical) (Supplementary Fig. 14 and Supplementary Table 1). The estimation process was the same as that previously described. The different estimation methods were likely to provide results with greater convergence.

Data analysis. Significant differences in observed variables were tested by performing nonparametric analysis. Specifically, tests with two independent samples (i.e., Mann–Whitney U test) were used for only two variables (i.e., to compare the contribution of HR to SR between pristine and drained peatlands), and tests with two or more independent samples (i.e., Kruskal–Wallis test and pairwise comparisons) were used if there were three or more variables (i.e., SOC, BD and R_{ps} due to oxidation in the boreal, temperate and tropical climate zones or different land uses). Linear or nonlinear regression analysis was performed to examine the relationships between the responses of SR and its components with environmental variables or the peat subsidence rate with drainage duration.

To reliably estimate the uncertainties in R_{ps} by oxidation, SOC, BD, drained peatland area, and relative contribution of HR to SR, bootstrap resampling with 10000 iterations was conducted using the boot package, and 95% CIs were calculated using the "basic" type. The ggplot 2 package in R software (R core team, 2019) was used for statistical analysis. Data were expressed as the means with their 95% CIs, and significance of the regression analyses was indicated at the level of $p < 0.05$ across the study.

Data availability

The global distributions of peatlands were obtained from https://www.sciencedirect.com/science/article/pii/S0341816217303004#s0035. All data used in this study were submitted as Supplementary data files which can be freely available at https://zenodo.org/record/7092932#.Y0fWi7ZBxPY.

Code availability

For enquiries about code availability, please contact the corresponding author.

Received: 15 October 2021; Accepted: 14 October 2022;
Published online: 29 October 2022

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Acknowledgements

We sincerely appreciate the researchers at all stations across the peatlands worldwide for their work under the harsh climate and efforts to make their datasets publicly accessible. Their contributions regarding the establishment of experimental platforms and measurement of the soil respiration and its components, and peat subsidence rates, as well as environmental factors made this study possible. This study was financially funded by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (Grant No. 2019QZKK0103) and "Double First-Class" Special Guidance Project of Lanzhou University (grant No. 561120206). We also acknowledged the technical help from Ms. Huiling Chen during mapping the global distributions of peatlands.

Author contributions
L.M. and H.C.Z. conceptualized the study, L.M. synthesized, compiled, and analyzed the data, L.M. drafted the first manuscript, K.Z. constructed the global peatland distribution map, and L.M., G.F.Z., B.L.C., K.Z., S.L.N., J.S.W., P.C., and H.C.Z. revised the manuscript and approved the final version.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-022-00590-8.

Correspondence and requests for materials should be addressed to Hongchao Zuo.

Peer review information *Communications Earth & Environment* thanks Haojie Liu, Jasper Steenvoorden, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Erika Buscardo and Clare Davis. Peer reviewer reports are available.