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Improved estimates of carbon dioxide emissions from drained peatlands support a reduction in emission factor

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Under the United Nations Framework Convention on Climate Change, Annex 1 countries must report annual carbon dioxide (CO_2) emissions from peatlands drained for extraction. However, the Tier 1 emission factor (EF) provided in the IPCC 2014 Wetland Supplement is based mainly on warm season data from a limited number of sites. Here we evaluate the current IPCC EF and revise it with newly published data. The updated EF is 2.46 ± 0.25 t C ha^{-1} yr^{-1}, a 12% reduction and a threefold decrease in the confidence interval compared to the current IPCC (2014) EF. We generate a Tier 3 EF, 1.4 ± 0.25 t C ha^{-1} yr^{-1} for a typical extraction site in eastern Canada using numerical CoupModel that explicitly considers seasonality and interannual climatic variability, and suggest how to account for seasonality for the previously published EFs. This reduction has implications for comparing alternatives to peat-based growing substrates, the assessment of offsets, and possible punitive carbon taxes or cap-and-trade schemes.

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Worldwide, ~14 million metric tons of peat is used for horticulture annually[1–3] and there is currently a debate about alternative growing media to replace peat, mainly due to the nonrenewable nature of peat and the large greenhouse gas emissions during extractions[1,4]. Approximately 12% of the global peatland area (381–463 M ha) has been degraded due to drainage and land-use change, including for peat extraction[5–10]. Owing to the increased microbial oxidation of stored carbon (C) and elimination of vegetation, peatlands managed for extraction emit carbon dioxide (CO_2) for decades to centuries if not restored[11–14]. However, quantification of these CO_2 emissions is still uncertain[7,15]. While estimates of global peat extraction areas are converging (1 to 2 M ha)[7,15], the emission factors (EFs, t CO_2-C ha^{-1} yr^{-1}) used to estimate the total emissions from the field (excludes the decomposition of extracted peat and particulate emission during the extraction) differ substantially. Currently, the EFs used in the national reporting required for Annex 1 countries of the United Nations Framework Convention on Climate Change (UNFCCC), vary from 0 to 3800 t CO_2-C ha^{-1} yr^{-1} with an average between 5 to 8.2 t CO_2-C ha^{-1} yr^{-1} (change over reported years, see Methods), which differs significantly from the 2.8 (95%CI, 1.1-4.2) t CO_2-C ha^{-1} yr^{-1} from the most recent IPCC EF[13].

Measured data represent the main resource for estimating the EFs and these data have been assembled to form the basis of the IPCC Tier 1 (default) methodology for emission reporting[16]. As more data become available, the IPCC EF for peat extraction has been updated. In the initial 1996 IPCC guideline for national greenhouse gas emission reporting, two EFs based on peatland nutrient status were suggested: nutrient-poor organic soil with an EF of 0.2 (0–0.63) t CO_2-C ha^{-1} yr^{-1} (IPCC EF database ID 513525) and nutrient-rich organic soil with an EF of 1.1 (0.03–2.9) t CO_2-C ha^{-1} yr^{-1} (IPCC EF database ID 513526)[17]. Only four studies, all from Finland or Sweden, were used to generate these EFs, and all sites were assumed a relatively shallow water table and not necessarily under peat extraction. In the 2006 guidelines, no update of the CO_2 EF for peat extraction was made (see Table 7.4 Chapter 7)[16]. Updates for peatland managed for peat extraction were made in the 2013 supplement to the 2006 IPCC guidelines (see Chapter 2). In this Supplement, the updated Tier 1 EF for the boreal and temperate zones, 2.8 (1.1–4.2) t CO_2-C ha^{-1} yr^{-1}, is much higher compared to the previous EFs, and is based on 10 study sites from Finland, Sweden and Canada, but is not further disaggregated by climate/vegetation region, nutrient level or drainage/management conditions[13]. Wilson, et al. [11] have critically reviewed the IPCC 2014 Tier 1 EF and compiled new data from Ireland and the UK. They proposed a Tier 2 Ireland-UK EF for peat extractions that is 40% lower than the IPCC (2014) Tier 1 EF. No updates were made in the most recent 2019 refinement to the 2006 IPCC guidelines (see Chapter 7)[18] despite many extra data having been published. He, et al.[19] used a process-based simulation model, CoupModel, to estimate the CO_2 emissions due to drainage and climate for an ongoing peat extraction site in eastern Canada. The model reproduces the measured emission data well and thus can be used to address IPCC Tier 3 EF (i.e. process-based modeling). All Tiers are intended to provide unbiased estimates, however, uncertainties are expected to decrease from Tier 1 to Tier 3[13].

To reduce current large uncertainties in the EF we first compiled a database of the available published emission data from peat extraction sites (see Methods). The new database contains 22 studies, doubling the number of studies included in the current IPCC 2013 Wetland Supplement, and includes regions such as Russia, the UK, Ireland, and middle/southern Europe that were previously not represented. The new database can be used to revise the current IPCC Tier 1 EF, and the larger number of emission measurements and environmental variables enables further disaggregation into specific EFs for climate/vegetation region, nutrient level, or drainage/management conditions. Second, we analyzed the dataset and highlight some of the shortcomings in directly using literature data to generate EFs and suggest these EFs have a bias towards summer measurements. We then present a method that combines a process-based model and field data to explicitly consider seasonality and climate variability in EF estimation. Finally, a simple approach of using the cumulative probability density distribution function of air temperature to correct seasonality is presented for future EF generation when measured data does not cover an entire year. Our results show current reporting largely overestimated CO_2 emissions from peat extraction.

Results

Revising IPCC (2014) emission factors. Using the new database, expanding the one in the IPCC 2013 Wetland Supplement, results in a default CO_2-C EF for northern peatlands managed for peat extraction of 2.46 ± 0.25 (95%CI 1.96–2.97) t CO_2-C ha^{-1} yr^{-1} ($n = 56$), a 12% reduction and a threefold decrease in the Confidence Interval compared to the current IPCC (2014) EF, 2.80 ± 0.76, (95%CI 1.17–4.43) t CO_2-C ha^{-1} yr^{-1} ($n = 20$) (see Methods and Supplementary Table 1). Grouping the emission data by the mean of water table depth over the measured period into deep (≥0.3 m below surface) and shallow (<0.3 m) drainage (see Methods) leads to significantly different ($p = 0.009$) EFs of 2.85 ± 0.43 (1.96–3.74) t CO_2-C ha^{-1} yr^{-1} ($n = 29$) and 1.37 ± 0.40 (0.38-2.35) t CO_2-C ha^{-1} yr^{-1} ($n = 7$), respectively. The published seasonal emission rates increase linearly with increasing water table depth ($p > 0.05$) and future revisions of the IPCC Tier 1 EF should include separation by drainage conditions. No significant statistical differences in EFs were found between ongoing versus abandoned/non-restored extraction sites, and for climate/vegetation zone, nutrient level, (historical) extraction method, and width of the field (see Methods and Supplementary Table 1). There was some evidence that seasonal emission rates increase with lower peat von post (VP) index ($R^2 = 0.17$, $p = 0.06$) and lower soil C/N ratio ($p > 0.05$). The number of years since site abandonment does not influence the emissions, and the long-term climate variables (air temperature and precipitation) show poor correlations with the emission sizes across sites.

Overall, the new database provides information for revising the current IPCC Tier 1 EF, but more importantly, it highlights the following shortcomings of directly using literature data to generate EFs. First, only five (out of 22) studies have reported year around data. A majority of the literature data was measured in the summer or growing season, which focuses on the peak emissions. Only one study used the eddy covariance method for continuous measurements but did not cover winter. All the other studies had a measurement frequency of monthly (majority) or weekly intervals (Supplementary Table 1). Second, a majority of the literature data was from only a single year, with six studies reporting two years, three for three years, and only two studies reporting four years (Supplementary Table 1). However, the long-term records on CO_2 net ecosystem exchange from undisturbed northern peatlands show considerable year-to-year variability[20–25]. Therefore, the EF generated by averaging available literature data could be biased by ignoring the seasonality and climate variability of CO_2 emissions[11,26,27].

Model-based EF to include the effect of seasonality and interannual climate variability. We argue only using the peak emission data measured in the warm season for generating EFs substantially overestimates the annual field emission. We use a

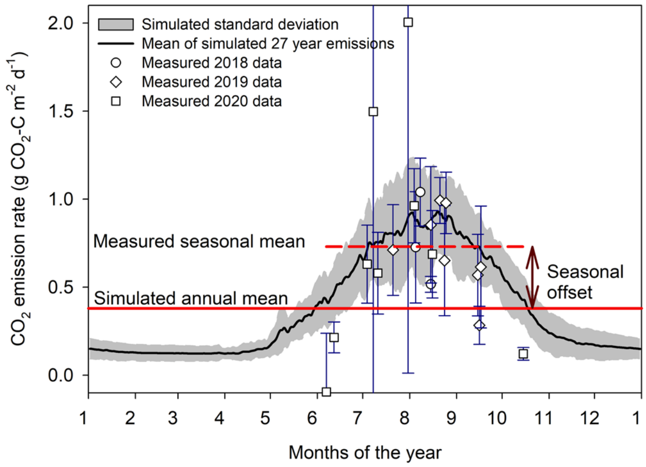

Fig. 1 Measured and simulated CO_2 emission rate. Measured seasonal CO_2 emission rate[14] for a peatland managed for extraction in eastern Canada, Rivière-du-Loup site and simulated data as mean of a 27-year CoupModel run using nearby (<1 km) climate data (station Rivière-du-Loup, ID 7056616) from 1994 to 2020. CoupModel was earlier evaluated against a detailed dataset from 2018 to 2021[19] (see Methods). Error bar indicates the standard deviation of the replicate measurements.

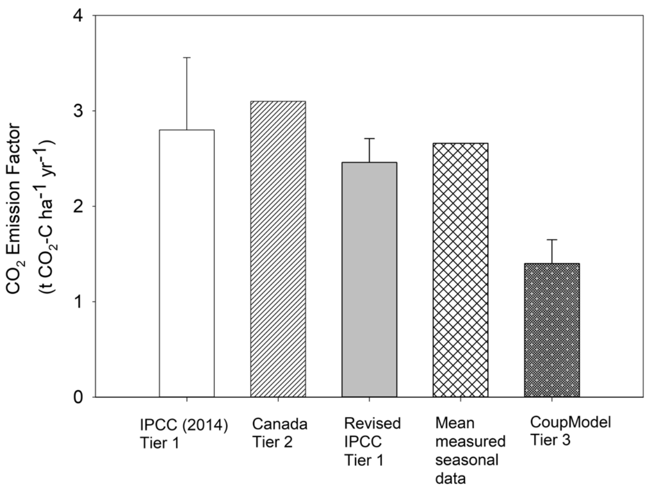

Fig. 2 CO_2 emission factors (EFs). EFs generated with different approaches for peatlands managed for extraction: Canada Tier 2 EF is for the drained areas[29], revised IPCC Tier 1 is from the dataset compiled in this study, mean of seasonal data measured in[14] and CoupModel Tier 3 EF using data from the Rivière-du-Loup site. Error bar of IPCC Tier 1 EFs indicates the standard deviation from compiled multi sites while error bar of CoupModel Tier 3 indicates the standard deviation over the simulated 27 years.

process-based model combined with field flux data and local long-term climate data to generate improved EFs for an eastern Canadian peat extraction site that explicitly considers seasonality and climate variability and thus represents an IPCC Tier 3 EF. The site was originally a forested continental peat bog with an average peat depth of ~4 m[28] that was vacuum harvested for 15 years, with a ~1 m depth and 30 m apart parallel drainage ditches (with more detailed information in the Methods section and He, et al.[19]).

The first approach is the average of our measurements from June to September over three years[14], which results in 0.73 g C m^{-2} d^{-1} (Fig. 1) corresponding to an EF of 2.66 t CO_2-C ha^{-1} yr^{-1}, close to that of the 2014 IPCC Tier 1 EF (Fig. 2). The corresponding simulated average is 0.72 g C m^{-2} d^{-1} (Fig. 1). A second approach is an average of simulated emissions using 27 years of local climate data to explicitly incorporate the influence of climate variabilities (see Methods)[14,19]. The simulated annual average CO_2 emission was 0.38 g C m^{-2} d^{-1} (Fig. 1), corresponding to 1.4 ± 0.25 t CO_2-C ha^{-1} yr^{-1} (Fig. 2), and ranging from 0.80 to 1.90 t CO_2-C ha^{-1} yr^{-1}, highlighting the influence of annual climate variation. The simulated annual average is 52% lower than the annual mean calculated from our measurements from June to September at the same extraction peatland (Fig. 2). This means that a typical horticulture peat extraction site in operation for 15 years with a continental climate in eastern Canada, would in average emit ~1.4 t CO_2-C ha^{-1} yr^{-1}. Our model-based EF is 50 % lower than the current IPCC Tier 1 and 55% lower than the domestic Tier 2 EF (3.1 t CO_2-C ha^{-1} yr^{-1}) that Canada is currently using for national greenhouse gas reporting (Fig. 2)[29]. The difference can be explained by our model-based EF additionally considers seasonality and climate variability (Fig. 1).

Discussion

Our results show the current EFs used for CO_2 emission reporting for peat extraction are overestimated by ~50% for eastern Canadian sites owing to not considering seasonality, and climate can additionally contribute to ~20% of annual emission variation. The difference between the EFs can be largely attributed to the fact that the data used to estimate the Tier 1 and 2 EFs are measured in the warm season and linearly extrapolated into annual numbers, which overestimates emissions from the cold season. Since most of the empirical data in the IPCC analysis lack seasonality and interannual variability, the results from eastern Canada are not likely due to significantly different peatlands, and therefore our results have broader applicability.

Data in the literature show the contribution of nongrowing season to annual CO_2 emission varies from 11% in Quebec, Canada[29], 6.5 to 17% in Finland[26] and 19% in Germany[30]. Our simulated non-growing season (Nov 1st to April 30th, 6 months) flux averaged over 27 years accounted for 19% of the annual emission, similar to the range reported in the literature.

An EF based on empirical observations is subject to the environmental conditions and the time of year the measurements were made, and transferring these into an annual EF that can be used for national reporting needs careful attention. It is unclear how the seasonality of each site included in the IPCC was handled. Our re-compilation of the literature data (of the 10 sites) suggests no seasonal correction was made as the averages of the seasonal data agree with the Tier 1 EF (see Supplementary Table 1). This suggests a revisit of the current EF by the IPCC is needed, together with additional data and possible disaggregation of EF into subgroups. Directly transferring the ratio of growing season emissions to annual emissions from one site to another is not possible, since the influence of seasonality and interannual variability is geographically dependent. Ideally, if the data were available, a suite of regional runs for extraction peatlands could be done to include seasonality and interannual variability. However, given that CO_2 emission is highly correlated with air temperature[11,19], we developed a simple bookkeeping model by using the cumulative probability density distribution function (CDF) of annual mean air temperature to account for the seasonality of the measured data if it covers an incomplete year (see Methods). As an example, we applied the CDF method to data measured in the eastern Canada site and the 10 sites of the IPCC (2014). The results show depending on the measured period, a correction factor from 0.5 to 0.7 is needed to convert the measured seasonal emissions into annual averages (Fig. 3). This ratio, (i.e. correction factors) differs for each geographical region.

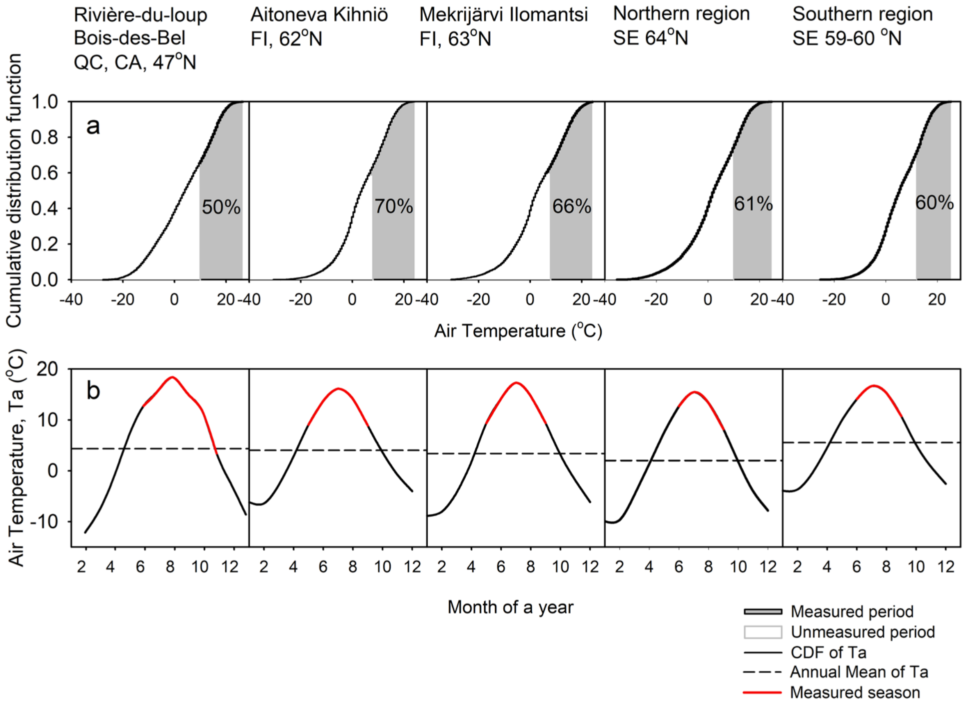

Fig. 3 Bookkeeping model results for the sites in IPCC (2014). Cumulative probability density distribution (CDF) of long-term mean air temperature (**a**, Ta), mean Ta and measured season (**b**) for the 10 peat extraction sites used in deriving the IPCC (2014) Tier 1 EF (Country code CA-Canada, FI-Finland, SE-Sweden). The integrated area ratio of the CDF over the measured period (i.e. grey areas in **a**) represents the proportion of a year the measured data covers and can be used to correct the EFs.

While the EU and UK are phasing out peat use[30], Canada remains a major producer and exporter of horticultural peat. Currently, the total area of peatland under extraction and unrestored area in Canada is estimated to be ~26,000 ha[29]. Assuming the same EF for active and non-restored former extraction sites as our literature data analysis suggests, the total onsite (not including emissions from peat after use) CO_2 emissions, using our Tier 3 EF, would be ~36,400 t CO_2-C yr^{-1} (or 0.13 Mt CO_2 yr^{-1}) corresponding to a ~55% lower than current estimates in national reporting. The C taxation and cap and trade policy in Canada would influence the peat extraction sector considerably. Given the current C price set by the Canadian government of ~65 CA$ per t of CO_2 emitted (expected to increase to ~170 CA$ per t in 2030)[31,32], depending on how the emission accounting will be done using our model-based EF or the domestic Tier 2 EF, this would result in an annual taxation difference of ~11 million CA$ (28 million CA$ in 2030) for the horticultural peat extraction industry. In addition, some of the peat harvested would further return to the atmosphere after use for horticulture within a few years. Over 2019–2021, 1.55 M t peat was produced annually in Canada which is roughly equivalent to 0.39 M t C[29]. Currently, it is assumed 5% of the peat will be lost after one year of horticultural use[33], this gives an additional emission of ~1.1 M t CO_2 yr^{-1} in 2021, calculated by the extracted volumes since 1990 and assuming that all losses take place in Canada. If including these emissions from peat after use into the total emission accounting, the peat extraction sector in Canada would emit 1.23 M t CO_2 yr^{-1}, and the total C tax, including emissions from the field, use and after use, would be ~80 M CA$ (209 M CA$ in 2030). A small amount of the emissions are offset when best practices of ecological restoration strategies are used after peat extraction[12], but to reach net-zero emissions, to offset the large amount of emissions during and, more importantly, after the extraction phase, large C uptake from other sources will be additionally needed. Taxation creates incentives for contemporary emission reductions but does not reduce the historical loading of atmospheric CO_2 by the peat industry. Therefore, our improved accounting of emissions has important implications for the C taxation of the peat extraction industry and the assessment of the alternative substrate of growing media for horticulture.

Methods

Data collection and processing. We first compiled the CO_2 emission data and the corresponding environmental/climate factors, site/peat properties, measurement period/method, and drainage/site/management parameters from the literature that were used to derive the Tier 1 default emission factor provided in the IPCC 2013 Wetland Supplement (Supplementary Table 1). We compiled new data (until March 2023) that have been published since the publication of the IPCC Wetland Supplement (2014) and data previously not included, following the general 2006 IPCC Guidelines for emission data inclusion[16]. Overall, this leads to 12 new studies (Supplementary Table 1). For the total number of observations (n), we adopt the same approach by counting (sub-) sites per measured season as used in the IPCC (2014)[13], and $n = 56$ in the new dataset compared to $n = 20$ in the IPCC (2014)[13]. Details of the dataset can be found in the Supplementary Table 1. Data on EF and total extracted areas of peat extraction used for national reporting were collected from the most recent national inventory report of the Annex 1 countries to UNFCCC (https://unfccc.int/ghg-inventories-annex-i-parties/2021).

Emission group categorization and classification. We grouped the data into different categories based on environmental conditions, management, peat properties etc., and conducted the statistical analysis to test if the selected variable showed regularities of the CO_2 emissions. The grouping criteria mostly followed the IPCC guidelines[16]. For instance, we grouped the emission data by drainage classes (deep vs shallow drained) defined according to the IPCC (2006) guidelines as the mean annual water table averaged over measured seasons less than 30 cm below the surface as the shallow drained, of 30 cm and deeper as deep drained. When the difference between the groups is statistically significant (T-Test with one tail, $p < 0.05$), then it shows the importance of the respective variable for emission values and the EF should consider these differences to increase the accuracy of emission accounting. Key results are reported in the results section (detailed data see Supplementary Table 1), other grouping results are shown below:

- Differentiating by climate/vegetation zone (defined by Table 4.1, Chapter 4, Volume 4 of the 2006 IPCC Guidelines), an EF_{Boreal}, 2.71 ± 0.37 (1.92–3.50) t CO_2-C ha^{-1} yr^{-1} ($n = 19$) and an $EF_{Temperate}$, 2.34 ± 0.33 (1.66–3.01) t CO_2-C ha^{-1} yr^{-1} ($n = 37$), without significant differences ($p = 0.23$) were obtained.
- Differentiating between ongoing extraction sites and postextraction, nonrestored sites, an $EF_{Ongoing}$ is 2.41 ± 0.27 (1.84–2.97) t CO_2-C ha^{-1} yr^{-1} ($n = 21$) and an $EF_{Nonrestored}$ is 2.81 ± 0.54 (1.68–3.94) t CO_2-C ha^{-1} yr^{-1} ($n = 23$), without significant differences ($p = 0.26$) were obtained.
- Differentiating by nutrient level (with ombrogenic peat being considered as nutrient-poor and minerogenic peat as nutrient-rich) leads to an $EF_{Nutrient\text{-}rich}$ of 2.22 ± 0.50 (1.12–3.32) t CO_2-C ha^{-1} yr^{-1} ($n = 13$) and an $EF_{Nutrient\text{-}poor}$ of 2.38 ± 0.33 (1.70-3.07) t CO_2-C ha^{-1} yr^{-1} ($n = 36$), without significant differences ($p = 0.40$).
- Differentiating by (historical) extraction method (block and milled peat extraction) gives an $EF_{Block\ cut}$ of 3.53 ± 2.10 (−2.29–9.36) t CO_2-C ha^{-1} yr^{-1} ($n = 5$) and an $EF_{Milling}$ of 2.36 ± 0.20 (1.96–2.76) t CO_2-C ha^{-1} yr^{-1} ($n = 51$), without significant differences ($p = 0.30$).
- Differentiating by the width of the field (30 m vs 20 m wide) leads to an $EF_{30\ m\ strips}$ of 3.11 ± 0.63 (1.76–4.46) t CO_2-C ha^{-1} yr^{-1} ($n = 17$) and an $EF_{20\ m\ strips}$ of 2.04 ± 0.34 (1.33–2.75) t CO_2-C ha^{-1} yr^{-1} ($n = 21$), without significant differences ($p = 0.08$).

Simulation by process-based CoupModel. CoupModel (www.coupmodel.com) and its parameterization were documented in He, et al.[19]. The model was used to simulate the soil CO_2 emissions (Fig. 1) and its associated hydrology due to drainage and climate for a typical ongoing peat extraction site, Rivière-du-Loup in eastern Canada. The dataset including 2018–2021 CO_2 flux data, water table depth, soil temperature, and moisture profiles were used to validate the model[19]. Here we ran the CoupModel with the 27-year long-term (1994-2020) climate data with a daily resolution, from the nearby Rivière-du-Loup climate station (climate ID 7056616, Environment Canada) located <1 km from the Rivière-du-Loup site, to simulate the interannual variability (Fig. 1).

A simple bookkeeping model to count for the seasonality. We developed a simple bookkeeping model by using the cumulative probability density distribution function (CDF) of annual mean air temperature (long-term average of ~30 years) to correct for the seasonality of the measured CO_2 data if they do not cover a complete year. This is based on the fact that CO_2 emission is highly correlated with air temperature at one individual site[11,19]. Therefore, for each available CO_2 data set, the air temperature during the measurement is identified over the CDF of long-term air temperatures. The integrated area ratio of the CDF over the measured period, the grey areas in Fig. 3, over the entire CDF represents the proportion of a year the measured data covers. This ratio then can be used as a correction factor to convert the incomplete seasonal dataset into an annual mean.

Data availability

The compiled dataset generated for the published raw data has been uploaded in the supplementary to this paper and are publicly archived on Zenodo and can be accessed at https://doi.org/10.5281/zenodo.10069468.

Code availability

The version of the CoupModel used to run the model simulations, including the source code is hosted on Zenodo (https://zenodo.org/record/3547628) and the executed CoupModel is available at www.coupmodel.com.

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Author contributions

H.H. and N.R. led the work and conceptualization. H.H. did the data collection and analysis, and model simulations with help from N.R. N.R acquired funding. H.H. drafted the original draft and both authors reviewed and edited the paper.

Competing interests

The authors declare no competing interests.

Additional information

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