



Paddy rice cultivation on drained peatlands as a greenhouse gas mitigation option — A systematic nano-review of global data

Chloé Wüst-Galley^{*} , Jens Leifeld 

Climate and Agriculture Group, Agroscope, Reckenholzstrasse 191, Zurich-Affoltern 8046, Switzerland

ARTICLE INFO

Keywords:

Organic soils
Paludiculture
Climate change mitigation
Methane
Carbon farming

ABSTRACT

Drained peatlands are greenhouse gas (GHG) emission hotspots. Where peatland restoration is not a suitable mitigation option, wet agriculture, i.e., agricultural production with a high water table, may provide an alternative. One possible crop is rice, which is already grown in wet conditions in many parts of the world, but its cultivation is associated with high CH₄ emissions. This systematic review aims to quantify whether or not paddy rice cultivation on degraded peatlands is, from the climate perspective, preferable to upland cropping. More specifically, it assesses whether a possible reduction in CO₂ (and less importantly N₂O) emissions offset the increase in CH₄ emissions. Flux measurements from paddy rice cultivation on degraded peatlands were obtained from twelve publications, mostly outside of the tropics. Many studies provided fluxes also from an adjacent upland crop, enabling a direct comparison of fluxes. Across all studies, paddy rice cultivation resulted in on average higher CH₄ emissions and significantly lower CO₂ and N₂O emissions than upland cropping. The combined changes of CH₄ and CO₂ could be compared for both cropping types in six studies. Five of these showed a reduction in global warming potential associated with paddy rice cultivation and we conclude that paddy rice cultivation of degraded peatlands is preferable, from the climate perspective, to drained cultivation of these soils. Using maps of global paddy rice production and of peatlands, we estimate that this mitigation measure could reduce emissions of degraded peatlands by 16.5 Mt CO₂-eq. per year.

1. Introduction

Worldwide peatland ecosystems cover 460 – 640 Mha and store up to 940 Pg C as peat in their soils (Leifeld and Menichetti, 2018; Widyastuti et al., 2025). More than 10% of this area is drained for agriculture, forestry or peat extraction, particularly in the tropical and temperate zones (UNEP, 2022). Draining peatland soils poses a range of problems such as high greenhouse gas (GHG) emissions from peat decomposition, physical subsidence, and loss of organic matter, meaning their use is unsustainable and additionally becomes difficult or even impossible over time (Erkens et al., 2016; Tanneberger et al., 2021). Furthermore, drained peatland use induces leaching of dissolved organic matter, nutrients, and negatively impacts biodiversity (Paul and Leifeld, 2023; Temmink et al., 2026).

The GHG emissions from managed peatlands, mostly in the form of CO₂, are approximately 2 Pg CO₂-eq. per year (UNEP, 2022). To contextualize, this is almost comparable in size to global CH₄ emissions from livestock and manure (Saunois et al., 2025). To halt the loss of organic matter and drastically reduce GHG emissions, it is widely

acknowledged that these soils have to be rewetted (Günther et al., 2020; Humpenöder et al., 2020; Tanneberger et al., 2021; Girkin et al., 2023). Furthermore, it has been shown that peatland rewetting and restoration are not only critical to reduce climate change, but also important for biodiversity (Parish et al., 2008), water retention, buffering and purification (Joosten and Clarke, 2002; Joosten et al., 2017), and their function as a carbon sink (Tanneberger et al., 2021). Rewetting however typically occurs at the expense of agricultural outputs (Freeman et al., 2022) making it difficult to justify as a measure for GHG mitigation option in situations, for example, where alternatives for either food production or ensuring farmers' livelihoods are not available. For such situations, a more suitable GHG mitigation scenario is therefore the use of these surfaces for "responsible agriculture" (Girkin et al., 2023). This encompasses several possible options but the most effective one is an increased water table (Girkin et al., 2023). This ties in with wet agriculture, i.e., production with a temporary or permanent high water table.

In terms of GHG balance, wet agriculture of drained peatland soils is a trade-off as it returns the soil to a mostly anaerobic condition and

^{*} Corresponding author.

E-mail addresses: chloe.wuest@agroscope.admin.ch (C. Wüst-Galley), jens.leifeld@agroscope.admin.ch (J. Leifeld).

<https://doi.org/10.1016/j.agee.2026.110596>

Received 30 April 2026; Received in revised form 9 June 2026; Accepted 11 June 2026

Available online 17 June 2026

0167-8809/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

therefore promotes CH₄ emissions, whereas it will, for the same reason, curb aerobic peat decomposition and therefore CO₂ emissions. In the past decade, several studies have shown that wet agriculture has a better GHG balance than agriculturally-used drained peatlands, even if carbon exports *via* harvesting are taken into account (Bianchi et al., 2021; Bockermann et al., 2025) and under certain conditions, wet agriculture may even sequester carbon (Günther et al., 2015; van den Berg et al., 2024; Bockermann et al., 2025). The cited studies, however, analysed the GHG balance of non-edible plants, i.e., wet cultivation of crops for biomass production such as reed, cattail or *Sphagnum*.

A food crop that might be promising for wet agriculture on degraded peatland soils is paddy rice, because it is a staple crop already grown in many parts of the world. Its consumption is approximately 19% of the world cereal market (FAO, 2026). One problem associated with paddy rice cultivation however is the high CH₄ emissions, accounting for approximately 9% of anthropogenic CH₄ emissions (Saunois et al., 2025). Indeed, rice in general has a higher calorific GHG flux than other crops (Linguist et al., 2012; Poore and Nemecek, 2018). Most paddy soils are mineral soils. Whilst the GHG emissions from such soils have been the subject of many studies and systematic reviews (e.g. Ouyang et al., 2023, Zhang et al., 2024), only a few studies have investigated the GHG balance of paddy rice cultivation on degraded peatland soils. These findings have not yet been analysed systematically.

This systematic review aims to address this, additionally assessing whether paddy rice is better or worse, from a climate perspective, than upland cropping on degraded peatland soils. To do this, we extracted GHG flux information (CH₄, N₂O and CO₂) from all studies reporting measured GHG fluxes from paddy rice cultivation on C-rich degraded peatland soils worldwide. Where studies reported GHG fluxes from paddy rice cultivation and from upland cropping, we compared both fluxes of individual gases and of the combination of GHGs (by applying the 100-year global warming potential, GWP₁₀₀, for CH₄ and N₂O) for the two management scenarios. We additionally assess the global relevance of paddy rice cropping of organic soils using maps of global paddy rice cultivation and the global peatland surface.

2. Methods

2.1. Literature search

We searched for studies reporting field-based GHG (CO₂, CH₄, N₂O) flux measurements from paddy rice cultivation on carbon rich soils (>12%, including soils with a mineral cover), from across the world, with measurements lasting a minimum of one growing season, and, where chamber measurements were used, a minimum measurement frequency of one month during the vegetation phase. A Google Scholar search (“peatland OR “organic soil”) AND “paddy rice” AND greenhouse” yielded 2040 results. Based on the title and abstract, 29 articles were initially selected, and three further publications were located from within a review paper (Kajiura et al., 2018). Scopus and Web of Science searches using the same search terms yielded no additional relevant articles. Of the resulting 32 articles, articles were excluded for the following reasons: Article did not contain relevant data (either no GHG flux data reported, or study not relevant) (5 articles); too few measurements (less than once a month during growing season) (2); measurement period too short (less than one growing season) (2); incubation experiments (2); wet site not paddy rice (2); soil not carbon rich enough (<12%) (2); insufficient quality of the article (either methodology inadequate, or inadequately described) (3); data replicated from another (already-considered) study (2). This resulted in twelve articles from which flux data from paddy rice cultivation were extracted. Together, these articles revealed 22, 8, 13 data points (site-years) for CH₄, CO₂ and N₂O, respectively, from paddy rice on organic soil. Seven of the above-mentioned twelve studies additionally included flux measurements from a (dry) upland crop on degraded peatland. For one additional study that had only paddy rice flux data, a comparable upland

crop flux data set i.e., measurements over a similar time period and from the same region, could be located (see Table S1).

2.2. Flux analyses

Flux measurements from multiple years at the same site were treated separately. Whereas average hourly CH₄ and N₂O fluxes are comparable between sites, the CO₂ fluxes are only comparable to a certain extent; four studies reported net ecosystem exchange, NEE, whereas two studies reported ecosystem respiration, R_{eco} (one on bare soil, one study with plants in the chamber).

The flux measurements of upland crops were used to calculate the effect sizes of the scenario ‘paddy rice cultivation’ as compared to baseline scenario ‘upland cultivation’. This (usually) *within*-study effect size was calculated as the absolute difference in mean hourly GHG fluxes between the paddy rice and the upland crop sites, for each measurement pair. For each gas, an intercept-only mixed-model (fit by REML) was used to test whether the distribution of measurement effect sizes is significantly different from zero. The random effect (“study”) was used to account for instances where fluxes from one paddy rice field were compared with fluxes from multiple upland crop fields or *vice versa*, or where multiple data points stemmed from one site (e.g., measurements across two years from the same site). A summary effect size i.e., the effect size across all studies, was not calculated because of the high expected variability between the between-study effect sizes, due to different gas sampling regimes. The GWP₁₀₀ metric (CH₄: 27; N₂O: 273; Smith et al., 2021) was used to assess the combined climate impact of either all three gases, or CH₄ and CO₂ (where N₂O measurements were missing), from six studies. Where fluxes from one paddy rice field were compared with fluxes from multiple upland crop fields or *vice versa*, the mean flux from the multiple fields was used to avoid pseudo-replication. Carbon losses through dissolved organic carbon (DOC) were considered, applying the emission factors (EFs) from IPCC (2014, chapters 2 and 3). More specifically, the EFs for rewetted peatlands were applied to paddy rice cultivation, and the EFs for drained peatlands to upland cropping.

2.3. Global distribution

The potential global distribution of paddy rice cultivation on degraded peatlands was estimated by calculating the overlap of peatlands and paddy rice cultivation. More specifically, the Global Peatland Map 2.0 (1 km x 1 km, Greifswald Mire Centre, 2022) was overlain with a map showing global rice distribution (“GloRice-exten-phsc” maps from Xie et al., 2025). The Global Peatland Map identifies surfaces that are either “peatland dominated” or “peat in a soil mosaic”. Both categories were used, allowing an assessment of uncertainty. The GloRice maps show the surface (ha) of paddy rice cropping in each 5-arc-minute cell (equivalent to 55–86 km², depending on latitude); these maps were re-sampled to 1.25 arc-minutes for analysis (equivalent to 3.5–5.4 km²). To minimise the impact of inter-annual variation of the rice cropping area, the overlap of peatlands and paddy rice was calculated for the years 2017–2021, and the mean surface considered. Because the spatial resolution of the GloRice maps is fairly low, the overlap of the two maps does not guarantee the co-occurrence of rice and peatland soils (with the exception of areas with high density of paddy rice cultivation and continuous peatland cover). We therefore consider the resulting map to represent the potential surface of paddy rice cultivation on degraded peatlands, rather than the status quo.

3. Results

The flux measurements for CH₄ and N₂O obtained from the twelve studies (Table S2) encompass the IPCC flux estimates for paddy rice cultivation on degraded peatlands in tropical regions (Fig. 1, IPCC flux estimates from non-tropical regions unavailable), with many fluxes higher than the corresponding confidence interval. Median fluxes for

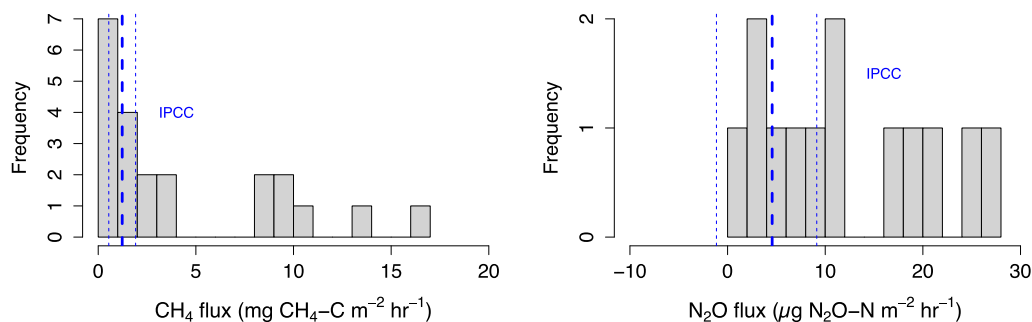


Fig. 1. Histograms of fluxes from paddy rice cultivation on degraded peatlands. Hourly CH_4 (left) and N_2O (right) fluxes from paddy rice cultivation on organic soil with the respective IPCC default estimate for tropical regions indicated in blue (bold line, mean estimate; thin lines, 95% confidence intervals; from IPCC, 2014 chapter 2).

paddy rice cultivation on degraded peatlands were $2.1 \text{ mg CH}_4\text{-C m}^{-2} \text{ hr}^{-1}$ and $10.3 \text{ µg N}_2\text{O-N m}^{-2} \text{ hr}^{-1}$.

Methane fluxes from paddy rice cultivation were in general higher than those of their upland crop counterparts, whereas N_2O fluxes and CO_2 fluxes (NEE, 7 comparisons from 4 studies; R_{eco} , 3 comparisons from 2 studies) from paddy rice cultivation were significantly ($\alpha = 0.05$) lower (Table 1, Fig. 2 and Table S3). The difference in GWP between paddy rice and upland crop cultivation was negative for five out of six comparisons (Table 2), meaning for these five cases, the cultivation of paddy rice had lower on-site GHG emissions.

The potential surface of paddy rice cultivation on peatlands, as estimated by calculating the overlap of paddy rice cultivation and the global peatland surface (using the “peatland dominated” area only), is $23,933 \text{ km}^2$ (range 2017–2021: $23,111 \text{ km}^2$ – $25,041 \text{ km}^2$). This distribution is dominated by the tropical climate zone, with particularly high-density areas in southeast Asia (Fig. 3). Additional regions with widespread but less dense paddy rice cultivation are along the Congo River, Central America and northern South America, and Eastern Europe. The potential surface of paddy rice cultivation on peatlands increases to $50,061 \text{ km}^2$ (range 2017–2021: $49,373 \text{ km}^2$ – $51,695 \text{ km}^2$) if the peatland surface with “peat in a soil mosaic” is additionally included.

4. Discussion

4.1. Paddy rice cultivation as a mitigation option

With this systematic review we aimed to test whether paddy rice cultivation of degraded peatland soils results in a lower GWP than upland crop production. Summarising the results from 15 site-year comparisons, an increase in CH_4 release and significant reductions in CO_2 and N_2O fluxes were associated with paddy rice cultivation. Out of the six studies for which a direct comparison of (at least) CO_2 and CH_4 fluxes—the two most important GHGs in this context—could be made, five showed a reduction in GWP (GWP_{100}). Thus, for these five sites, a GWP reduction resulting from lower CO_2 and N_2O emissions from the paddy

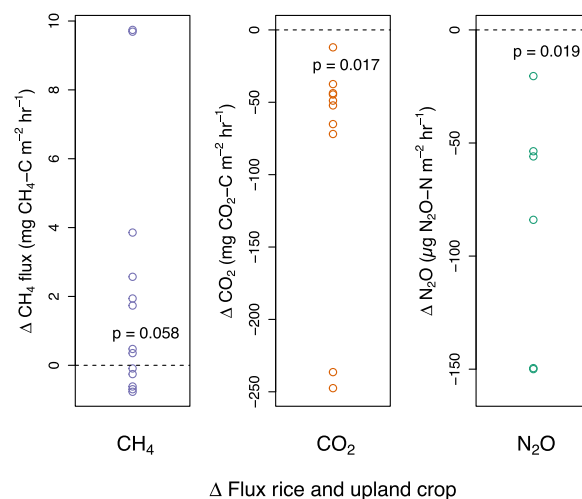


Fig. 2. Flux differences i.e., effect sizes, between each paddy rice site and its associated upland crop site. Negative numbers denote lower emissions from paddy rice relative to the upland crop, positive numbers higher emissions; where one paddy rice site was associated with more than one upland crop site (or vice versa), the fluxes from that paddy rice site (or upland crop site) are used in multiple comparisons, i.e., each comparison is shown as a point in the graph. The p -values are the result of the random effects model testing whether the flux differences between paddy rice and the upland crop cultivation are significantly different or not.

rice cultivation offset the increased CH_4 release. Together, this suggests that in terms of GHG emissions, paddy rice cultivation is preferable to dry upland cultivation on managed peatlands under a wide range of climate conditions.

To evaluate the global significance of these findings in terms of agricultural practice and GHG mitigation potential, we estimated the potential extent of paddy rice production on peatland soils. This surface, using the more conservative approach, i.e., the (smaller) peatland-dominated surface from Greifswald Mire Centre (2022), is 2.4 Mha (Table S4). This is a small proportion of the paddy rice surface overall (approx. 2%; Xie et al., 2025), yet it is roughly 12.2% of the surface of degraded peatlands outside of the Boreal zone (Evans et al., 2021). This implies that the impact of GHG emissions’ savings from this agricultural practice could be relevant. Indeed, multiplying the average annual mitigation potential from Table 2 ($6.9 \text{ t CO}_2\text{-eq ha}^{-1}$, using only those values considering NEE) with the estimated potential surface of paddy rice cultivation on degraded peatlands shows that the mitigation potential could be as high as $16.5 \text{ Mt CO}_2\text{-eq yr}^{-1}$ compared to if these soils were cultivated with upland crops. This is approx. 3.4% of current emissions from degraded cropped peatlands (Evans et al., 2021). A wider mitigation potential can likewise be identified by considering the

Table 1

Minimum and maximum effect sizes, i.e., pairwise flux differences, for each of the three gases; a negative effect size denotes lower fluxes with paddy rice cultivation compared to upland cropping.

Gas	Number of comparisons	Number of studies	Min. effect size, i.e., flux difference	Max. effect size, i.e., flux difference
CH_4	13	8	$-0.8 \text{ mg CH}_4\text{-C m}^{-2} \text{ hr}^{-1}$	$9.7 \text{ mg CH}_4\text{-C m}^{-2} \text{ hr}^{-1}$
N_2O	6	4	$-20.4 \text{ µg N}_2\text{O-N m}^{-2} \text{ hr}^{-1}$	$-150.0 \text{ µg N}_2\text{O-N m}^{-2} \text{ hr}^{-1}$
CO_2 (NEE, and R_{eco} only)	10	6	$-12.0 \text{ mg CO}_2\text{-C m}^{-2} \text{ hr}^{-1}$	$-247.5 \text{ mg CO}_2\text{-C m}^{-2} \text{ hr}^{-1}$

Table 2

Global warming potential (GWP₁₀₀) of the difference in emissions between paddy rice upland crop cultivation in the six cases where at least CO₂ and CH₄ were measured, with and without dissolved organic carbon, DOC; a negative value indicates a lower GWP for paddy rice cultivation.

Reference	Country	Temporary drainage in rice?	MAT (°C)	Chamber-based or eddy-covariance measurements	ΔGWP between paddy rice and upland crop cultivation (t CO ₂ -eq ha ⁻¹ yr ⁻¹)	
					Without DOC	Incl. DOC
Furukawa et al., (2005) [§]	Indonesia	no	25.8	Chamber	-52.1	-53.4
Hadi et al., (2005) [§]	Indonesia	no information	26.4	Chamber	-46.9	-48.2
Widmer et al., (2026)	Switzerland	mid-season drainage	9.8	Chamber	-19.1	-19.4
Knox et al., (2015)*	USA	no, except for fertilisation	14.9	Eddy-covariance	-15.4	-15.7
Hatala et al., (2012)*	USA	no, except for fertilisation	14.5	Eddy-covariance	-14.3	-14.7
Naser et al., (2005) ⁺	Japan	mid-season drainage	7.3	Chamber	+ 21.2	+ 20.9

[§] CO₂ fluxes represent R_{eco} only (dark flux); * no N₂O measurements, ΔGWP based on CO₂ and CH₄ only; ⁺ CO₂ fluxes represent daytime NEE only.

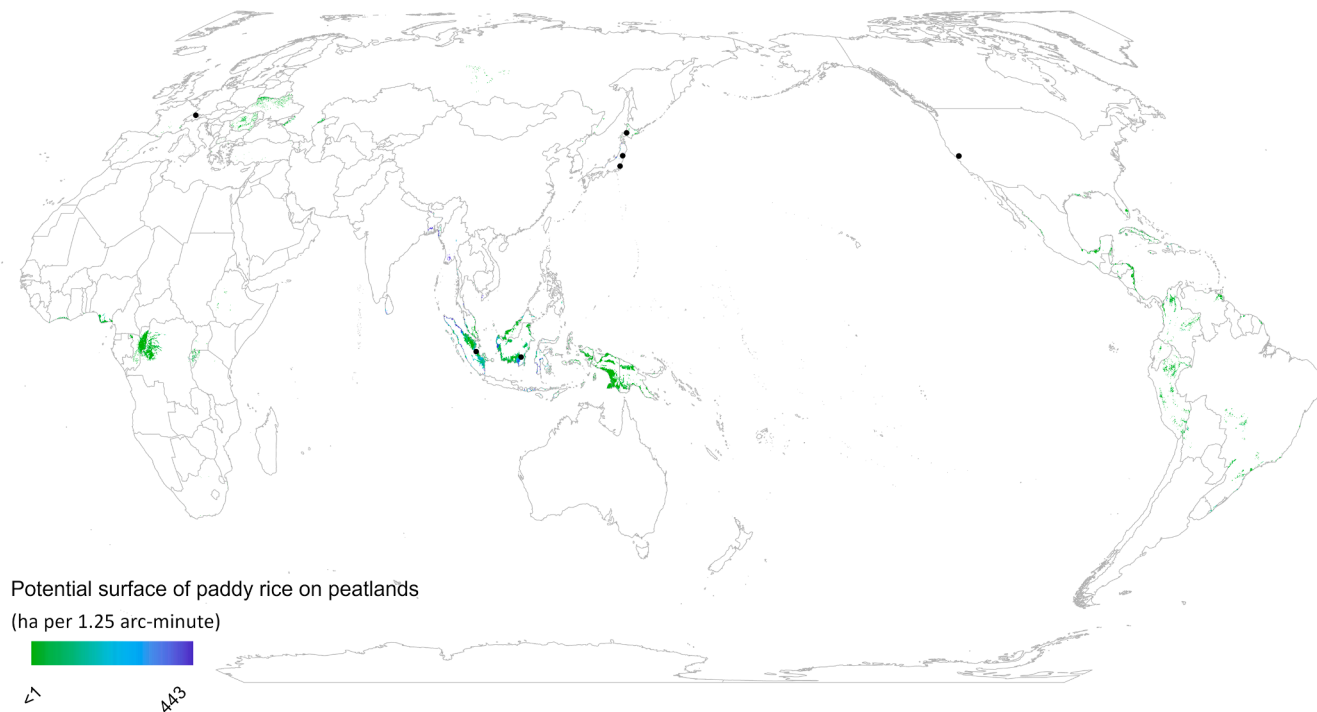


Fig. 3. The potential distribution and density of paddy rice cultivation on peatlands. Black dots show the locations of sites measuring greenhouse gas emissions from paddy rice cultivation on degraded peatland soils included in this study; the distribution of paddy rice is from 2021.

entire cropped peatland surface minus that potentially already used for paddy rice cropping. Because paddy rice cultivation in the temperate zone is partly constrained by climate, we calculated this for the tropics only. Here, the cropped peatlands surface (9.4 Mha, from Evans et al., 2021), minus that potentially already used for paddy rice cropping (2.1 Mha), yields a potential emission saving of 50.1 Mt CO₂-eq yr⁻¹, or 12.7% of current emissions from tropical cropped degraded peatlands (7.3 Mha not yet managed with rice). It must however be noted that the uncertainty associated with both mitigation potentials is huge and difficult to quantify at the same time, in part because the surface estimate of paddy rice production on peatlands has been calculated using maps of medium (peatland surface) to low (paddy rice extent) spatial resolution, and in part because the emissions saving estimate is based on so few studies. Aside from this loosely constrained estimate there is, however, ample evidence in the literature that paddy rice is produced on organic soil in different regions of the world (Allamah et al., 2019; Liu et al., 2021; Qin et al., 2024; Anon, 2025).

It must additionally be noted that not all peatlands are suitable for agricultural management and rice production. An alerting example was the Mega Rice Project in the 1990s in Central Kalimantan, Indonesia where about 1.5 Mha of wetland, mainly peatland, were deeply drained

and converted into rice fields. Owing to unfavourable peat properties (nutrient poor, acidic, unsuitable hydraulic properties), rice did not prosper and the area became a wasteland subject to flooding in the rainy season and drought in the dry season, emitting large amounts of C (Rieley et al., 2008). This well-known example points towards the need to carefully study site properties before converting agricultural peat into rice production, particularly in the tropics. More recent examples indicate that, with appropriate management interventions, rice cropping is partially suitable on these soils (Barchia et al., 2021; Alwi et al., 2022). Furthermore, there are further edible plants that can be cultivated as paludicultures in the tropics (e.g., sago (*Metroxylon* spp.), illipe nut (*Shorea* spp.) water spinach (*Ipomoea aquatica*) and kelakai (*Stenochlaena palustris*), Prastyaningsih et al., 2019; Uda et al., 2020), meaning that agricultural production on managed but wet peatlands could be maintained with crops other than rice. Lastly, it is important to consider peatland restoration as an alternative where socio-economic factors allow (Yuwati et al., 2021; Girkin et al., 2023).

4.2. Emission factors

In spite of the small data set (43 data points for 3 gases, from twelve

studies), we identified a lot of variation in the CH₄ and N₂O flux rates from paddy rice cultivation, indeed more than is captured by the IPCC estimate of flux uncertainty. The IPCC 2013 flux estimates are at the lower end of the CH₄ and N₂O distributions identified in this study. This is surprising, because the IPCC flux estimates are for tropical regions, and due to the temperature dependence of CH₄ and N₂O emissions (Yvon-Durocher et al., 2014; Pärn et al., 2018; Ouyang et al., 2023), lower flux estimates in our study, that includes sites outside the tropics, would be expected for these gases as compared to IPCC 2013. The fact that the opposite is found suggests the higher variation identified in this study cannot simply be due to the wider climatic range of the studies we considered. This in turn implies that there is room for improvement for the IPCC flux estimates, possibly by the incorporation of other factors (e.g., water regime, straw addition) for the estimation of CH₄ emissions, as is already implemented for mineral paddy soils (IPCC et al., 2019). Additionally, many of the publications used in this study were not yet available at the time of the IPCC report, calling for revised IPCC emission factors for paddy rice on organic soils in the future.

4.3. Limitations of the analysis

Our systematic review is the first to bring together evidence on a possible climate mitigation effect of paddy rice cultivation on degraded peatland soils compared to the cultivation of upland crops. The analysis however faces a number of limitations, particularly with respect to CO₂ fluxes.

Firstly, the representativeness of the reported gas fluxes for paddy rice cultivation on peatlands is limited, partly due to the small number of studies and partly due to a geographical bias in these studies, which increases the risk that global trends cannot be identified. Although 93% of the potential paddy rice cultivation on peatlands is in the tropics (Beck et al., 2023), only two studies (both in Indonesia) reported fluxes from these climate regions. Furthermore, no measurements were found from Central or South America, or the African continent, all of which contain widespread areas of potential paddy rice cultivation on degraded peatlands.

Secondly, the CO₂ flux measurements, and thus the type of flux measured, varied between references. Fluxes were obtained either i) by eddy-covariance, thus incorporating daytime and night-time fluxes; ii) by chamber measurements together with modelling continuous fluxes using calibrated temperature- and global radiation-models (night-time and daytime fluxes estimated explicitly); iii) as a mean of R_{eco} measurements; or iv) as a mean of daytime NEE measurements. The heterogeneous nature of these measurement campaigns means studies estimated different CO₂ flux compartments. A related issue is that an accurate CO₂ flux estimate requires measurements from a wide range of conditions, including day- and night-time measurements, as well as different weather conditions. Capturing this temporal heterogeneity requires either eddy-C measurements (e.g., Knox et al., 2015) or a dense measurement campaign, with continuous (modelled) NEE and R_{eco} estimates (e.g., Widmer et al., 2026). Having only daytime measurements is particularly limiting for C-rich soils, because the CO₂ flux differences between the daytime (when CO₂ uptake due to photosynthesis will partially compensate CO₂ emissions due to soil respiration) and night-time (when only soil and plant respiration occurs) are different for the two systems investigated, i.e., flooded vs. drained systems, because drained peatland soils have such high soil respiration rates. In short, daytime-only NEE measurements lead to an underestimation of CO₂ emissions in upland cultivation but not in the paddy rice cultivation. Therefore, for the study where daytime NEE was measured (see Table 2), the GHG emission savings calculated for paddy rice cultivation (vs. upland cultivation) is an underestimate. We reduced the impact of these problems by limiting calculations where CO₂ was involved to the pairwise (typically within-study) comparisons of GHG fluxes from paddy rice and upland crop cultivation. It must also be noted that measuring only daytime fluxes is also an issue for CH₄, as night-time and daytime

CH₄ fluxes can differ systematically. For example, higher fluxes have been recorded either during the daytime (Morin et al., 2014) or night-time (e.g., Dooling et al., 2018), and in some cases the bias is temperature- and/or water-level dependent (e.g. Bansal et al., 2018; Li et al., 2024). All chamber-based studies we identified (Table S1) measured only daytime CH₄ fluxes.

Lastly, a full C balance is required to fully assess differences in C flows between the two management scenarios. This requires, in addition to the complete CO₂ and CH₄ flux, information on the amount of C imported (through organic amendments such as straw or farmyard manures) and exported (through harvest). Several studies have shown that non-CO₂-C imports and exports form a substantial part of the C balance of peatlands (e.g., harvest exports, Knox et al., 2015; Widmer et al., 2026). For several reasons however, we do not expect that the finding, that paddy rice cultivation on peatland soils is associated with a lower GWP than upland cultivation, would be changed if full C balances were included. Firstly, for the two studies where a full C balance was reported, a recalculation of the ΔGWP values (as in Table 2) using the C balance instead of NEE still led to negative ΔGWPs (−7.1 t CO₂-eq ha^{−1} for Knox et al., 2015; −20.6 t CO₂-eq ha^{−1} for Widmer et al., 2026), meaning paddy rice cultivation still reduced emissions. Secondly, for the other studies for which an emission saving was calculated, the C losses (from C imports and exports in combination) would have to be considerably greater in paddy rice cultivation (at least 4 t C greater; 14.3 ÷ 3.67) than in the upland cultivation for a reduction in GWP associated with paddy rice cultivation to disappear. Lastly, we used IPCC values to account for CO₂ emissions caused by losses of DOC. More recent studies (Moore et al., 2013; Evans et al., 2016) indicate that the differences between DOC losses in drained and undrained sites might be greater than that indicated by the IPCC i.e., DOC losses from drained sites are probably even greater – compared to losses from undrained sites – than we have assumed. This implies that the GWP savings incurred by paddy rice cultivation might even be greater than indicated in this study.

5. Conclusions and outlook

Our results identify paddy rice cultivation on organic soils as a promising GHG mitigation strategy compared to drained upland cropping, as the reductions in CO₂ emissions—and to a lesser extent N₂O—offset the increase in CH₄ release. At the global scale, GHG emission reductions on degraded peatlands are already being realized by the cultivation of paddy rice, and this approach has the potential to further substantially reduce GHG emissions from managed peatlands if existing upland crops were to be replaced. Care must be taken to evaluate site properties beforehand as not all environmental settings are suitable for paddy rice cultivation, as highlighted by past failures of rice cultivation projects on organic soils unsuitable for this purpose. The number of studies we identified was very limited, and suffered from a strong geographical bias. The estimates reported in this review should therefore be considered ‘first estimates’ and we urge further research to broaden the basis for these estimates. A focus should lie in the tropics, in part because this is where the mitigation option could be—in terms of surface—most promising. Methodologically we urge full GHG balances to be carried out, including CO₂ and CH₄ at a minimum, with CO₂ estimates based on either continuous flux data or partitioned fluxes (NEE and R_{eco}), and lastly, the including of C imports and exports to and from sites. Finally, from a broader environmental perspective, we stress that rewetting aimed at restoring a wider range of ecosystem functions provides additional benefits beyond GHG mitigation, such as biodiversity, water filtration, and buffering of the water-cycle, and should be preferred where socio-economic conditions allow (Girkin et al., 2023).

Supplementary information

The list of studies identified in this systematic review is given in the file “Supplementary information”.

CRedit authorship contribution statement

Chloé Wüst-Galley: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jens Leifeld:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2026.110596](https://doi.org/10.1016/j.agee.2026.110596).

Data Availability

The articles used in this study are listed in Table S1 of the supplementary information (SI). The data generated as part of this study are given in Tables S2, S3 and S4 of the SI.

References

- Allamah, A., Hapsah, H., Wawan, W., Dini, I.R., 2019. The growth and yield of rice (*Oryza sativa* L.) with organic and inorganic fertilizer application by cellulolytic microbes in peat. *Indones. J. Agric. Res.* 1, 295–306.
- Alwi, M., Hairani, A., Noor, M., Suratman, 2022. Perspectives on the changing properties of peat soils used for agriculture: the case of Talio Hulu Village. *IOP Conference Series Earth Environmental Science* 1025, 012036. <https://doi.org/10.1088/1755-1315/1025/1/012036>.
- Anon, 2025. National Greenhouse Gas Inventory Document of Japan 2025. In: *Greenhouse Gas Inventory Office of Japan and Ministry of the Environment. Center for Global Environmental Research, Earth System Division, National Institute for Environmental Studies, Japan*, p. 800.
- Bansal, S., Tangen, B., Finocchiaro, R., 2018. Diurnal patterns of methane flux from a seasonal wetland: mechanisms and methodology. *Wetlands* 38, 933–943. <https://doi.org/10.1007/s13157-018-1042-5>.
- Barchia, M.F., Ishak, A., Utama, S.P., Novanda, R.R., 2021. Sustainability status of paddy cultivation on marginal peat soils in Indonesia. *Bulg. J. Agric. Sci.* 27, 259–270.
- Beck, H.E., McVicar, T.R., Vergopolan, N., Berg, A., Lutsko, N.J., Dufour, A., Zeng, Z., Jiang, X., van Dijk, A.I.J.M., Miralles, D.G., 2023. High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections. *Sci. Data* 10, 724. <https://doi.org/10.1038/s41597-023-02549-6>.
- Bianchi, A., Larmola, T., Kekkonen, H., Saarnio, S., Lång, K., 2021. Review of greenhouse gas emissions from rewetted agricultural soils. *Wetlands* 41, 108. <https://doi.org/10.1007/s13157-021-01507-5>.
- Bockermann, C., Eickenscheidt, T., Dröslér, M., 2025. Greenhouse gas mitigation potential of temperate fen paludicultures. *Glob. Chang. Biol.* 31, e70385. <https://doi.org/10.1111/gcb.70385>.
- Dooling, G.P., Chapman, P.J., Baird, A.J., Shepherd, M.J., Kohler, T., 2018. Daytime-only measurements underestimate CH₄ emissions from a restored bog. *Écoscience* 25, 259–270. <https://doi.org/10.1080/11956860.2018.1449442>.
- Erkens, G., van der Meulen, M.J., Middelkoop, H., 2016. Double trouble: subsidence and CO₂ respiration due to 1,000 years of Dutch coastal peatlands cultivation. *Hydrogeol. J.* 24, 551–568. <https://doi.org/10.1007/s10040-016-1380-4>.
- Evans, C.D., Renou-Wilson, F., Strack, M., 2016. The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands. *Aquat. Sci.* 78, 573–590. <https://doi.org/10.1007/s00027-015-0447-y>.
- Evans, C.D., Peacock, M., Baird, A.J., Artz, R.R.E., Burden, A., Callaghan, N., Chapman, P.J., Cooper, H.M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R.P., Helfter, C., Heppell, C.M., Holden, J., Jones, D.L., Kaduk, J., Levy, P., Matthews, R., McNamara, N.P., Misselbrook, T., Oakley, S., Page, S.E., Rayment, M., Ridley, L.M., Stanley, K.M., Williamson, J.L., Worrall, F., Morrison, R., 2021. Overriding water table control on managed peatland greenhouse gas emissions. *Nature* 593, 548–552. <https://doi.org/10.1038/s41586-021-03523-1>.
- FAO, 2026. FAO Cereal supply and demand brief. In: Food and Agriculture Organization. (<https://www.fao.org/worldfoodsituation/cssdb/en>).
- Freeman, B.W.J., Evans, C.D., Musarika, S., Morrison, R., Newman, T.R., Page, S.E., Wiggs, G.F.S., Bell, N.G.A., Styles, D., Wen, Y., Chadwick, D.R., Jones, D.L., 2022. Responsible agriculture must adapt to the wetland character of mid-latitude peatlands. *Glob. Chang. Biol.* 28, 3795–3811. <https://doi.org/10.1111/gcb.16152>.
- Furukawa, Y., Inubushi, K., Ali, M., Itang, A.M., Tsuruta, H., 2005. Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands. *Nutr. Cycl. Agroecosyst* 71, 81–91. <https://doi.org/10.1007/s10705-004-5286-5>.
- Günther, A., Huth, V., Jurasinski, G., Glatzel, S., 2015. The effect of biomass harvesting on greenhouse gas emissions from a rewetted temperate fen. *GCB Bioenergy* 7, 1092–1106. <https://doi.org/10.1111/gcb.12214>.
- Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebisch, F., Couwenberg, J., 2020. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nat. Commun.* 11, e1644. <https://doi.org/10.1038/s41467-020-15499-z>.
- Girkin, N.T., Burgess, P.J., Cole, L., Cooper, H.V., Honorio Coronado, E., Davidson, S.J., Hannam, J., Harris, J., Holman, I., McCloskey, C.S., McKeown, M.M., Milner, A.M., Page, S., Smith, J., Young, D., 2023. The three-peat challenge: business as usual, responsible agriculture, and conservation and restoration as management trajectories in global peatlands. *Carbon Manag.* 14, e2275578. <https://doi.org/10.1080/17583004.2023.2275578>.
- Greifswald Mire Centre, 2022. Global Peatland Map 2.0. Underlying dataset of the UNEP Global Peatland Assessment - The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands [dataset]. Global Peatlands Initiative. United Nations Environment Programme, Nairobi. (<https://globalpeatlands.org/>).
- Hadi, A., Inubushi, K., Furukawa, Y., Purnomo, E., Rasmadi, M., Tsuruta, H., 2005. Greenhouse gas emissions from tropical peatlands of Kalimantan. *Indones. Nutr. Cycl. Agroecosyst.* 71, 73–80. <https://doi.org/10.1007/s10705-004-0380-2>.
- Hatala, J.A., Detto, M., Sonnentag, O., Deverel, S.J., Verfaillie, J., Baldocchi, D.D., 2012. Greenhouse gas (CO₂, CH₄, H₂O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. *Agr. Ecosyst. Environ.* 150, 1–18. <https://doi.org/10.1016/j.agee.2012.01.009>.
- Humpenöder, F., Karstens, K., Lotze-Campen, H., Leifeld, J., Menichetti, L., Barthelmes, A., Popp, A., 2020. Peatland protection and restoration are key for climate change mitigation. *Environ. Res. Lett.* 15, e104093. <https://doi.org/10.1088/1748-9326/abae2a>.
- IPCC, 2014. In: Hiraishi, Krug, T., Tanabe, T., Srivastava, K., Baasansuren, N., Fukuda, J., Troxler, M., T., G. (Eds.), 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. IPCC, Switzerland.
- IPCC, 2019. In: Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S. (Eds.), 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Switzerland (Published: IPCC, Switzerland. In: Buendia, E.C., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S. (Eds.)).
- Joosten, H., Clarke, D., 2002. Wise use of mires and peatlands. *International Mire Conservation Group. Greifswald, Germany / International Peat Society, Jyväskylä, Finland*.
- Joosten, H., Tanneberger, F., Moen, A. (Eds.), 2017. *Mires and peatlands of Europe*. Schweizerbart Science Publishers, Stuttgart, Germany.
- Kajiura, M., Minamikawa, K., Tokida, T., Shirato, Y., Wagai, R., 2018. Methane and nitrous oxide emissions from paddy fields in Japan: An assessment of controlling factor using an intensive regional data set. *Agr. Ecosyst. Environ.* 252, 51–60. <https://doi.org/10.1016/j.agee.2017.09.035>.
- Knox, S.H., Sturtevant, C., Matthes, J.H., Koteen, L., Verfaillie, J., Baldocchi, D., 2015. Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO₂ and CH₄) fluxes in the Sacramento-San Joaquin Delta. *Glob. Chang. Biol.* 21, 750–765. <https://doi.org/10.1111/gcb.12745>.
- Leifeld, J., Menichetti, L., 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. *Nat. Commun.* 9, 1–7. <https://doi.org/10.1038/s41467-018-03406-6>.
- Li, H., Peng, C., Helbig, M., Zhao, M., Guo, H., Zhao, B., 2024. Nocturnal peak methane flux diel patterns in rice paddy fields. *Agric. For. Meteorol.* 358, e110238. <https://doi.org/10.1016/j.agrformet.2024.110238>.
- Linquist, B., van Groenigen, K.J., Adviento-Borbe, M.A., Pittelkow, C., van Kessel, C., 2012. An agronomic assessment of greenhouse gas emissions from major cereal crops. *Glob. Chang. Biol.* 18, 194–209. <https://doi.org/10.1111/j.1365-2486.2011.02502.x>.
- Liu, Y., Ge, T., van Groenigen, K.J., Yang, Y., Wang, P., Cheng, K., Zhu, Z., Wang, J., Li, Y., Guggenberger, G., Sardans, J., Penuelas, J., Wu, J., Kuzyakov, Y., 2021. Rice paddy soils are a quantitatively important carbon store according to a global synthesis. *Commun. Earth Environ.* 2, e154. <https://doi.org/10.1038/s43247-021-00229-0>.
- Moore, S., Evans, C.D., Page, S.E., Garnett, M.H., Jones, T.G., Freeman, C., Hooijer, A., Wiltshire, A.J., Limin, S.H., Gauci, V., 2013. Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. *Nature* 493, 660–663. <https://doi.org/10.1038/nature11818>.
- Morin, T.H., Bohrer, G., Naor-Azrieli, L., Mesi, S., Kenny, W.T., Mitsch, W.J., Schäfer, K. V.R., 2014. The seasonal and diurnal dynamics of methane flux at a created urban wetland. *Ecol. Eng.* 72, 74–83. <https://doi.org/10.1016/j.ecoleng.2014.02.002>.
- Naser, H.M., Hatano, R., Nagata, O., 2005. Greenhouse gas fluxes and global warming potentials in crop fields on soil-dressed peatland in Hokkaido, Japan. *Phyton Ann. Rei Bot. Horn.* 45, 285–293.
- Ouyang, Z., Jackson, R.B., McNicol, G., Fluet-Chouinard, E., Runkle, B.R.K., Papale, D., Knox, S.H., Cooley, S., Delwiche, K.B., Feron, S., Irvin, J.A., Malhotra, A., Muddasir, M., Sabbatini, S., Alberto, M.C.R., Cescatti, A., Chen, C.-L., Dong, J., Fong, B.N., Guo, H., Hao, L., Iwata, H., Jia, Q., Ju, W., Kang, M., Li, H., Kim, J., Reba, M.L., Nayak, A.K., Roberti, D.R., Ryu, Y., Swain, C.K., Tsuang, B., Xiao, X., Yuan, W., Zhang, G., Zhang, Y., 2023. Paddy rice methane emissions across Monsoon Asia. *Remote. Sens. Environ.* 284, e113335. <https://doi.org/10.1016/j.rse.2022.113335>.
- Pärn, J., Verhoeven, J.T.A., Butterbach-Bahl, K., Dise, N.B., Ullah, S., Aasa, A., Egorov, S., Espenberg, M., Järveoja, J., Jauhiainen, J., Kasak, K., Klemetsson, L.,

- Kull, A., Laggoun-Défarge, F., Lapshina, E.D., Lohila, A., Lohmus, K., Maddison, M., Mitsch, W.J., Müller, C., Niinemets, Ü., Osborne, B., Pae, T., Salm, J.-O., Sgouridis, F., Sohar, K., Soosaar, K., Storey, K., Teemusk, A., Tenywa, M.M., Tournebize, J., Truu, J., Veber, G., Villa, J.A., Zaw, S.S., Mander, Ü., 2018. Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots. *Nat. Commun.* 9, e1135. <https://doi.org/10.1038/s41467-018-03540-1>.
- Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M., Stringer, L., 2008. Assessment on peatlands, biodiversity and climate change: Main report. Global Environment Centre, Kuala Lumpur, Malaysia / Wetlands International, Wageningen, The Netherlands, p. 179.
- Paul, S., Leifeld, J., 2023. Management of organic soils to reduce soil organic carbon losses. In: Rumpel, C. (Ed.), *Understanding and fostering soil carbon sequestration*. Burleigh Dodds Scientific Publishing, Cambridge, UK, pp. 617–680.
- Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360, 987–992. <https://doi.org/10.1126/science.aag0216>.
- Prastyaningih, S.R., Hardiwinoto, S., Agus, C., Musyafa, 2019. Development paludiculture on tropical peatland for productive and sustainable ecosystem in Riau. *Int. Conf. Environ. Resour. Manag. Glob. Reg.* 256, 1–7. <https://doi.org/10.1088/1755-1315/256/1/012048>.
- Qin, L., Tian, W., Freeman, C., Jia, Z., Yin, X., Gao, C., Zou, Y., Jiang, M., 2024. Changes in bacterial communities during rice cultivation remove phenolic constraints on peatland carbon preservation. *ISME Commun.* 4, ycae022. <https://doi.org/10.1093/ismeco/ycae022>.
- Rieley, J.O., Notohadiprawiro, T., Setiadi, B., Limin, S.H., 2008. In: Wosten, J.H.M., Rieley, J.O., Page, S.E. (Eds.), *Restoration of tropical peatlands: Why, Where and How? Restoration of tropical peatlands*. Wageningen University and Research Centre, and the EU INCO – RESTORPEAT Partnership, Wageningen, the Netherlands, p. 252.
- Saunois, M., Martinez, A., Poulter, B., Zhang, Z., Raymond, P.A., Regnier, P., Canadell, J.G., Jackson, R.B., Patra, P.K., Bousquet, P., Ciais, P., Dlugokencky, E.J., Lan, X., Allen, G.H., Bastviken, D., Beerling, D.J., Belikov, D.A., Blake, D.R., Castaldi, S., Crippa, M., Deemer, B.R., Dennison, F., Etiope, G., Gedney, N., Höglund-Isaksson, L., Hoggerson, M.A., Hopcroft, P.O., Hugelius, G., Ito, A., Jain, A.K., Janardan, R., Johnson, M.S., Kleinen, T., Krummel, P.B., Lauerwald, R., Li, T., Liu, X., McDonald, K.C., Melton, J.R., Mühle, J., Müller, J., Murguía-Flores, F., Niwa, Y., Noce, S., Pan, S., Parker, R.J., Peng, C., Ramonet, M., Riley, W.J., Rocher-Ros, G., Rosentreter, J.A., Sasakawa, M., Segers, A., Smith, S.J., Stanley, E.H., Thanwerdas, J., Tian, H., Tsuruta, A., Tubiello, F.N., Weber, T.S., van der Werf, G.R., Worthy, D.E.J., Xi, Y., Yoshida, Y., Zhang, W., Zheng, B., Zhu, Q., Zhu, Q., Zhuang, Q., 2025. Global Methane Budget 2000–2020. *Earth Syst. Sci. Data* 17, 1873–1958. <https://doi.org/10.5194/essd-17-1873-2025>.
- Smith, C., Nicholls, Z.R.J., Armour, K., Collins, W., Forster, P., Meinshausen, M., Palmer, M.D., Watanabe, M., 2021. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, M., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–2391.
- Tanneberger, F., Appulo, L., Ewert, S., Lakner, S., O Brolcháin, N., Peters, J., Wichtmann, W., 2021. The power of nature-based solutions: How peatlands can help us to achieve key EU sustainability objectives. *Adv. Sustain. Syst.* 5, e2000146. <https://doi.org/10.1002/adsu.202000146>.
- Temminck, R.J.M., Lång, K., Vroom, R.J.E., Leifeld, J., Fritz, C., Zeug, W., Thrän, D., Kleinspehn, C., Gaudig, G., Neubert, J., Kreyling, J., Rhymes, J.M., Evans, C.D., Kotowski, W., Nordt, A., Tanneberger, F., 2026. Agriculture on wet peatlands: the sustainability potential of paludiculture. *Agric. Syst.* 231, e104561. <https://doi.org/10.1016/j.agsy.2025.104561>.
- Uda, S.K., Hein, L., Adventa, A., 2020. Towards better use of Indonesian peatlands with paludiculture and low-drainage food crops. *Wetl. Ecol. Manag.* 28, 509–526. <https://doi.org/10.1007/s11273-020-09728-x>.
- UNEP, 2022. *Global Peatlands Assessment – The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands*. Main Report. Global Peatlands Initiative. United Nations Environment Programme, UNEP, Nairobi, Kenya, p. 425.
- van den Berg, M., Gremmen, T.M., Vroom, R.J.E., van Huissteden, J., Boonman, J., van Huissteden, C.J.A., van der Velde, Y., Smolders, A.J.P., van de Riet, B.P., 2024. A case study on topsoil removal and rewetting for paludiculture: effect on biogeochemistry and greenhouse gas emissions from *Typha latifolia*, *Typha angustifolia*, and *Azolla filiculoides*. *Biogeosciences* 21, 2669–2690. <https://doi.org/10.5194/bg-21-2669-2024>.
- Widmer, A., Tamagni, L., Wüst-Galley, C., Paul, S., Jocher, M., Volpe, V., Doetterl, S., Keller, T., Leifeld, J., 2026. Mitigating greenhouse gas emissions of a managed organic soil by paddy rice cultivation in the cool temperate zone. *Agr. Ecosyst. Environ.* 399, e110146. <https://doi.org/10.1016/j.agee.2025.110146>.
- Widyastuti, M.T., Minasny, B., Padarian, J., Maggi, F., Aitkenhead, M., Beucher, A., Connolly, J., Fiantis, D., Kidd, D., Ma, Y., Macfarlane, F., Robb, C., Rudiyanto, Setiawan, B.I., Taufik, M., 2025. Digital mapping of peat thickness and carbon stock of global peatlands. *CATENA* 258, e109243. <https://doi.org/10.1016/j.catena.2025.109243>.
- Xie, H., Li, J., Li, T., Lu, X., Hu, Q., Qin, Z., 2025. GloRice, a global rice database (v1.0): I. Gridded paddy rice annual distribution from 1961 to 2021. *Sci. Data* 12, 182. <https://doi.org/10.1038/s41597-025-04483-1>.
- Yuwati, T.W., Rachmanadi, D., Pratiwi, Turjaman, M., Indrajaya, Y., Nugroho, H.Y., Qirom, M.A., Narendra, B.H., Winarno, B., Lestari, S., Santosa, P.B., Adi, R.N., Savitri, E., Putra, P.B., Wahyuningtyas, R.S., Prayudyaningsih, R., Halwany, W., Nasrul, B., Bastoni, Mendham, D., 2021. Restoration of Degraded Tropical Peatland in Indonesia: A Review. *Land*, pp. 1170.
- Yvon-Durocher, G., Allen, A.P., Bastviken, D., Conrad, R., Gudasz, C., St-Pierre, A., Thanh-Duc, N., del Giorgio, P.A., 2014. Methane fluxes show consistent temperature dependence across microbial to ecosystem scales. *Nature* 507, 488–491. <https://doi.org/10.1038/nature13164>.
- Zhang, Z., Macedo, I., Linquist, B.A., Sander, B.O., Pittelkow, C.M., 2024. Opportunities for mitigating net system greenhouse gas emissions in Southeast Asian rice production: A systematic review. *Agric. Ecosyst. & Environ.* 361, e108812. <https://doi.org/10.1016/j.agee.2023.108812>.