ENVIRONMENTAL RESEARCH LETTERS

PURPOSE-LED PUBLISHING™

Part of the ENVIRONMENTAL RESEARCH SERIES

Towards improved accounting and mitigation of greenhouse gas emissions from ditches and canals

To cite this article before publication: Teresa Silverthorn *et al* 2025 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ae31f9

Towards improved accounting and mitigation of greenhouse gas emissions from ditches and canals

Teresa Silverthorn[1*], John Connolly[2], Wahaj Habib[2], Sarian Kosten[3], Tuula Larmola[4], José R. Paranaíba[3], Jackie Webb[5,6,7], Sivakiruthika Balathandayuthabani[8], Stewart J. Clarke[9], Corianne Tatariw[10], Sarah Cook[11], Jennifer L. Williamson[12], Laurie E. Friday[13,14], Alan Law[15], Luke O. Andrews[16], Judith van der Knaap[3], Chris D. Evans[12], Jeremy A. Fonvielle[13,14], David Bryan[15], Zhifeng Yan[17], Magdalena Bieroza[18], Merit van den Berg[19], Matthew J. Hill[20], Laura Baugh[1], Stephanie Evers[16], Ricky M. Mwanake[21], Sofia Baliña[3], Hamidreza Rahimi[14], Emily Simpson[15], Quinten Struik[3], Antti J. Rissanen[4,22], Mike Peacock[1,18*]

1. Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Liverpool, UK
2. Discipline of Geography, School of Natural Sciences, Trinity College Dublin, Dublin, Ireland
3. Department of Ecology, Radboud Institute for Biological and Environmental Sciences, Radboud University, Nijmegen, the Netherlands
4. Natural Resources Institute Finland (Luke), Helsinki, Finland
5. School of Agriculture & Environmental Science, University of Southern Queensland, Toowoomba, Queensland, Australia
6. Centre for Agricultural Engineering, University of Southern Queensland, Toowoomba, Queensland, Australia
7. Centre for Sustainable Agricultural Science, University of Southern Queensland, Toowoomba, Queensland, Australia

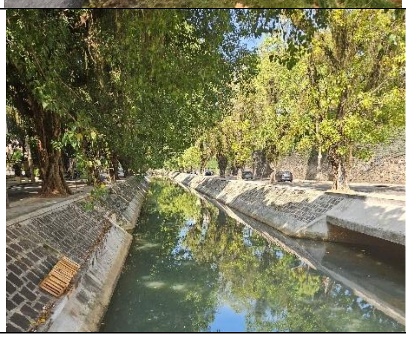
8. Tamil Nadu Agricultural University, Coimbatore, India
9. National Trust, Heelis, Swindon, UK
10. Department of Environmental Science, Rowan University, Glassboro, NJ, USA
11. School of Life Sciences, University of Warwick, Coventry, UK
12. UK Centre for Ecology & Hydrology, Deiniol Road, Bangor, LL57 2UW, UK
13. Department of Plant Sciences, University of Cambridge, Cambridge, CB2 3EA, UK
14. Centre for Landscape Regeneration, University of Cambridge, Cambridge, CB2 3QZ, UK
15. Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, Scotland
16. School of Biological and Environmental Sciences, Liverpool John Moores University, James Parsons Building, Byrom Street, Liverpool, L3 3AF, UK
17. School of Earth System Science, Institute of Surface-Earth System Science, Tianjin University, Tianjin, China
18. Swedish University of Agricultural Sciences, 75007 Uppsala, Sweden
19. UK Centre for Ecology & Hydrology, Benson Ln, Wallingford, OX10 8BB, UK
20. Department of Agriculture and Environment, Harper Adams University, Newport, Shropshire, TF10 8NB, UK
21. Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Kreuzeckbahnstrasse 19, Garmisch-Partenkirchen 82467, Germany
22. Faculty of Engineering and Natural Sciences, Tampere University, Korkeakoulunkatu 8, 33720 Tampere, Finland

*Corresponding authors: Teresa Silverthorn (teresa.silverthorn@gmail.com) and Mike Peacock (m.peacock@liverpool.ac.uk)

1. Introduction

Ditches and canals are important but largely unaccounted for components of global greenhouse gas (GHG) budgets. These human-made, linear waterways have a vast range of typologies and conditions (see Clifford et al., 2025 for a detailed review). In general, ditches tend to be narrower, variably inundated, and primarily used for drainage of wet soils for agriculture or forestry, while canals tend to be wider, used for transportation or irrigation, more likely to be made of impermeable substrate and perennially inundated (but these two terms are sometimes used interchangeably) (**Table 1**). The cumulative extent of ditches and canals is large; often rivalling stream and river length at regional scales (Brown et al., 2006), but remains poorly quantified at the global scale. Recent global syntheses have shown that ditches and canals emit notable amounts of methane (CH_4) (Gan et al., 2024; Peacock et al., 2021) as well as carbon dioxide (CO_2) and nitrous oxide (N_2O); often more per unit area than other inland waters (Silverthorn et al., 2025), and in some landscapes, even exceeding emissions from adjacent terrestrial areas (van der Knaap et al., 2025). These elevated emissions largely result from high nutrient and carbon inputs from the intensively managed agricultural and urban landscapes where these waterways are typically found (Peacock et al., 2021). Although local-scale studies about GHG emissions from ditches and canals have increased (**Figure 1A**), these water bodies remain overlooked in global inland water GHG budgets and national inventory reporting, despite Intergovernmental Panel on Climate Change (IPCC) recommendations to include emission from ditches draining organic soils (IPCC, 2014) and subsequently from all ditches and canals (IPCC, 2019). Improved reporting would enable mitigation measures leading to reduced ditch and canal emissions to be recognised in Nationally Determined Contributions to the UN Framework Convention on Climate Change (UNFCCC). Moreover, reducing ditch and canal emissions should be recognized as an important measure for achieving net-zero emission targets set by many nations. Given the importance of ditch and canal GHG emissions, we (1) identify key knowledge and data gaps that must be addressed to better constrain global estimates of GHG emissions from ditches and canals, and (2) explore potential strategies for mitigating these emissions.

Table 1. Functional and physical descriptions of five common ditch and canal types. These types may be referred to by other names (e.g. agricultural ditch or agricultural canal; roadside ditch or swale). This list is not exhaustive as other ditch types exist (see Clifford et al., 2025), such as residential canals, transportation canals, sewage ditches, peat extraction ditches, moats, and hydropower channels.

Ditch type	Description and representative study	Photo
Forest ditch	Ditches used for draining wet soils for commercial tree growth. Typically narrow (~1m wide) and found in the northern hemisphere (Rissanen et al., 2023).	
Agricultural ditch	Ditches used for draining wet soils for agricultural use. Variable widths, typically <10m, found around the world (Wu et al., 2023).	
Roadside ditch	Ditches used for collecting and transporting excess water from roads and to prevent their flooding. Variable widths, intermittently flooded, often vegetated, typically <2m, found around the world (McPhillips et al., 2016).	
Urban canal	Canals used for providing transportation, aesthetic, flood control, and other functions in urban settings. Substrate is often impermeable, variable widths (Pelsma et al., 2023).	

Irrigation canal	Canals used to transport water for agricultural production. Substrate can be impermeable, variable widths, found around the world (Palmia et al., 2021).	

Photos: forest ditch in Sweden (M. Peacock); agricultural ditch in Hebei province, China (Z. Yan); Roadside ditch in Ontario, Canada (K. Kolman); Urban canal in Rio de Janeiro, Brazil (S. Kosten); Irrigation canal in India (S. Balathandayuthabani).

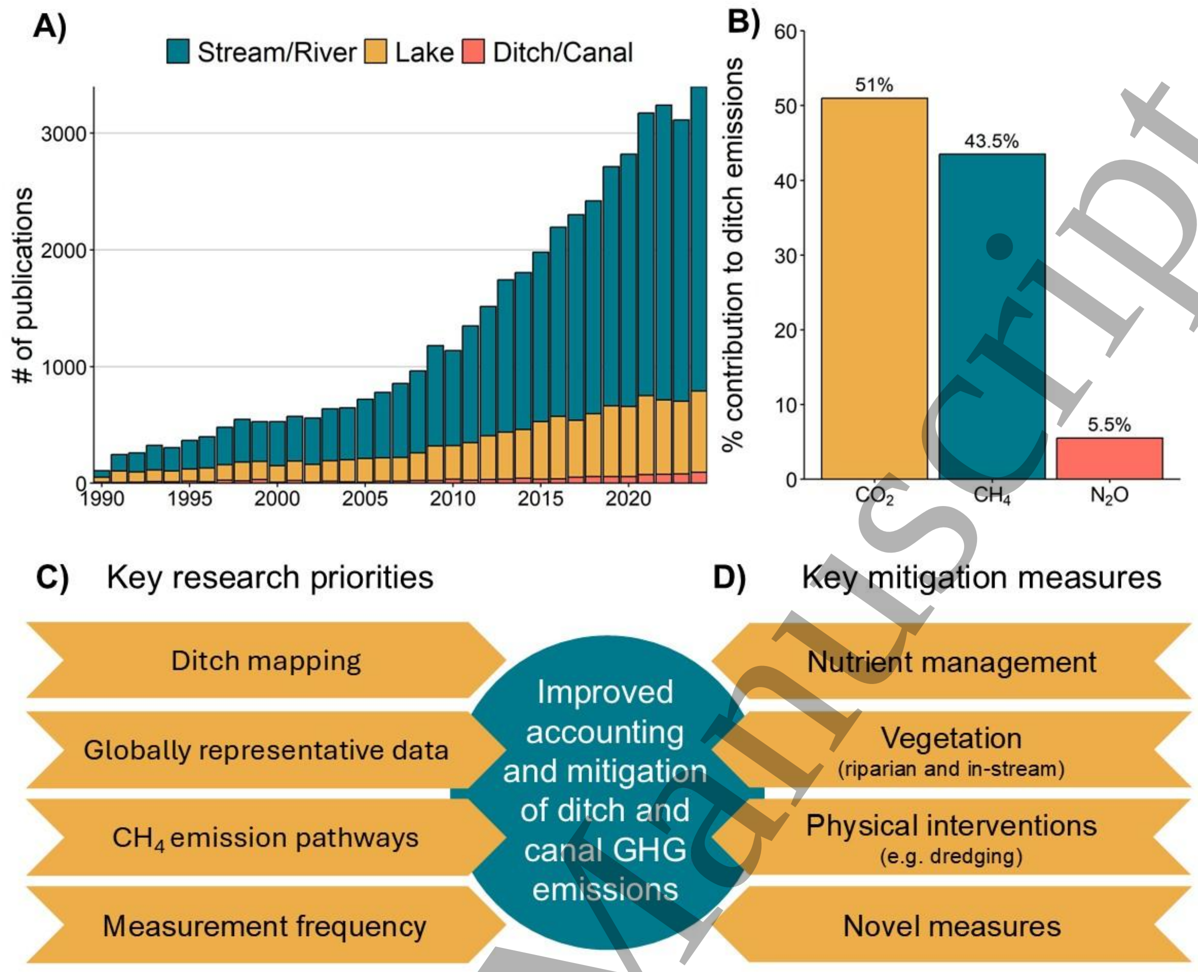


Figure 1. Conceptual synthesis of current knowledge and priorities for improved accounting and mitigation of greenhouse gas (GHG) emissions from ditches and canals. **A)** Annual number of peer-reviewed articles related to GHG emissions from ditches compared to other inland waters; **B)** Relative contribution of each gas to ditch GHG emissions in terms of CO_2-equivalents from $n = 22$ studies (Silverthorn et al., 2025); Summary of **C)** key knowledge gaps; and **D)** mitigation measures. Figure details in Supplementary Materials.

2. Knowledge gaps

The key gaps in data and in our understanding of ditch and canal GHG emissions are associated with (1) lack of accurate and representative estimates of GHG emissions, with particular focus on CO_2 and CH_4, which contribute the most to climatic warming (**Figure 1B**); and (2) the mapping of the global extent of ditches and canals (**Figure 1C**). Addressing these gaps is critical for improving global estimates of ditch and canal emissions and for accurate reporting in national inventories. For inventory reporting, key challenges include both completeness (reporting all emissions) and avoiding double-counting ditch and canal emissions with agricultural, wetland, or urban wastewater emissions.

2.1. Knowledge and data gaps in GHG emissions

The growing, but still limited, dataset of ditch and canal emissions that has accumulated since the 1990s has allowed global upscaling of all three main GHGs (Peacock et al., 2021; Silverthorn et al., 2025). However, current estimates rely on a single global average ("emission factor") for each GHG, which could be refined and disaggregated through consideration of climate zones, trophic state, temporal variability, etc. To improve global estimates, we suggest three critical gaps must be addressed: (1) the global bias of data, (2) the underrepresentation of ebullitive and plant-mediated CH_4 emissions, and (3) insufficient measurement frequency.

Half of the data points from the global syntheses of Peacock et al. (2021) and Silverthorn et al. (2025) are from Europe. Although Australia, North America, and Asia are moderately well-covered, to date, there is just one study from South America and none from Africa. Missing national- or continental-scale data leads to fundamental uncertainty in global upscaling. Moreover, measurements from these under-represented regions are needed to refine global estimates according to geographic and/or climate regions, as has been done for other inland waters (IPCC, 2019; Lauerwald et al., 2023).

Although some early studies measured ditch CH_4 ebullition (Minkkinen et al., 1996), it remains largely neglected. Those that have measured ebullition have often found it to be the dominant emission pathway, making up 80% of total CH_4 emissions (Silverthorn et al., 2025), although some cases of negligible ebullition contributions also have been reported (Köhn et al., 2021). The magnitude of ebullitive relative to diffusive fluxes will likely depend on sediment properties, trophic state, water velocity, and water depth (which can influence sediment temperature). In addition, few studies have measured plant-mediated transport of CH_4, presumably due to logistical difficulties of measuring emissions from tall emergent vegetation such as *Phragmites* and *Typha*. However, the presence of plants with aerenchymatous tissue can enhance CH_4 emissions (Bastviken et al., 2023). More measurements of these two pathways will allow for better estimates of CH_4 emissions to be incorporated into future global estimates.

Most ditch and canal GHG studies rely on non-continuous measurements (although see Harrison et al., 2005; Paranaíba et al., 2025) which are then extrapolated to annual estimates, despite their poor ability to capture diel cycles and episodic events (e.g. droughts, storms, and management interventions) that can significantly influence GHG emissions. For example, peaks in ditch CO_2 and CH_4 emissions have been observed post-flood (Webb et al., 2016), while continuously inundated ditches have higher N_2O emissions compared to ditches that periodically dry out (Silverthorn et al., 2025). In addition, higher ditch CO_2 and CH_4 emissions have been observed at night than during the day (Paranaíba et al., 2025), suggesting that relying solely on daytime measurements (when photosynthetic uptake by ditch vegetation is occurring) may lead to an underestimation of total emissions. These dynamics highlight the need for continuous, sensor-based GHG monitoring to more accurately capture temporal variability.

2.2. Knowledge and data gaps in mapping and mapping methods

We have yet to map the global extent of ditches and canals due to knowledge and data gaps pertaining to (1) the limited availability of drainage maps, (2) a lack of harmonised labelled training data (e.g., ground truthed features) and (3) limitations to scale current mapping efforts. Existing regional and national maps remain outdated, inconsistent, or incomplete, especially where waterways are small and/or obscured with vegetation canopy (Lidberg et al., 2023). To address this, remote sensing and image analysis techniques have been explored, although methodological and data gaps persist.

Optical aerial or high resolution satellite imagery can be used for ditch and canal mapping, but vegetation, canopy cover, and persistent cloud cover can limit its effectiveness, particularly in dense forested, agricultural or peatland areas (Connolly & Holden, 2017; Habib et al., 2024). Airborne LiDAR can overcome these issues and detect subtle geomorphological features like ditches and canals (Lidberg et al., 2023). However, its limited spatial coverage and high cost hinder broader application. Similarly, Synthetic Aperture Radar (e.g., Sentinel-1) provides all-weather capabilities and has been used for mapping water level in ditches (Al-Khudhairy et al., 2001), but it lacks the spatial resolution to resolve narrow waterways.

For image analysis, traditional pixel-based classification methods are often inadequate due to the small size and complex morphology of many ditches and canals. Object-Based Image Analysis improves detection by incorporating spatial and geometric contexts (Connolly & Holden, 2017). More recently, Deep Learning methods such as Convolutional Neural Networks have shown considerable promise for the automated identification of ditches (Habib et al., 2024). However, Deep Learning approaches require extensive training data, lack transferability across geographic areas, and are computationally intensive, limiting scalability. Overcoming these challenges will require harmonised multi-sensor frameworks, transferable Machine Learning models, and collaborative data generation.

3. Mitigation

Mitigation of ditch and canal GHG emissions can be achieved through a diverse range of strategies (**Figure 1D, Figure 2**). Advancing their implementation will require both further research into their effectiveness as well as supportive government policies and incentives.

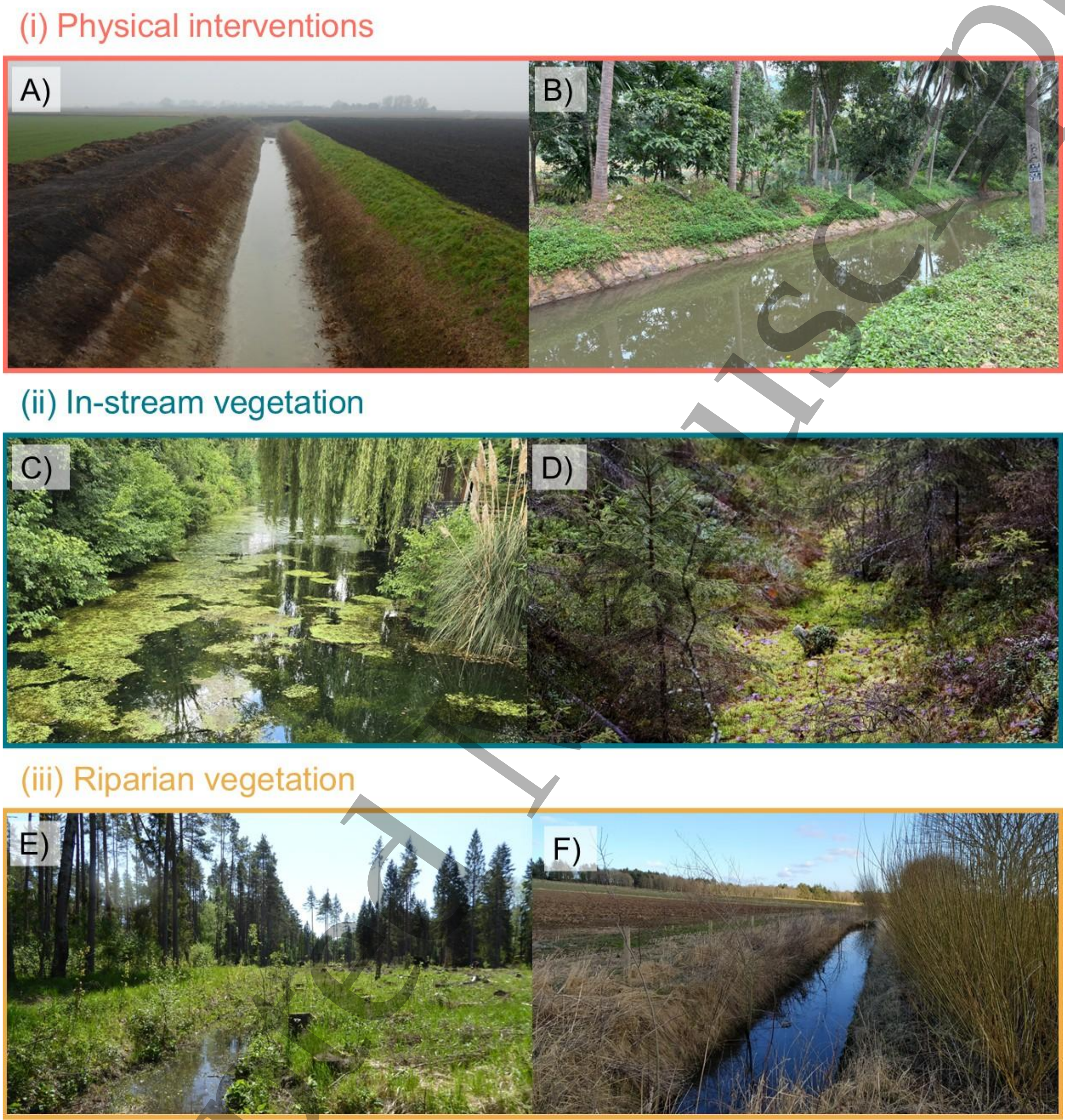


Figure 2. Photographs of ditches and canals with various greenhouse gas (GHG) emission mitigation measures related to physical interventions, in-stream vegetation, and riparian vegetation: (**A**) Recently dredged agricultural lowland peat ditch in England; (**B**) Recently dredged irrigation canal in Tamil Nadu, India; (**C**) Urban canal with submerged macrophytes and floating algae in the Netherlands; (**D**) *Sphagnum* moss-covered forest ditch in Finland; (**E**) Continuous cover forestry (selective cutting) around a forest ditch in Sweden; (**F**) Agricultural ditch in Scotland with *Salix* riparian vegetation periodically harvested for biomass. Photos: M. Peacock (A, E), S. Balathandayuthabani (B), J.R. Paranaíba (C), M. Kurki (Luke) (D), and D. Bryan (F).

3.1. Nutrient management

Measures that reduce the inputs of nutrients and organic matter into ditches and canals can help lower GHG emissions. Excessive nitrogen and phosphorus loading, often from agricultural runoff or urban stormwater, can increase organic matter production (e.g., algal growth) and accelerate its decomposition. This decomposition, in turn, fuels microbial processes such as methanogenesis, nitrification, and denitrification, all of which release GHGs (Wu et al., 2023). High nutrient inputs can therefore drive emissions both by enhancing organic matter accumulation and by directly stimulating microbial activity (Zhou et al., 2025). Thus, mitigating point-source pollution from sources such as wastewater treatment plants and infrastructure like boat docks can reduce GHG emissions from canals (Martinez-Cruz et al., 2017; Mwanake et al., 2024). While reducing fertiliser application rates and other nutrient amendments at the catchment scale, together with improving crop nutrient use efficiency and excluding livestock from riparian areas, can mitigate GHG emissions from agricultural ditches.

3.2. Riparian vegetation

Riparian vegetation can help mitigate inputs of nutrients and sediments by intercepting them before reaching the waterway, thereby reducing aquatic GHG production (Fisher et al., 2014). However, impervious substrate and banks may limit the effectiveness of this strategy for many canals. Although organic matter inputs from vegetated riparian zones can fuel respiration, increasing CO_2 and CH_4 emissions, these can be reduced through vegetation harvesting (Bai et al., 2022). Additionally, riparian shading may reduce water temperature (Roth et al., 2010), reducing microbial activity rates and therefore GHG emissions (Yvon-Durocher et al., 2010). For forest ditches, maintaining a continuous riparian forest canopy by using selective cutting instead of clear-cutting can attenuate post-harvest water table rise and thus reduce nutrient leaching from peat soils into ditches (Nieminen et al., 2018).

3.3. In-stream vegetation

Within ditches and canals, vegetation can play a critical role in regulating GHG dynamics (Bodmer et al., 2024; Theus & Holgerson, 2025). Submerged plants can facilitate CH_4 oxidation by transporting atmospheric oxygen to the rhizosphere through their aerenchyma tissues, creating micro-oxic zones in anoxic sediments which support methanotrophic bacteria that consume CH_4 (Lemoine et al., 2012). Floating plants can decrease the diffusive flux of GHGs to the atmosphere, resulting in a large proportion of CH_4 oxidized below the plants, but they may increase CH_4 ebullition thereby potentially leading to an overall increase in emissions (Theus & Holgerson, 2025). In forest ditches, CH_4 emissions can be significantly lower in *Sphagnum* moss-covered ditches compared to "cleaned", moss-free ditches (Rissanen et al., 2023). Therefore, measures that protect or restore submerged macrophytes and *Sphagnum* moss can play a critical role in reducing ditch CH_4 emissions. However, aquatic vegetation can augment emissions by providing a carbon source during seasonal plant senescence (Theus & Holgerson, 2025) and emergent rooted plants can be direct conduits of CH_4 from sediments to the atmosphere (Bodmer et al., 2024). The effects of aquatic vegetation on GHG fluxes are therefore challenging to disentangle, and vary by plant type (e.g. submerged, floating, emergent, non-vascular) and time of year, with more ditch and canal-specific research needed. This strategy is mostly unsuitable for navigation canals as in-stream vegetation can obstruct vessel movement, but separated, shallow margins have been trialled as a way to increase aquatic plant abundance without obstructing boat traffic (Boedeltje et al., 2001).

3.4. Dredging

Dredging, routine in many agricultural ditches, may help reduce GHG emissions by removing accumulated sediments rich in organic matter and nutrients, along with the microbial communities that drive carbon and nitrogen cycling (Paranaíba et al., 2025). While dredging can trigger short-term emission spikes, it has been associated with a longer-term reduction in agricultural ditch GHG emissions: ~35% less CO_2-equivalent emissions within one year following dredging (Paranaíba et al., 2025). However, emissions from the displaced ditch sediments must be accounted for (Paranaíba et al., 2023), and dredging disturbs aquatic habitats, including benthic communities. The effects of dredging frequency, timing, and methods on GHG mitigation remain poorly understood and require further attention. In addition to dredging, we argue that other physical considerations such as channel design, water depth, and flow rates should be explored for their potential to reduce ditch GHG emissions.

3.5. Novel mitigation measures

Novel measures, such as biochemical manipulation and enhanced rock weathering, are gaining recognition as a promising frontier in ecosystem management. Although still in its early stages and largely limited to experimental settings, microbial inoculations in sediments, such as with nitrite/nitrate-dependent anaerobic methane-oxidizing microorganisms (Legierse et al., 2023) and stimulation of iron-dependent anaerobic methane-oxidizing bacteria through iron chloride additions (Struik et al., 2024), show promise in agricultural ditches as innovative strategies to mitigate CH_4 emissions. These specialized microbial communities can oxidize CH_4 using nitrite, nitrate, or iron as electron acceptors, playing a key role in reducing CH_4 emissions under anoxic conditions commonly found in ditch sediments. Chemical weathering of rocks is a natural process that absorbs CO_2, and this process can be enhanced by applying crushed rocks to the land surface or aquatic systems. As the minerals dissolve in water, the dissolution products are transported to the ocean where the carbon is stored (Strefler et al., 2018). Other novel measures include nutrient-binding amendments, and using salinization, oxygenation, and sulphate additions to reduce anaerobic CH_4 production (Paranaíba & Kosten, 2024; Varjo et al., 2003). However, uncertainties remain about large-scale implementation of these novel measures, including long-term efficiency, transferability across ecosystems, unintended ecological impacts, and economic viability.

4. Conclusions and implications

Ditches and canals are important but overlooked sources of GHG emissions. Moving forward, policymakers and land managers should integrate ditch and canal GHG mitigation into broader climate and land-use planning. Ditch and canal emissions should also be incorporated into global inland water GHG models, particularly predictive models assessing the impacts of global change, such as warming and eutrophication, which are expected to increase emissions from these waterbodies. The riparian zones of ditches (located at the terrestrial-aquatic interface) can also be emission hotspots (van der Knaap et al., 2025). Thus, to obtain the full picture, these areas should be included in landscape scale upscaling. Additionally, legislative frameworks should be updated to recognize ditches and canals as fundamental and functional ecosystems that influence landscape carbon and nitrogen cycles. Much of the current knowledge on mitigation remains in the experimental phase, therefore accelerating research in collaboration with stakeholders and policymakers is crucial. Addressing key research priorities in mapping, geography, emission pathways, and measurement frequency will improve understanding of ditch and canal GHG production and emissions to refine global upscaling. Through improved accounting and emission reductions, ditches and canals can be important actors in climate change mitigation.

Author contributions

Funding acquisition: TS and MP received funding for the symposium where this manuscript was planned. **Conceptualization:** this manuscript was conceptualized through discussions with all co-authors. **Writing - Original Draft**: TS wrote the introduction and conclusions; JC, WH, and MP wrote the section on knowledge gaps; SK, TL, and JRP wrote the section on mitigation. **Visualization**: TS prepared the figures. **Writing - Review & Editing**: All authors reviewed and contributed to the manuscript drafts. Author order was assigned alphabetically by last name for the core authors (excluding the first and last authors), and the order of the remaining authors was assigned using a random number generator.

Data Availability

The data and code used to make Figure 1 can be found on Github at https://github.com/TeresaSilverthorn/Ditch-symposium and on Zenodo at https://doi.org/10.5281/zenodo.17069240

Acknowledgements

MP and TS acknowledge the University of Liverpool's EPSRC Impact Acceleration Account (Network and Impact Cultivation Funding) award, which funded the symposium where this manuscript was conceptualized. We acknowledge the contributions of others who attended the symposium but did not contribute to this paper. TL was funded by the European Union projects H2020 Holisoils (grant number 101000289) and HE Alfawetlands (grant number 101056844). RMM was funded by the Helmholtz Association through the joint program Changing Earth – Sustaining Our Future (ATMO - PoF IV) program at Karlsruhe Institute of Technology. SK and JRP were supported by the NWO-TTW project (grant number 18661); SK also by NWO-VIDI (grant number 203.098). SB was funded by the Ramanujan Fellowship by the Anusandhan National Research Foundation of the Government of India

301 (grant number RJF/2020/000015). JF and LEF were funded by NERC's Changing the
302 Environment programme (grant number NE/W00495X/1).

303

304

References

Al-Khudhairy, D. H. A., Leemhuis, C., Hoffmann, V., Calaon, R., Shepherd, I. M., Thompson, J. R., Gavin, H., & Gasca-Tucker, D. L. (2001). Monitoring wetland ditch water levels in the North Kent Marshes, UK, using Landsat TM imagery and ground-based measurements. *Hydrological Sciences Journal*, *46*(4), 585–597. https://doi.org/10.1080/02626660109492852

Bai, X., Cheng, C., Xu, Q., Tang, B., He, Q., & Li, H. (2022). Regulating autogenic vegetation in the riparian zone reduces carbon emissions: Evidence from a microcosm study. *Science of The Total Environment*, *840*, 156715. https://doi.org/10.1016/j.scitotenv.2022.156715

Bastviken, D., Treat, C. C., Pangala, S. R., Gauci, V., Enrich-Prast, A., Karlson, M., Gålfalk, M., Romano, M. B., & Sawakuchi, H. O. (2023). The importance of plants for methane emission at the ecosystem scale. *Aquatic Botany*, *184*, 103596. https://doi.org/10.1016/j.aquabot.2022.103596

Bodmer, P., Vroom, R. J. E., Stepina, T., del Giorgio, P. A., & Kosten, S. (2024). Methane dynamics in vegetated habitats in inland waters: Quantification, regulation, and global significance. *Frontiers in Water*, *5*. https://doi.org/10.3389/frwa.2023.1332968

Boedeltje, G., Smolders, A. J. P., Roelofs, J. G. M., & Van Groenendael, J. M. (2001). Constructed shallow zones along navigation canals: Vegetation establishment and change in relation to environmental characteristics. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *11*(6), 453–471. https://doi.org/10.1002/aqc.487

Brown, C. D., Turner, N., Hollis, J., Bellamy, P., Biggs, J., Williams, P., Arnold, D., Pepper, T., & Maund, S. (2006). Morphological and physico-chemical properties of British aquatic habitats potentially exposed to pesticides. *Agriculture, Ecosystems & Environment*, *113*(1–4), 307–319. https://doi.org/10.1016/j.agee.2005.10.015

330 Clifford, C., Bieroza, M., Clarke, S. J., Pickard, A., Stratigos, M. J., Hill, M. J., Raheem, N., Tatariw, C., Wood, P. J., Arismendi, I., Audet, J., Aviles, D., Bergman, J. N., Brown, A. G., Burns, R. E., Connolly, J., Cook, S., Crabot, J., Cross, W. F., … Peacock, M. (2025). Lines in the landscape. *Communications Earth & Environment*, *6*(1), 693. https://doi.org/10.1038/s43247-025-02699-y

335 Connolly, J., & Holden, N. M. (2017). Detecting peatland drains with Object Based Image Analysis and Geoeye-1 imagery. *Carbon Balance and Management*, *12*(1). https://doi.org/10.1186/s13021-017-0075-z

338 Fisher, K., Jacinthe, P. A., Vidon, P., Liu, X., & Baker, M. E. (2014). Nitrous Oxide Emission from Cropland and Adjacent Riparian Buffers in Contrasting Hydrogeomorphic Settings. *Journal of Environmental Quality*, *43*(1), 338–348. https://doi.org/10.2134/jeq2013.06.0223

342 Gan, D., Zhang, Z., Li, H., Yu, D., Li, Z., Long, R., Niu, S., Zuo, H., Meng, X., Wang, J., & Ma, L. (2024). Ditch emissions partially offset global reductions in methane emissions from peatland drainage. *Communications Earth & Environment*, *5*(1), 640. https://doi.org/10.1038/s43247-024-01818-5

346 Habib, W., Cresson, R., McGuinness, K., & Connolly, J. (2024). Mapping artificial drains in peatlands—A national-scale assessment of Irish raised bogs using sub-meter aerial imagery and deep learning methods. *Remote Sensing in Ecology and Conservation*, *10*(4), 551–562. https://doi.org/10.1002/rse2.387

350 Harrison, J. A., Matson, P. A., & Fendorf, S. E. (2005). Effects of a diel oxygen cycle on nitrogen transformations and greenhouse gas emissions in a eutrophied subtropical stream. *Aquatic Sciences*, *67*(3), 308–315. https://doi.org/10.1007/s00027-005-0776-3

IPCC. (2014). *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds).* IPCC, Switzerland.

IPCC. (2019). *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, forestry and other land use (AFOLU). Chapter 7: Wetlands. Lovelock, C.E., Evans, C., Barros, N., Prairie, Y., Alm, J., Bastviken, D., Beaulieu, J.J., Garneau, M., Harby, A., Harrison, J., Pare, D., Raadal, H.L., Sherman, B., Zhang, C., Ogle, S.M., Grinham, A., Deemer, B., Aurelio dos Santos, M., Kosten, S., Peacock, M., Li, Z. and Stepanenko, V.* IPCC, Switzerland.

Köhn, D., Welpelo, C., Günther, A., & Jurasinski, G. (2021). Drainage ditches contribute considerably to the CH_4 budget of a drained and a rewetted temperate fen. *Wetlands*, *41*(6), 1–15. https://doi.org/10.1007/s13157-021-01465-y

Lauerwald, R., Allen, G. H., Deemer, B. R., Liu, S., Maavara, T., Raymond, P., Alcott, L., Bastviken, D., Hastie, A., Holgerson, M. A., Johnson, M. S., Lehner, B., Lin, P., Marzadri, A., Ran, L., Tian, H., Yang, X., Yao, Y., & Regnier, P. (2023). Inland Water Greenhouse Gas Budgets for RECCAP2: 2. Regionalization and Homogenization of Estimates. *Global Biogeochemical Cycles*, *37*(5). https://doi.org/10.1029/2022gb007658

Legierse, A., Struik, Q., Smith, G., Echeveste Medrano, M. J., Weideveld, S., van Dijk, G., Smolders, A. J., Jetten, M., Veraart, A. J., & Welte, C. U. (2023). Nitrate-dependent anaerobic methane oxidation (N-DAMO) as a bioremediation strategy for waters affected by agricultural runoff. *FEMS Microbiology Letters*, *370*, fnad041. https://doi.org/10.1093/femsle/fnad041

Lemoine, D. G., Mermillod-Blondin, F., Barrat-Segretain, M.-H., Massé, C., & Malet, E. (2012). The ability of aquatic macrophytes to increase root porosity and radial oxygen loss determines their resistance to sediment anoxia. *Aquatic Ecology*, *46*(2), 191–200. https://doi.org/10.1007/s10452-012-9391-2

Lidberg, W., Paul, S. S., Westphal, F., Richter, K. F., Lavesson, N., Melniks, R., Ivanovs, J., Ciesielski, M., Leinonen, A., & Ågren, A. M. (2023). Mapping Drainage Ditches in Forested Landscapes Using Deep Learning and Aerial Laser Scanning. *Journal of Irrigation and Drainage Engineering*, *149*(3), 04022051. https://doi.org/10.1061/JIDEDH.IRENG-9796

Martinez-Cruz, K., Gonzalez-Valencia, R., Sepulveda-Jauregui, A., Plascencia-Hernandez, F., Belmonte-Izquierdo, Y., & Thalasso, F. (2017). Methane emission from aquatic ecosystems of Mexico City. *Aquatic Sciences*, *79*(1), 159–169. https://doi.org/10.1007/s00027-016-0487-y

McPhillips, L. E., Groffman, P. M., Schneider, R. L., & Walter, M. T. (2016). Nutrient Cycling in Grassed Roadside Ditches and Lawns in a Suburban Watershed. *Journal of Environmental Quality*, *45*(6), 1901–1909. https://doi.org/10.2134/jeq2016.05.0178

Minkkinen, K., Laine, J., Nykänen, H., & Martikainen, P. (1996). Role of drainage ditches in emissions of methane from mires drained for forestry. *IN GLOBAL CLIMATIC CHANGE*, *1*, 110.

Mwanake, R. M., Imhof, H. K., & Kiese, R. (2024). Divergent drivers of the spatial variation in greenhouse gas concentrations and fluxes along the Rhine River and the Mittelland Canal in Germany. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-024-33394-8

Nieminen, M., Palviainen, M., Sarkkola, S., Laurén, A., Marttila, H., & Finér, L. (2018). A synthesis of the impacts of ditch network maintenance on the quantity and quality of runoff from drained boreal peatland forests. *Ambio*, *47*(5), 523–534. https://doi.org/10.1007/s13280-017-0966-y

Palmia, B., Leonardi, S., Viaroli, P., & Bartoli, M. (2021). Regulation of CO_2 fluxes along gradients of water saturation in irrigation canal sediments. *Aquatic Sciences*, *83*(1), 18. https://doi.org/10.1007/s00027-020-00773-5

Paranaíba, J. R., & Kosten, S. (2024). Mitigating inland waters' greenhouse gas emissions: Current insights and prospects: Kilham Memorial Lecture on occasion of the 37th SIL Congress, Iguazu Falls, Brazil, 2024. *Inland Waters*, 1–14. https://doi.org/10.1080/20442041.2024.2372229

Paranaíba, J. R., Struik, Q., Erdociain, M., van Dijk, G., Smolders, A. J., van der Knaap, J., Veraart, A. J., & Kosten, S. (2023). CO_2, CH_4, and N_2O emissions from dredged material exposed to drying and zeolite addition under field and laboratory conditions. *Environmental Pollution*, *337*, 122627.

Paranaíba, J. R., Struik, Q., Shendurnikar, S., Ma, Y., Quadra, G. R., & Kosten, S. (2025). Summer CH_4 ebullition strongly determines year-round greenhouse gas emissions from agricultural ditches despite frequent dredging. *Journal of Environmental Management*, *373*, 123813. https://doi.org/10.1016/j.jenvman.2024.123813

Peacock, M., Audet, J., Bastviken, D., Futter, M. N., Gauci, V., Grinham, A., Harrison, J. A., Kent, M. S., Kosten, S., & Lovelock, C. E. (2021). Global importance of methane emissions from drainage ditches and canals. *Environmental Research Letters*, *16*(4), 044010. https://doi.org/10.1088/1748-9326/abeb36

Pelsma, K. A. J., Verhagen, D. A. M., Dean, J. F., Jetten, M. S. M., & Welte, C. U. (2023). Methanotrophic potential of Dutch canal wall biofilms is driven by Methylomonadaceae. *FEMS Microbiology Ecology*, *99*(10), fiad110. https://doi.org/10.1093/femsec/fiad110

Rissanen, A. J., Ojanen, P., Stenberg, L., Larmola, T., Anttila, J., Tuominen, S., Minkkinen, K., Koskinen, M., & Mäkipää, R. (2023). Vegetation impacts ditch methane emissions from boreal forestry-drained peatlands—Moss-free ditches have an order-of-magnitude higher emissions than moss-covered ditches. *Frontiers in Environmental Science*, *11*, 1121969. https://doi.org/10.3389/fenvs.2023.1121969

Roth, T. R., Westhoff, M. C., Huwald, H., Huff, J. A., Rubin, J. F., Barrenetxea, G., Vetterli, M., Parriaux, A., Selker, J. S., & Parlange, M. B. (2010). Stream Temperature Response to Three Riparian Vegetation Scenarios by Use of a Distributed Temperature Validated Model. *Environmental Science & Technology*, *44*(6), 2072–2078. https://doi.org/10.1021/es902654f

Silverthorn, T., Audet, J., Evans, C. D., Van Der Knaap, J., Kosten, S., Paranaíba, J., Struik, Q., Webb, J., Wu, W., Yan, Z., & Peacock, M. (2025). The Importance of Ditches and Canals in Global Inland Water CO_2 and N_2O Budgets. *Global Change Biology*, *31*(3), e70079. https://doi.org/10.1111/gcb.70079

Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, *13*(3), 034010. https://doi.org/10.1088/1748-9326/aaa9c4

Struik, Q., Paranaíba, J. R., Glodowska, M., Kosten, S., Meulepas, B. M., Rios-Miguel, A. B., Jetten, M. S., Lürling, M., Waajen, G., & Nijman, T. P. (2024). Fe (II) Cl2 amendment suppresses pond methane emissions by stimulating iron-dependent anaerobic oxidation of methane. *FEMS Microbiology Ecology*, *100*(5), fiae061. https://doi.org/10.1093/femsec/fiae061

Theus, M. E., & Holgerson, M. A. (2025). Freshwater plant communities influence water column greenhouse gases. *Aquatic Botany*, *201*, 103927. https://doi.org/10.1016/j.aquabot.2025.103927

van der Knaap, J., Harpenslager, S. F., Aben, R. C. H., Weideveld, S. T. J., van Giersbergen, Q., van Dijk, G., Wintjen, P., Buzacott, A. J. V., Fritz, C., Kruijt, B., & Kosten, S.

(2025). Disproportionately High Contribution of Ditches to Landscape Greenhouse Gas Emissions in Drained Peatlands. *Ecosystems*, *28*(5), 58. https://doi.org/10.1007/s10021-025-01005-3

Varjo, E., Liikanen, A., Salonen, V.-P., & Martikainen, P. J. (2003). A new gypsum-based technique to reduce methane and phophorus release from sediments of eutrophied lakes: (Gypsum treatment to reduce internal loading). *Water Research*, *37*(1), 1–10. https://doi.org/10.1016/S0043-1354(02)00264-6

Webb, J. R., Santos, I. R., Tait, D. R., Sippo, J. Z., Macdonald, B. C. T., Robson, B., & Maher, D. T. (2016). Divergent drivers of carbon dioxide and methane dynamics in an agricultural coastal floodplain: Post-flood hydrological and biological drivers. *Chemical Geology*, *440*, 313–325. https://doi.org/10.1016/j.chemgeo.2016.07.025

Wu, W., Niu, X., Yan, Z., Li, S., Comer-Warner, S. A., Tian, H., Li, S.-L., Zou, J., Yu, G., & Liu, C.-Q. (2023). Agricultural ditches are hotspots of greenhouse gas emissions controlled by nutrient input. *Water Research*, *242*, 120271. https://doi.org/10.1016/j.watres.2023.120271

Yvon-Durocher, G., Jones, J. I., Trimmer, M., Woodward, G., & Montoya, J. M. (2010). Warming alters the metabolic balance of ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1549), 2117–2126. https://doi.org/10.1098/rstb.2010.0038

Zhou, L., Zhou, Y., Paranaíba, J. R., Peacock, M., Jeppesen, E., & Hamilton, D. P. (2025). Agricultural ditches and stream networks are overlooked hotspots of carbon emissions. *National Science Review*, *12*(5), nwaf111. https://doi.org/10.1093/nsr/nwaf111