

Title: AI4 plant trait-based wetland CH₄ predictions

Authors/Affiliations: Avni Malhotra (PNNL), Tiia Määttä (University of Zurich), Etienne Fluet-Chouinard (PNNL), Housen Chu (LBL), Gavin McNichol (University of Illinois-Chicago), Kyle Delwiche (UC Berkeley)

Focal Area(s):

- Approaches that support the transfer of mechanistic knowledge gained in the laboratory to make predictions in the field, and vice versa.
- Key uncertainties and knowledge gaps in CH₄ where new AI technology can advance plant-trait based predictive understanding of the wetland methane cycle.
- The importance of high potential datasets (FLUXNET-CH₄, COSORE, plant/root trait databases, network data and experiments such as NEON, COMPASS, SPRUCE) and how the combination of data across spatial or temporal scales or scientific domains may lead to new scientific insights, either within or across fields.

Science or Technological Challenge: predicting highly variable wetland CH₄

Wetlands are the largest natural source of CH₄ to the atmosphere and remain a key uncertainty in the global CH₄ budget, emitting between 100–180 Tg CH₄ yr⁻¹ (1). Wetlands also face unique pressures (drainage, salinization, etc) from human land uses (2) and climate change (3), often driving these systems into disequilibrium (4). Uncertainty in wetland CH₄ emissions is partly due to the dynamic nature of wetland biogeochemistry, hydrology as well as processes involved in CH₄ flux (methanogenesis, methanotrophy, gas transport etc). The variability of wetland ecosystem structure and function is hypothesized to further increase with increasing environmental stressors (5) and expected to further hinder CH₄ predictions and scaling.

Plants are integrators of the high spatiotemporal variability in wetland ecosystems, responding to and influencing microbial structure and function, soil moisture, nutrient status, etc. Thus, fine-scale (~1 m²/hourly to 1 km²/seasonal) heterogeneity in plant properties (hereafter, traits) is often closely related to wetland CH₄ flux variability (6–9) and plant trait incorporation into empirical and predictive models of CH₄ could help reduce uncertainties from fine-scale variability. Advances in high potential CH₄ flux (10, 11) and plant trait (12, 13) databases, wetland CH₄ modeling (14) and deep neural network technologies (15, 16), combined with process-knowledge derived from controlled laboratory and manipulative field experiments can help refine our understanding and predictions of wetland CH₄.

Rationale: above and belowground plant traits to improve CH₄ predictions

Advances in incorporating a mechanistic and scalable understanding of how plant traits influence wetland CH₄ emissions have been hindered by several research gaps: 1) We lack a synthetic view of which plant traits most affect CH₄ processes and can be best used as predictors. Knowledge

gaps particularly remain around the mechanistic links between root traits and CH₄ fluxes (e.g., root biomass, rooting depth, exudation, aerenchyma size)(17), **2)** While chamber-based CH₄ measurements are often coupled with plant trait information, quantification of wetland plant traits at the footprint scale of CH₄ eddy covariance towers is usually difficult. **3)** Also lacking are frameworks to connect relatively-easy-to-measure and remotely sensible aboveground with belowground traits, **4)** High-potential validation datasets on CH₄ flux and plant traits, particularly root traits, that would allow for scaling mechanistic information from lab and field studies to site and regional scales were unavailable until recently.

Narrative: AI-enabled mechanistic linkages between plant traits and wetland CH₄

We propose to incorporate lab/field-scale mechanistic understanding of plant trait drivers of CH₄ into site and regional scales using a combination of lab and field studies, data syntheses and deep neural network modeling. Our approach is broadly divided into two steps:

A) Developing and synthesizing mechanistic frameworks from new lab studies, and existing gradients and experiments: Controlled laboratory studies, such as wetland soil incubation experiments with isotopically labeled root material to trace the fate of root-carbon in CH₄ emissions, will be used as one tool to generate functions of CH₄ response to trait variability. We will also synthesize plant trait and CH₄ data from natural gradient studies and databases such as NEON and FRED (13), and from existing manipulative experiments providing a gradient of plant trait values. For example, SPRUCE (18) provides root trait and CH₄ flux gradients across a peatland warming study (19, 20) and COMPASS sites provide elevational gradients across coastal wetlands. We will also partner with ongoing experimental data synthesis efforts such as the [DeepSOIL2100](#). Through these lab and synthetic studies, we will develop specific model structures and parameters on trait-CH₄ links for our AI predictions in (B).

B) Predictive modeling of the mechanistic links between plant traits and wetland CH₄: We will test mechanistic model structures developed in (A) linking CH₄-relevant plant traits and CH₄ processes as frameworks for hybrid AI methods such as Neural Ordinary Differential Equations (ODE) (15). Such hybrid approaches allow learning process parameters, latent variables and functional relationships across a number of hypothesized structural constraints and complexity. Input data for these models will originate from experiments and syntheses highlighted in (A). High potential datasets such as the FLUXNET-CH₄ and COSORE databases (10, 21) would serve as the key validation datasets. In particular, combining chamber and eddy covariance tower measurements from the same sites will allow us to test trait-CH₄ linkages in a Neural ODE across spatial scales to evaluate the generalizability of the learned parameters and functional relationships.

Through the integration of lab, field and synthetic data into a hybrid modeling approach, this project will allow us to identify key mechanistic constraints and sources of uncertainty of the relationship between plant traits and CH₄ emissions in wetlands.

References

1. M. Saunois, A. R. Stavert, B. Poulter, P. Bousquet, J. G. Canadell, R. B. Jackson, P. A. Raymond, E. J. Dlugokencky, S. Houweling, P. K. Patra, P. Ciais, V. K. Arora, D. Bastviken, P. Bergamaschi, D. R. Blake, G. Brailsford, L. Bruhwiler, K. M. Carlson, M. Carroll, S. Castaldi, N. Chandra, C. Crevoisier, P. M. Crill, K. Covey, C. L. Curry, G. Etiope, C. Frankenberg, N. Gedney, M. I. Hegglin, L. Höglund-Isaksson, G. Hugelius, M. Ishizawa, A. Ito, G. Janssens-Maenhout, K. M. Jensen, F. Joos, T. Kleinen, P. B. Krummel, R. L. Langenfelds, G. G. Laruelle, L. Liu, T. Machida, S. Maksyutov, K. C. McDonald, J. McNorton, P. A. Miller, J. R. Melton, I. Morino, J. Müller, F. Murguia-Flores, V. Naik, Y. Niwa, S. Noce, S. O'Doherty, R. J. Parker, C. Peng, S. Peng, G. P. Peters, C. Prigent, R. Prinn, M. Ramonet, P. Regnier, W. J. Riley, J. A. Rosentreter, A. Segers, I. J. Simpson, H. Shi, S. J. Smith, L. P. Steele, B. F. Thornton, H. Tian, Y. Tohjima, F. N. Tubiello, A. Tsuruta, N. Viovy, A. Voulgarakis, T. S. Weber, M. van Weele, G. R. van der Werf, R. F. Weiss, D. Worthy, D. Wunch, Y. Yin, Y. Yoshida, W. Zhang, Z. Zhang, Y. Zhao, B. Zheng, Q. Zhu, Q. Zhu, Q. Zhuang, The global methane budget 2000–2017. *Earth Syst. Sci. Data.* **12**, 1561–1623 (2020).
2. E. Fluet-Chouinard, B. D. Stocker, Z. Zhang, A. Malhotra, J. R. Melton, B. Poulter, J. O. Kaplan, K. K. Goldewijk, S. Siebert, T. Minayeva, G. Hugelius, H. Joosten, A. Barthelmes, C. Prigent, F. Aires, A. M. Hoyt, N. Davidson, C. M. Finlayson, B. Lehner, R. B. Jackson, P. B. McIntyre, Extensive global wetland loss over the past three centuries. *Nature.* **614**, 281–286 (2023).
3. S. Peng, X. Lin, R. L. Thompson, Y. Xi, G. Liu, D. Hauglustaine, X. Lan, B. Poulter, M. Ramonet, M. Saunois, Y. Yin, Z. Zhang, B. Zheng, P. Ciais, Wetland emission and atmospheric sink changes explain methane growth in 2020. *Nature.* **612**, 477–482 (2022).
4. P. Camill, J. S. Clark, Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *Am. Nat.* **151**, 207–222 (1998).
5. A. Malhotra, N. T. Roulet, Environmental correlates of peatland carbon fluxes in a thawing landscape: do transitional thaw stages matter? *Biogeosciences.* **12**, 3119–3130 (2015).
6. J. M. Waddington, N. T. Roulet, R. V. Swanson, Water table control of CH₄emission enhancement by vascular plants in boreal peatlands. *J. Geophys. Res.* **101**, 22775–22785 (1996).
7. S. H. Knox, S. Bansal, G. McNicol, K. Schafer, C. Sturtevant, M. Ueyama, A. C. Valach, D. Baldocchi, K. Delwiche, A. R. Desai, E. Euskirchen, J. Liu, A. Lohila, A. Malhotra, L. Melling, W. Riley, B. R. K. Runkle, J. Turner, R. Vargas, Q. Zhu, T. Alto, E. Fluet-Chouinard, M. Goeckede, J. R. Melton, O. Sonnentag, T. Vesala, E. Ward, Z. Zhang, S. Feron, Z. Ouyang, P. Alekseychik, M. Aurela, G. Bohrer, D. I. Campbell, J. Chen, H. Chu, H. J. Dalmagro, J. P. Goodrich, P. Gottschalk, T. Hirano, H. Iwata, G. Jurassiński, M. Kang, F. Koebisch, I. Mammarella, M. B. Nilsson, K. Ono, M. Peichl, O. Peltola, Y. Ryu, T. Sachs, A. Sakabe, J. P. Sparks, E.-S. Tuittila, G. L. Vourlitis, G. X. Wong, L.

- Windham-Myers, B. Poulter, R. B. Jackson, Identifying dominant environmental predictors of freshwater wetland methane fluxes across diurnal to seasonal time scales. *Glob. Chang. Biol.* **27**, 3582–3604 (2021).
8. D. Y. F. Lai, T. R. Moore, N. T. Roulet, Spatial and temporal variations of methane flux measured by autochambers in a temperate ombrotrophic peatland. *J. Geophys. Res. Biogeosci.* **119**, 864–880 (2014).
 9. E. M. Goud, T. R. Moore, N. T. Roulet, Predicting peatland carbon fluxes from non-destructive plant traits. *Funct. Ecol.* **31**, 1824–1833 (2017).
 10. K. B. Delwiche, S. H. Knox, A. Malhotra, E. Fluet-Chouinard, G. McNicol, S. Feron, Z. Ouyang, D. Papale, C. Trotta, E. Canfora, Y.-W. Cheah, D. Christianson, M. C. R. Alberto, P. Alekseychik, M. Aurela, D. Baldocchi, S. Bansal, D. P. Billesbach, G. Bohrer, R. Bracho, N. Buchmann, D. I. Campbell, G. Celis, J. Chen, W. Chen, H. Chu, H. J. Dalmagro, S. Dengel, A. R. Desai, M. Dett, H. Dolman, E. Eichelmann, E. Euskirchen, D. Famulari, K. Fuchs, M. Goeckede, S. Gogo, M. J. Gondwe, J. P. Goodrich, P. Gottschalk, S. L. Graham, M. Heimann, M. Helbig, C. Helfter, K. S. Hemes, T. Hirano, D. Hollinger, L. Hörtagnagl, H. Iwata, A. Jacotot, G. Jurasiczki, M. Kang, K. Kasak, J. King, J. Klatt, F. Koebsch, K. W. Krauss, D. Y. F. Lai, A. Lohila, I. Mammarella, L. Belelli Marchesini, G. Manca, J. H. Matthes, T. Maximov, L. Merbold, B. Mitra, T. H. Morin, E. Nemitz, M. B. Nilsson, S. Niu, W. C. Oechel, P. Y. Oikawa, K. Ono, M. Peichl, O. Peltola, M. L. Reba, A. D. Richardson, W. Riley, B. R. K. Runkle, Y. Ryu, T. Sachs, A. Sakabe, C. R. Sanchez, E. A. Schuur, K. V. R. Schäfer, O. Sonnentag, J. P. Sparks, E. Stuart-Haëntjens, C. Sturtevant, R. C. Sullivan, D. J. Szutu, J. E. Thom, M. S. Torn, E.-S. Tuittila, J. Turner, M. Ueyama, A. C. Valach, R. Vargas, A. Varlagin, A. Vazquez-Lule, J. G. Verfaillie, T. Vesala, G. L. Vourlitis, E. J. Ward, C. Wille, G. Wohlfahrt, G. X. Wong, Z. Zhang, D. Zona, L. Windham-Myers, B. Poulter, R. B. Jackson, FLUXNET-CH4: a global, multi-ecosystem dataset and analysis of methane seasonality from freshwater wetlands. *Earth Syst. Sci. Data.* **13**, 3607–3689 (2021).
 11. S. H. Knox, R. B. Jackson, B. Poulter, G. McNicol, E. Fluet-Chouinard, Z. Zhang, G. Hugelius, P. Bousquet, J. G. Canadell, M. Saunois, Others, FLUXNET-CH 4 synthesis activity: Objectives, observations, and future directions. *Bull. Am. Meteorol. Soc.* **100**, 2607–2632 (2019).
 12. J. Kattge, S. Diaz, S. Lavorel, I. C. Prentice, P. Leadley, G. Boenisch, C. Wirth, "The global database of plant traits: TRY version 5.0-more data, publicly available" in *Geophysical Research Abstracts* (2019);
<https://search.ebscohost.com/login.aspx?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=10297006&AN=140485469&h=lDD4mJbWU%2FjRp8LeOqBCgcVRfQ7zgTqCwxKlbDjET9XGHwfYmd6be0aBw1ZbSvQCEwSEhog%2BYckJMvP%2BJyX9Q%3D%3D&crl=c>, vol. 21.
 13. C. M. Iversen, M. L. McCormack, A. S. Powell, C. B. Blackwood, G. T. Freschet, J. Kattge, C. Roumet, D. B. Stover, N. A. Soudzilovskaia, O. J. Valverde-Barrantes, P. M. van Bodegom, C. Violle, A global Fine-Root Ecology Database to address below-ground challenges in plant ecology. *New Phytol.* **215**, 15–26 (2017).

14. E. Salmon, F. Jégou, B. Guenet, L. Jourdain, C. Qiu, V. Bastrikov, C. Guimbaud, D. Zhu, P. Ciais, P. Peylin, S. Gogo, F. Laggoun-Défarge, M. Aurela, M. S. Bret-Harte, J. Chen, B. H. Chojnicki, H. Chu, C. W. Edgar, E. S. Euskirchen, L. B. Flanagan, K. Fortuniak, D. Holl, J. Klatt, O. Kolle, N. Kowalska, L. Kutzbach, A. Lohila, L. Merbold, W. Pawlak, T. Sachs, K. Ziemblińska, Assessing methane emissions for northern peatlands in ORCHIDEE-PEAT revision 7020. *Geosci. Model Dev.* **15**, 2813–2838 (2022).
15. R. T. Q. Chen, Y. Rubanova, J. Bettencourt, D. Duvenaud, Neural ordinary differential equations. *arXiv [cs.LG]* (2018), (available at <https://proceedings.neurips.cc/paper/2018/hash/69386f6bb1dfed68692a24c8686939b9-Abstract.html>).
16. M. Reichstein, G. Camps-Valls, B. Stevens, M. Jung, J. Denzler, N. Carvalhais, Prabhat, Deep learning and process understanding for data-driven Earth system science. *Nature*. **566**, 195–204 (2019).
17. A. E. Sutton-Grier, J. P. Megonigal, Plant species traits regulate methane production in freshwater wetland soils. *Soil Biol. Biochem.* **43**, 413–420 (2011).
18. P. J. Hanson, J. S. Riggs, W. R. Nettles, J. R. Phillips, M. B. Krassovski, L. A. Hook, L. Gu, A. D. Richardson, D. M. Aubrecht, D. M. Ricciuto, J. M. Warren, C. Barbier, Attaining whole-ecosystem warming using air and deep-soil heating methods with an elevated CO₂ atmosphere. *Biogeosciences*. **14**, 861–883 (2017).
19. A. Malhotra, D. J. Brice, J. Childs, J. D. Graham, E. A. Hobbie, H. Vander Stel, S. C. Feron, P. J. Hanson, C. M. Iversen, Peatland warming strongly increases fine-root growth. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 17627–17634 (2020).
20. P. J. Hanson, N. A. Griffiths, C. M. Iversen, R. J. Norby, S. D. Sebestyen, J. R. Phillips, J. P. Chanton, R. K. Kolka, A. Malhotra, K. C. Oleheiser, J. M. Warren, X. Shi, X. Yang, J. Mao, D. M. Ricciuto, Rapid net carbon loss from a whole-ecosystem warmed peatland. *AGU Advances*. **1** (2020), doi:10.1029/2020av000163.
21. B. Bond-Lamberty, D. S. Christianson, A. Malhotra, S. C. Pennington, D. Sihi, A. AghaKouchak, H. Anjileli, M. Altaf Arain, J. J. Armesto, S. Ashraf, M. Ataka, D. Baldocchi, T. Andrew Black, N. Buchmann, M. S. Carbone, S. Chang, P. Crill, P. S. Curtis, E. A. Davidson, A. R. Desai, J. E. Drake, T. S. El-Madany, M. Gavazzi, C. Görres, C. M. Gough, M. Goulden, J. Gregg, O. Gutiérrez del Arroyo, J. He, T. Hirano, A. Hopple, H. Hughes, J. Järveoja, R. Jassal, J. Jian, H. Kan, J. Kaye, Y. Kominami, N. Liang, D. Lipson, C. A. Macdonald, K. Maseyk, K. Mathes, M. Mauritz, M. A. Mayes, S. McNulty, G. Miao, M. Migliavacca, S. Miller, C. F. Miniat, J. G. Nietz, M. B. Nilsson, A. Noormets, H. Norouzi, C. S. O'Connell, B. Osborne, C. Oyonarte, Z. Pang, M. Peichl, E. Pendall, J. F. Perez-Quetzada, C. L. Phillips, R. P. Phillips, J. W. Raich, A. A. Renchon, N. K. Ruehr, E. P. Sánchez-Cañete, M. Saunders, K. E. Savage, M. Schrumpf, R. L. Scott, U. Seibt, W. L. Silver, W. Sun, D. Szutu, K. Takagi, M. Takagi, M. Teramoto, M. G. Tjoelker, S. Trumbore, M. Ueyama, R. Vargas, R. K. Varner, J. Verfaillie, C. Vogel, J. Wang, G. Winston, T. E. Wood, J. Wu, T. Wutzler, J. Zeng, T. Zha, Q. Zhang, J. Zou, COSORE: A community

database for continuous soil respiration and other soil-atmosphere greenhouse gas flux data.
Glob. Chang. Biol. **24**, 434 (2020).