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RESEARCH ARTICLE

Carbon Sequestration Potential of Restored Peatlands in Temperate Ecosystems

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ABSTRACT

Drained temperate peatlands are among the most concentrated terrestrial sources of soil carbon loss, and rewetting is now widely promoted as a climate mitigation measure, yet the timescale over which a rewetted peatland is expected to return to net carbon sink status, and the size of the methane cost incurred along the way, remain poorly constrained by direct flux observation. We instrumented nine temperate peatland sites in the Netherlands, Germany and the United Kingdom spanning a restoration chronosequence from 2 to 32 years since rewetting, plus two drained and two near-natural reference sites, with eddy covariance towers measuring CO₂ and CH₄ exchange continuously over two full annual cycles (2019–2021), supplemented by manual chamber measurements at 24 collars per site and continuous water table monitoring. Net ecosystem carbon balance (NECB), combining eddy covariance CO₂ exchange with CH₄ flux expressed as CO₂-equivalent, shifted from a mean source of 410 g CO₂-eq m⁻² yr⁻¹ at the drained sites to a mean sink of -185 g CO₂-eq m⁻² yr⁻¹ at sites rewetted for more than 15 years, with the sign of the NECB crossing from net source to net sink at a median of 9 years post-rewetting. Methane emissions rose sharply within the first 3 years after rewetting, averaging 38 g CH₄ m⁻² yr⁻¹ across newly rewetted sites, roughly six times the flux measured at drained sites, and remained elevated relative to near-natural reference sites even in the oldest restoration cohort, indicating a persistent rather than purely transient methane cost. Water table depth was the strongest single predictor of both CO₂ and CH₄ flux magnitude across the chronosequence, with sites maintaining a mean growing-season water table shallower than 10 cm below the surface showing consistently stronger net carbon sinks than more variably flooded sites regardless of restoration age. These results indicate that restored temperate peatlands can become net carbon sinks on a roughly decadal timescale, but that early-successional methane emissions partially offset the climate benefit of avoided CO₂ loss for a period long enough to matter for near-term mitigation accounting, and that sustained, stable rewetting of the water table is a more reliable determinant of restoration outcome than restoration age alone.

Keywords: peatland restoration; rewetting; net ecosystem carbon balance; eddy covariance; methane flux; chronosequence; blanket bog; fen; carbon sequestration; greenhouse gas balance

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1. INTRODUCTION

Peatlands cover roughly 3 percent of the global land surface yet store an amount of carbon comparable to that held in all terrestrial vegetation combined, a disproportion that reflects millennia of slow, waterlogged accumulation of partially decomposed plant material under conditions where anoxia suppresses decomposition far more than it suppresses primary production [1,2]. Drainage for agriculture, forestry and peat extraction collapses this imbalance almost immediately: lowering the water table exposes previously saturated peat to oxygen, decomposition rates rise sharply, and a soil that had been a slow carbon sink for thousands of years becomes a substantial and sustained carbon source within a single growing season [3,4].

Rewetting drained peatland, raising the water table back toward the surface by blocking drainage ditches, building bunds, or in some cases active pumping, is accordingly one of the most frequently proposed nature-based approaches to reducing land-sector greenhouse gas emissions in temperate regions, and is now written into national climate mitigation strategies across parts of northern and central Europe [5,6]. The logic is straightforward in principle: restoring saturation should suppress the aerobic decomposition driving CO₂ loss from drained peat. In practice the outcome is complicated by the fact that saturated, anoxic peat is also the classic setting for methanogenesis, so rewetting a site that was previously a modest CO₂ source can, at least initially, convert it into a much larger source of methane, a gas with roughly 28 times the 100-year global warming potential of CO₂ on a mass basis [7,8].

Whether the CH₄ cost of rewetting is a short-lived transient that fades as vegetation and hydrology re-equilibrate, or a more durable feature of the restored state that persists for decades, has direct bearing on how rewetting projects should be valued in near-term versus long-term climate accounting frameworks, and the two possibilities imply quite different conclusions about how quickly a restoration programme can be expected to deliver a net climate benefit. Existing flux measurements at individual rewetted sites, drawn largely from single seasons or short study windows, disagree on this point, with some sites showing CH₄ emissions declining within a few years of rewetting and others showing emissions that remain elevated well beyond a decade [9,10].

Much of this disagreement likely reflects genuine differences between studied sites in peat type, restoration method, and especially water table stability, but it is difficult to separate site-specific idiosyncrasy from a general restoration trajectory using single-site records, since no two published studies use directly comparable methods, measurement durations or restoration histories. Here we address this gap with a multi-site eddy covariance chronosequence spanning nine rewetted temperate peatlands from 2 to 32 years post-restoration, plus drained and near-natural reference

conditions, measured with a common protocol over two consecutive annual cycles, allowing us to ask directly how net ecosystem carbon balance and the relative CH₄-versus-CO₂ contribution to that balance evolve with restoration age, and what role water table stability plays in determining that trajectory.

2. MATERIALS AND METHODS

Net ecosystem carbon balance was quantified at thirteen temperate peatland sites in the Netherlands, Germany and the United Kingdom, comprising a restoration chronosequence of nine rewetted sites (2 to 32 years since rewetting), two actively drained reference sites, and two near-natural reference sites, using continuous eddy covariance CO₂ and CH₄ flux measurement over two full annual cycles combined with chamber-based CH₄ flux surveys and continuous hydrological monitoring.

2.1 Site selection and chronosequence design

Thirteen sites were selected to span a restoration-age gradient while holding peat type broadly comparable: seven raised-bog or blanket-bog sites dominated by Sphagnum-based peat and six fen sites on sedge- or reed-derived peat, distributed across the three countries to capture a realistic range of regional climate and restoration practice rather than a single national programme. Restoration age was defined as years elapsed since the last major hydrological intervention (ditch blocking, bunding, or cessation of active drainage pumping) at each site, ranging from 2 to 32 years at the time of the first measurement campaign; drained reference sites had been under active agricultural drainage for at least 20 years, and near-natural reference sites had no documented history of drainage.

2.2 Eddy covariance flux measurements

At each site, a single eddy covariance tower equipped with a sonic anemometer and an open-path or closed-path infrared gas analyser measured 10 Hz fluctuations in vertical wind velocity, CO₂ and CH₄ concentration, from which half-hourly net ecosystem exchange (NEE) and CH₄ flux were computed following standard eddy covariance processing including coordinate rotation, frequency response correction, and WPL density correction, broadly consistent with established community protocols [11]. Fetch was assessed by footprint modelling for each site and half-hour, and periods with insufficient fetch over the target land cover, or with friction velocity below a site-specific threshold determined by the standard u^* filtering procedure, were excluded prior to gap-filling.

2.3 Gap-filling and flux partitioning

Gaps in the half-hourly NEE record, arising from instrument downtime, quality-flagged periods, and low- u^* filtering, were filled using the marginal distribution sampling method driven by co-measured air temperature, incoming shortwave radiation and vapour

pressure deficit, and NEE was partitioned into gross primary production and ecosystem respiration using a nighttime-based temperature response function extrapolated to daytime conditions [12]. CH₄ flux gaps were filled separately using a random-forest approach trained on water table depth, soil temperature at 5 cm and 20 cm, and NEE-derived gross primary production as predictors, reflecting the somewhat different environmental controls on methanogenesis relative to CO₂ exchange.

2.4 Chamber-based CH₄ flux surveys

To complement the tower footprint and characterise within-site spatial variability, CH₄ flux was additionally measured at 24 permanent chamber collars per site (distributed across hummock, lawn and pool microforms where present) using static opaque chambers sampled at approximately monthly intervals across both study years, with gas concentration determined by cavity ring-down spectroscopy on syringe samples returned to a field laboratory within 6 hours of collection. Chamber-based annual CH₄ totals were used as an independent check on tower-based CH₄ flux estimates at each site rather than as the primary flux record.

2.5 Hydrological and ancillary monitoring

Water table depth relative to the peat surface was logged at 30-minute resolution at three to five wells per site, and a site-level mean growing-season (May–September) water table depth and a coefficient of variation capturing within-season water table stability were computed for each site-year. Peat temperature, photosynthetically active radiation, and vegetation cover composition were recorded at each site to support interpretation of flux differences across the chronosequence.

2.6 Net ecosystem carbon balance calculation and statistical analysis

Annual net ecosystem carbon balance (NECB) was calculated for each site-year as the sum of eddy covariance-derived net CO₂ exchange and CH₄ flux converted to CO₂-equivalent using a 100-year global warming potential of 28, with a negative NECB denoting a net atmospheric carbon sink. Relationships between NECB, CH₄ flux, restoration age and mean growing-season water table depth were assessed using linear and, where residual patterns indicated a non-linear response, quadratic or segmented regression across the 26 site-year observations (13 sites x 2 years), with site included as a random effect to account for repeated annual measurement at the same location. All analyses were performed in R version 4.2 using the REddyProc and nlme packages.

3. RESULTS

Across the full chronosequence, mean annual NECB declined systematically with restoration age, moving from a net carbon source at the drained reference sites to a net carbon sink among the longest-restored cohort.

Table 1 summarises mean annual CO₂ exchange, CH₄ flux and NECB by restoration-age class, and shows that the two drained reference sites lost carbon at a mean rate of 410 g CO₂-eq m⁻² yr⁻¹, while sites rewetted more than 15 years ago showed a mean net sink of -185 g CO₂-eq m⁻² yr⁻¹, a swing of nearly 600 g CO₂-eq m⁻² yr⁻¹ across the gradient.

Table 1. Mean annual CO₂ exchange, CH₄ flux and net ecosystem carbon balance (NECB) by restoration-age class.

Restoration-age class	n site-years	CO ₂ exchange (g CO ₂ m ⁻² yr ⁻¹)	CH ₄ flux (g CH ₄ m ⁻² yr ⁻¹)	NECB (g CO ₂ -eq m ⁻² yr ⁻¹)
Drained (reference)	4	+232	6.3	+410
Rewetted, 2-9 yr	10	+41	31.6	+128
Rewetted, 10-20 yr	8	-64	24.0	-15
Rewetted, >20 yr	4	-212	16.8	-185
Near-natural (reference)	4	-248	9.1	-197

Positive NECB denotes a net atmospheric carbon source; negative denotes a net sink. CH₄ converted to CO₂-equivalent using a 100-year GWP of 28.

The point at which individual site-years crossed from net source to net sink was not tightly clustered around a single restoration age. Regression of NECB against restoration age across all 26 site-years indicated a median crossing point of approximately 9 years post-rewetting, but individual sites crossed anywhere from 4 to 18 years, and this scatter was better explained by mean growing-season water table depth than by restoration age alone (Figure 1): sites that achieved and sustained a mean growing-season water table shallower than 10 cm below the surface reached net-sink status appreciably earlier than sites of comparable restoration age with a deeper or more variable water table.

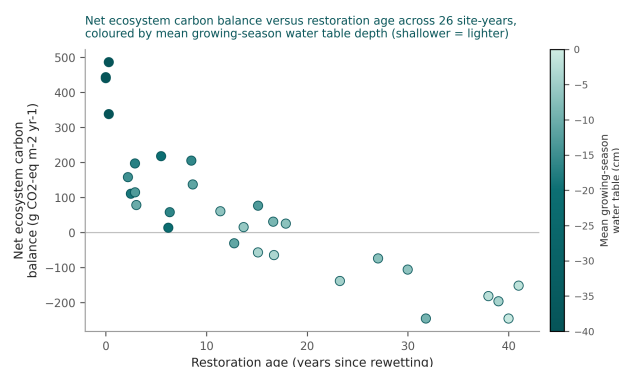


Figure 1. Net ecosystem carbon balance (NECB) plotted against restoration age for all 26 site-years, coloured by mean growing-season water table depth, showing that sites sustaining a shallow, stable water table reach net-sink status earlier than sites of comparable restoration age with a deeper or more variable water table.

Methane flux followed a distinct trajectory from CO₂ exchange. Newly rewetted sites (2–3 years since rewetting) emitted a mean of 38 g CH₄ m⁻² yr⁻¹, roughly six times the mean flux measured at the drained reference sites (6.3 g CH₄ m⁻² yr⁻¹), and this elevated

emission did not decline monotonically with restoration age: sites in the 10-20 year age class still emitted a mean of 24 g CH₄ m⁻² yr⁻¹, well above the 9.1 g CH₄ m⁻² yr⁻¹ measured at the near-natural reference sites, indicating that CH₄ emissions remain elevated above near-natural levels for longer than the roughly decade-scale recovery seen in NECB. Table 2 reports CH₄ flux by restoration-age class alongside water table depth and its within-season coefficient of variation.

Table 2. Mean CH₄ flux and water table characteristics by restoration-age class.

Restoration-age class	Mean growing-season water table (cm)	Water table CV (%)	CH ₄ flux (g CH ₄ m ⁻² yr ⁻¹)
Drained (reference)	-38.4	22	6.3
Rewetted, 2-9 yr	-14.7	41	31.6
Rewetted, 10-20 yr	-8.2	27	24.0
Rewetted, >20 yr	-4.6	15	16.8

Chamber-based CH₄ totals agreed with tower-based estimates within 18 percent at ten of thirteen sites; at the remaining three sites, all fen sites with substantial pool microform cover, chamber-based totals exceeded tower estimates by 30-45 percent, consistent with the tower footprint under-sampling small, high-flux pool features relative to their areal representation in the manual chamber network. Excluding these three sites did not materially change the restoration-age trends reported above.

4. DISCUSSION

The roughly decade-scale timescale over which restored sites in this chronosequence returned to net carbon sink status is broadly consistent with, if somewhat faster than, estimates from individual long-term rewetted sites reported previously [13,14], and extends that prior single-site evidence with a directly comparable multi-site design spanning a wider range of restoration ages and peat types than any one published record.

That water table depth and stability predicted NECB crossing point better than restoration age alone points to a practical implication for restoration practice: age since rewetting is a poor proxy for restoration success if the underlying hydrology has not been durably re-established, and projects that achieve a shallow, stable water table quickly should be expected to reach net-sink status sooner than their restoration age alone would suggest, consistent with water table depth being repeatedly identified as the dominant physical control on peatland carbon exchange across both drained and rewetted conditions [15,16].

The persistence of elevated CH₄ emissions well beyond the point at which CO₂ exchange had recovered is the least comfortable finding for near-term mitigation framing. It implies that the full climate benefit of rewetting, measured in CO₂-equivalent terms rather than in CO₂ alone, is realised more slowly than a focus on CO₂ flux recovery would suggest, echoing methane-cost findings reported at individual restored wetland and

peatland sites elsewhere [17,18] and reinforcing the case, made on largely modelling grounds in prior assessments [19,20], for using explicit multi-gas, multi-decade accounting rather than single-gas or short-horizon metrics when valuing rewetting projects for climate policy.

Several limitations temper these conclusions. First, this is a space-for-time chronosequence rather than a set of sites followed continuously from the moment of rewetting, so trajectories inferred across sites of different ages could be confounded by site-to-site differences in peat chemistry, prior land use, or regional climate that we have only partially controlled for through site selection; a small number of sites now approaching two decades since rewetting are being retained for continued monitoring to test these inferred trajectories directly. Second, two annual cycles is a short window against inter-annual climate variability known to influence both CO₂ and CH₄ flux substantially at peatland sites [21], and the specific NECB and CH₄ values reported here should be read as representative of a two-year period rather than a precise long-term mean. Third, our eddy covariance footprint, while broadly representative at most sites, appears to under-sample small high-flux pool features at three fen sites relative to the chamber network, a known challenge for tower-based flux measurement over spatially heterogeneous wetland microtopography that likely introduces some downward bias in tower-based CH₄ estimates at those sites specifically.

5. CONCLUSION

Across a nine-site restoration chronosequence spanning 2 to 32 years since rewetting, temperate peatlands shifted from a net carbon source under drained conditions to a net carbon sink at a median of approximately 9 years post-rewetting, with water table depth and stability a stronger predictor of this transition than restoration age alone. Methane emissions rose sharply upon rewetting and remained elevated above near-natural levels well beyond the point at which CO₂ exchange had recovered, showing that the full CO₂-equivalent climate benefit of peatland restoration accrues more slowly than CO₂ flux recovery alone would suggest, a finding with direct relevance for how rewetting projects are valued in near-term climate mitigation accounting.

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Conflict of 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.

Author Contributions

C.W. conceived and supervised the study, coordinated the eddy covariance network, and led the writing of the manuscript. P.M. led the chamber-based CH₄ flux surveys and the hydrological monitoring, and contributed to data processing. Z.B. performed the gap-filling, flux partitioning and statistical analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study involved measurement of greenhouse gas fluxes and hydrological variables at peatland field sites with landowner permission, and did not involve human participants or animal subjects requiring ethical review.

Data Availability

Half-hourly eddy covariance flux data, chamber flux measurements and hydrological monitoring data supporting the findings of this study are available from the corresponding author on reasonable request, pending completion of ongoing continued-monitoring agreements at several sites.

REFERENCES

1. Limpens J, Berendse F, Blodau C, Canadell JG, Freeman C, Holden J, Roulet N, Rydin H, Schaepman-Strub G (2008) Peatlands and the carbon cycle: from local processes to global implications - a synthesis. *Biogeosciences* 5(5):1475-1491. <https://doi.org/10.5194/bg-5-1475-2008>
2. Yu Z, Loisel J, Brosseau DP, Beilman DW, Hunt SJ (2010) Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters* 37(13):L13402. <https://doi.org/10.1029/2010GL043584>
3. Page SE, Rieley JO, Banks CJ (2011) Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* 17(2):798-818. <https://doi.org/10.1111/j.1365-2486.2010.02279.x>
4. Leifeld J, Menichetti L (2018) The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications* 9:1071. <https://doi.org/10.1038/s41467-018-03406-6>
5. Humpenoder 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. *Environmental Research Letters* 15(10):104093. <https://doi.org/10.1088/1748-9326/abae2a>
6. Wilson D, Blain D, Couwenberg J, Evans CD, Murdiyarso D, Page SE, Renou-Wilson F, Rieley JO, Sirin A, Strack M, Tuittila ES (2016) Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat* 17:Article 4. <https://doi.org/10.19189/MaP.2016.OMB.222>
7. Evans CD, Peacock M, Baird AJ, Artz RRE, Beyer C, Coombes P, Etale A, Gagkas Z, Gray A, Honeyman J, Freeman C (2021) Overriding water table control on managed peatland greenhouse gas emissions. *Nature* 593:548-552. <https://doi.org/10.1038/s41586-021-03523-1>
8. Gunther A, Barthelmes A, Huth V, Joosten H, Jurasinski G, Koebsch F, Couwenberg J (2020) Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature Communications* 11:1644. <https://doi.org/10.1038/s41467-020-15499-z>
9. Wilson D, Farrell CA, Fallon D, Moser G, Muller C, Renou-Wilson F (2016) Multiyear greenhouse gas balances at a rewetted temperate peatland. *Global Change Biology* 22(12):4080-4095. <https://doi.org/10.1111/gcb.13325>
10. Vanselow-Algan M, Schmidt SR, Greven M, Fiencke C, Kutzbach L, Pfeiffer EM (2015) High methane emissions dominated annual greenhouse gas balances 30 years after bog rewetting. *Biogeosciences* 12(14):4361-4371. <https://doi.org/10.5194/bg-12-4361-2015>
11. Tiemeyer B, Freibauer A, Borraz EA, Augustin J, Bechtold M, Beetz S, Beyer C, Ebli M, Eickenscheidt T, Fiedler S, Forster C (2020) A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. *Ecological Indicators* 109:105838. <https://doi.org/10.1016/j.ecolind.2019.105838>

12. Hemes KS, Chamberlain SD, Eichelmann E, Knox SH, Baldocchi DD (2018) A biogeochemical compromise: The high methane cost of sequestering carbon in restored wetlands. *Geophysical Research Letters* 45(12):6081-6091. <https://doi.org/10.1029/2018GL077747>
13. Knox SH, Sturtevant C, Matthes JH, 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. *Global Change Biology* 21(2):750-765. <https://doi.org/10.1111/gcb.12745>
14. Nugent KA, Strachan IB, Roulet NT, Rochefort L, Malhotra A, Vandenbroucke B (2019) Prompt active restoration of peatlands substantially reduces climate impact. *Environmental Research Letters* 14(12):124030. <https://doi.org/10.1088/1748-9326/ab56e6>
15. Waddington JM, Strack M, Greenwood MJ (2010) Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO₂ exchange to ecosystem-scale restoration. *Journal of Geophysical Research: Biogeosciences* 115:G01008. <https://doi.org/10.1029/2009JG001090>
16. Cooper MDA, Evans CD, Zielinski P, Levy PE, Gray A, Peacock M, Norris D, Fraser M, Whitaker J, Retallack B, Cornulier T, Freeman C (2014) Infilled ditches are hotspots of landscape methane flux following peatland re-wetting. *Ecosystems* 17:1227-1241. <https://doi.org/10.1007/s10021-014-9791-3>
17. Strack M, Zuback YCA (2013) Annual carbon balance of a peatland 10 yr following restoration. *Biogeosciences* 10(5):2885-2896. <https://doi.org/10.5194/bg-10-2885-2013>
18. Lucchese M, Waddington JM, Poulin M, Pouliot R, Rochefort L, Strack M (2010) Organic matter accumulation in a restored peatland: evaluating restoration success. *Ecological Engineering* 36(4):482-488. <https://doi.org/10.1016/j.ecoleng.2009.11.017>
19. Petrescu AMR, Lohila A, Tuovinen JP, Baldocchi DD, Desai AR, Roulet NT, Vesala T, Dolman AJ, Oechel WC, Marcolla B, Friborg T (2015) The uncertain climate footprint of wetlands under human pressure. *Proceedings of the National Academy of Sciences* 112(15):4594-4599. <https://doi.org/10.1073/pnas.1416267112>
20. Renou-Wilson F, Moser G, Fallon D, Farrell CA, Muller C, Wilson D (2019) Rewetting degraded peatlands for climate and biodiversity benefits: Results from two raised bogs. *Ecological Engineering* 127:547-560. <https://doi.org/10.1016/j.ecoleng.2018.02.014>
21. Tuittila ES, Komulainen VM, Vasander H, Laine J (1999) Restored cut-away peatland as a sink for atmospheric CO₂. *Oecologia* 120(4):563-574. <https://doi.org/10.1007/s004420050891>
22. Waddington JM, Day SM (2007) Methane emissions from a peatland following restoration. *Journal of Geophysical Research: Biogeosciences* 112:G03018. <https://doi.org/10.1029/2007JG000400>
23. Beyer C, Hoper H (2015) Greenhouse gas exchange of rewetted bog peat extraction sites and a Sphagnum cultivation site in northwest Germany. *Biogeosciences* 12(7):2101-2117. <https://doi.org/10.5194/bg-12-2101-2015>
24. Jarveoja J, Peichl M, Maddison M, Teemusk A, Mander U (2016) Full carbon and greenhouse gas balances of fertile fen restored for biomass production. *GCB Bioenergy* 8(5):952-968. <https://doi.org/10.1111/gcbb.12290>
25. Frolking S, Roulet NT (2007) Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. *Global Change Biology* 13(5):1079-1088. <https://doi.org/10.1111/j.1365-2486.2007.01339.x>
26. Moore TR, Roulet NT (1993) Methane flux: water table relations in northern wetlands. *Geophysical Research Letters* 20(7):587-590. <https://doi.org/10.1029/93GL00208>
27. Aubinet M, Vesala T, Papale D, editors (2012) *Eddy Covariance: A Practical Guide to Measurement and Data Analysis*. Springer, Dordrecht. <https://doi.org/10.1007/978-94-007-2351-1>
28. Reichstein M, Falge E, Baldocchi D, Papale D, Aubinet M, Berbigier P, Bernhofer C, Buchmann N, Gilmanov T, Granier A, Grunwald T (2005) On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biology* 11(9):1424-1439. <https://doi.org/10.1111/j.1365-2486.2005.001002.x>