

# neonSoilFlux: An R Package for Continuous Sensor-Based Estimation of Soil CO<sub>2</sub> Fluxes

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## <sup>24</sup> **Conflict of Interest Statements**

<sup>25</sup> None of the authors have a financial, personal, or professional conflict of interest related to this  
<sup>26</sup> work.

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<sup>39</sup> Project Administration: John Zobitz, Naupaka Zimmerman; Funding Acquisition: John Zobitz,  
<sup>40</sup> Naupaka Zimmerman.

<sup>41</sup> **Data Availability**

<sup>42</sup> Data available via <https://doi.org/10.5281/zenodo.17516319> (Zobitz & Zimmerman, 2025).  
<sup>43</sup> Field-collected data, `neonSoilFlux` calculated outputs, and manuscript-generating code are  
<sup>44</sup> provided within this repository.

45 **1 Abstract**

- 46 1. Accurate quantification of soil carbon fluxes is essential to reduce uncertainty in estimates  
47 of the terrestrial carbon sink. However, these fluxes vary over time and across ecosystem  
48 types and so it can be difficult to estimate them accurately across large scales. The flux  
49 gradient method estimates soil carbon fluxes using co-located measurements of soil CO<sub>2</sub>  
50 concentration, soil temperature, soil moisture, and other soil properties. The National  
51 Ecological Observatory Network (NEON) provides such data across 20 ecoclimatic domains  
52 spanning the continental U.S., Puerto Rico, Alaska, and Hawai‘i.
- 53 2. We present an R software package (`neonSoilFlux`) that acquires soil environmental data  
54 to compute half-hourly soil carbon fluxes for each soil replicate plot at a given terrestrial  
55 NEON site. To assess the computed fluxes, we visited six focal NEON sites and measured  
56 soil carbon fluxes using a closed-dynamic chamber approach.
- 57 3. Outputs from the `neonSoilFlux` showed agreement with measured fluxes ( $R^2$  between  
58 measured and `neonSoilFlux` outputs ranging from 0.04 to 0.81 depending on calculation  
59 method used); measured outputs generally fell within the range of calculated uncertainties  
60 from the gradient method. Calculated fluxes from `neonSoilFlux` aggregated to the daily  
61 scale exhibited expected site-specific seasonal patterns.
- 62 4. While the flux gradient method is broadly effective, its accuracy is highly sensitive  
63 to site-specific inputs, including the extent to which gap-filling techniques are used to  
64 interpolate missing sensor data and to estimates of soil diffusivity and moisture content.  
65 Future refinement and validation of `neonSoilFlux` outputs can contribute to existing  
66 databases of soil carbon flux measurements, providing near real-time estimates of a critical  
67 component of the terrestrial carbon cycle.

68 **1.1 Keywords**

69 Soil carbon, carbon dioxide, flux gradient, carbon cycle, field validation, soil respiration,  
70 ecosystem variability, diffusion

71 **2 Introduction**

72 Soils contain the planet's largest reservoir of terrestrial carbon (Jobbág & Jackson, 2000). A  
73 critical component of this reservoir is soil organic matter, the accumulation of which is influenced  
74 by biotic factors such as above-ground plant inputs (Jackson et al., 2017). These inputs in  
75 turn are influenced by environmental factors such as growing season length, temperature, and  
76 moisture (Desai et al., 2022), which also affect the breakdown of soil organic matter and its  
77 return to the atmosphere. Across heterogeneous terrestrial landscapes, the interplay between  
78 these biotic and abiotic factors influence the size of the soil contribution to the terrestrial  
79 carbon sink (Friedlingstein et al., 2025). However, the heterogeneity of these processes across  
80 diverse ecosystems in the context of rapid environmental change leads to large uncertainty  
81 about the magnitude of this sink in the future, and thus there remains a pressing need to  
82 quantify changes in soil carbon pools and fluxes across scales.

83 Ecological observation networks such as the United States' National Ecological Observatory  
84 Network (NEON) and others (e.g. the globally-distributed FLUXNET or the European Inte-  
85 grated Carbon Observation System) present a significant advancement in the nearly continuous  
86 observation of biogeochemical processes at the continental scale. Notably, at 47 terrestrial  
87 sites across the continental United States that span 20 ecoclimatic domains, NEON provides  
88 half-hourly measurements of soil CO<sub>2</sub> concentration, temperature, and moisture at different  
89 vertical depths. Each of these NEON sites also encompasses measurements of the cumulative  
90 sum of all ecosystem carbon fluxes in an airshed using the eddy covariance technique (Baldocchi,

91 Soil observations provided by NEON are on the same timescale and standardized with  
92 eddy covariance measurements from FLUXNET. These types of nearly continuous observational  
93 data (NEON and FLUXNET) can be used to reconcile differences between model-derived  
94 or data-estimated components of ecosystem carbon flux (Jian et al., 2022; Luo et al., 2011;  
95 Phillips et al., 2017; J. Shao et al., 2015; P. Shao et al., 2013; Sihi et al., 2016).

96 Estimated or observed soil carbon fluxes are a key metric for understanding change in soil  
97 carbon pools over time (Bond-Lamberty et al., 2024). A soil carbon flux to the atmosphere ( $F_S$ ,  
98 units  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), represents the aggregate process of transfer of soil  $\text{CO}_2$  to the atmosphere  
99 from physical and biological processes (e.g. diffusion and respiration). Soil carbon fluxes can  
100 be assumed to encompass soil carbon respiration from autotrophic or heterotrophic sources  
101 (Davidson et al., 2006) and modeled with a exponential  $Q_{10}$  paradigm (Bond-Lamberty et al.,  
102 2004; Chen & Tian, 2005; Hamdi et al., 2013).

103 One common method by which  $F_S$  is measured in the field is through the use of soil chambers  
104 in a closed, well-mixed system (Norman et al., 1997) with headspace trace gas concentrations  
105 measured with an infrared gas analyzer (IRGA).  $F_S$  can also be estimated from soil  $\text{CO}_2$   
106 measurements at different depths in the soil using the flux-gradient method (Maier & Schack-  
107 Kirchner, 2014). Closed-chamber IRGA measurements, while being the most common method,  
108 require either frequent in-person site visits or expensive and fragile automated systems. The  
109 potential of the gradient method is that fluxes can be estimated from continuous data recorded  
110 by robust solid-state sensors. The flux-gradient method is an approach that uses conservation of  
111 mass to calculate flux at a vertical soil depth  $z$  at steady state by applying Fick's law of diffusion.  
112 A simplifying assumption for the flux-gradient method is that there is no mass transfer in the  
113 other spatial dimensions  $x$  and  $y$  (Maier & Schack-Kirchner, 2014). The diffusivity profile, a  
114 key component of this calculation, varies across the soil depth as a function of soil temperature,  
115 soil volumetric water content, atmospheric air pressure, and soil bulk density (Millington &

116 Shearer, 1971; Moldrup et al., 1999; Sallam et al., 1984).

117 Databases such as the Soil Respiration Database (SRDB) or the Continuous Soil Respiration  
118 Database (COSORE) add to the growing network of resources for making collected observations  
119 of soil fluxes available to other researchers (Bond-Lamberty, 2018; Bond-Lamberty et al., 2020;  
120 Bond-Lamberty & Thomson, 2010; Jian et al., 2021; Jiang et al., 2024). However, these  
121 databases currently encompass primarily direct soil measurements of fluxes (i.e. those using  
122 methods like the closed-chamber method described above). Currently, NEON provides all  
123 measurements to calculate  $F_S$  from Fick's law, but soil flux as a derived data product was  
124 descoped from the initial network launch due to budget constraints (Berenbaum et al., 2015).  
125 Deriving estimates of  $F_S$  using continuous sensor data across NEON sites using NEON data  
126 thus remains a high priority.

127 This study describes an R software package, `neonSoilFlux`, that computes a standardized  
128 estimate of  $F_S$  at all terrestrial NEON sites using the flux-gradient method. Using direct  
129 chamber-based field observations of soil carbon dioxide flux from a subset of terrestrial NEON  
130 sites spanning six states, we provide a direct validation of  $F_S$  from `neonSoilFlux`. While  
131 open source R software tools currently exist for processing chamber-based flux measurements  
132 (Jurasinski et al., 2022; Pedersen, 2024; Rheault et al., 2024; Wilson et al., 2024; Zhao, 2019),  
133 to our knowledge this is the first package that incorporates NEON data directly.

134 Key objectives of this study are to:

135 1. Apply the flux-gradient method to estimate soil CO<sub>2</sub> flux from continuous sensor mea-  
136 surements across six NEON sites.  
137 2. Benchmark estimated soil carbon fluxes against field measurements (e.g. direct chamber  
138 measurements of soil flux).

- 139        3. Identify sources of error in the flux-gradient approach across diverse sites in order to  
140                  guide future work.

141        **3 Materials and Methods**

142        **3.1 Field methods**

143        **3.1.1 Focal NEON Sites**

144        In order to acquire field data to validate model predictions of flux, we selected six terrestrial  
145                  NEON sites for analysis. We conducted roughly week-long field measurement campaigns at  
146                  these sites, which span a range of environmental gradients and terrestrial domains (Table 1).  
147        SJER, SRER, and WREF were visited during May and June of 2022, and WOOD, KONZ, and  
148                  UNDE during May and June of 2024. Permits or waivers were sought and approved prior to  
149                  field work at all six sites. In 2022, research activities were conducted whole or in part on the  
150                  Wind River Experimental Forest within the Gifford Pinchot National Forest. No permit was  
151                  required for this work. Approval for research at San Joaquin Experimental Range was granted  
152                  by Dr. Angela White in May 2022 and for research at Santa Rita Experimental Range by  
153                  Dr. Mitch McClaran in May 2022. In 2024, permits were received for work at WOOD (Chase  
154                  Lake WMD; permit number 62515-24-020), KONZ (Konza Prairie Biological Station; permit  
155                  number 766), and UNDE (University of Notre Dame Environmental Research Center; permit  
156                  number UNDERC-2024-5).

<sup>157</sup> **3.1.2 Soil collar placement**

<sup>158</sup> Either one (2022 sampling campaign) or two (2024 sampling campaign) PVC soil collars (20.1  
<sup>159</sup> cm inside diameter) were installed in close proximity to the permanent NEON soil sensors at  
<sup>160</sup> each site (Figure 1). As instruments in the NEON soil sensor arrays can occasionally break  
<sup>161</sup> down or stop working, the specific soil plot where we made measurements was chosen at each  
<sup>162</sup> site in consultation with NEON staff to maximize likelihood of quality soil sensor measurements  
<sup>163</sup> during the duration of the IRGA measurements. The plot selected at each site (out of the 5 in  
<sup>164</sup> each replicate array at each site) are presented in the last column of Table 1. After installation,  
<sup>165</sup> collar(s) were left to equilibrate for approximately 24 hours prior to any measurements being  
<sup>166</sup> taken.

<sup>167</sup> **3.1.3 Infrared gas analyzer measurements of soil CO<sub>2</sub> flux**

<sup>168</sup> In 2022, we then made measurements of flux on an hourly interval for 8 hours each day.  
<sup>169</sup> Measurements were taken from roughly 8 am to 4 pm, with the time interval selected to  
<sup>170</sup> capture the majority of the diurnal gradient of soil temperature each day. These measurements  
<sup>171</sup> were made using a LI-6800 infrared gas analyzer instrument (LI-COR Environmental, Lincoln,  
<sup>172</sup> NE) fitted with a soil chamber attachment (attachment 6800-09). In 2024, we again used the  
<sup>173</sup> same LI-6800 instrument, but made half-hourly measurements over an approximately 8 hour  
<sup>174</sup> period. In addition, in 2024 we also installed a second collar and used a second instrument, an  
<sup>175</sup> LI-870 CO<sub>2</sub> IRGA, connected to an automated robotic chamber (LI-COR chamber 8200-104)  
<sup>176</sup> controlled by an LI-8250 multiplexer to make automated measurements. The multiplexer was  
<sup>177</sup> configured to take half-hourly measurements 24 hours a day for the duration of our sampling  
<sup>178</sup> bout at each site. Each instrument was paired with a soil temperature and moisture probe  
<sup>179</sup> (Stevens HydraProbe, Stevens Water, Portland, OR) that was used to make soil temperature  
<sup>180</sup> and moisture measurements concurrent with the CO<sub>2</sub> flux measurements. Chamber volumes

were set by measuring collar offsets at each site. System checks were conducted daily for the LI-6800 and weekly for the LI-8250. Instruments were factory calibrated before each field season.

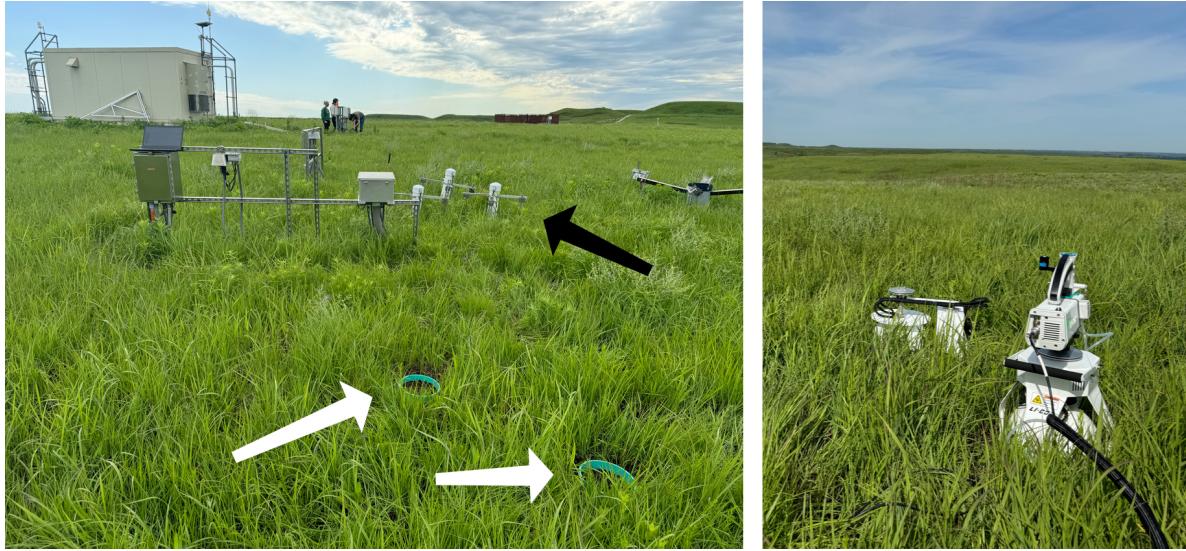


Figure 1: Spatial layout of field sampling using a closed-dynamic chamber setup at a representative NEON site (KONZ). Left image shows collars (white arrows) and permanent soil sensor installation (black arrow) and right image shows the LI-6800 (foreground) and LI-8200-104 (background) instruments placed on the collars.

Table 1: Listing of NEON sites studied for field work and analysis. Site refers to NEON site codes: Santa Rita Experimental Range (SRER), San Joaquin Experimental Range (SJER), Wind River Experimental Forest (WREF), Chase Lake National Wildlife Refuge (WOOD), Konza Prairie Biological Station (KONZ), and the University of Notre Dame Environmental Research Center (UNDE). Location is reported in decimal degrees of latitude and longitude. Other abbreviations include Mean Annual Temperature (MAT);  $\bar{T}_S$ : average soil temperature during field measurements;  $\bar{SWC}$ : average soil water content during field measurements. Dates refer to field measurement dates for each site. Plot refers to the particular location in the soil sensor array (denoted as HOR by NEON) where field measurements were made.

Site	Location	Ecosystem	MAT	$\bar{T}_S$	MAP	$\bar{SWC}$	Dates	Plot
SRER	31.91068, -110.83549	Shrubland	19.3 °C	47.6 °C	346 mm	4.0%	May 29– June 1 2022	004
SJER	37.10878, -119.73228	Oak woodland	16.4 °C	41.7 °C	540 mm	1.2%	June 1–4 2022	005
WREF	45.82049, -121.95191	Evergreen forest	9.2 °C	15.3 °C	2225 mm	27.2%	June 7–9 2022	001

Table 1: Listing of NEON sites studied for field work and analysis. Site refers to NEON site codes: Santa Rita Experimental Range (SRER), San Joaquin Experimental Range (SJER), Wind River Experimental Forest (WREF), Chase Lake National Wildlife Refuge (WOOD), Konza Prairie Biological Station (KONZ), and the University of Notre Dame Environmental Research Center (UNDE). Location is reported in decimal degrees of latitude and longitude. Other abbreviations include Mean Annual Temperature (MAT);  $\bar{T}_S$ : average soil temperature during field measurements;  $\bar{SWC}$ : average soil water content during field measurements. Dates refer to field measurement dates for each site. Plot refers to the particular location in the soil sensor array (denoted as HOR by NEON) where field measurements were made.

Site	Location	Ecosystem	MAT	$\bar{T}_S$	MAP	$\bar{SWC}$	Dates	Plot
WOOD	47.1282, -99.241334	Restored prairie	4.9 °C	14.9 °C	495 mm	14.9%	June 3–9 2024	001
KONZ	39.100774, -96.563075	Tallgrass prairie	12.4 °C	23.4 °C	870 mm	23.4%	May 29– June 1 2024	001
UNDE	46.23391, -89.537254	Deciduous forest	4.3 °C	13.0 °C	802 mm	13.0%	May 22–25 2024	004

### **3.1.4 Post-collection processing of field data**

We used LI-COR SoilFluxPro software (v 5.3.1) to assess the data after collection and to inform sampling parameters. We checked appropriateness of dead band and measurement durations using built-in evaluation tools. Based on this, the deadband period was set for 30-40 seconds, depending on the site, and the measurement duration was 180 seconds with a 30 second pre-purge and a 30 second post-purge at most sites, and a 90 second pre- and post-purge at sites with higher humidity due to recent precipitation events. We also assessed the  $R^2$  of linear and exponential model fits to measured CO<sub>2</sub> to verify measurement quality.

### **3.2 neonSoilFlux R package**

We developed an R package called `neonSoilFlux` (Zobitz et al., 2024) to compute half-hourly soil carbon fluxes and uncertainties from NEON data. The objective of the `neonSoilFlux`

195 package is a unified workflow (Figure 2) for soil data acquisition and analysis that supplements  
196 the existing `neonUtilities` data acquisition R package (Lunch et al., 2025).

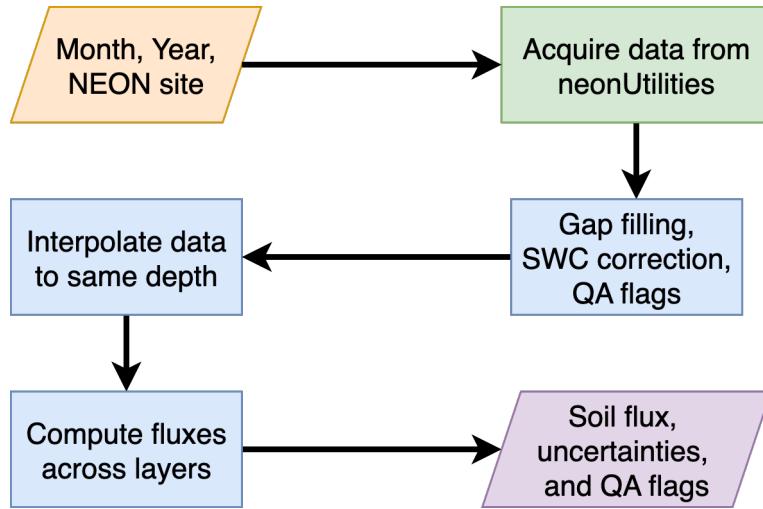


Figure 2: Diagram of `neonSoilFlux` R package. For a given month, year, and NEON site (orange parallelogram), the package acquires all relevant data to compute  $F_S$  using the `neonUtilities` R package (green rectangle). Data are gap-filled according to reported QA flags and adjusted for changes in soil water content (SWC) calibration coefficients, then interpolated to the same measurement depth before computing the soil flux, uncertainties, and final QA flags (blue rectangles). The package reports the associated soil flux, uncertainties, and quality assurance (QA) flags for the user (purple parallelogram).

197 At a given NEON site there are five replicate soil plots, each with measurements of soil  
198  $\text{CO}_2$  concentration, soil temperature, and soil moisture at different depths (Figure 3). The  
199 `neonSoilFlux` package acquires measured soil  $\text{CO}_2$  concentration (NEON, 2024b), soil temper-  
200 ature (NEON, 2024d), soil water content (NEON, 2024e), barometric pressure from the nearby  
201 tower (NEON, 2024a), and soil properties (e.g. bulk density) (NEON, 2024c) from a range of  
202 different NEON data products. The static soil properties were collected by NEON staff from a  
203 nearby soil pit during initial site characterization and are assumed to be constant at each site.  
204 A soil flux calculation is computed at each replicate soil plot.

205 The workflow to compute a value of  $F_S$  with `neonSoilFlux` consists of three primary steps,

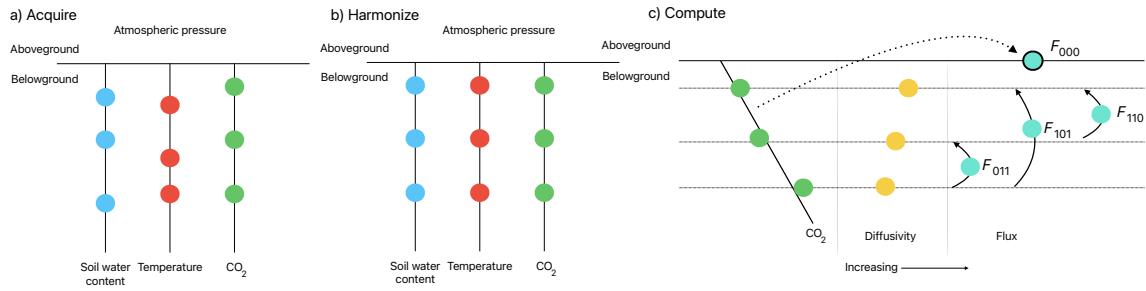


Figure 3: Model diagram of the data workflow for the `neonSoilFlux` R package. a) Acquire: Data are obtained for a given NEON location and horizontal sensor location, which includes soil water content, soil temperature,  $\text{CO}_2$  concentration, and atmospheric pressure. All data are screened for quality assurance; if gap-filling of missing data occurs, it is flagged for the user. b) Harmonize: Any belowground data are then harmonized to the same depth as  $\text{CO}_2$  concentrations using linear regression. c) Compute: The flux across a given depth is computed via Fick's law, denoted with  $F_{ijk}$ , where  $i$ ,  $j$ , or  $k$  are either 0 or 1 denoting the layers the flux is computed across ( $i =$  closest to surface,  $k =$  deepest).  $F_{000}$  represents a flux estimate where the gradient  $dC/dz$  is the slope of a linear regression of  $\text{CO}_2$  with depth.

206 illustrated in Figure 3. First, NEON data are acquired for a given site and month via the  
 207 `neonUtilities` R package (yellow parallelogram and green rectangle in Figure 2 and Panel a  
 208 in Figure 3). Acquired environmental data can be exported to a comma separated value file for  
 209 additional analysis. Quality assurance (QA) flags are reported as an indicator variable. Since  
 210 the calibration coefficients on the soil water content sensors have changed over time (NEON,  
 211 2024e), raw sensor measurements were back-calculated and soil-specific calibrations were applied  
 212 following Ayres et al. (2024) to generate a consistent time series at each measurement location.

213 The second step is harmonizing the data to compute soil fluxes across soil layers. This  
 214 step consists of three different actions (blue rectangles in Figure 2 and Panel b in Figure 3).  
 215 If a given observation by NEON is reported as not passing a quality assurance check, we  
 216 applied a gap filling method to replace that measurement with its monthly mean at that same  
 217 depth (Section 3.2.1). Belowground measurements of soil water and soil temperature are then  
 218 interpolated to the same depth as soil  $\text{CO}_2$  measurements. The diffusivity (Section 3.2.2) and

219 soil flux across different soil layers (Section 3.2.3) are then computed.

220 The third and final step is computing a surface soil flux through extrapolation to the surface  
221 (purple parallelogram in Figure 2 and Panel c in Figure 3). Uncertainty on a soil flux  
222 measurement is computed through quadrature. An aggregate quality assurance (QA) flag for  
223 each environmental measurement is also reported, representing if any gap-filled measurements  
224 were used in the computation of a soil flux. Within the soil flux-gradient method, several  
225 different approaches can be used to derive a surface flux (Maier & Schack-Kirchner, 2014); the  
226 `neonSoilFlux` package reports four different possible values for soil surface flux (Section 3.2.3)  
227 for each of two different methods of diffusivity estimation, for a total of eight estimates of  
228 flux.

### 229 3.2.1 Gap-filling routine

230 NEON reports QA flags as binary values for each measurement and half-hourly interval. For a  
231 given half-hour, if any input variable (soil CO<sub>2</sub> concentration, soil temperature, or soil moisture)  
232 at depth  $z$  is flagged, computation of  $F_S$  is not possible. To address this, flagged measurements  
233 and their uncertainties were replaced with a bootstrapped monthly mean ( $\bar{m}$ ) and monthly  
234 standard deviation ( $\bar{s}$ ) (Efron & Tibshirani, 1994).

235 For each month, depth  $z$ , and variable, we computed bootstrapped estimates of  $\bar{m}$  and  $\bar{s}$   
236 from the vectors of unflagged measurements (**m**), reported standard errors ( $\sigma$ ), and the 95%  
237 confidence interval ( $\epsilon$ , or expanded uncertainty; Farrance & Frenkel (2012)). We also defined a  
238 bias vector  $\mathbf{b} = \sqrt{\epsilon^2 - \sigma^2}$ , which quantifies the spread of uncertainty in a given period and is  
239 incorporated into  $\bar{m}$ .

240 From these, 5000 bootstrap samples were generated for **m**,  $\sigma$ , and **b**. For each sample ( $m_k, b_k, \sigma_k$ ),  
241 we generated a vector **n** (length  $N = 5000$ ) by drawing from a normal distribution with mean

242  $m_k + b_k$  and standard deviation  $\sigma_k$ . The sample mean and standard deviation were then  
243 computed from  $\mathbf{n}$ . The resulting distributions of sample means and sample standard deviations  
244 provided the bootstrapped monthly mean ( $\bar{m}$ ) and standard error ( $\bar{s}$ ) respectively.

245 This gap-filling procedure provides a consistent treatment across all data streams. However,  
246 alternative approaches may be better suited for longer gaps (e.g., correlations with other NEON  
247 measurement levels or soil plots) or for variable-specific conditions. We discuss the effect of  
248 gap-filling on our results in Section 5.1.

### 249 3.2.2 Soil diffusivity

250 Soil diffusivity  $D_a$  at a given measurement depth is the product of the diffusivity in free air  
251  $D_{a,0}$  ( $\text{m}^2 \text{ s}^{-1}$ ) and the tortuosity  $\xi$  (no units) (Millington & Shearer, 1971).

252 We compute  $D_{a,0}$  with Equation 1:

$$D_{a,0} = 0.0000147 \cdot \left( \frac{T_i + 273.15}{293.15} \right)^{1.75} \cdot \left( \frac{P}{101.3} \right) \quad (1)$$

253 where  $T_i$  is soil temperature ( $^\circ\text{C}$ ) at depth  $i$  (NEON, 2024d) and  $P$  surface barometric pressure  
254 (kPa) (NEON, 2024a).

255 Previous studies by Sallam et al. (1984) and Tang et al. (2003) demonstrated the sensitivity  
256 of modeled  $F_S$  depending on the tortuosity model ( $\xi$ ) used to compute diffusivity. At low  
257 soil water content, the choice of tortuosity model can lead to order-of-magnitude differences  
258 in  $D_a$ , which in turn affect modeled  $F_S$ . The `neonSoilFlux` package currently includes two  
259 approaches to calculate  $\xi$ , representing the range of tortuosity behavior reported in Sallam et  
260 al. (1984).

261 The first approach is the Millington-Quirk model (Millington & Shearer, 1971), in which  
262 tortuosity depends on both porosity and soil water content:

$$\xi = \frac{(\phi - SWC_i)^{10/3}}{\phi^2} \quad (2)$$

263 In Equation 2,  $SWC$  is the soil water content at depth  $i$  (NEON, 2024e) and  $\phi$  is the porosity,  
264 which in turn is a function of soil physical properties (NEON, 2024c):

$$\phi = \left(1 - \frac{\rho_s}{\rho_m}\right) (1 - f_V) \quad (3)$$

265 In Equation 3,  $\rho_m$  is the particle density of mineral soil ( $2.65 \text{ g cm}^{-3}$ ),  $\rho_s$  the soil bulk density  
266 ( $\text{g cm}^{-3}$ ) excluding coarse fragments greater than 2 mm (NEON, 2024c), and  $f_V$  is a site-specific  
267 value that accounts for the proportion of soil fragments between 2-20 mm. Soil fragments  
268 greater than 20 mm were not estimated due to limitations in the amount of soil that can be  
269 analyzed (NEON, 2024c). We assume that rock fragments contain no internal pores.

270 The Millington-Quirk model assumes  $\xi$  is modulated by the amount of fluid saturation in soil  
271 pores (Millington & Shearer, 1971). In contrast, the Marshall model (Marshall, 1959) expresses  
272 tortuosity as only a function of porosity ( $\xi = \phi^{1.5}$ ), with  $\phi$  defined from Equation 3. The  
273 Marshall model is independent of soil water content and assumes tortuosity is only governed  
274 by soil structure. The `neonSoilFlux` package allows users to choose the tortuosity model most  
275 appropriate for site-specific conditions and research goals.

276 **3.2.3 Soil flux computation**

277 We applied Fick's law (Equation 4) to compute the soil flux  $F_{ij}$  ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) across two soil  
278 depths  $i$  and  $j$ :

$$F_{ij} = -D_a \frac{dC}{dz} \quad (4)$$

279 where  $D_a$  is the diffusivity ( $\text{m}^2 \text{s}^{-1}$ ) and  $\frac{dC}{dz}$  is the gradient of  $\text{CO}_2$  molar concentration ( $\mu\text{mol}$   
280  $\text{m}^{-3}$ , so the gradient has units of  $\mu\text{mol m}^{-3} \text{m}^{-1}$ ). The soil surface flux is theoretically defined  
281 by applying Equation 4 to measurements collected at the soil surface and directly below the  
282 surface. Measurements of soil temperature, soil water content, and soil  $\text{CO}_2$  molar concentration  
283 across the soil profile allow for application of Equation 4 across different soil depths. Each  
284 site had three measurement layers, so we denote the flux as a three-digit subscript  $F_{ijk}$  with  
285 indicator variables  $i$ ,  $j$ , and  $k$  indicate if a given layer was used (written in order of increasing  
286 depth), according to the following:

- 287 •  $F_{000}$  is a surface flux estimate using the intercept of the linear regression of  $D_a$  with  
288 depth and the slope from the linear regression of  $\text{CO}_2$  with depth (which represents  $\frac{dC}{dz}$   
289 in Fick's Law). Tang et al. (2003) used this approach to compute fluxes in an oak-grass  
290 savannah.
- 291 •  $F_{110}$  is a flux estimate across the two shallowest measurement layers.
- 292 •  $F_{011}$  is a flux estimate across the two deepest measurement layers.
- 293 •  $F_{101}$  is a flux estimate across the shallowest and deepest measurement layers.

294 For  $F_{110}$ ,  $F_{011}$ , and  $F_{101}$ , the diffusivity used in Fick's Law is always at the deeper measurement  
295 layer. When used as a surface flux estimate we assume  $\text{CO}_2$  remains constant above this flux  
296 depth. Uncertainty in all  $F_{ijk}$  values was quantified using quadrature (Taylor, 2022). These

297 computed fluxes could provide the basis for additional soil flux estimates. For example, Tang et  
298 al. (2005) estimated surface flux by linearly extrapolating  $F_{110}$  and  $F_{011}$  to the soil surface.

299 **3.3 Post processing evaluation**

300 Following collection of field measurements and calculation of the soil fluxes from `neonSoilFlux`  
301 package, we compared measured  $F_S$  based on closed-dynamic chamber measurements with the  
302 LI-COR instruments to a given soil flux calculation from `neonSoilFlux` for each site and flux  
303 computation method and quantified the relationship statistically ( $R^2$ ). Finally, for a half-hourly  
304 interval we also computed a *post hoc* diffusivity ( $D_a$ ) using the LI-COR flux along with the  
305  $\text{CO}_2$  surface gradient reported by NEON using the measurement levels closest to the surface.

306 **4 Results**

307 **4.1 Concordance between modelled and measured soil  $\text{CO}_2$  flux**

308 The sites we visited ranged substantially in both their annual average temperature and  
309 precipitation as well as their biome type (Table 2). These differences also influenced the wide  
310 range of observed flux rates across sites.

311 The timeseries of the measured fluxes from the LI-COR 6800 and 870/8250 were compared  
312 to modeled soil fluxes from the `neonSoilFlux` R package (Figure 4). We also assessed year-  
313 long estimated flux time series and compared those to field measurements made at each site  
314 (Figure 5). Results are reported in local time. Where applicable, sites are displayed from left  
315 to right by increasing soil temperature (Table 1). Positive values of the flux indicate that there  
316 is a flux moving towards the surface. Overall, with the exception of SRER (discussed later) the  
317 computed fluxes determined using a variety of plausible methods spanned the field-measured

Table 2: Summary of measured soil characteristics and flux results from field measurements across six NEON sites using a LI-COR 6800 (LI-870/8250 measurements omitted to enable direct comparability) via the closed-dynamic chamber method. Numeric values for soil CO<sub>2</sub> flux, soil temperature, and volumetric soil water content (VSWC) are the mean and standard deviation of field measurements at each site.

Site	Flux μmol m <sup>-2</sup> s <sup>-1</sup>	Soil temp °C	VSWC cm <sup>3</sup> cm <sup>-3</sup>	n
UNDE	2.55 ± 0.26	14.33 ± 0.77	0.33 ± 0.02	61
WOOD	3.02 ± 0.4	16.01 ± 1.54	0.28 ± 0.01	53
WREF	3.62 ± 0.3	15.34 ± 1.76	0.27 ± 0.06	21
KONZ	6.35 ± 0.97	27.28 ± 4.14	0.37 ± 0.01	44
SJER	0.94 ± 0.02	41.68 ± 11.22	0.01 ± 0.01	32
SRER	0.72 ± 0.09	47.64 ± 7.46	0.04 ± 0.01	32

<sup>318</sup> fluxes, but the specific flux-gradient method that best approximated field measurements varied  
<sup>319</sup> by site.

<sup>320</sup> We calculated a statistical relationship between the various estimates of soil flux computed by  
<sup>321</sup> `neonSoilFlux` and the field-measured fluxes within daily interval periods. Statistics for these  
<sup>322</sup> comparisons are reported in Figure 6, which also shows how these fall relative to a 1:1 line.

## <sup>323</sup> 4.2 Effects of method choice on diffusivity estimates

<sup>324</sup> In four of six field sites, the *post hoc*  $D_a$  estimate fell roughly between the two diffusion  
<sup>325</sup> estimation methods; however this was less the case in the two driest sites, SJER and SRER  
<sup>326</sup> (Table 1), where the field estimate of diffusivity was either lower or higher than both of the  
<sup>327</sup> other methods (Figure 7).

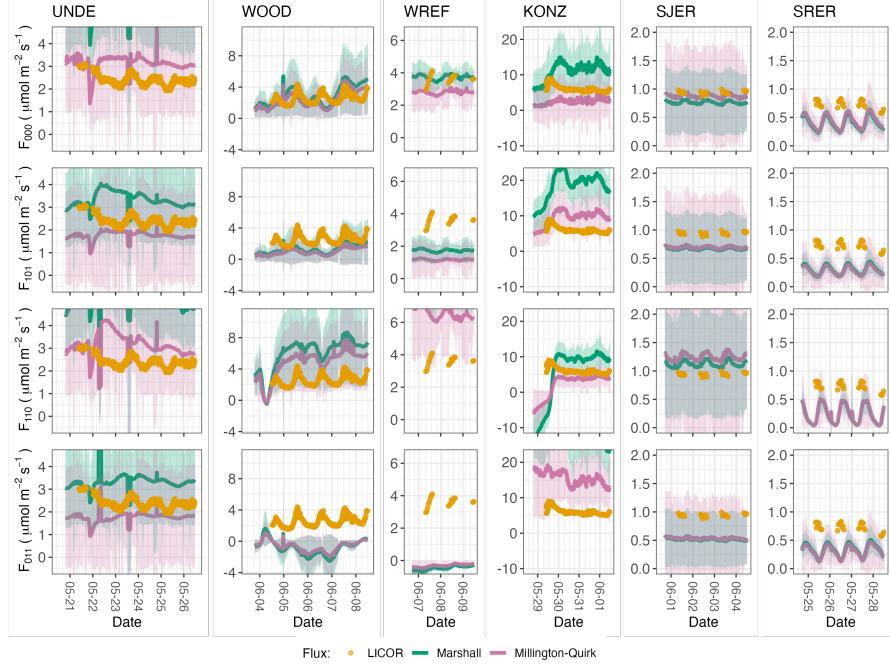


Figure 4: Timeseries of soil surface flux ( $F_S$ ) from field-measured (yellow lines) and modeled soil fluxes (green or purple lines) by the `neonSoilFlux` R package. Fluxes from the `neonSoilFlux` R package are separated by the diffusivity model used (Millington-Quirk or Marshall, Section 3.2.2). Individual vertical axis labels in the first column represent the measurement levels where the flux-gradient approach is applied (Section 3.2.3). Ribbons for modeled soil fluxes represent  $\pm 1$  standard deviation. Results are reported in local time. WREF, SJER, and SRER were sampled in 2022, and UNDE, WOOD, and KONZ were sampled in 2024. Sites (columns) are arranged from left to right in terms of increasing mean annual temperature.

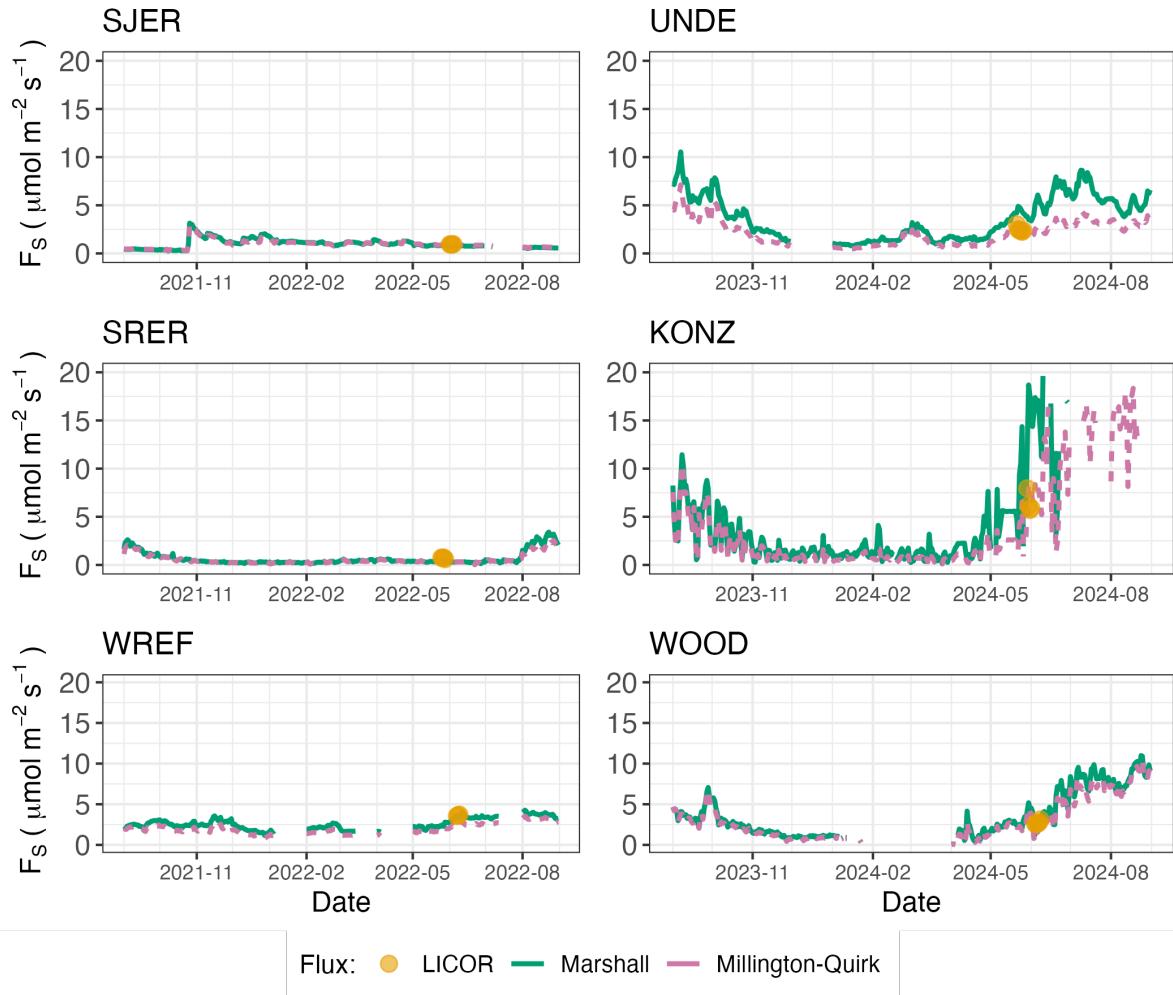


Figure 5: Timeseries of both daily-averaged field  $F_S$  (yellow circles) and daily ensemble averaged soil fluxes (average of  $F_{000}$ ,  $F_{101}$ ,  $F_{011}$ ,  $F_{110}$ , Section 3.2.3) by the `neonSoilFlux` R package, separated by the diffusivity model used (green or purple lines, Millington-Quirk or Marshall, Section 3.2.2).

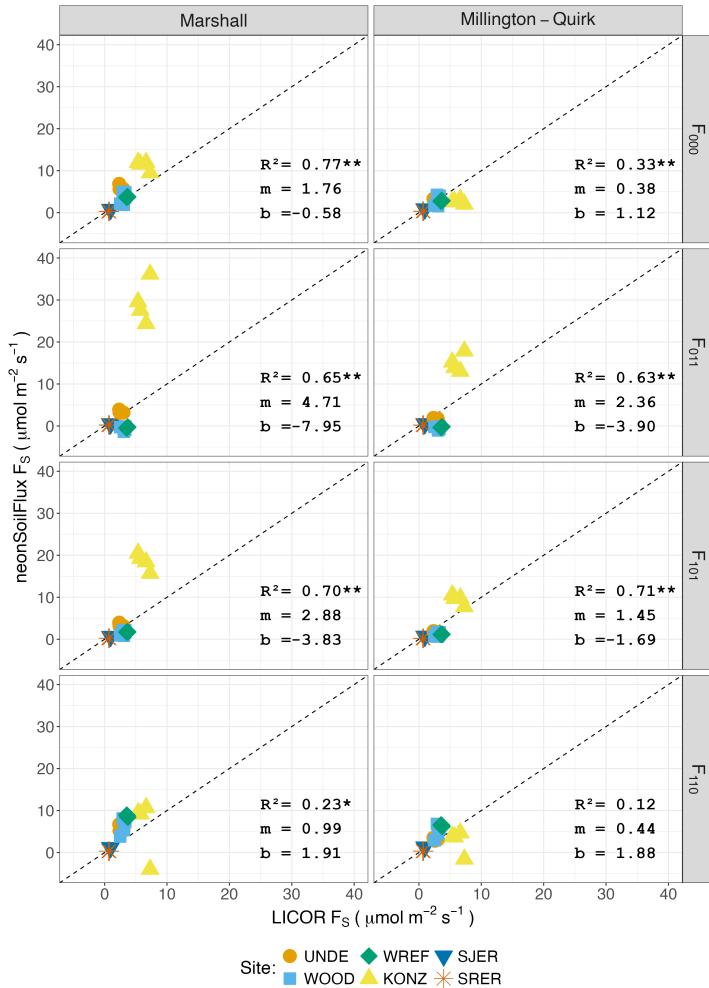


Figure 6: Statistical comparison between measured fluxes at each NEON site with fluxes reported by `neonSoilFlux` with the different flux calculation approaches and diffusivity calculations applied. Points are daily averages and LICOR  $F_S$  values are from the 6800 instrument only, for consistency. The dotted line represents a 1:1 relationship, and the reported  $R^2$  quantifies the relationship between field-measured and `neonSoilFlux` estimated fluxes. \* = significance at the 5% level, \*\* = significance at the 1% level. The slope ( $m$ ) and intercept ( $b$ ) of the linear regression between measured and modeled fluxes are also reported. The low-value outlier from KONZ in the  $F_{110}$  Marshall plot is an example of the effect of inverted  $\text{CO}_2$  gradients causing an estimated flux to be negative, bringing down the daily mean, which later resolved as the soils dried back out. Intervals where calculated fluxes were  $< 0$  ( $n = 12$ ) were excluded from the plot; 3 each from WREF and WOOD when using ( $F_{011}$  approach).

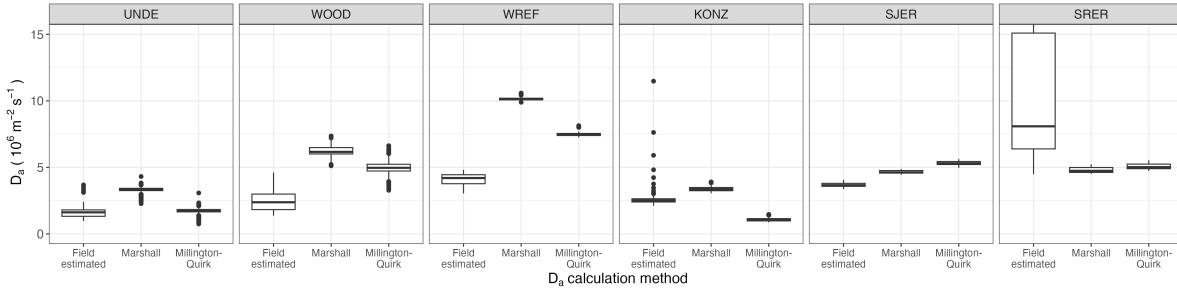


Figure 7: Distribution of diffusivity ( $D_a$ ) at each study site. Values of  $D_a$  were provided by the `neonSoilFlux` package, computed from the Millington-Quirk or Marshall models (Section 3.2.2). A post-hoc estimate of diffusivity (labeled as “Field estimated”) was computed through the field measured flux (Figure 4), divided by the CO<sub>2</sub> gradient from the measurement levels closest to the soil surface, as reported by NEON. We only used  $F_S$  measured by the LICOR 6800 at all sites to standardize comparisons. Some outliers (n = 2 from the field estimated values at KONZ and n = 9 from field estimated values at SRER) are excluded from the plot to allow better comparative visualization across sites.

## 328 5 Discussion

329 This study presents a unified data science workflow to efficiently process automated measurements  
 330 of belowground soil CO<sub>2</sub> concentrations, soil water content, and soil temperature to  
 331 infer estimates of soil surface CO<sub>2</sub> effluxes through application of Fick’s Law (Equation 4).  
 332 Our core goals in this study were: (1) to generate estimates of soil flux from continuous soil  
 333 sensor data at terrestrial NEON sites using the flux-gradient method and then (2) to compare  
 334 those estimates to field-measured fluxes based on the closed chamber approach at six NEON  
 335 focal sites. We discuss our progress toward these core goals through (1) an overall evaluation  
 336 of the flux-gradient approach (and uncertainty calculation) and (2) site-specific evaluation of  
 337 differences in estimated vs measured fluxes.

338 **5.1 General evaluation of flux-gradient approach**

339 Key assumptions of the flux-gradient approach are that CO<sub>2</sub> concentrations increase throughout  
340 the soil profile such that the highest concentrations are observed in the deepest layers. Addition-  
341 ally, field flux measurements should correlate with  $F_{000}$  because they represent surface fluxes.  
342 Periods where this gradient condition are not met generally are connected to processes that occur  
343 during soil wetting events, where more shallow soil layers produce higher concentrations of CO<sub>2</sub>  
344 due to microbial respiration pulses following rewetting. This effect is likely to be largest at sites  
345 with rich organic soils (e.g. KONZ). Based on this reasoning, in these types of situations we would  
346 *a priori* expect  $F_{011}$  (deepest layers)  $\leq F_{101} \leq F_{110}$  (shallow layers)  $\leq F_{000}$  (all layers) be-  
347 cause the previous flux estimates rely primarily on CO<sub>2</sub> concentrations at deeper depths, and  
348 could miss high concentrations of CO<sub>2</sub> produced in shallower layers.

349 When modeling soil respiration, typically a non-linear response function that also considers soil  
350 type is used (Bouma & Bryla, 2000; Yan et al., 2016, 2018). For the `neonSoilFlux` package,  
351 soil type is connected to the measurement of bulk density, which was characterized at each  
352 NEON site. This bulk density estimate is based on replicate samples collected from the site  
353 megapit at a subset of soil horizons, with an estimated uncertainty of  $\pm 5\%$  (NEON, 2024c).  
354 Coarse fragment estimates also have very large uncertainties, but because the volume fraction  
355 tends to be low in surface soils it is unlikely to contribute much additional flux uncertainty.

356 Our results suggest that the most important way to improve reliability of the flux estimate is  
357 to reduce the usage of gap-filled data. The current approach to gap filling in `neonSoilFlux`  
358 uses monthly mean data to gap fill—this approach decreases the ability of the estimate to be  
359 responsive to short-term pulses that occur with rapid weather shifts. Four sites (KONZ, SRER,  
360 WREF, and UNDE) had more than 75% of half-hourly periods with no-gap filled measurements  
361 (Figure S1, Supplementary Information). Two sites (SJER and WOOD) had more than 75% of  
362 half-hourly intervals with just one gap-filled measurement. The large uncertainty evident in

363 Figure 4 for estimates from WOOD and SJER are thus due in part to the gap-filling used in  
364 these sites (Figure S1). While we did not need to use gap-filled measurements to compute the  
365 flux at WREF, field data collection occurred following a severe rainstorm, with soils at the  
366 beginning of the sampling week near their water holding capacity. In general, we recommend  
367 that whenever possible, knowledge of local field conditions should influence analysis decisions  
368 in addition to any QA filtering protocols in the `neonSoilFlux` package.

369 We recognize that this gap-filling approach may lead to gap-filled values that are quite different  
370 from the actual values, such as an underestimate of soil moisture following rain events. Further  
371 extensions of the gap filling method could use more sophisticated gap-filling routines, similar to  
372 what is used for net ecosystem carbon exchange (Falge et al., 2001; Liu et al., 2023; Mariethoz  
373 et al., 2015; Moffat et al., 2007; Zhang et al., 2023). Additionally, since the deepest temperature  
374 and soil moisture sensors are located below the deepest CO<sub>2</sub> sensors at NEON sites, it is  
375 possible that excluding these deeper layers from consideration prior to analysis would lead to a  
376 reduced need for gap filling. Future iterations of the `neonSoilFlux` package may incorporate  
377 this as an option. The current gap-filling routine provides a consistent approach that can be  
378 applied to each data stream, but further work may explore alternative gap-filling approaches.

## 379 **5.2 Evaluation of flux-gradient approach at each site**

380 Derived results from the `neonSoilFlux` package have patterns that are broadly consistent with  
381 those directly measured in the field (Figure 4 and Figure 5), even though statistical comparisons  
382 between the field-measured and `neonSoilFlux` values were quite variable (e.g.  $R^2$  ranging  
383 from 0.04 to 0.81; Figure 6). One advantage of the `neonSoilFlux` package is its ability to  
384 calculate fluxes across different soil depths (Figure 3), which allows for additional site-specific  
385 customization. We believe the package can provide a useful baseline estimate of soil fluxes that  
386 can always be complemented through additional field measurements.

387 The six locations studied provide a range of case studies that suggest different considerations  
388 may apply to different sites when applying the flux-gradient method. For example, the Santa  
389 Rita Experimental Range (SRER) is a desert site characterized by sandy soil, which also was  
390 the location of the highest field soil temperatures that we observed (Table 2). At SRER the  
391 flux across the top two layers ( $F_{110}$ ) produced a pattern of soil flux most consistent with the  
392 observed field data. The remaining methods  $F_{101}$ ,  $F_{011}$ , or  $F_{000}$  are derived from information  
393 taken from the deepest layer, which seems to have been decoupled from the surface layers both  
394 in terms of temperature and CO<sub>2</sub> concentration. This may be a general circumstance where  
395 there are large diurnal temperature extremes that rapidly change during the course of a day  
396 and overnight, leading to lags in the timing of when temperature increases propagate down to  
397 deeper soil layers.

398 Immediately prior to our visit to Konza Prairie (KONZ), that site that experienced a significant  
399 rain event that led to wet soils that gradually dried out over the course of our time there.  
400 This pulse of precipitation increased the soil CO<sub>2</sub> concentration at the top layer above the  
401 concentrations in lower layers, leading to negative estimated flux values at the start of the field  
402 sampling period. In this case it was only when the soil began to return to a baseline level that  
403 the assumptions of the flux-gradient method were again met.

404 Both of the previous cases also provide context for the variable statistical comparisons between  
405 field-measured soil fluxes and `neonSoilFlux` outputs (Figure 6). When considering systematic  
406 deployment of this method across a measurement network, there are a number of independent  
407 challenges that require careful consideration. There are clear tradeoffs between (1) accuracy of  
408 modeled fluxes (defined here as closeness to field-measured  $F_S$  and the uncertainty reduction  
409 factor  $\epsilon$ ), (2) precision (which could be defined by the signal to noise ratio), and (3) the  
410 choice of the diffusivity model (Section 3.2.2) or flux computation method (Section 3.2.3). A  
411 sensitivity analysis (Figure S2, Supplemental Information) found that flux output uncertainty

412 was dominated by measurement uncertainty ( $T_S$ ,  $P$ ,  $SWC$ , or  $CO_2$ ) rather than by the diffusivity  
413 method used to compute soil flux. Notably, the  $F_{110}$  method was least sensitive to measurement  
414 uncertainty likely because it best aligns with the surface chamber measurement assumptions.

415 Finally, comparing the effects of different diffusivity estimation methods on the match between  
416 modeled and measured fluxes (Figure 5) highlights the sensitivity of  $F_{ijk}$  to diffusivity. The  
417 comparison between diffusivity estimates compared to field estimated diffusivity (Figure 7)  
418 demonstrates that site parameters can dictate which measure of diffusivity is most likely to be  
419 accurate in a given environmental context. Site-specific differences are largely a reflection of  
420 differences in soil moisture across the sites (Table 1), as not all diffusivity estimation methods  
421 incorporate soil moisture equivalently. While we here have compares two approaches to calculate  
422 diffusivity (the Millington-Quirk and Marshall models), it may be valuable to evaluate other  
423 diffusivity models (e.g. the Moldrup model; Moldrup et al. (1999)) as well. Ultimately the  
424 choice of a particular diffusivity model could be determined based on knowledge of site-specific  
425 evaluations or a set of these models could be used to generate a model ensemble average as a  
426 means to trade precision for a more general approach.

### 427 **5.3 Recommendations for future method development**

428 The `neonSoilFlux` package provides several approaches to estimate soil flux using the gradient  
429 method. We believe these approaches enable the software to be used across a range of site-  
430 specific assumptions (Maier & Schack-Kirchner, 2014). We note, however, that this choice  
431 can have a determinative approach on the calculated values. Ensemble averaging approaches  
432 (Elshall et al., 2018; Raftery et al., 2005) may be one way to address this problem if the goal is  
433 to calculate fluxes using the same method at a diverse range of different sites. Two other ideas  
434 would be to apply machine learning algorithms (e.g. random forest) to generate a single flux  
435 estimate across diverse sites, or using co-located estimates of net ecosystem carbon exchange

<sup>436</sup> from eddy-flux towers to further constrain results or to assess soil flux results for plausibility  
<sup>437</sup> (Phillips et al., 2017).

<sup>438</sup> These challenges notwithstanding, the method used here and made available in the  
<sup>439</sup> `neonSoilFlux` R package has the potential to produce nearly continuous estimates of flux  
<sup>440</sup> across all terrestrial NEON sites. These estimates are a significant improvement on available  
<sup>441</sup> approaches to constrain the portion of ecosystem respiration attributable to the soil. This, in  
<sup>442</sup> turn, also aids in our ability to understand the soil contribution to the net ecosystem flux  
<sup>443</sup> measured at these sites using the co-located eddy flux towers.

## <sup>444</sup> **6 Conclusions**

<sup>445</sup> We used the R package `neonSoilFlux` to estimate soil CO<sub>2</sub> fluxes with the flux-gradient method  
<sup>446</sup> using data from buried soil sensors at NEON terrestrial sites. We compared the predicted  
<sup>447</sup> fluxes to those measured directly using a field-based closed chamber approach. Soil fluxes  
<sup>448</sup> from `neonSoilFlux` were broadly effective at producing estimates of flux comparable to those  
<sup>449</sup> measured in the field using a chamber-based technique. However `neonSoilFlux` outputs are  
<sup>450</sup> quite sensitive to a number of issues, including: missing data (and thus gap-filling of input  
<sup>451</sup> measurement datasets), the selection of soil depths used to best calculate the gradient (which  
<sup>452</sup> may vary between sites), and finally the choice of method used for estimating soil diffusivity.  
<sup>453</sup> The flexibility of the `neonSoilFlux` package allows the user to evaluate each of these issues  
<sup>454</sup> with site-specific knowledge and contexts. Future refinements and subsequent validation of  
<sup>455</sup> `neonSoilFlux` outputs will feed forward into evaluating soil carbon fluxes broader spatial scales  
<sup>456</sup> to enhance understanding of the ways in which soils across diverse ecosystems are responding  
<sup>457</sup> to a changing climate.

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