

## **1 Abstract**

- 2     1. Accurate quantification of soil carbon fluxes is essential to reduce uncertainty in estimates  
3         of the terrestrial carbon sink. However, these fluxes vary over time and across ecosystem  
4         types and so it can be difficult to estimate them accurately across large scales. The flux  
5         gradient method estimates soil carbon fluxes using co-located measurements of soil CO<sub>2</sub>  
6         concentration, soil temperature, soil moisture, and other soil properties. The National  
7         Ecological Observatory Network (NEON) provides such data across 20 ecoclimatic domains  
8         spanning the continental U.S., Puerto Rico, Alaska, and Hawai‘i.
- 9     2. We present an R software package (`neonSoilFlux`) that acquires soil environmental data  
10        to compute half-hourly soil carbon fluxes for each soil replicate plot at a given terrestrial  
11        NEON site. To assess the computed fluxes, we visited six focal NEON sites and measured  
12        soil carbon fluxes using a closed-dynamic chamber approach.
- 13    3. Outputs from the `neonSoilFlux` showed agreement with measured fluxes ( $R^2$  between  
14        measured and `neonSoilFlux` outputs ranging from 0.12 to 0.77 depending on calculation  
15        method used); measured outputs generally fell within the range of calculated uncertainties  
16        from the gradient method. Calculated fluxes from `neonSoilFlux` aggregated to the daily  
17        scale exhibited expected site-specific seasonal patterns.
- 18    4. While the flux gradient method is broadly effective, its accuracy is highly sensitive  
19        to site-specific inputs, including the extent to which gap-filling techniques are used to  
20        interpolate missing sensor data and to estimates of soil diffusivity and moisture content.  
21        Future refinement and validation of `neonSoilFlux` outputs can contribute to existing  
22        databases of soil carbon flux measurements, providing near real-time estimates of a critical  
23        component of the terrestrial carbon cycle.

<sup>24</sup> **1.1 Keywords**

<sup>25</sup> Soil carbon, carbon dioxide, flux gradient, carbon cycle, field validation, soil respiration,  
<sup>26</sup> ecosystem variability, diffusion

<sup>27</sup> **2 Introduction**

<sup>28</sup> Soils contain the planet's largest reservoir of terrestrial carbon (Jobbág & Jackson, 2000). A  
<sup>29</sup> critical component of this reservoir is soil organic matter, the accumulation of which is influenced  
<sup>30</sup> by biotic factors such as above-ground plant inputs (Jackson et al., 2017). These inputs in  
<sup>31</sup> turn are influenced by environmental factors such as growing season length, temperature, and  
<sup>32</sup> moisture (Desai et al., 2022), which also affect the breakdown of soil organic matter and its  
<sup>33</sup> return to the atmosphere. Across heterogeneous terrestrial landscapes, the interplay between  
<sup>34</sup> these biotic and abiotic factors influence the size of the soil contribution to the terrestrial  
<sup>35</sup> carbon sink (Friedlingstein et al., 2025). However, the heterogeneity of these processes across  
<sup>36</sup> diverse ecosystems in the context of rapid environmental change leads to large uncertainty  
<sup>37</sup> about the magnitude of this sink in the future, and thus there remains a pressing need to  
<sup>38</sup> quantify changes in soil carbon pools and fluxes across scales.

<sup>39</sup> Ecological observation networks such as the United States' National Ecological Observatory  
<sup>40</sup> Network (NEON) and others (e.g. the globally-distributed FLUXNET or the European Inte-  
<sup>41</sup> grated Carbon Observation System) present a significant advancement in the nearly continuous  
<sup>42</sup> observation of biogeochemical processes at the continental scale. Notably, at 47 terrestrial  
<sup>43</sup> sites across the continental United States that span 20 ecoclimatic domains, NEON provides  
<sup>44</sup> half-hourly measurements of soil CO<sub>2</sub> concentration, temperature, and moisture at different  
<sup>45</sup> vertical depths. Each of these NEON sites also encompasses measurements of the cumulative  
<sup>46</sup> sum of all ecosystem carbon fluxes in an airshed using the eddy covariance technique (Baldocchi,

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

52 Estimated or observed soil carbon fluxes are a key metric for understanding change in soil  
53 carbon pools over time (Bond-Lamberty et al., 2024). A soil carbon flux to the atmosphere ( $F_S$ ,  
54 units  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), represents the aggregate process of transfer of soil  $\text{CO}_2$  to the atmosphere  
55 from physical and biological processes (e.g. diffusion and respiration). Soil carbon fluxes can  
56 be assumed to encompass soil carbon respiration from autotrophic or heterotrophic sources  
57 (Davidson et al., 2006) and modeled with a exponential  $Q_{10}$  paradigm (Bond-Lamberty et al.,  
58 2004; Chen & Tian, 2005; Hamdi et al., 2013).

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

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

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

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

90 Key objectives of this study are to:

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

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

97        **3 Materials and Methods**

98        **3.1 Field methods**

99        **3.1.1 Focal NEON Sites**

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

<sup>113</sup> **3.1.2 Soil collar placement**

<sup>114</sup> Either one (2022 sampling campaign) or two (2024 sampling campaign) PVC soil collars (20.1  
<sup>115</sup> cm inside diameter) were installed in close proximity to the permanent NEON soil sensors at  
<sup>116</sup> each site (Figure 1). As instruments in the NEON soil sensor arrays can occasionally break  
<sup>117</sup> down or stop working, the specific soil plot where we made measurements was chosen at each  
<sup>118</sup> site in consultation with NEON staff to maximize likelihood of quality soil sensor measurements  
<sup>119</sup> during the duration of the IRGA measurements. The plot selected at each site (out of the 5 in  
<sup>120</sup> each replicate array at each site) are presented in the last column of Table 1. After installation,  
<sup>121</sup> collar(s) were left to equilibrate for approximately 24 hours prior to any measurements being  
<sup>122</sup> taken.

<sup>123</sup> **3.1.3 Infrared gas analyzer measurements of soil CO<sub>2</sub> flux**

<sup>124</sup> In 2022, we then made measurements of flux on an hourly interval for 8 hours each day.  
<sup>125</sup> Measurements were taken from roughly 8 am to 4 pm, with the time interval selected to  
<sup>126</sup> capture the majority of the diurnal gradient of soil temperature each day. These measurements  
<sup>127</sup> were made using a LI-6800 infrared gas analyzer instrument (LI-COR Environmental, Lincoln,  
<sup>128</sup> NE) fitted with a soil chamber attachment (attachment 6800-09). In 2024, we again used the  
<sup>129</sup> same LI-6800 instrument, but made half-hourly measurements over an approximately 8 hour  
<sup>130</sup> period. In addition, in 2024 we also installed a second collar and used a second instrument, an  
<sup>131</sup> LI-870 CO<sub>2</sub> IRGA, connected to an automated robotic chamber (LI-COR chamber 8200-104)  
<sup>132</sup> controlled by an LI-8250 multiplexer to make automated measurements. The multiplexer was  
<sup>133</sup> configured to take half-hourly measurements 24 hours a day for the duration of our sampling  
<sup>134</sup> bout at each site. Each instrument was paired with a soil temperature and moisture probe  
<sup>135</sup> (Stevens HydraProbe, Stevens Water, Portland, OR) that was used to make soil temperature  
<sup>136</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.

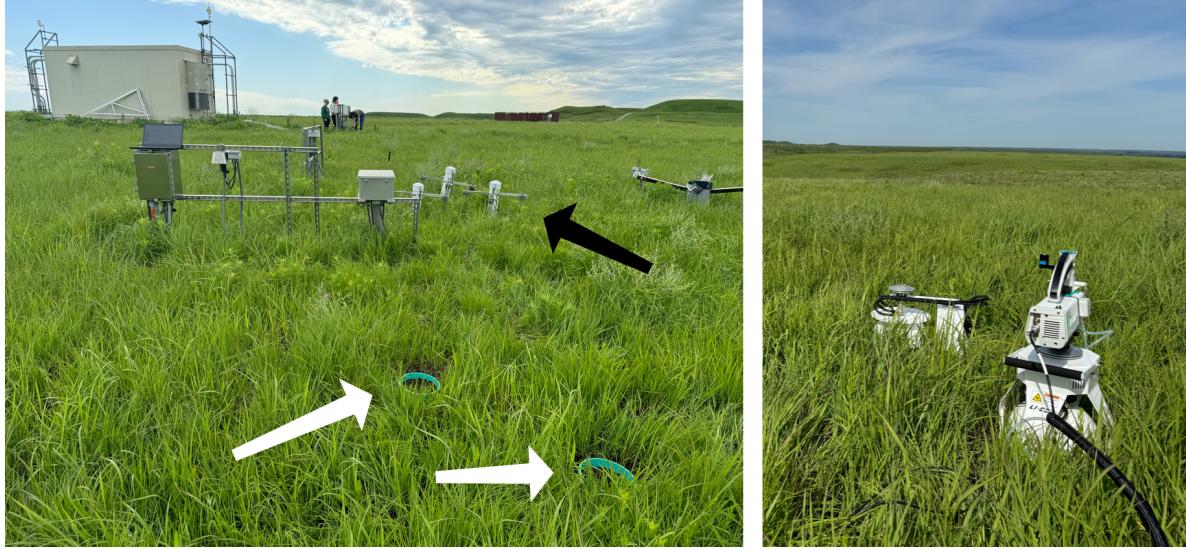


Figure 1: Spatial layout of field sampling using a closed-dynamic chamber setup at a representative NEON site (KONZ). Left image shows collars (white arrows) and permanent soil sensor installation (black arrow) and right image shows the LI-6800 (foreground) and LI-8200-104 (background) instruments placed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

### <sup>140</sup> 3.1.4 Post-collection processing of field data

<sup>141</sup> We used LI-COR SoilFluxPro software (v 5.3.1) to assess the data after collection and to  
<sup>142</sup> inform sampling parameters. We checked appropriateness of dead band and measurement  
<sup>143</sup> durations using built-in evaluation tools. Based on this, the deadband period was set for 30-40  
<sup>144</sup> seconds, depending on the site, and the measurement duration was 180 seconds with a 30  
<sup>145</sup> second pre-purge and a 30 second post-purge at most sites, and a 90 second pre- and post-purge  
<sup>146</sup> at sites with higher humidity due to recent precipitation events. We also assessed the  $R^2$  of  
<sup>147</sup> linear and exponential model fits to measured CO<sub>2</sub> to verify measurement quality.

### <sup>148</sup> 3.2 neonSoilFlux R package

<sup>149</sup> We developed an R package called `neonSoilFlux` (Zobitz et al., 2024) to compute half-hourly  
<sup>150</sup> soil carbon fluxes and uncertainties from NEON data. The objective of the `neonSoilFlux`

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

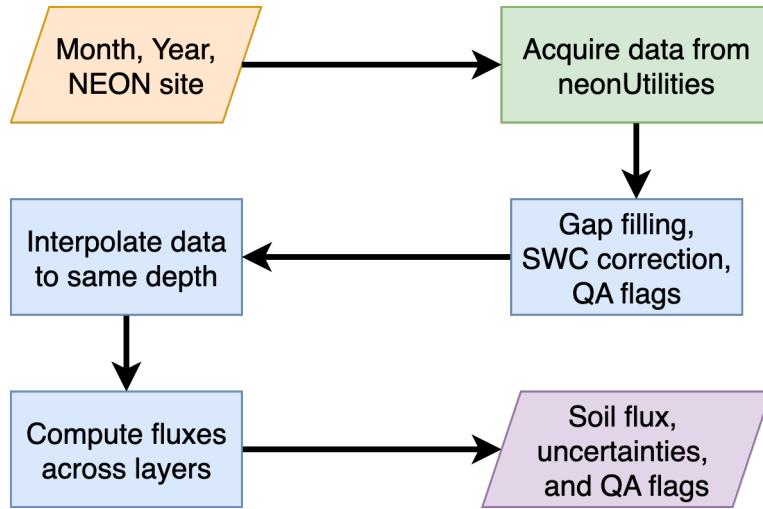


Figure 2: Diagram of `neonSoilFlux` R package. For a given month, year, and NEON site (orange parallelogram), the package acquires all relevant data to compute  $F_S$  using the `neonUtilities` R package (green rectangle). Data are gap-filled according to reported QA flags and adjusted for changes in 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).

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

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

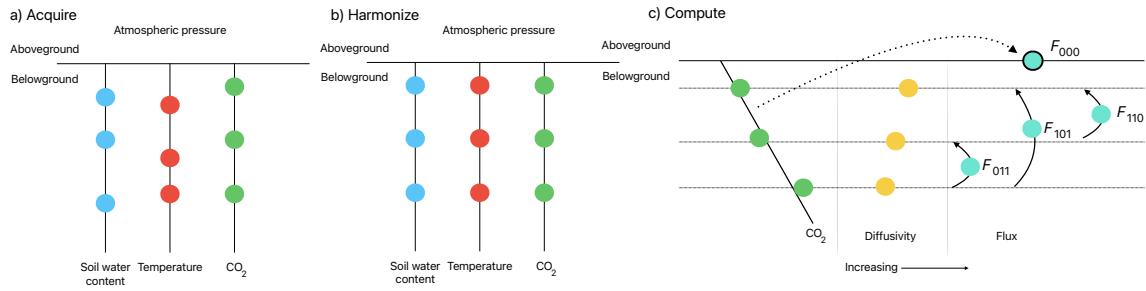


Figure 3: Model diagram of the data workflow for the `neonSoilFlux` R package. a) Acquire: Data are obtained for a given NEON location and horizontal sensor location, which includes soil water content, soil temperature,  $\text{CO}_2$  concentration, and atmospheric pressure. All data are screened for 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.

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

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

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

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

### 185 3.2.1 Gap-filling routine

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

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

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

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

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

### 205 3.2.2 Soil diffusivity

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

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

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

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

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

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

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

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

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

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

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

232 **3.2.3 Soil flux computation**

233 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  
234 depths  $i$  and  $j$ :

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

235 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 ( $\mu\text{mol}$   
236  $\text{m}^{-3}$ , so the gradient has units of  $\mu\text{mol m}^{-3} \text{m}^{-1}$ ). The soil surface flux is theoretically defined  
237 by applying Equation 4 to measurements collected at the soil surface and directly below the  
238 surface. Measurements of soil temperature, soil water content, and soil  $\text{CO}_2$  molar concentration  
239 across the soil profile allow for application of Equation 4 across different soil depths. Each  
240 site had three measurement layers, so we denote the flux as a three-digit subscript  $F_{ijk}$  with  
241 indicator variables  $i$ ,  $j$ , and  $k$  indicate if a given layer was used (written in order of increasing  
242 depth), according to the following:

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

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

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

255 **3.3 Post processing evaluation**

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

262 **4 Results**

263 **4.1 Concordance between modelled and measured soil  $\text{CO}_2$  flux**

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

267 The timeseries of the measured fluxes from the LI-COR 6800 and 870/8250 were compared  
268 to modeled soil fluxes from the `neonSoilFlux` R package (Figure 4). We also assessed year-  
269 long estimated flux time series and compared those to field measurements made at each site  
270 (Figure 5). Results are reported in local time. Where applicable, sites are displayed from left  
271 to right by increasing soil temperature (Table 1). Positive values of the flux indicate that there  
272 is a flux moving towards the surface. Overall, with the exception of SRER (discussed later) the  
273 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>274</sup> fluxes, but the specific flux-gradient method that best approximated field measurements varied  
<sup>275</sup> by site.

<sup>276</sup> We calculated a statistical relationship between the various estimates of soil flux computed by  
<sup>277</sup> `neonSoilFlux` and the field-measured fluxes within daily interval periods. Statistics for these  
<sup>278</sup> comparisons are reported in Figure 6, which also shows how these fall relative to a 1:1 line.

## <sup>279</sup> 4.2 Effects of method choice on diffusivity estimates

<sup>280</sup> In one of the six field sites, the *post hoc*  $D_a$  estimate fell roughly between the two diffusion  
<sup>281</sup> estimation methods. At UNDE, WOOD, WREF, and SJER, the median field estimate of  
<sup>282</sup> diffusivity was lower than both of the other methods. At the driest sites, SRER (Table 1),  
<sup>283</sup> the median field estimate of diffusivity was higher than both of the other methods and values  
<sup>284</sup> showed a large amount of variation (Figure 7).

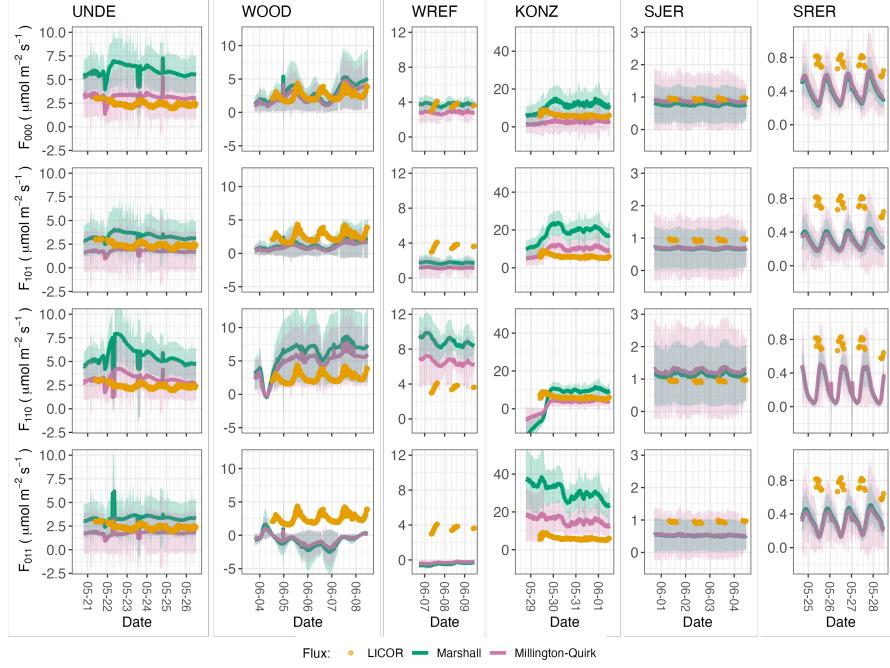


Figure 4: Timeseries of soil surface flux ( $F_S$ ) from field-measured (yellow lines) and modeled soil fluxes (green or purple lines) by the `neonSoilFlux` R package. Fluxes from the `neonSoilFlux` R package are separated by the diffusivity model used (Millington-Quirk or Marshall, Section 3.2.2). Individual 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 approximately  $\pm 1$  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.

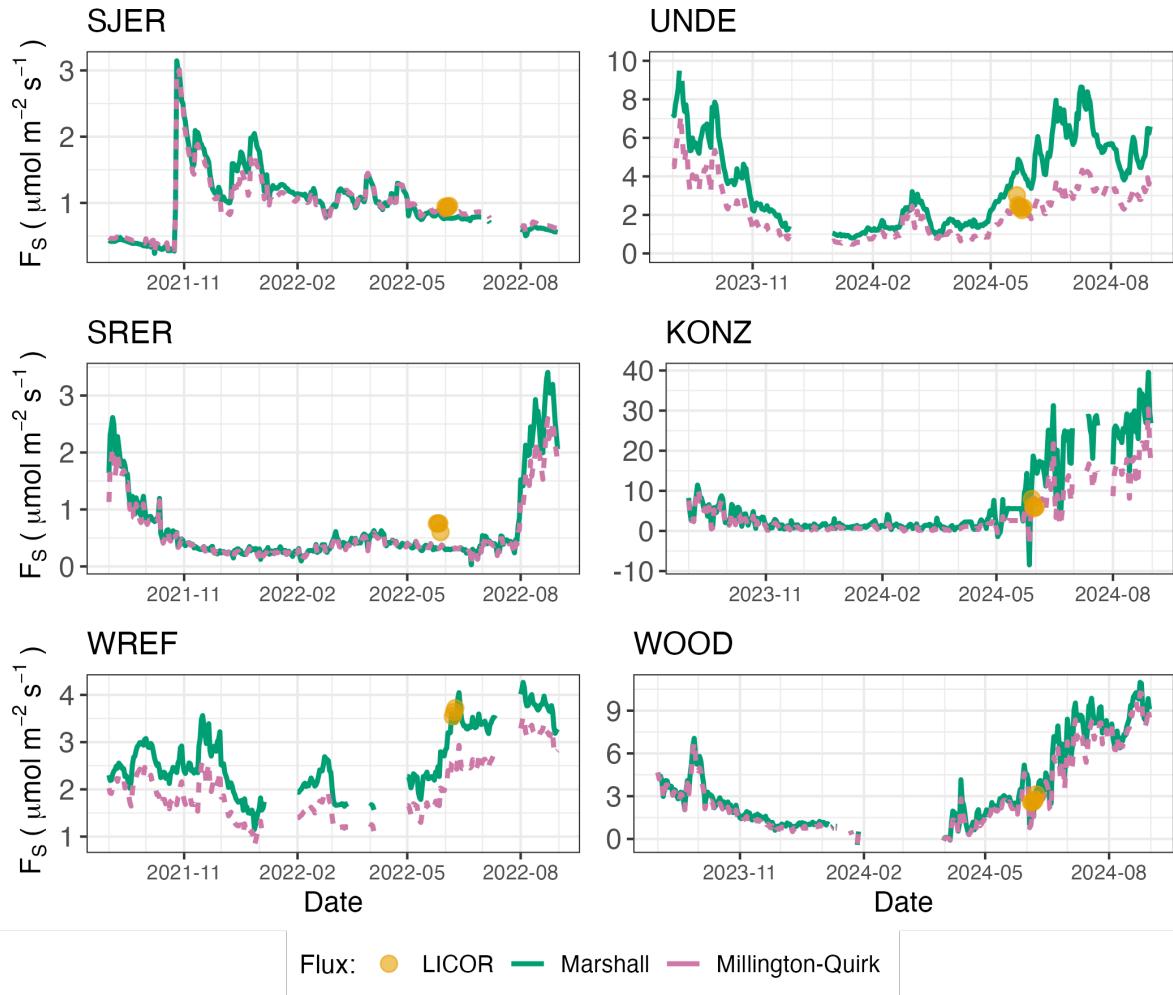


Figure 5: Timeseries of both daily-averaged field  $F_S$  (yellow circles) and daily ensemble averaged soil fluxes (average of  $F_{000}$ ,  $F_{101}$ ,  $F_{011}$ ,  $F_{110}$ , Section 3.2.3) by the `neonSoilFlux` R package, separated by the diffusivity model used (green or purple lines, Millington-Quirk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

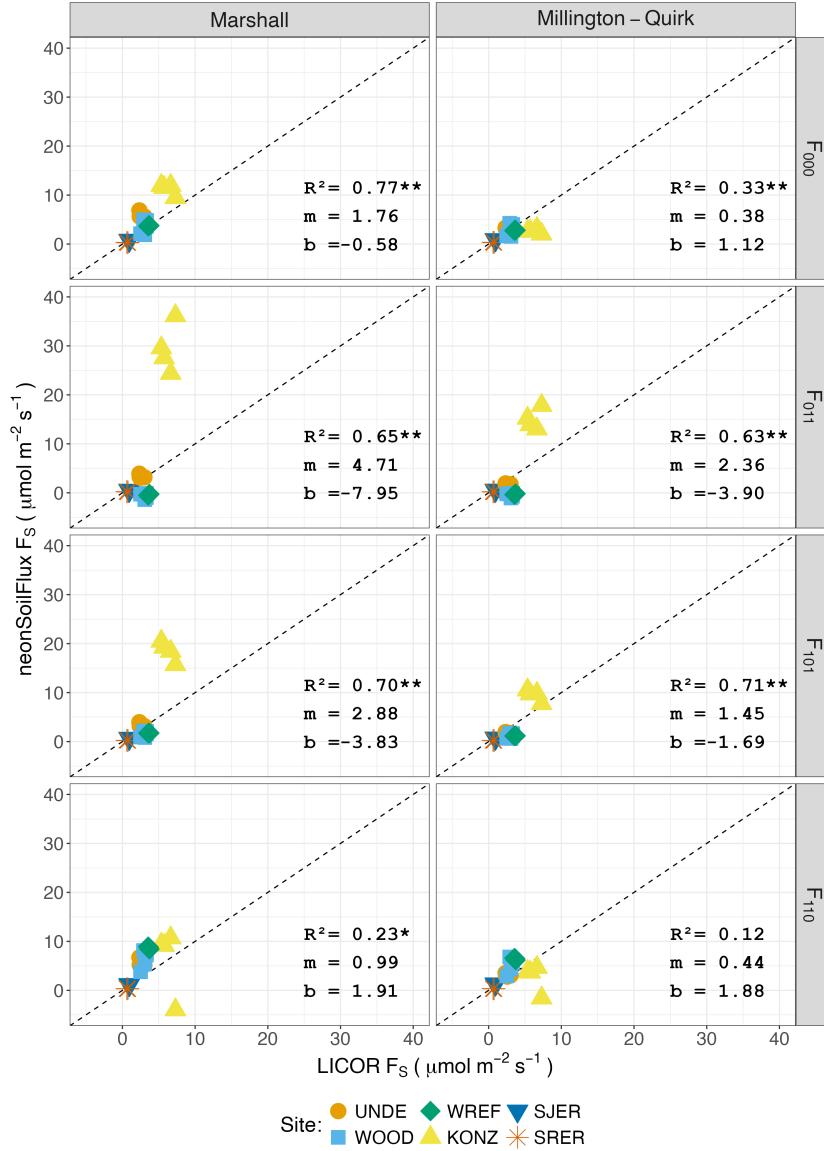


Figure 6: Statistical comparison between measured fluxes at each NEON site with fluxes reported by `neonSoilFlux` with the different flux calculation approaches and diffusivity calculations applied. Points are daily averages and LICOR  $F_S$  values are from the 6800 instrument only, for consistency. 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 CO<sub>2</sub> gradients causing an estimated flux to be negative, bringing down the daily mean, which later resolved as the soils dried back out.

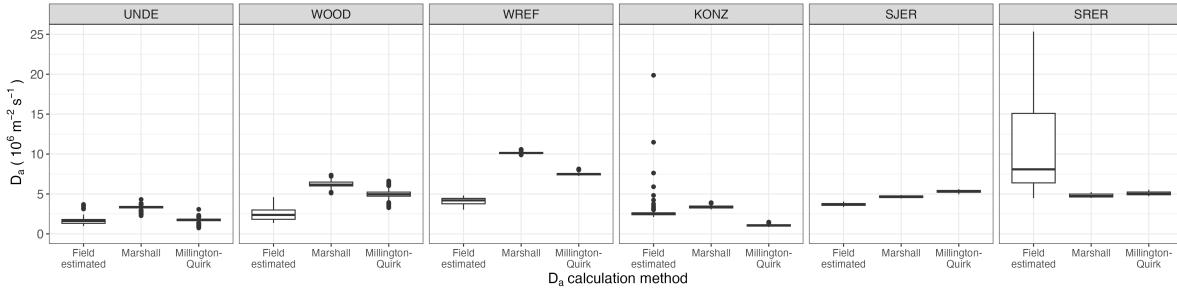


Figure 7: Distribution of diffusivity ( $D_a$ ) at each study site. Values of  $D_a$  were provided by the `neonSoilFlux` package, computed from the Millington-Quirk or Marshall models (Section 3.2.2). A post-hoc estimate of diffusivity (labeled as “Field estimated”) was computed through the field measured 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 ( $n = 1$  from the field estimated values at KONZ and  $n = 6$  from field estimated values at SRER) are excluded from the plot to allow better comparative visualization across sites.

## 285 5 Discussion

286 This study presents a unified data science workflow to efficiently process automated measurements of belowground soil CO<sub>2</sub> concentrations, soil water content, and soil temperature to  
 287 infer estimates of soil surface CO<sub>2</sub> effluxes through application of Fick’s Law (Equation 4).  
 288 Our core goals in this study were: (1) to generate estimates of soil flux from continuous soil  
 289 sensor data at terrestrial NEON sites using the flux-gradient method and then (2) to compare  
 290 those estimates to field-measured fluxes based on the closed chamber approach at six NEON  
 291 focal sites. We discuss our progress toward these core goals through (1) an overall evaluation  
 292 of the flux-gradient approach (and uncertainty calculation) and (2) site-specific evaluation of  
 293 differences in estimated vs measured fluxes.  
 294

295 **5.1 General evaluation of flux-gradient approach**

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

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

313 Our results suggest that the most important way to improve reliability of the flux estimate is  
314 to reduce the usage of gap-filled data. The current approach to gap filling in `neonSoilFlux`  
315 uses monthly mean data to gap fill—this approach decreases the ability of the estimate to  
316 be responsive to short-term pulses that occur with rapid weather shifts. All sites had more  
317 than 75% of half-hourly periods with no-gap filled measurements (Figure S1, Supplementary  
318 Information). At five out of six sites (all except SRER), we used at least some gap-filled  
319 measurements of Soil Water Content (SWC). At WREF, field data collection occurred following

320 a severe rainstorm, with soils at the beginning of the sampling week near their water holding  
321 capacity, which can influence the soil moisture sensor accuracy. In general, we recommend that  
322 whenever possible, knowledge of local field conditions should influence analysis decisions in  
323 addition to any QA filtering protocols in the `neonSoilFlux` package.

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

## 334 **5.2 Evaluation of flux-gradient approach at each site**

335 Derived results from the `neonSoilFlux` package have patterns that are broadly consistent with  
336 those directly measured in the field (Figure 4 and Figure 5), even though statistical comparisons  
337 between the field-measured and `neonSoilFlux` values were quite variable (e.g.  $R^2$  ranging  
338 from 0.12 to 0.77; Figure 6). One advantage of the `neonSoilFlux` package is its ability to  
339 calculate fluxes across different soil depths (Figure 3), which allows for additional site-specific  
340 customization. We believe the package can provide a useful baseline estimate of soil fluxes that  
341 can always be complemented through additional field measurements.

342 The six locations studied provide a range of case studies that suggest different considerations

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

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

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

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

### 5.3 Recommendations for future method development

The `neonSoilFlux` package provides several approaches to estimate soil flux using the gradient method. We believe these approaches enable the software to be used across a range of site-specific assumptions (Maier & Schack-Kirchner, 2014). We note, however, that this choice can have a determinative approach on the calculated values. Ensemble averaging approaches (Elshall et al., 2018; Raftery et al., 2005) may be one way to address this problem if the goal is to calculate fluxes using the same method at a diverse range of different sites. Two other ideas would be to apply machine learning algorithms (*e.g.* random forest) to generate a single flux estimate across diverse sites, or using co-located estimates of net ecosystem carbon exchange from eddy-flux towers to further constrain results or to assess soil flux results for plausibility (Phillips et al., 2017).

These challenges notwithstanding, the method used here and made available in the

392 `neonSoilFlux` R package has the potential to produce nearly continuous estimates of flux  
393 across all terrestrial NEON sites. These estimates are a significant improvement on available  
394 approaches to constrain the portion of ecosystem respiration attributable to the soil. This, in  
395 turn, also aids in our ability to understand the soil contribution to the net ecosystem flux  
396 measured at these sites using the co-located eddy flux towers.

## 397 **6 Conclusions**

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

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