

<sup>1</sup> **neonSoilFlux: An R Package for Continuous  
2 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.

## <sup>27</sup> **Author Contributions**

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<sup>40</sup> Naupaka Zimmerman.

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

<sup>42</sup> Anonymous field-collected data, `neonSoilFlux` calculated outputs, and manuscript-generating  
<sup>43</sup> code for peer review are provided as supplemental files. An anonymous link for peer-review  
<sup>44</sup> is here: <https://doi.org/10.5281/zenodo.1695117>. This will be made publicly available upon  
<sup>45</sup> publication.

46 **1 Abstract**

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

<sup>69</sup> **1.1 Keywords**

<sup>70</sup> Soil carbon, carbon dioxide, flux gradient, carbon cycle, field validation, soil respiration,  
<sup>71</sup> ecosystem variability, diffusion

<sup>72</sup> **2 Data for peer review**

<sup>73</sup> Anonymous field-collected data, `neonSoilFlux` calculated outputs, and manuscript-generating  
<sup>74</sup> code for peer review are provided as supplemental files. An anonymous link for peer-review  
<sup>75</sup> is here: <https://doi.org/10.5281/zenodo.16951117>. This will be made publicly available upon  
<sup>76</sup> publication.

<sup>77</sup> **3 Introduction**

<sup>78</sup> Soils contain the planet's largest reservoir of terrestrial carbon (Jobbágy & Jackson, 2000). A  
<sup>79</sup> critical component of this reservoir is soil organic matter, the accumulation of which is influenced  
<sup>80</sup> by biotic factors such as above-ground plant inputs (Jackson et al., 2017). These inputs in  
<sup>81</sup> turn are influenced by environmental factors such as growing season length, temperature, and  
<sup>82</sup> moisture (Desai et al., 2022), which also affect the breakdown of soil organic matter and its  
<sup>83</sup> return to the atmosphere. Across heterogeneous terrestrial landscapes, the interplay between  
<sup>84</sup> these biotic and abiotic factors influence the size of the soil contribution to the terrestrial  
<sup>85</sup> carbon sink (Friedlingstein et al., 2025). However, the heterogeneity of these processes across  
<sup>86</sup> diverse ecosystems in the context of rapid environmental change leads to large uncertainty  
<sup>87</sup> about the magnitude of this sink in the future, and thus there remains a pressing need to  
<sup>88</sup> quantify changes in soil carbon pools and fluxes across scales.

89 Ecological observation networks such as the United States' National Ecological Observatory  
90 Network (NEON) and others (e.g. the globally-distributed FLUXNET or the European Inte-  
91 grated Carbon Observation System) present a significant advancement in the nearly continuous  
92 observation of biogeochemical processes at the continental scale. Notably, at 47 terrestrial  
93 sites across the continental United States that span 20 ecoclimatic domains, NEON provides  
94 half-hourly measurements of soil CO<sub>2</sub> concentration, temperature, and moisture at different  
95 vertical depths. Each of these NEON sites also encompasses measurements of the cumulative  
96 sum of all ecosystem carbon fluxes in an airshed using the eddy covariance technique (Baldocchi,  
97 2014). Soil observations provided by NEON are on the same timescale and standardized with  
98 eddy covariance measurements from FLUXNET. These types of nearly continuous observational  
99 data (NEON and FLUXNET) can be used to reconcile differences between model-derived  
100 or data-estimated components of ecosystem carbon flux (Jian et al., 2022; Luo et al., 2011;  
101 Phillips et al., 2017; J. Shao et al., 2015; P. Shao et al., 2013; Sihi et al., 2016).

102 Estimated or observed soil carbon fluxes are a key metric for understanding change in soil  
103 carbon pools over time (Bond-Lamberty et al., 2024). A soil carbon flux to the atmosphere ( $F_S$ ,  
104 units  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), represents the aggregate process of transfer of soil CO<sub>2</sub> to the atmosphere  
105 from physical and biological processes (e.g. diffusion and respiration). Soil carbon fluxes can  
106 be assumed to encompass soil carbon respiration from autotrophic or heterotrophic sources  
107 (Davidson et al., 2006) and modeled with a exponential  $Q_{10}$  paradigm (Bond-Lamberty et al.,  
108 2004; Chen & Tian, 2005; Hamdi et al., 2013).

109 One common method by which  $F_S$  is measured in the field is through the use of soil chambers  
110 in a closed, well-mixed system (Norman et al., 1997) with headspace trace gas concentrations  
111 measured with an infrared gas analyzer (IRGA).  $F_S$  can also be estimated from soil CO<sub>2</sub>  
112 measurements at different depths in the soil using the flux-gradient method (Maier & Schack-  
113 Kirchner, 2014). Closed-chamber IRGA measurements, while being the most common method,

114 require either frequent in-person site visits or expensive and fragile automated systems. The  
115 potential of the gradient method is that fluxes can be estimated from continuous data recorded  
116 by robust solid-state sensors. The flux-gradient method is an approach that uses conservation of  
117 mass to calculate flux at a vertical soil depth  $z$  at steady state by applying Fick's law of diffusion.  
118 A simplifying assumption for the flux-gradient method is that there is no mass transfer in the  
119 other spatial dimensions  $x$  and  $y$  (Maier & Schack-Kirchner, 2014). The diffusivity profile, a  
120 key component of this calculation, varies across the soil depth as a function of soil temperature,  
121 soil volumetric water content, atmospheric air pressure, and soil bulk density (Millington &  
122 Shearer, 1971; Moldrup et al., 1999; Sallam et al., 1984).

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

133 This study describes an R software package, `neonSoilFlux`, that computes a standardized  
134 estimate of  $F_S$  at all terrestrial NEON sites using the flux-gradient method. Using direct  
135 chamber-based field observations of soil carbon dioxide flux from a subset of terrestrial NEON  
136 sites spanning six states, we provide a direct validation of  $F_S$  from `neonSoilFlux`. While  
137 open source R software tools currently exist for processing chamber-based flux measurements  
138 (Jurasinski et al., 2022; Pedersen, 2024; Rheault et al., 2024; Wilson et al., 2024; Zhao, 2019),

<sup>139</sup> to our knowledge this is the first package that incorporates NEON data directly.

<sup>140</sup> Key objectives of this study are to:

- <sup>141</sup> 1. Apply the flux-gradient method to estimate soil CO<sub>2</sub> flux from continuous sensor mea-
- <sup>142</sup> surements across six NEON sites.
- <sup>143</sup> 2. Benchmark estimated soil carbon fluxes against field measurements (e.g. direct chamber
- <sup>144</sup> measurements of soil flux).
- <sup>145</sup> 3. Identify sources of error in the flux-gradient approach across diverse sites in order to
- <sup>146</sup> guide future work.

## <sup>147</sup> **4 Materials and Methods**

### <sup>148</sup> **4.1 Field methods**

#### <sup>149</sup> **4.1.1 Focal NEON Sites**

<sup>150</sup> In order to acquire field data to validate model predictions of flux, we selected six terrestrial  
<sup>151</sup> NEON sites for analysis. We conducted roughly week-long field measurement campaigns at  
<sup>152</sup> these sites, which span a range of environmental gradients and terrestrial domains (Table 1).  
<sup>153</sup> SJER, SRER, and WREF were visited during May and June of 2022, and WOOD, KONZ,  
<sup>154</sup> and UNDE during May and June of 2024.

#### <sup>155</sup> **4.1.2 Soil collar placement**

<sup>156</sup> Either one (2022 sampling campaign) or two (2024 sampling campaign) PVC soil collars (20.1  
<sup>157</sup> cm inside diameter) were installed in close proximity to the permanent NEON soil sensors at

158 each site (Figure 1). As instruments in the NEON soil sensor arrays can occasionally break  
159 down or stop working, the specific soil plot where we made measurements was chosen at each  
160 site in consultation with NEON staff to maximize likelihood of quality soil sensor measurements  
161 during the duration of the IRGA measurements. The plot selected at each site (out of the 5 in  
162 each replicate array at each site) are presented in the last column of Table 1. After installation,  
163 collar(s) were left to equilibrate for approximately 24 hours prior to any measurements being  
164 taken.

165 **4.1.3 Infrared gas analyzer measurements of soil CO<sub>2</sub> flux**

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

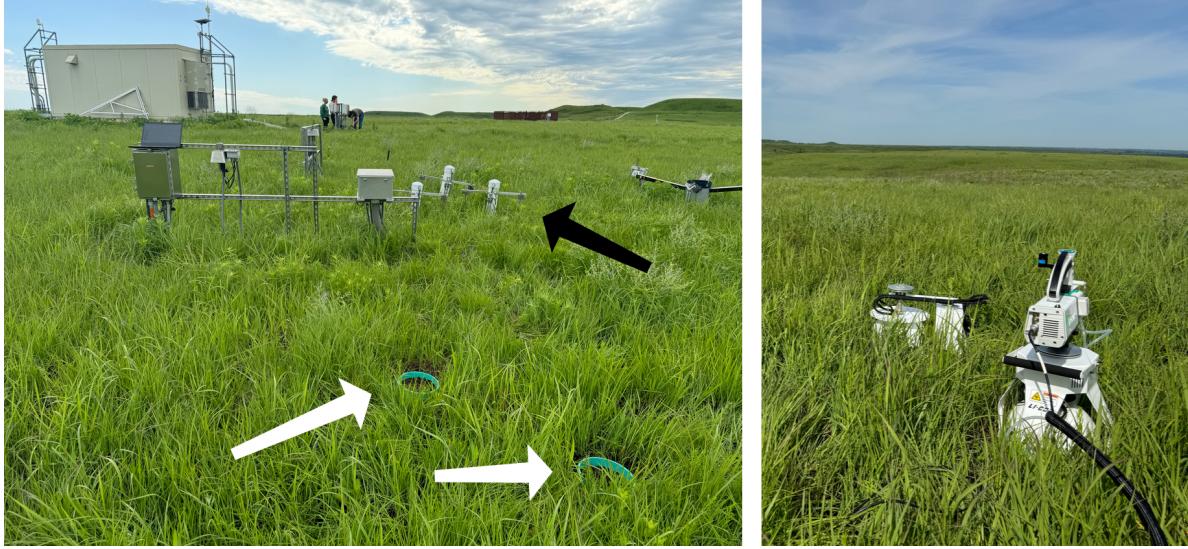


Figure 1: Spatial layout of field sampling using a closed-dynamic chamber setup at a representative NEON site (KONZ). Left image shows collars (white arrows) and permanent soil sensor installation (black arrow) and right image shows the LI-6800 (foreground) and LI-8200-104 (background) instruments placed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

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
UNDE	46.23391, -89.537254	Deciduous forest	4.3 °C	13.0 °C	802 mm	13.0%	May 22–25 2024	004

#### 182 4.1.4 Post-collection processing of field data

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

#### 190 4.2 neonSoilFlux R package

191 We developed an R package called `neonSoilFlux` (Zobitz et al., 2024) to compute half-hourly  
 192 soil carbon fluxes and uncertainties from NEON data. The objective of the `neonSoilFlux`  
 193 package is a unified workflow (Figure 2) for soil data acquisition and analysis that supplements  
 194 the existing `neonUtilities` data acquisition R package (Lunch et al., 2025).

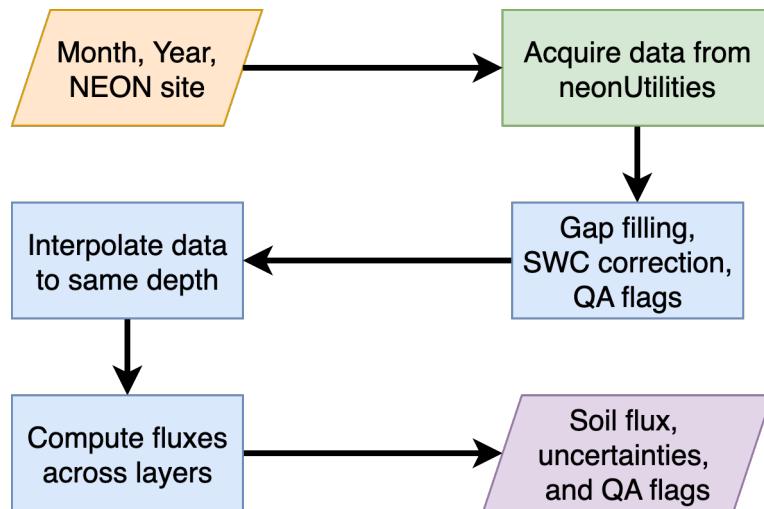


Figure 2: Diagram of `neonSoilFlux` R package. For a given month, year, and NEON site (orange parallelogram), the package acquires all relevant data to compute  $F_S$  using the `neonUtilities` R package (green rectangle). Data are gap-filled according to reported QA flags and adjusted for changes in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

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

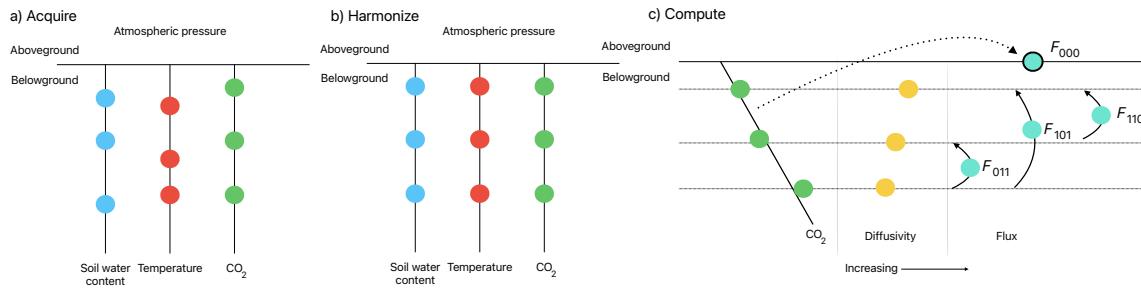


Figure 3: Model diagram of the data workflow for the `neonSoilFlux` R package. a) Acquire: Data are obtained for a given NEON location and horizontal sensor location, which includes soil water content, soil temperature,  $\text{CO}_2$  concentration, and atmospheric pressure. All data are screened for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

203 The workflow to compute a value of  $F_S$  with `neonSoilFlux` consists of three primary steps,  
 204 illustrated in Figure 3. First, NEON data are acquired for a given site and month via the  
 205 `neonUtilities` R package (yellow parallelogram and green rectangle in Figure 2 and Panel a  
 206 in Figure 3). Acquired environmental data can be exported to a comma separated value file for  
 207 additional analysis. Quality assurance (QA) flags are reported as an indicator variable. Since

208 the calibration coefficients on the soil water content sensors have changed over time (NEON,  
209 2024e), raw sensor measurements were back-calculated and soil-specific calibrations were applied  
210 following Ayres et al. (2024) to generate a consistent time series at each measurement location.

211 The second step is harmonizing the data to compute soil fluxes across soil layers. This  
212 step consists of three different actions (blue rectangles in Figure 2 and Panel b in Figure 3).  
213 If a given observation by NEON is reported as not passing a quality assurance check, we  
214 applied a gap filling method to replace that measurement with its monthly mean at that same  
215 depth (Section 4.2.1). Belowground measurements of soil water and soil temperature are then  
216 interpolated to the same depth as soil CO<sub>2</sub> measurements. The diffusivity (Section 4.2.2) and  
217 soil flux across different soil layers (Section 4.2.3) are then computed.

218 The third and final step is computing a surface soil flux through extrapolation to the surface  
219 (purple parallelogram in Figure 2 and Panel c in Figure 3). Uncertainty on a soil flux  
220 measurement is computed through quadrature. An aggregate quality assurance (QA) flag for  
221 each environmental measurement is also reported, representing if any gap-filled measurements  
222 were used in the computation of a soil flux. Within the soil flux-gradient method, several  
223 different approaches can be used to derive a surface flux (Maier & Schack-Kirchner, 2014); the  
224 `neonSoilFlux` package reports four different possible values for soil surface flux (Section 4.2.3)  
225 for each of two different methods of diffusivity estimation, for a total of eight estimates of  
226 flux.

#### 227 4.2.1 Gap-filling routine

228 NEON reports QA flags as binary values for each measurement and half-hourly interval. For a  
229 given half-hour, if any input variable (soil CO<sub>2</sub> concentration, soil temperature, or soil moisture)  
230 at depth  $z$  is flagged, computation of  $F_S$  is not possible. To address this, flagged measurements

231 and their uncertainties were replaced with a bootstrapped monthly mean ( $\bar{m}$ ) and monthly  
232 standard deviation ( $\bar{s}$ ) (Efron & Tibshirani, 1994).

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

238 From these, 5000 bootstrap samples were generated for  $\mathbf{m}$ ,  $\sigma$ , and  $\mathbf{b}$ . For each sample ( $m_k, b_k, \sigma_k$ ),  
239 we generated a vector  $\mathbf{n}$  (length  $N = 5000$ ) by drawing from a normal distribution with mean  
240  $m_k + b_k$  and standard deviation  $\sigma_k$ . The sample mean and standard deviation were then  
241 computed from  $\mathbf{n}$ . The resulting distributions of sample means and sample standard deviations  
242 provided the bootstrapped monthly mean ( $\bar{m}$ ) and standard error ( $\bar{s}$ ) respectively.

243 This gap-filling procedure provides a consistent treatment across all data streams. However,  
244 alternative approaches may be better suited for longer gaps (e.g., correlations with other NEON  
245 measurement levels or soil plots) or for variable-specific conditions. We discuss the effect of  
246 gap-filling on our results in Section 6.1.

247 **4.2.2 Soil diffusivity**

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

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

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

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

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

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

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

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

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

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

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

274 **4.2.3 Soil flux computation**

275 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  
276 depths  $i$  and  $j$ :

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

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

- 285 •  $F_{000}$  is a surface flux estimate using the intercept of the linear regression of  $D_a$  with  
286 depth and the slope from the linear regression of  $\text{CO}_2$  with depth (which represents  $\frac{dC}{dz}$

in Fick's Law). Tang et al. (2003) used this approach to compute fluxes in an oak-grass savannah.

- $F_{110}$  is a flux estimate across the two shallowest measurement layers.
- $F_{011}$  is a flux estimate across the two deepest measurement layers.
- $F_{101}$  is a flux estimate across the shallowest and deepest measurement layers.

For  $F_{110}$ ,  $F_{011}$ , and  $F_{101}$ , the diffusivity used in Fick's Law is always at the deeper measurement layer. When used as a surface flux estimate we assume CO<sub>2</sub> remains constant above this flux depth. Uncertainty in all  $F_{ijk}$  values was quantified using quadrature (Taylor, 2022). These computed fluxes could provide the basis for additional soil flux estimates. For example, Tang et al. (2005) estimated surface flux by linearly extrapolating  $F_{110}$  and  $F_{011}$  to the soil surface.

### 4.3 Post processing evaluation

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

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

## 5 Results

### Concordance between modelled and measured soil CO<sub>2</sub> flux

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

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

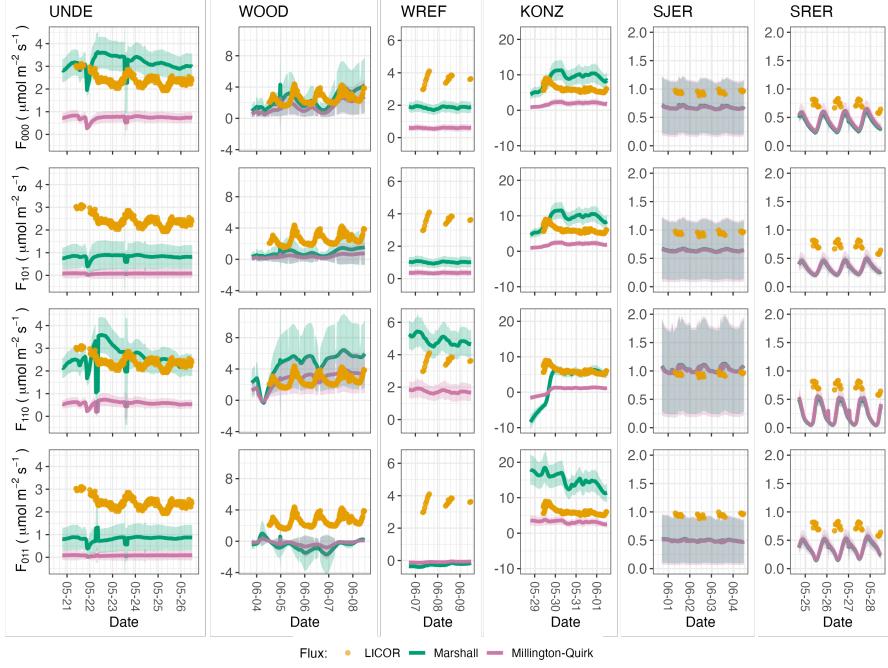


Figure 4: Timeseries of soil surface flux ( $F_S$ ) from field-measured (yellow lines) and modeled soil fluxes (green or purple lines) by the `neonSoilFlux` R package. Fluxes from the `neonSoilFlux` R package are separated by the diffusivity model used (Millington-Quirk or Marshall, Section 4.2.2). Individual vertical axis labels in the first column represent the measurement levels where the flux-gradient approach is applied (Section 4.2.3). 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.

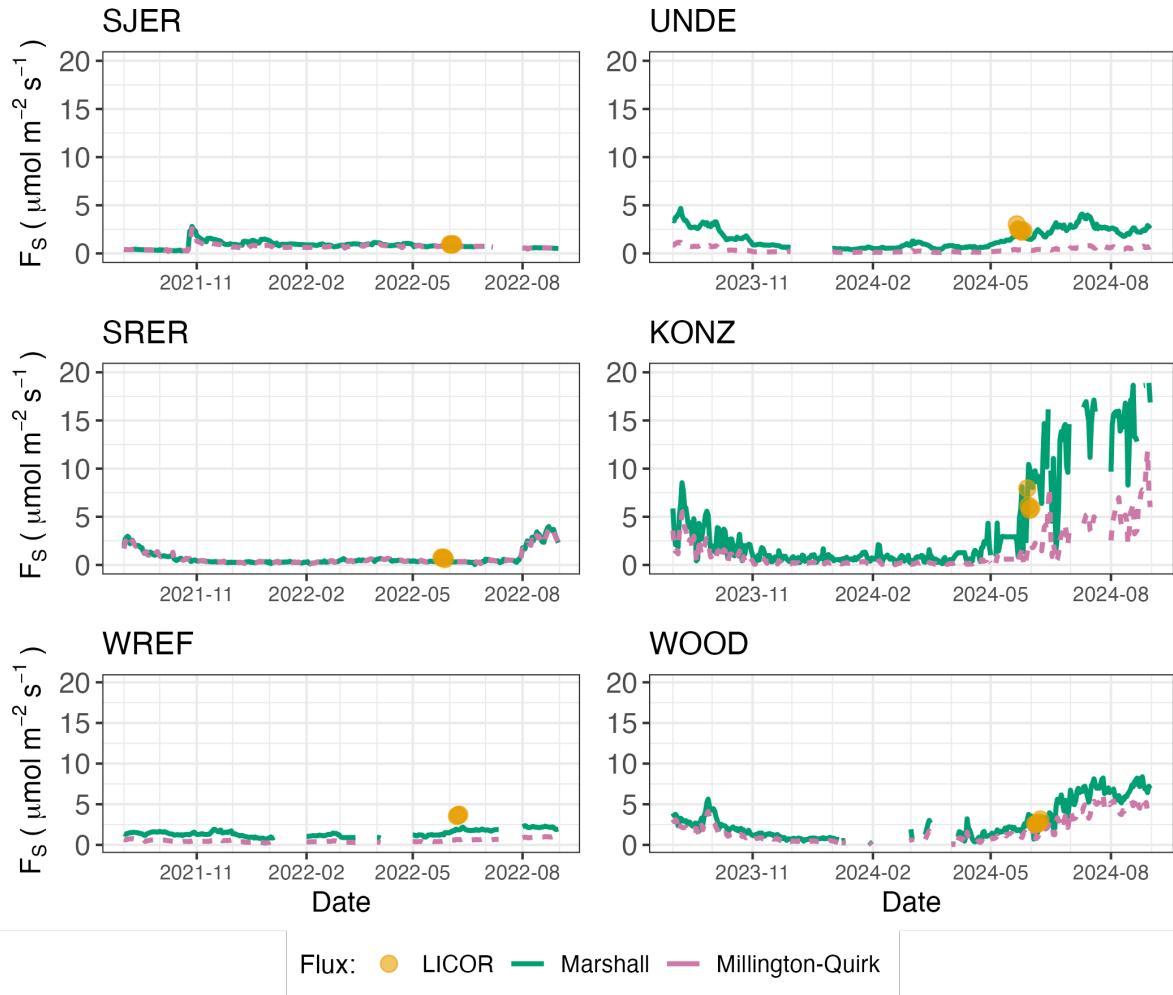


Figure 5: Timeseries of both daily-averaged field  $F_S$  (yellow circles) and daily ensemble averaged soil fluxes (average of  $F_{000}$ ,  $F_{101}$ ,  $F_{011}$ ,  $F_{110}$ , Section 4.2.3) by the `neonSoilFlux` R package, separated by the diffusivity model used (green or purple lines, Millington-Quirk or Marshall, Section 4.2.2).

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

321 **5.2 Effects of method choice on diffusivity estimates**

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

326 **6 Discussion**

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

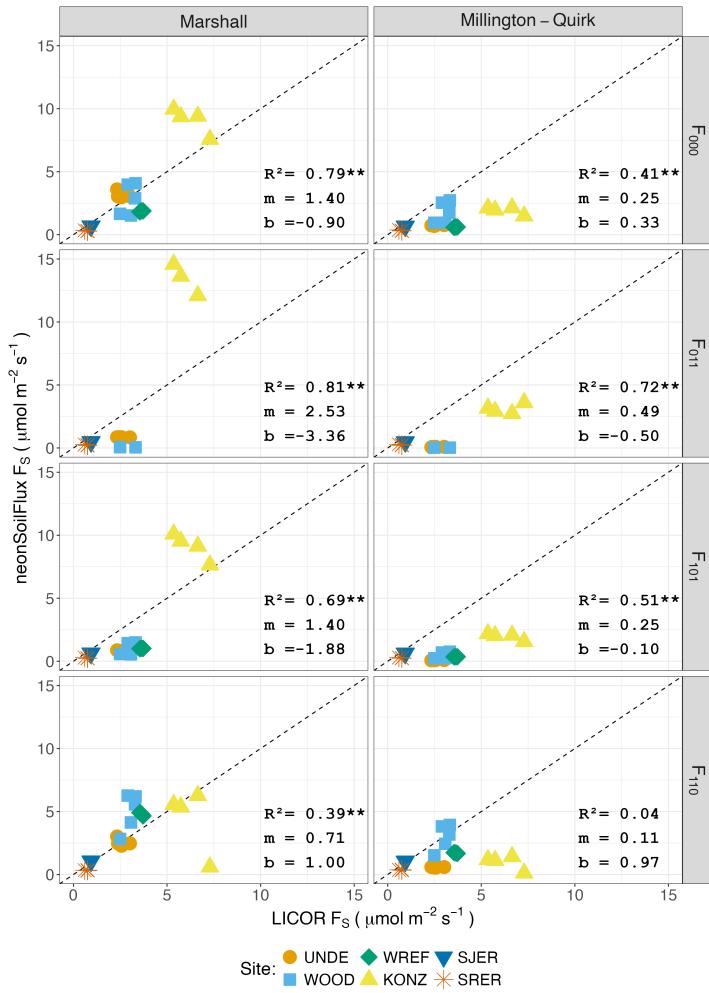


Figure 6: Statistical comparison between measured fluxes at each NEON site with fluxes reported by `neonSoilFlux` with the different flux calculation approaches and diffusivity calculations applied. Points are daily averages and LICOR  $F_S$  values are from the 6800 instrument only, for consistency. 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.

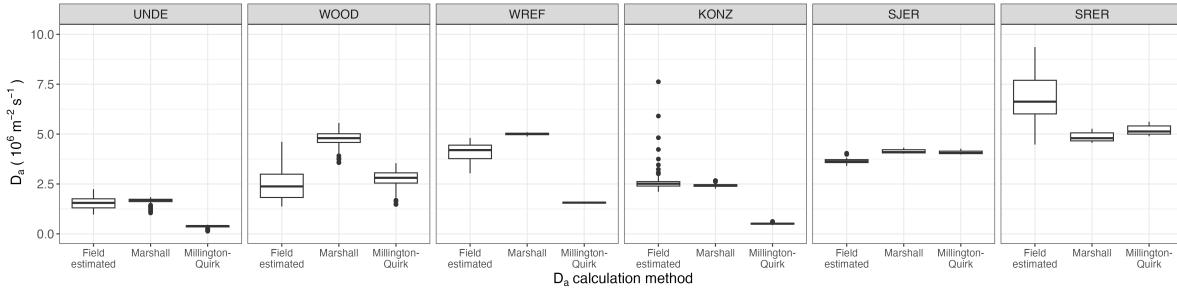


Figure 7: Distribution of diffusivity ( $D_a$ ) at each study site. Values of  $D_a$  were provided by the `neonSoilFlux` package, computed from the Millington-Quirk or Marshall models (Section 4.2.2). A post-hoc estimate of diffusivity (labeled as “Field estimated”) was computed through the field measured 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.

### 336 6.1 General evaluation of flux-gradient approach

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

347 When modeling soil respiration, typically a non-linear response function that also considers soil  
 348 type is used (Bouma & Bryla, 2000; Yan et al., 2016, 2018). For the `neonSoilFlux` package,  
 349 soil type is connected to the measurement of bulk density, which was characterized at each  
 350 NEON site. This bulk density estimate is based on replicate samples collected from the site

351 megapit at a subset of soil horizons, with an estimated uncertainty of  $\pm 5\%$  (NEON, 2024c).  
352 Coarse fragment estimates also have very large uncertainties, but because the volume fraction  
353 tends to be low in surface soils it is unlikely to contribute much additional flux uncertainty.

354 Our results suggest that the most important way to improve reliability of the flux estimate is  
355 to reduce the usage of gap-filled data. The current approach to gap filling in `neonSoilFlux`  
356 uses monthly mean data to gap fill—this approach decreases the ability of the estimate to be  
357 responsive to short-term pulses that occur with rapid weather shifts. Four sites (KONZ, SRER,  
358 WREF, and UNDE) had more than 75% of half-hourly periods with no-gap filled measurements  
359 (Figure S1, Supplementary Information). Two sites (SJER and WOOD) had more than 75% of  
360 half-hourly intervals with just one gap-filled measurement. The large uncertainty evident in  
361 Figure 4 for estimates from WOOD and SJER are thus due in part to the gap-filling used in  
362 these sites (Figure S1). While we did not need to use gap-filled measurements to compute the  
363 flux at WREF, field data collection occurred following a severe rainstorm, with soils at the  
364 beginning of the sampling week near their water holding capacity. In general, we recommend  
365 that whenever possible, knowledge of local field conditions should influence analysis decisions  
366 in addition to any QA filtering protocols in the `neonSoilFlux` package.

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

376 applied to each data stream, but further work may explore alternative gap-filling approaches.

## 377 **6.2 Evaluation of flux-gradient approach at each site**

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

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

396 Immediately prior to our visit to Konza Prairie (KONZ), that site that experienced a significant  
397 rain event that led to wet soils that gradually dried out over the course of our time there.  
398 This pulse of precipitation increased the soil CO<sub>2</sub> concentration at the top layer above the

399 concentrations in lower layers, leading to negative estimated flux values at the start of the field  
400 sampling period. In this case it was only when the soil began to return to a baseline level that  
401 the assumptions of the flux-gradient method were again met.

402 Both of the previous cases also provide context for the variable statistical comparisons between  
403 field-measured soil fluxes and `neonSoilFlux` outputs (Figure 6). When considering systematic  
404 deployment of this method across a measurement network, there are a number of independent  
405 challenges that require careful consideration. There are clear tradeoffs between (1) accuracy of  
406 modeled fluxes (defined here as closeness to field-measured  $F_S$  and the uncertainty reduction  
407 factor  $\epsilon$ ), (2) precision (which could be defined by the signal to noise ratio), and (3) the  
408 choice of the diffusivity model (Section 4.2.2) or flux computation method (Section 4.2.3). A  
409 sensitivity analysis (Figure S2, Supplemental Information) found that flux output uncertainty  
410 was dominated by measurement uncertainty ( $T_S$ ,  $P$ ,  $SWC$ , or  $CO_2$ ) rather than by the diffusivity  
411 method used to compute soil flux. Notably, the  $F_{110}$  method was least sensitive to measurement  
412 uncertainty likely because it best aligns with the surface chamber measurement assumptions.

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

<sup>424</sup> means to trade precision for a more general approach.

### <sup>425</sup> **6.3 Recommendations for future method development**

<sup>426</sup> The `neonSoilFlux` package provides several approaches to estimate soil flux using the gradient  
<sup>427</sup> method. We believe these approaches enable the software to be used across a range of site-  
<sup>428</sup> specific assumptions (Maier & Schack-Kirchner, 2014). We note, however, that this choice  
<sup>429</sup> can have a determinative approach on the calculated values. Ensemble averaging approaches  
<sup>430</sup> (Elshall et al., 2018; Raftery et al., 2005) may be one way to address this problem if the goal is  
<sup>431</sup> to calculate fluxes using the same method at a diverse range of different sites. Two other ideas  
<sup>432</sup> would be to apply machine learning algorithms (e.g. random forest) to generate a single flux  
<sup>433</sup> estimate across diverse sites, or using co-located estimates of net ecosystem carbon exchange  
<sup>434</sup> from eddy-flux towers to further constrain results or to assess soil flux results for plausibility  
<sup>435</sup> (Phillips et al., 2017).

<sup>436</sup> These challenges notwithstanding, the method used here and made available in the  
<sup>437</sup> `neonSoilFlux` R package has the potential to produce nearly continuous estimates of flux  
<sup>438</sup> across all terrestrial NEON sites. These estimates are a significant improvement on available  
<sup>439</sup> approaches to constrain the portion of ecosystem respiration attributable to the soil. This, in  
<sup>440</sup> turn, also aids in our ability to understand the soil contribution to the net ecosystem flux  
<sup>441</sup> measured at these sites using the co-located eddy flux towers.

## <sup>442</sup> **7 Conclusions**

<sup>443</sup> We used the R package `neonSoilFlux` to estimate soil CO<sub>2</sub> fluxes with the flux-gradient method  
<sup>444</sup> using data from buried soil sensors at NEON terrestrial sites. We compared the predicted

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

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