Modeling Soil Fluxes with NEON Data

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The learning outcomes of this activity are:

- Understand the dynamic environmental and biological properties affecting soil CO_2 efflux.
- Apply Fick's Law of Diffusion to estimate of soil gas efflux.
- Investigate a multi-year timeseries of soil water content, soil temperature, and soil gas efflux derived from Fick's Law to infer process-level changes in soil CO_2 efflux.

Instructions: Read carefully and in your groups *working together* answer the numbered questions on your response paper. If you get stuck, please ask!

Introduction

The global carbon cycle has many different components, but of particular importance is the amount of carbon in soils. Scientists believe soils have the largest reservoir of carbon (Jobbágy and Jackson 2000). A key quantity is the soil carbon flux, or the rate of change per unit area of the amount of carbon leaving the soil and entering the atmosphere. This activity will guide you through the measurements used to model and compute soil fluxes using data collected from the National Ecological Observatory Network, or NEON for short.

1. Read more about NEON: LINK. After reviewing the information on this page, what did you wonder or notice? What would you like to know more about? **Please answer the question on the response sheet.**

2. One site in NEON is the San Joaquin Experimental Range website and record three facts you find interesting or important. What scientific or ecological questions do you think could be studied here? **Please answer the question on the response sheet.**

Fick's law

We will denote the soil carbon flux as F_s, measured in μmol m^{-2} s^{-1}. The key equation to compute the soil flux at a given location is **Fick's law of Diffusion**:

$$F_s = -D_a \cdot f(T) \cdot g(W) \cdot \frac{dC}{dz}, \tag{1}$$

The negative sign in Fick's Law makes F_s a positive value, which means carbon is *leaving* the soil. The other terms are:

- D_a is called the **diffusion coefficient** (units $m^2 \ s^{-1}$). Values of D_a also includes considerations for soil density and air pressure.
- $\frac{dC}{dz}$ is the (vertical) gradient in CO_2. We measure CO_2 in molar concentration (units μmol m^{-3}).
- The function $f(T)$ is a function that characterizes the temperature response T (no units).
- The function $g(W)$ is a function that characterizes the response due to soil water content W (no units).

We will investigate $f(T)$ and $g(W)$ separately below. Usually the values of $f(T)$ and $g(W)$ range between 0 to 1, meaning they increase or decrease the baseline value D_a through a scaling factor.

Dependence of Fick's Law on soil water and temperature

Understanding $g(W)$

Water in soils also reduces pore spaces (or *porosity*), which is quantified by the *soil water content* or *W*. Soil water content is measured on a scale between 0 to 1, where $W = 0$ means the soil is completely dry, and $W = 1$ then soil is completely saturated.

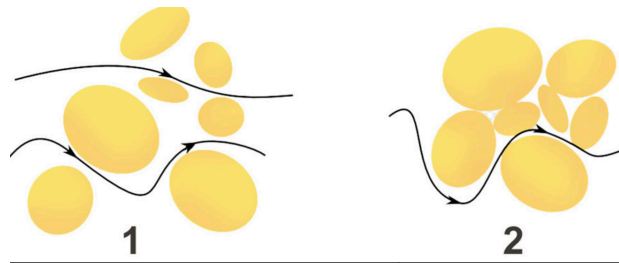See Figure 1 for a conceptual diagram of this LINK.

Figure 1: Conceptual model of diffusion. Panel 1 has higher porosity compared to Panel 2, allowing carbon dioxide to diffuse more freely.

3. Based on this information, when soils are completely dry, we would expect **more / less** diffusion compared to when soils are completely wet. **Please circle the correct answer on the response sheet.**

We will consider the effect of W on soil diffusion with a function $g(W)$ that reduces diffusion by a proportional amount. One possibility for $g(W)$ is:

- $g(W) = 1$ when $W = 0$ (meaning that there is no effect when soils are dry)
- $g(W) = 0$ is when $W = 1$ (meaning when soils are completely saturated there is no soil diffusion).
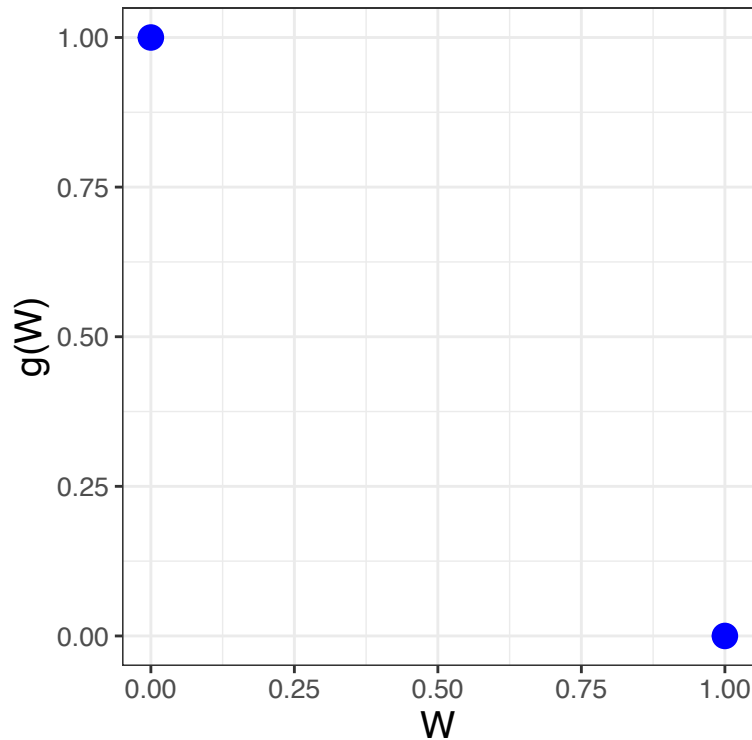
These two points are labeled in Figure 2.

Figure 2: Grid for drawing $g(W)$ for different models.

4. Let's assume the function $g(W)$ is **linear**. Sketch a linear equation between the two points in Figure 2 for $0 \leq W \leq 1$. **Sketch the function on the grid in the response sheet.** Then determine the formula for the linear function $g(W)$ on your response sheet, showing your work appropriately. **Please answer the question on the response sheet.**

Another possibility for the function $g(W)$, which represents the effect of soil water on D_s. A possible equation for $g(W)$ is the following (Moyano et al. 2012):

$$g(W) = \begin{cases} \dfrac{(.42 - W)^{(10/3)}}{.1764}, & 0 \leq W \leq 0.42 \\ 0 & 0.42 < W \end{cases} \tag{2}$$

5. Evaluate $g(W)$ for different values of W, filling in Table 1 below **on your response sheet**:

3

Table 1: Comparison of different response functions to increasing soil water content W.

W	0	0.2	0.4	0.6	0.8	1
$g(W)$ (linear)						
$g(W)$ (Equation 2)						

6. Use the information in Table 1 to add the Moyano model for $g(W)$ in Figure 2. **Sketch the function on the grid in the response sheet.** What do you notice about the Moyano model in comparison to your linear model? **Please answer the question on the response sheet.**

7. Using the information in Table 1 and Figure 2, as W increases, compared to the linear model the Moyano model is more / less sensitive to changes in soil water content because the linear model for $g(W)$ is greater than / less than the Moyano model at the same value of W. **Please circle the correct answers on the response sheet.**

8. Since $g(W)$ ultimately affects D_s, which in turn is directly proportional to F_s, interpret your previous graph to determine for what values of W would cause soil flux, F_s, to increase? to decrease? **Please answer the question on the response sheet.**

Understanding $f(T)$

Temperature also affects soil diffusion. The equation for $f(T)$ is the following:

$$f(T) = \left(\frac{T + 273.15}{293.15} \right)^{1.75} \tag{3}$$

9. Evaluate $f(T)$ for different values of T, filling in entries in Table 2 below **on your response sheet**:

Table 2: Evaluation of $f(T)$ for different soil temperatures T

T	10	15	20	25	30	35	40	45	50
$f(T)$ (°C)									

10. Next use the information in Table 2, along with other additional points, to make a plot of $f(T)$ in Figure 3. **Graph the function on your response sheet.**

11. Based on the information in Table 2 and Figure Figure 3, $f(T)$ is **increasing / decreasing** as temperature T increases. **Circle the correct answer on the response sheet.**

Next let's consider how $f(T)$ changes over the course of a day. At a given hour h in the day, soil temperature near the surface can be represented with the following equation:
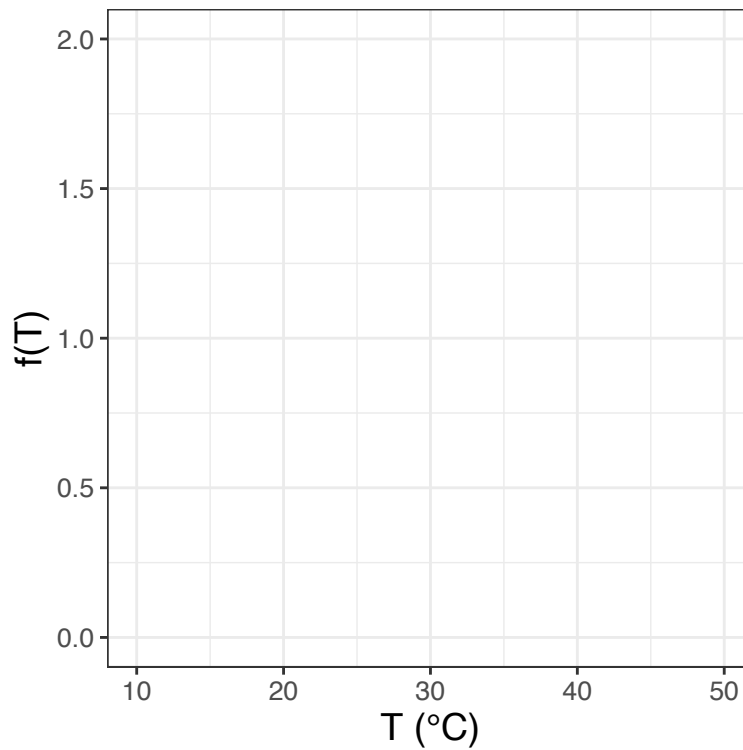
Figure 3: Grid for drawing $f(T)$.

$$T(h) = 30 - 10 \sin\left(\frac{\pi h}{12}\right) \qquad (4)$$

12. Complete Table 3 for different values of h, first by evaluating $T(h)$ and then by evaluating $f(T)$. **Fill in the table on the response sheet.**

Table 3: Evaluation of $f(T)$ for different soil temperatures T

h	0	4	8	12	16	20	24	50
$T(h)$ (°C)								
$f(T)$								

13. Finally use the information Table 3 along with other values to sketch $f(T)$ over the course of the day in Figure 4. **Sketch your graph on the grid in the response sheet.**
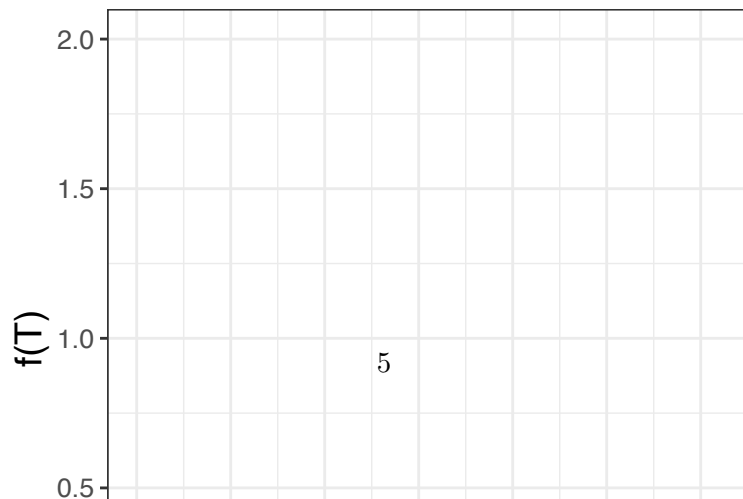
largest. At what hours of the day is F_s the smallest? Increasing or decreasing the quickest? **Please answer the question on the response sheet.**

Summarizing up

Soil water W and soil temperature T are considered *environmental* factors affecting soil CO_2. *Biological* factors such as plant roots and soil microbes. Plant roots respire CO_2 respire CO_2 into the soil, called *autotrophic respiration.* Soil microbes may utilize soil carbon for growth, but also respire CO_2, called *heterotrophic respiration.*

16. In Table 4 indicate if the following factor increases or decreases soil CO_2 by making a check ($\checkmark$) for yes or X for noin the appropriate column. **Complete the table on the response sheet.**

Table 4: Evaluation of different factors that influence soil CO_2.

Factor	Increase soil CO_2	Decrease soil CO_2
Temperature		
Soil moisture		
Plant roots		
Soil microbes		

Understanding and estimating concentration gradients

The second term to calculate F_s is $\dfrac{dC}{dz}$, which represents the gradient in CO_2 *at the soil surface.* This soil gradient is estimated $\dfrac{dC}{dz}$ using continuous CO_2 sensors buried in the soil.

Figure 5 shows an example profile, with the data listed in Table 5.

Table 5: Data for a CO_2 profile at different soil depths.

Depth (cm)	CO_2 (ppm)
3	735
9	1345
21	2879

Notice how Figure 5 and Table 5 have CO_2 concentration on the horizontal axis and the depth is on the vertical axis, in reverse order (confusing - I know!)
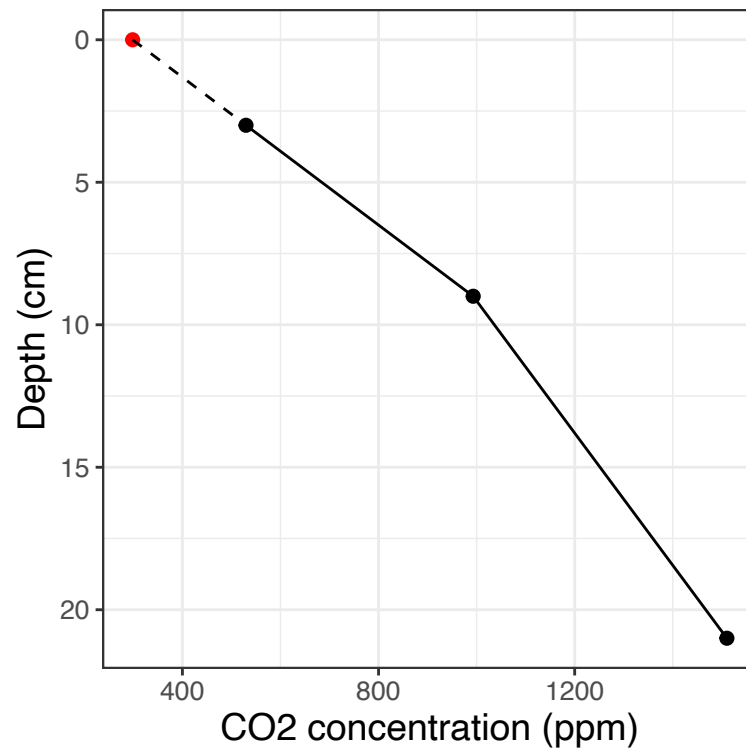
Figure 5: CO_2 profile measured at different depths. The dashed line is an extension of the line between the two closest measurements near the surface (red point).

17. The two depths closest to the soil surface occur at 3 and 9 cm. Using the values in Table 5, Compute the rate of change in CO_2 for each unit change in depth using the two depths closest to the soil surface (this occurs at 3 and 9 cm). **Please answer the question on the response sheet.**

$$\frac{dC}{dz} \approx \frac{C_{\text{at 9 cm}} - C_{\text{at 3 cm}}}{9 - 3} \tag{5}$$

Remember to include units with your answer.

We will assume that this rate of change remains constant to the soil surface (dashed line in Figure 5), so our average rate of change equals $m \approx \dfrac{dC}{dz}$.

18. Table 6 provides data for another CO_2 profile. Using the information in the table, estimate $\dfrac{dC}{dz}$. **Please answer the question on the response sheet.**

Table 6: Another CO_2 profile at different depths.

Depth (cm)	CO_2 (ppm)
3	735
9	1345
21	2879

19. Which CO_2 profile (Table 5 or Table 6) would predict a larger value of F_s? Provide a quick explanation why. **Please answer the question on the response sheet.**

Evaluating patterns in soil fluxes and environmental measurements

Ok, we are set to calculate the flux F_s! Well ... almost. You may notice that in the CO_2 profile above measurements of CO_2 has units of ppm, or parts per million, which needs to be converted into molar concentrations. Additionally barometric air pressure also plays a role in computing F_s. However, once these measurements are converted, F_s can then be computed.

Unit conversions aside, the San Joaquin Experimental Range site for the National Ecological Observatory Network makes all these measurements and publicly distributes these measurements so the soil flux can be computed. The figure below shows a multi-year computation of the flux at half-hourly intervals.
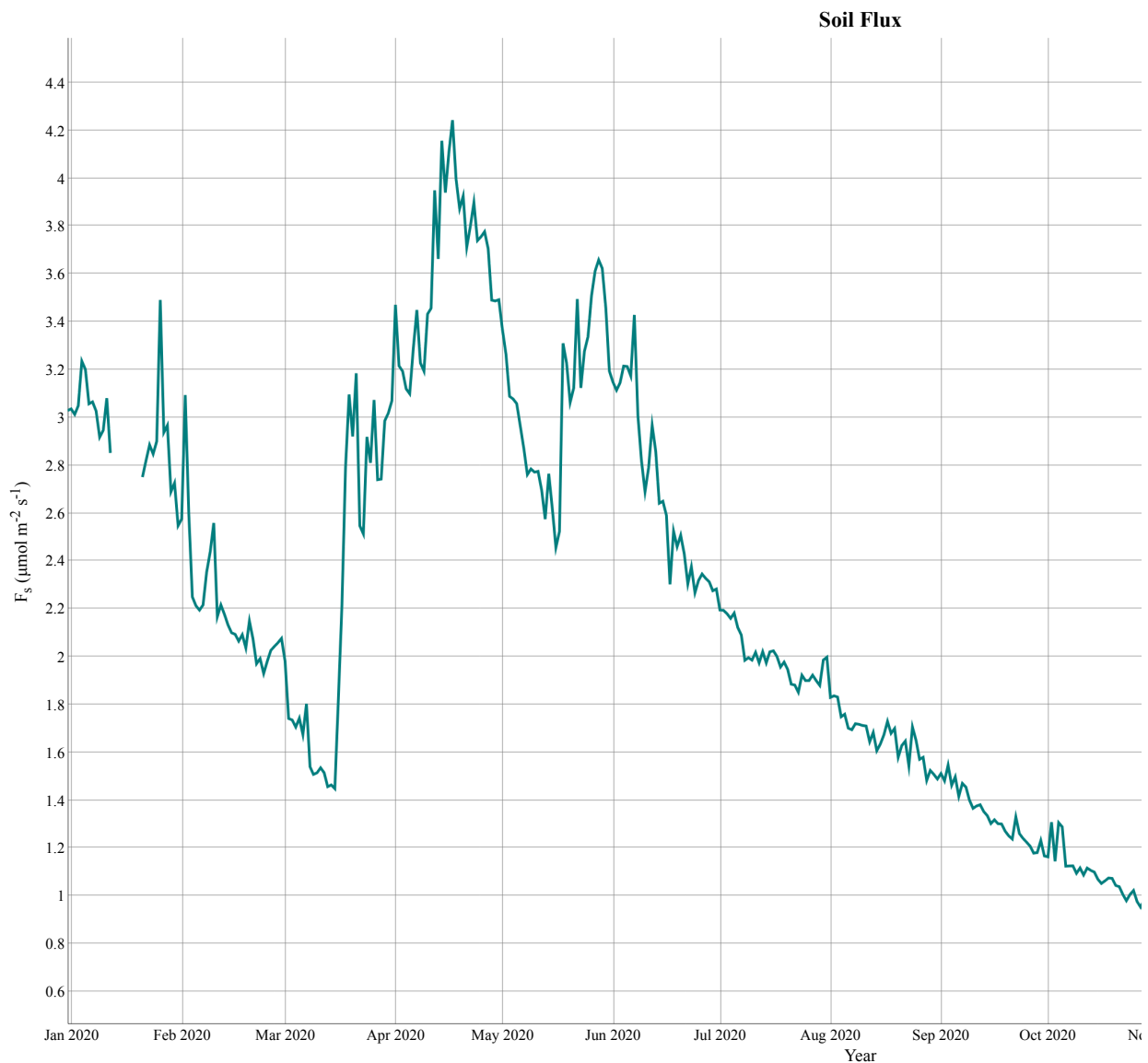
Figure 6: Soil flux at the San Joaquin Experimental Range

20. Study the above interactive figure. Working with your group, identify:

- time intervals where F_s increases rapidly.
- time intervals where F_s steadily increases.
- time intervals where F_s has several fluctuations.

Please answer the question on the response sheet.

21. Next co-locate these intervals with measurements of T (Figure 7) and W (Figure 8). Explain how the measurements of T and W during these intervals would lead to larger or smaller values of F_s. **Please answer the question on the response sheet.**
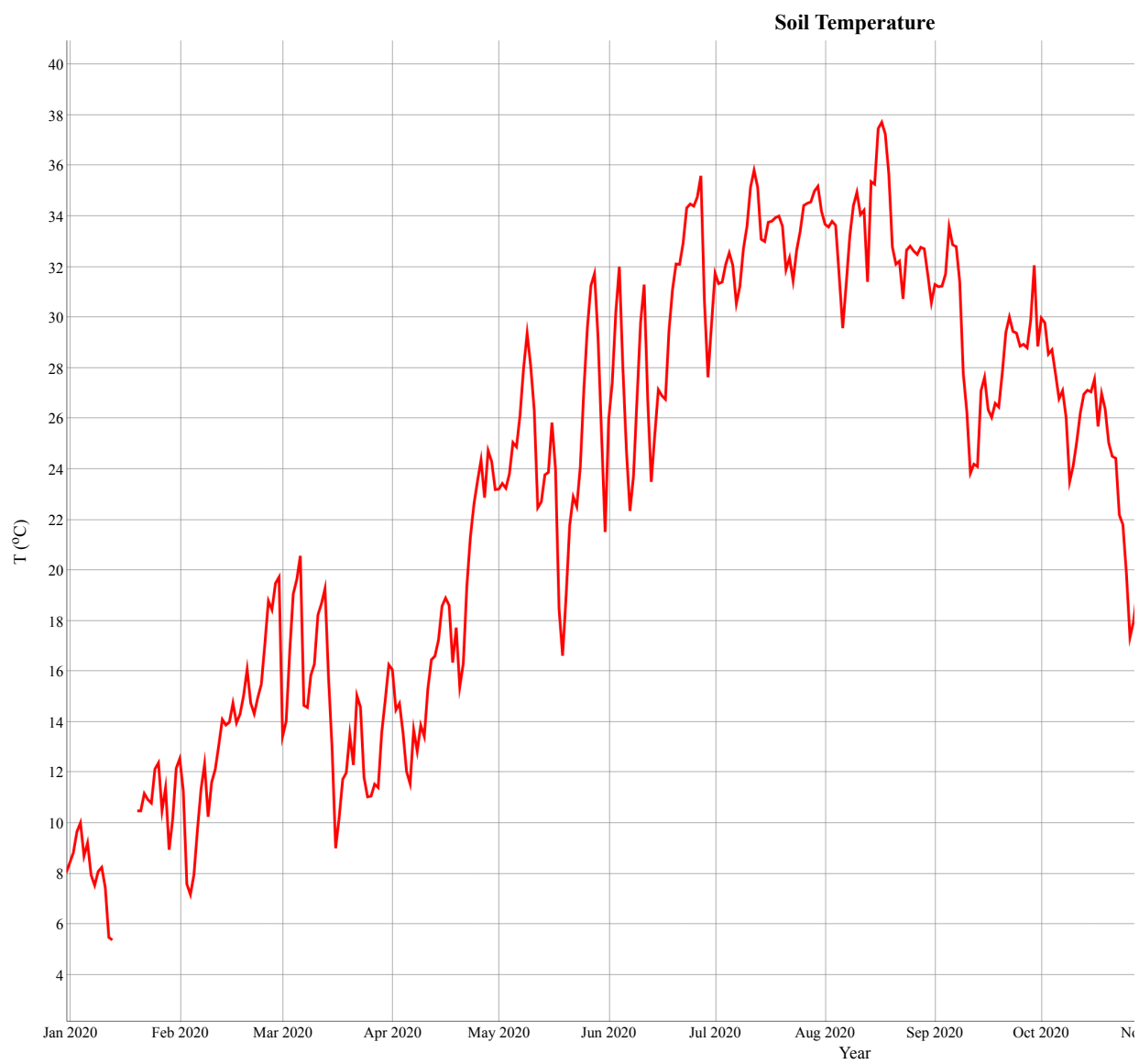
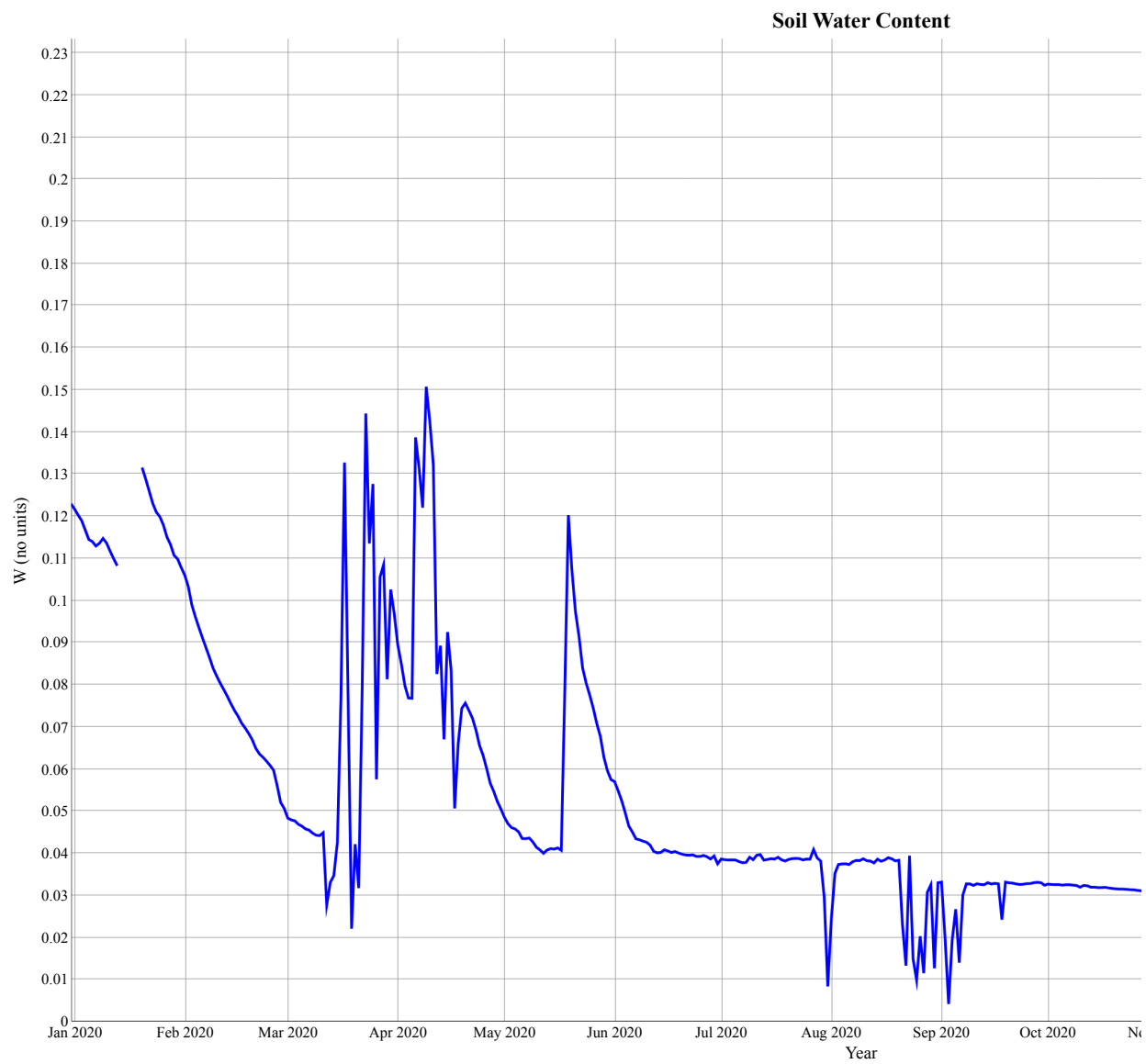Figure 7: Soil temperature at 2 cm in the San Joaquin Experimental Range

Figure 8: Surface soil water content in the San Joaquin Experimental Range

22. Choose two particular half-hours that correspond to where F_s is low and another where F_s is high and record your values of F_s, T, and W in Table 7. Compute $f(T)$ and $g(W)$ at each of these times. Explain how these computations provide evidence / support for the calculated value of F_s. **Please fill in the table on the response sheet.**

Table 7: Summary table comparing two fluxes

h	T	W	$f(T)$	$g(W)$	F_s
F_s low:					
F_s high:					

23. Here is a link to nearby weather station located by the San Joaquin Experimental Range: LINK. Look at the historical weather during the dates and intervals you selected to see if you can infer any additional evidence and support for what observed in T, W, D_s, or F_s. **Please answer the question on the response sheet.**

Additional questions for exploration

24. Which CO_2 profile (Table 5 or Table 6) might produce a higher uncertainty for $\dfrac{dC}{dz}$? Explain your reasoning. **Please answer the question on the response sheet.**

25. Draw a conceptual picture of a soil CO_2 profile following a heavy rainstorm that re-charged the soil, but the day following the top soil layers dried out. Explain why the soil profile should look that way. **Please answer the question on the response sheet.**

Jobbágy, Esteban G., and Robert B. Jackson. 2000. "The Vertical Distribution of Soil Organic Carbon and Its Relation to Climate and Vegetation." *Ecological Applications* 10 (2): 423–36. https://doi.org/10.1890/1051-0761(2000)010%5B0423:TVDOSO%5D2.0.CO;2.

Moyano, F. E., N. Vasilyeva, L. Bouckaert, F. Cook, J. Craine, J. Curiel Yuste, A. Don, et al. 2012. "The Moisture Response of Soil Heterotrophic Respiration: Interaction with Soil Properties." *Biogeosciences* 9 (3): 1173–82. https://doi.org/10.5194/bg-9-1173-2012.