Water and Carbon Flux Responses to Soil Moisture Pulses in the Western United States

by

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Submitted to the Department of Earth, Atmospheric and Planetary Sciences

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Bachelor of Science in Earth, Atmospheric and Planetary Sciences

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Abstract

In this study, the relationships among plant water and carbon flux responses to soil moisture resource pulses in semi-arid lands of the Western United States were diagnosed. Measurements from twelve AmeriFlux tower (*in situ*) and SMAP (satellite) sites across the region were used to estimate relationships between carbon flux and resource availability. The differences between respiration and photosynthesis dominant regimes and the transition from water to energy limited regimes could be observed. Water use efficiency of plants in the regions was estimated to be around 5.0 grams of carbon dioxide per 1 kilograms of water when water was excess. Response patterns were shared among the similar ecosystems. The role of water and carbon flux response to intermittency resource availability could lead to improved estimation of land carbon budgets.

Thesis Supervisor: Dara Entekhabi Title: Professor

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Introduction

Overview

Vegetation plays a major role in the climate system by regulating exchanges of water, carbon, and energy between the surface and the atmosphere. Many studies have evaluated seasonal and annual vegetation response to water and light limitations, but there is less study of ecosystem responses on shorter timescales, for example, to individual precipitation events and soil moisture resource availability. Plants in energy-limited regions depends on their photosynthesis assimilation capacity. Plants in water-limited regions (e.g., semi-arid or arid regions), in particular, have a strong dependence on soil moisture resource availability. One of the hypotheses that could explain the energy-limited and water-limited regimes is the pulse-reserve hypothesis. The hypothesis, first studied in the early 1970s, states that plants in dry regions are dormant until a pulse of rain triggers a pulse of growth and generates a reserve of carbon, nutrients, and energy when the soil dries up (Noy Meir, 1973). Although the pulse-reserve hypothesis has been used to explain this phenomenon for more than 40 years, spatial variations of this phenomenon among ecosystems are not yet fully understood because of data limitations.

This study aims to better understand the short-timescale responses of the plants in these regions, which might further our knowledge of the plant behaviors in a water-limited environment. New observation-based knowledge knowledge may enable us to predict how the regional water, energy, and carbon cycles would respond to changes in climate and the intermittency of weather events. Ultimately, a generalized model of plant behaviours and how water availability will impact global carbon cycle will be proposed. One of the current techniques for studying pulse-reserve response in global scale is using soil water content and vegetation optical depth data products from Soil Moisture Active Passive (SMAP) satellite. As a part of the attempt to study soil moisture on a global scale, SMAP was launched in 2015 to provide more accurate global soil moisture measurements without field data collection. Konings et al. (2016) developed an algorithm to simultaneously estimate both soil moisture and vegetation water content from SMAP measurements. Feldman et al. (2018) used these combined datasets to evaluate the pulses of moisture availability and vegetation water content response purely from SMAP in Africa, Australia, and South America. The study found that the pulse-reserve behavior was indeed observed across the regions with up to 1000mm/year of precipitation, and most prominently in drylands with the least rainfall. The finding advanced the idea of detecting vegetation water responses on short time scales globally from SMAP or satellite data in general. To explore new applications of SMAP, our study aims to extend the findings of Feldman et al. (2018) by examining the pulse-response behavior alongside measurements of water and carbon fluxes at available flux towers in the Western United States. The region has potential to exhibit pulse-response behavior to be observed. AmeriFlux towers make direct measurements of water energy and carbon land-atmosphere exchange (Boden et al., 2013). While spatial coverage is more sparse compared to the satellite-scale measurements, confidence is gained in the accuracy of the in-situ tower measurements and variable relationships derived thereafter.

In addition to utilizing SMAP data and comparing them to AmeriFlux data, this research project also aims to directly evaluate carbon flux responses to precipitation events, which would not be possible to analyze based on SMAP data alone. The study is only possible when the in-situ measurements of latent heat and carbon fluxes, which are driven by plant photosynthesis and respiration, are avaliable. The *in situ* and satellite data comparison aims to better understand how soil moisture controls several vegetative processes ranging from plant water uptake from soils, to transpiration, to carbon uptake, to water use efficiency of vegetation in the region. A better understanding of pulse-reserve characteristics based on SMAP and *in situ* data will characterize vegetation responses to soil moisture, introduce new research questions in plant ecology and provide more insights into global vegetation productivity, as terrestrial ecosystems are the largest source of variability in the the global carbon budget.

Background

Pulse-Reserve Behavior

Primary production of vegetation and photosynthesis in semi-arid to arid lands have unclear correlations with pulses of sporadic rains and moisture resources availability. Similarly, vegetation water content (VWC), an indirect measurement that could capture plant behavior, also responds to precipitation events. Represented by VWC, plant water stress is also a function of precipitation and other parameters. When plants are stressed, their primary productivity and photosynthesis would decrease by either closing stomata to increase water use efficiency or through actual damage to physiological structures. As a result of changes in primary production and photosynthesis, VWC also changes. After a pulse of rain, VWC initially increases during decreasing soil water content periods after a pulse of rain, known as a drydown, until the soil water availability drops below a certain threshold depending on the soil texture and proximity to the wilting point (Feldman et al., 2018). Rainfall triggers "pulses" of water uptake, primary production, and "reserves" of carbon and energy for the dry periods in the form of seeds, roots, and stems (Reynolds et al., 2004). In 1974, Noy-Meir proposed a hypothesis on pulse-reserve phenomena, which is based on these three main attributes of arid ecosystems: (a) low precipitation is a limiting factor for biological processes; (b) precipitation is sporadic, sparse, and variable; (c) a significant part of precipitation variability is unpredictable. Ever since Noy-Meir proposed his hypothesis, the pulse-reserve hypothesis has served as one of the principles that explains this "pulse" of primary production growth after a rainfall and "reserve" of carbon and energy during the following dry period (Ogle & Reynolds, 2004).

Soil Moisture Active-Passive and AmeriFlux Data

Soil Moisture Active-Passive (SMAP) and land-surface flux tower data are used in this study project because the integration of spatial soil moisture data and in-situ climatology data allows the vegetation-productivity hypotheses to be verified in the region of interest. SMAP provides global soil moisture and VOD (which is proportional to VWC) while the flux towers measure and capture some key ecosystem processes (carbon uptake, radiation partitioning into latent and sensible heat fluxes) that SMAP cannot provide.

SMAP, a satellite that makes measurements of global soil moisture available without physically sampling the data in the field, was launched by The National Aeronautics and Space Administration (NASA) in 2015 to produce detailed maps of global soil moisture data for the advancement of drought monitoring, weather forecasting, flood prediction, crop productivity, and earth systems linking (Entekhabi et al., 2010; Das et al., 2018). After the implementation of the multi-temporal dual channel algorithm (MT-DCA) on the SMAP measurements by Konings et al. (2016), global vegetation water content data became available every two to three days from April 1st, 2015 up until the present on a nine-by-nine-kilometer grid (Das et al., 2018).

To complement SMAP data, the AmeriFlux Network provide in-situ data for specific locations based on towers across the United States. Compared to SMAP, land-based towers provide relatively fine temporal resolution and high quality and direct flux measurements. The AmeriFlux Network provides data on sub-daily land observational soil water content, exchanges of CO_2 flux, other greenhouse gases, water, and energy.

Statement of the Problem

Although the pulse-reserve hypothesis was first proposed more than 40 years ago, the study of plant responses to pulses of rainfall or other resources (e.g. nitrogen, phosphorus, etc.) in arid environments is still limited (Nano & Pavey, 2013; Rodríguez-Moreno & Bullock, 2014). This paradigm could be more valuable if details of conceptual models and quantitative models of resource pulses translating into primary production were more fully understood (Reynolds et al., 2004). Current studies of pulse-reserve hypotheses are limited to particular areas for which only one kind of data is available: either in-situ soil water content data (Reynolds et al., 2000; Cheng et al., 2006; Muldavin et al., 2008; Yang et al., 2008; Heisler-White et al., 2008; Berdugo et al., 2014) or SMAP data (Feldman et al., 2018). They remotely evaluated pulses and reserves based on vegetation water content response in Africa and South America using SMAP data. They also found that the pulse-reserve behavior is present in most sub-boreal biomes and was strongest in the driest regions, but the results have not yet been validated with land-based data due to the limitation of land-based towers in the region of interest.

Significance of the Project

Focusing on water, this study establishes the connection between water and carbon flux dynamics and the response of vegetation to pulse availability of soil moisture resources. Ecosystems might respond to changes or shifts in the intermittency of weather events comprising regional climates or might even respond to intermittent events (e.g. droughts) themselves, even without the shifts. The prediction will inform estimates of the sensitivity of ecosystem carbon budgets to water availability.

If there are unique response-to-precipitation patterns among different types of vegetation, understanding the response pattern of each plant type is essential for larger scale vegetation assessment. The knowledge may allow better productivity and survival prediction for the plants of interest. In addition to direct impacts of rain pulses on plant productivity, the CO_2 flux relationship from in-situ towers may provide new insights for the global carbon cycle and, ultimately, climate change. This CO_2 flux relationship also contributes to the broader understanding of how the carbon, energy, and water cycles are coupled through vegetation activity.

Besides direct impacts of new knowledge of pulse-reserve variations across the Western United States, the project will generate new research questions related to pulse-reserve phenomena for future studies based on observations that could not be done in the past. For example, why did plants in the nearby regions respond to pulses of rain differently? Answering this question would not be feasible if the spatial scale observations are not adequate.

To summarize, To summarize, this project has four aims:

(1) to provide the better understanding of the relationship between carbon dioxide flux and vegetation water content during soil moisture drydowns (week-scale periods following precipitation events) using SMAP and AmeriFlux data

(2) to determine observability of pulse responses in conditions varying in temperature, vegetation water content, carbon flux, and intermittent precipitation across the Western United States

(3) to compare pulse-reserve responses across the Western United States based on SMAP and AmeriFlux data

(4) to provide additional insights for vegetation productivity in water-limited land regions.

Terminology

Flux of Carbon (FC)

Summation of two contrasting processes, the uptake of carbon through photosynthesis (negative) and the release of carbon through heterotrophic respiration (positive), results in the measured flux of carbon (FC) (Keenan et al., 2019)

Latent Heat of Vaporization (LE) and Evaporative Fraction (EF)

The latent heat flux (LE) for water vaporization, one of the two types of turbulent heat exchange with the atmosphere, determines surrounding temperature and humidity of the area. The partitioning of available energy into sensible and latent heat fluxes (H and LE respectively) depends on the availability of the summation of latent heat of vaporization and sensible heat flux, which can be expressed as the Evaporative Fraction (EF) of the system. Evaporative Fraction is defined as

$$EF = \frac{LE}{LE + H}.$$

Since the available energy is equal to the summation of turbulent heat losses in surface energy balance.

$$R_n - G = LE + H$$

Evaporative Fraction is also defined as

$$EF = \frac{LE}{R_n - G}.$$

Here R_n is net radiation, and G is ground heat flux.

Water Use Efficiency (WUE)

Water Use Efficiency (WUE or -FC/LE) is an inverse function of leaf stomata efficiency in term or FC and the surrounding atmosphere in term of LE (Gianotti et al., 2019). Plants generally have active control over WUE through the opening and closing of stomatal apertures. Higher WUE typical is typically found in dry water-limited conditions while low WUE is found in water abundance conditions.

Vegetation Optical Depth (VOD)

Unlike AmeriFlux towers, SMAP provides Microwave vegetation optical depth (VOD) instead of FC or other parameters. VOD is typically modeled as being linearly proportional to above-ground vegetation water content, which can be used as an indicator for understanding vegetation seasonality.

Aridity Index

An aridity index is defined as daily mean net radiation (W/m^2) divided by latent heat of vaporization (2.26×10^3 kJ/g) and daily mean precipitation (mm/m^2). This index is a measure of aridity that is independent of the SMAP soil moisture observations. Higher values indicate greater aridity.

Methodology

Overview

Determining plant responses requires measurements of soil moisture, precipitation, CO_2 flux, water vapor flux, and vegetation water content during drydowns. All of these data were obtained from SMAP and flux towers of the AmeriFlux Network. Drydowns in this project were determined by searching for any three consecutive days of soil water content drop after at least 0.1% soil water content increases. Surface fluxes overlapping the drydown periods were analyzed as a function of time after previous precipitation events. Each tower had a different distribution of drydown lengths due to its unique climatology.

Because of the data availability constraint from AmeriFlux Network, very few places have both datasets. The Southwest region of the United States was selected for this project. Utah, Arizona, Colorado, and New Mexico were selected as samples of arid lands. Southern California and Texas were selected as less arid lands that might have weaker responses to rainfall.

To achieve the first two goals of understanding pulse-response in different conditions, biome dependent plant-soil water relations during soil moisture drydowns were visually inspected and analyzed based on available data.

Tower Selection and Grouping

Although more than 51 AmeriFlux towers across 12 states in the arid to semi-arid lands of Western United States were originally considered, only 18 towers in Utah, Arizona, Colorado, and New Mexico had measurements overlapping to the period after SMAP was launched. Fours additional towers were taken out because the towers were in flooded wetlands, where pulses of rain would not alter water availability of the plants. Two more towers were taken out because soil moisture data were not available. The final 12 towers were distributed among grassland, desert and woody savanna, evergreen, cropland, and open shrubland regions (shown in Table 1.). Arid lands were the areas that pulse-reserve responses were expected to by observed while less-arid lands like evergreen forests or extremely arid land like deserts were used as control regions--expecting weaker responses to pulses of rains. ARM SGP milo field, one of the AmeriFlux towers, was in a cropland area, where agricultural activities could potentially interfere with the plant responses.

Table 1: Twelve AmeriFlux Towers of Interest in the Western United States

	States	Lat	Lon	# of AmeriFlux drydowns	# of SMAP drydowns
1. Evergreen					
Sierra Critical Zone, Sierra Transect, Ponderosa Pine Forest, Soaproot Saddle	CA	37.0311	-119.2566	10 (2010 - 2017)	17
Sierra Critical Zone, Sierra Transect, Sierran Mixed Conifer, P301	CA	37.0674	-119.1951	8 (2008 - 2016)	19
GLEES	WY	41.3665	-106.2399	43 (2004 - 2015)	26
2. Desert & Woody Savanna					
Amargosa Desert Research Site	NV	36.7653	-116.6933	10 (2011 - 2018)	18
Santa Rita Mesquite	AZ	31.8214	- 110.8661	94 (2004 - 2018)	18
3. Grassland					
ARM-SGP Medford hay pasture	OK	36.8193	-97.8198	21 (2015 - 2017)	34
Southern California Climate Gradient - Grassland	CA	33.7365	-117.6946	12 (2007 - 2017)	21
Santa Rita Grassland	AZ	31.7894	-110.8277	70 (2008 - 2018)	23
4. Cropland					
ARM SGP milo field	OK	36.8085	-97.5489	14 (2010 - 2017)	29
5. Open Shrublands					

Southern California Climate Gradient - Coastal Sage	CA	33.7343	-117.696	16 (2016 - 2017)	21
Southern California Climate Gradient - Pinyon/Juniper Woodland	CA	33.6047	-116.4527	18 (2007 - 2016)	61
Walnut Gulch Lucky Hills Shrub	AZ	31.7438	-110.0522	87 (2007 - 2018)	50

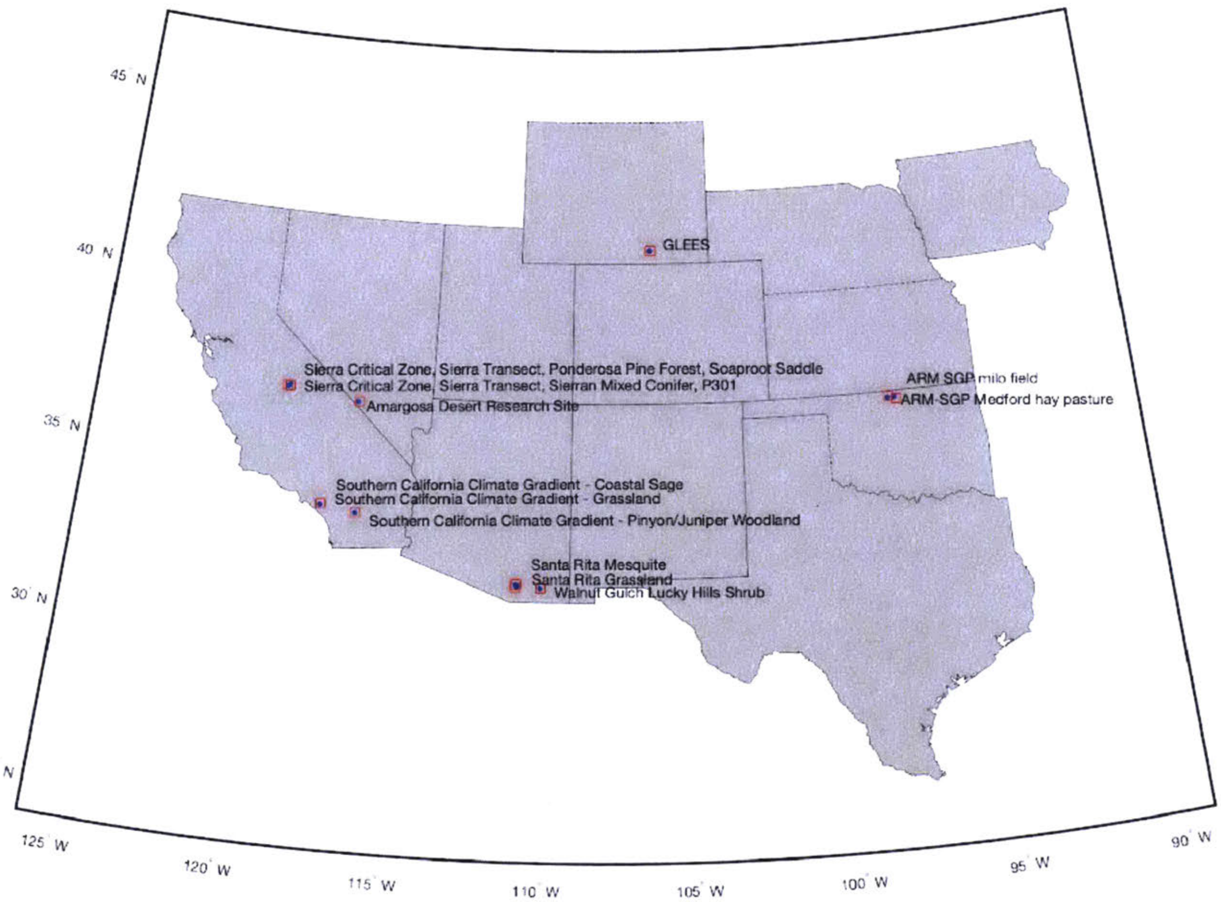


Figure 1: Map of the Twelve AmeriFlux Stations of Interest in the Western United States. Dots represent AmeriFlux stations of Interest. Squares represent corresponding SMAP grid cells

AmeriFlux Data Processing

AmeriFlux raw data were processed from 30-minute interval to to daily average values. The processed data were used to represent properties of each day. Daily average from 10 AM to 4 PM was used for the most reasonable daytime average values. Only days in summers (May 1st to September 30th) were analyzed. The variables of interest include Soil Water Content, Net Radiation, Carbon Dioxide (CO_2) Turbulent Flux, Latent Heat Turbulent Flux, Atmospheric Pressure (PA), Precipitation, Soil Temperature, Water (H_2O) Vapor Mole Fraction, and Sensible Heat Turbulent Flux.

Table 2: Variables of Interest from AmeriFlux Towers

Variables of Interest	Units
Soil Water Content (SWC)	% Volumetric (volume of water to the total soil volume)
Net Radiation (Rn)	W m^{-2}
Carbon Dioxide (CO_2) Turbulent Flux (FC)	$\mu molCO_2$ m^{-2} s^{-1}
Latent Heat Turbulent Flux (LE)	W m^{-2}
Atmospheric Pressure (Pa)	kPa
Precipitation (P)	mm
Soil Temperature (T_s)	Degree Celsius
Sensible Heat Turbulent Flux (H)	W m^{-2}

SMAP Data Processing

To make comparison between AmeriFlux data and SMAP data, corresponding SMAP grid cells that overlay AmeriFlux towers of interest were selected and calculated for daily average with some missing days in between as the satellite returns to the same location every 3-4 days.

Characterization of Drydowns

In order to test whether plant function and ecosystem carbon exchange with the atmosphere would respond systematically to pulse soil moisture resource availability, we isolated soil moisture drydown periods and examined the evolution and dynamics of flux exchanges as a function of drydown evolution.

Drydowns were defined as at least 3 consecutive days of decreasing soil water content after any soil water content peaks. The ends of drydowns were defined as any troughs that had following soil water content greater than 0.5% increase. The choice of consecutive days and 0.5% increase were from balancing potential instrumental noise and avoiding selection bias. Among captured drydowns, seasonal drydowns could also be characterized when the length of drydowns are longer than 14 days. Unlike regular drydowns that capture spontaneous processes and plant responses, seasonal drydowns represent phenological changes that last up to a season. These types of drydowns were excluded from the pulse-reserve hypothesis tests.

To determine drydowns, a MATLAB script was coded to first detect all greater than 0.5% jumps to be the starting points of the drydowns. All the troughs in soil water content were determined as potential ends of the drydowns. The starting points were matched with the potential ends that make the longest drydown length without crossing other drydowns or overlapping with missing data.

Selected drydowns were also separated into two subcategories depending on the length of drydowns: short-term drydowns and seasonal drydowns. If drydowns were longer than 14 days, the drydowns would considered as seasonal drydowns. Short-term drydowns were the main interest of this project due to the fact that they were more likely to capture pulses of growth. Unlike short-term drydowns, seasonal drydowns represented growth in longer time scale. The pulses of growth would be inseparable from the rest of the drydowns. Seasonal drydowns represented vegetation dying off in the dry season, which would be different from waiting for rain and then taking up high quantity of water in short-term drydowns. Seasonal drydowns can be problematic as they may represent vegetation dying off in the dry season, which is fundamentally different from taking up high quantity of water from pulses of rain and dying off shortly after.

Once all the drydowns were determined, the corresponding time of drydowns were matched to other variable timestamps. Latent heat flux, evaporative fraction, and water use efficiency values corresponding to the periods of drydowns were determined. The numbers of selected drydowns were shown in last two columns of Table 1. The numbers of drydowns from AmeriFlux towers were varied based on the numbers of years that data were available. In contrast, the numbers of drydowns from SMAP were less varied due to the same length of data availability of all the sites of interest. However, drydowns from both AmeriFlux towers and SMAP share the general trends of having relatively fewer drydowns in evergreen biomes and more drydowns in grasslands.

Results & Analysis

Drydowns Phase-Space Plot

Integrating both AmeriFlux and SMAP measurements allowed us to assess the larger scale plant water response to SWC variability. The relations between the plant variables of interest and soil water content were captured through phase-space diagrams, a space that captures the coevolution of all the possible variables in a system of interest.

In this study, there are four two-variable systems of interest from AmeriFlux towers: (i) soil water content in-situ and carbon flux, (ii) soil water content and evaporative fraction, (iii) soil water content and latent heat turbulent flux, and (iv) soil water content and water use efficiency. One two-variable system of interest from the SMAP data is soil moisture and vegetation optical depth.

In an illustrative phase-space diagram (Figure 2), each drydown is represented by a black line, starting with a green dot at the beginning, and ending with a red dot at the end. The blue line represents the moving average of every 20% of FC data points. The shaded blue area represents the standard error of the average. Ten percent of each end was ignored after calculating the moving average. Because a drydown starts after a pulse of rain, the SWC would be relatively high at the beginning. As the time passes, the soil dries up. SWC goes from right to left in relatively low SWC at the end. As shown in Figure 2, pulses of rain can increase SWC up to about 13% in this case and then decrease to almost zero during the absence of rain.

The relationship between SWC and all the variables will be discussed further in this section.

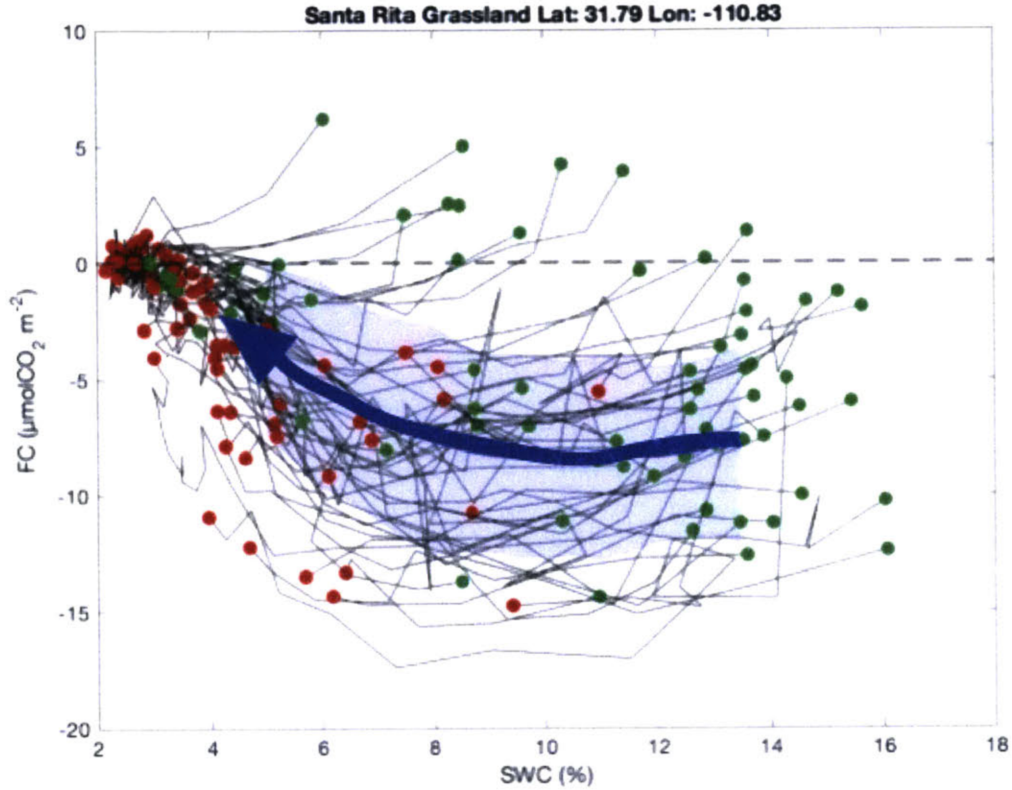
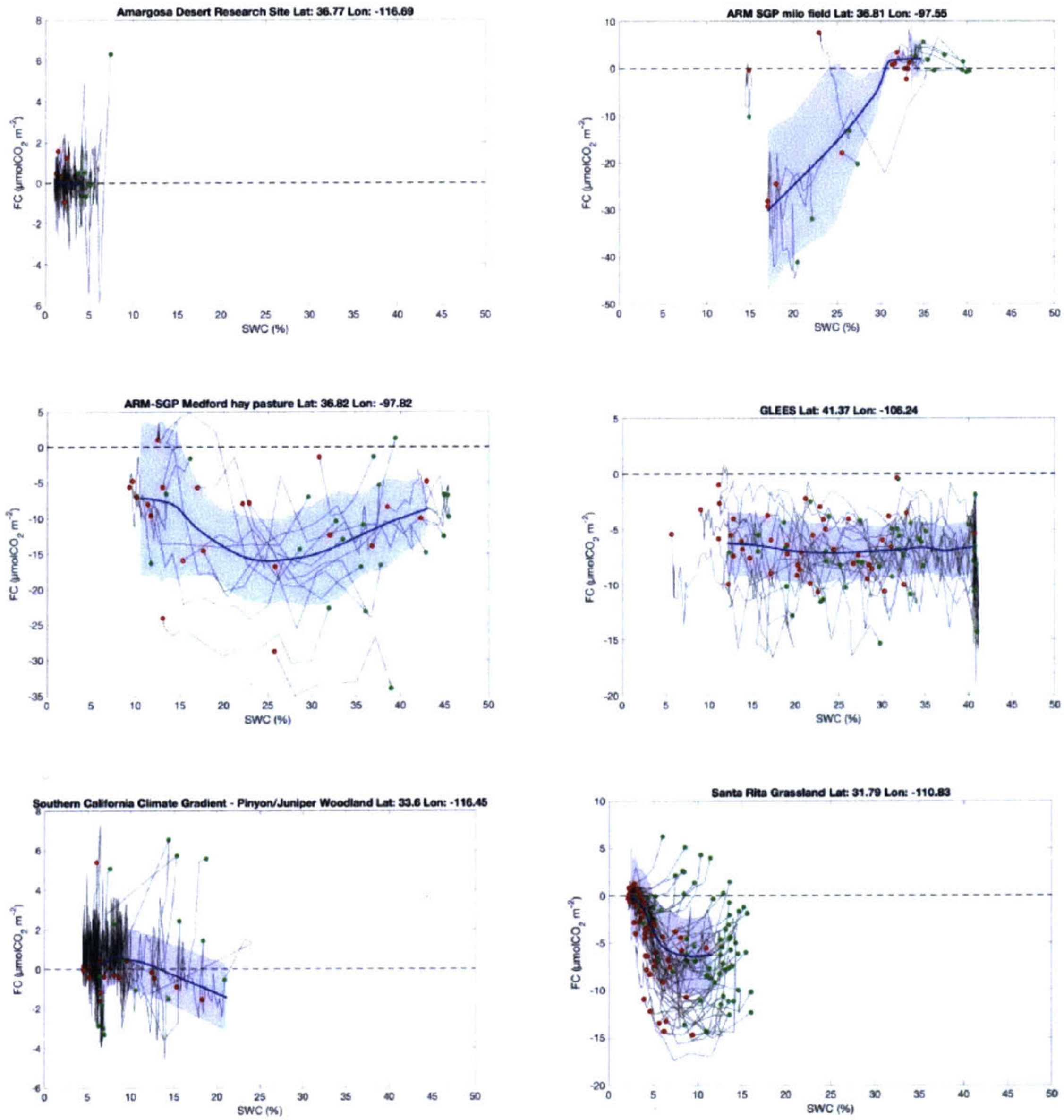


Figure 2: Soil Water Content is high at the beginning of drydowns and decreases over time as shown in the blue arrow. The evolution of carbon flux is shown for each drydown.

1. Soil Water Content and Carbon Flux

Negative FC means carbon being taken out of the atmosphere and going into the land surface. Photosynthesis and primary productivity are responsible for the negative FC. In contrast, heterotrophic respiration is responsible for the positive FC by producing and releasing carbon out of the landdcape into the atmosphere. For arid land regions of interest, FC is relatively high at the beginning and decreases (more negative) during drydowns until SWC drops below a certain threshold. After SWC drops below the threshold, FC starts to increase again. When plants are growing, FC is likely to decrease as more CO2 was used by the plants, resulting in more CO2 flux down towards the surface from the atmosphere. As water becomes less available, plant growth reduces, and soil respiration dominates the system resulting in an increase of FC. However, the relationship was not observed in desert (Amargosa) or evergreen forest areas (Southern California Pinyon Juniper). Phase-space plots are shown in Fig. 3.



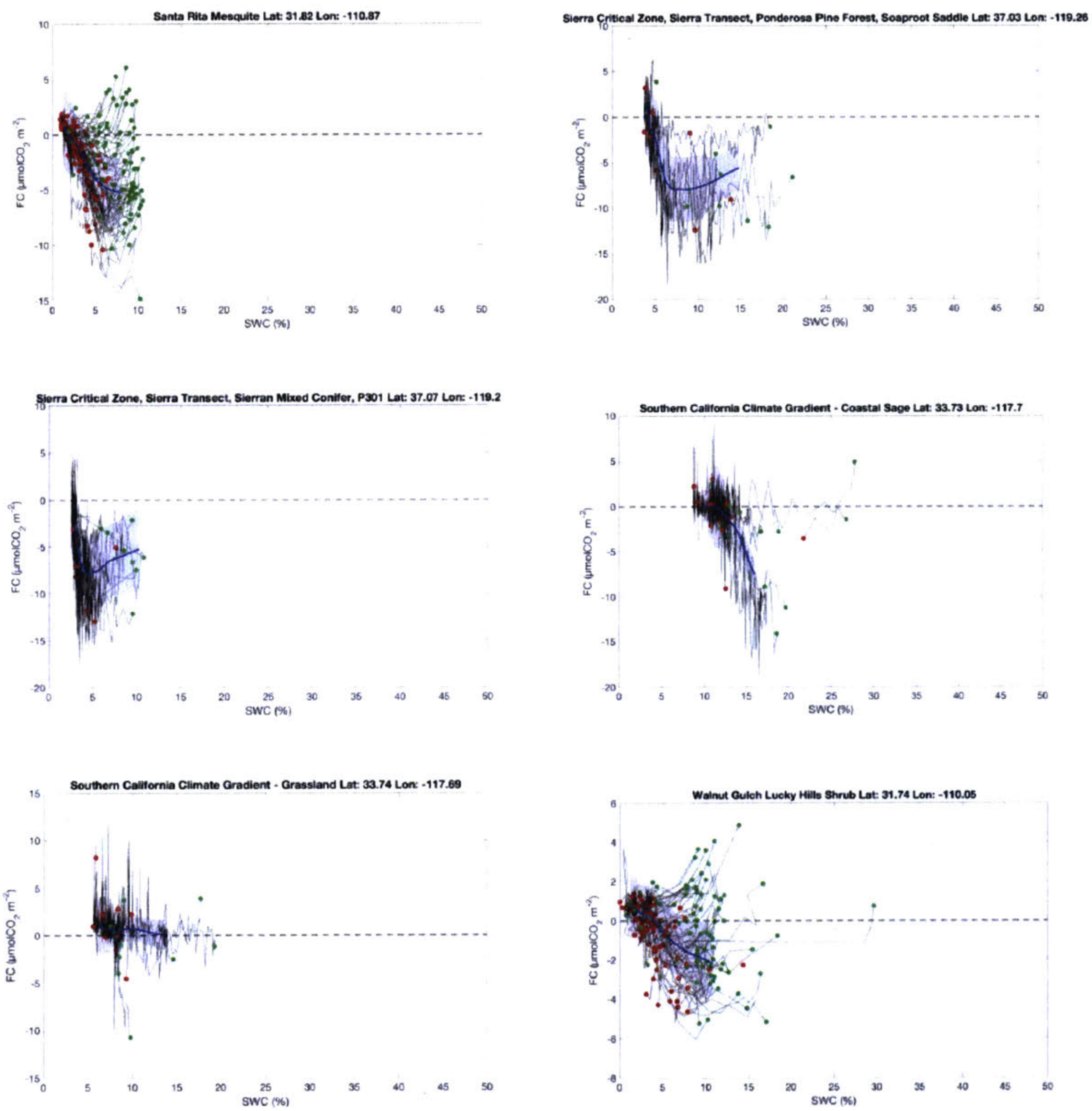


Figure 3: Phase-space plots of Soil Water Content and Flux of Carbon relationship at all twelve AmeriFlux sites with available data.

All drydown summaries from all the towers are plotted on the same phase space in order to assess large-scale FC behaviour in Western United States (shown in Fig. 4). Depending on the towers, the critical SWC values that FC switch from decreasing to increasing are different. The critical values are somewhere between 5 - 15%. ARM milo agricultural field is the outlier that does not share the same trend with the rest of the towers because the site is a managed ecosystem with anthropogenic disturbance.

All the drydowns are color coded by their Aridity Index (AI), where lower AI values represent less arid lands and high AI values represent more arid lands. From Figure 4, less arid sites have higher variability in FC compared to more arid sites. Due to the bigger range of SWC in less arid sites, evolution of FC ranges from constant, to decreasing, and to increasing depending on the SWC. Because the SWC range is smaller in arid land, the evolution of FC in arid lands only switches between decreasing or increasing. The variation of FC evolution among sites is undetermined. A site in a biome might be less similar to a site that shared the same biome yet more similar to a site in other biome. However, the SWC-FC phase-space lines of the sites that are located close to one another (e.g. all the sites in Southern California Climate Gradient) do cluster together. More investigation is needed in order to explain why FC does not depend on the biomes yet depends on the locations.

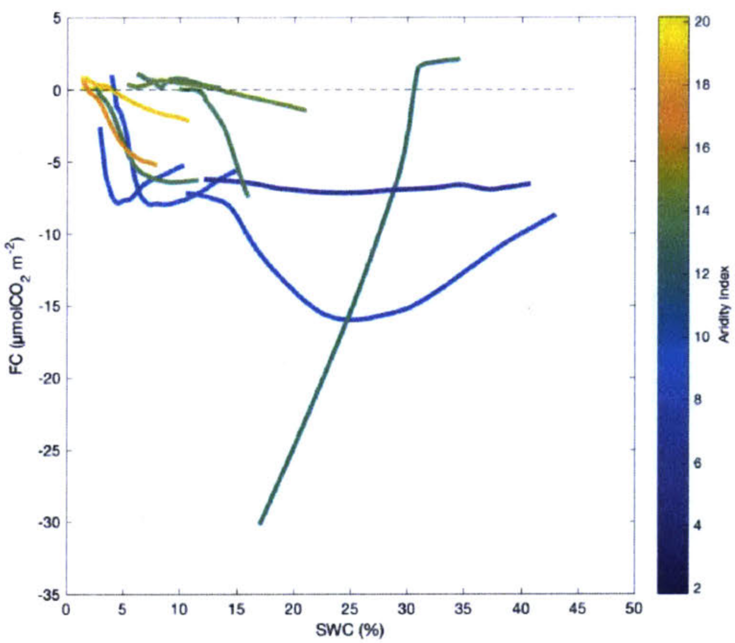
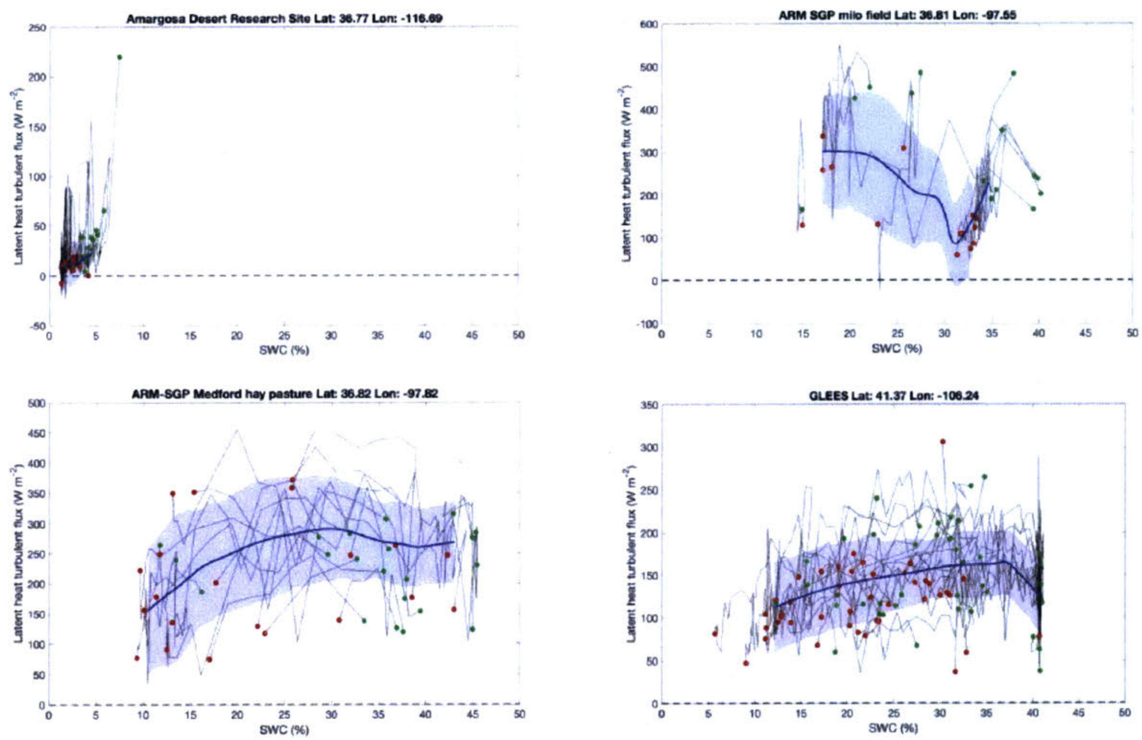


Figure 4: Summary Plot of Soil Water Content and Flux of Carbon relationship from AmeriFlux towers of interest. Flux of Carbon is relatively constant when Soil Water Content is above 5 - 15%. Below the threshold, Flux of Carbon starts to increase.

2. *Soil Water Content and Latent Heat Flux*

For arid land regions, LE or the available heat for plant activity is relatively constant at the beginning of a drydown and decreases when SWC drops below a certain threshold. These two phases before and after the threshold can be identified as energy-limited phase (the beginning when photosynthesis capacity limits plant activities) and water-limited phase (towards the end when water limits plant activities). As water becomes less available, the system shifts from an energy-limited phase to a water-limited phase. During the water-limited phase, LE decreases as SWC decreases because LE has a linear relationship with water availability. SWC-LE phase-space plots of all towers are shown in Fig. 5.



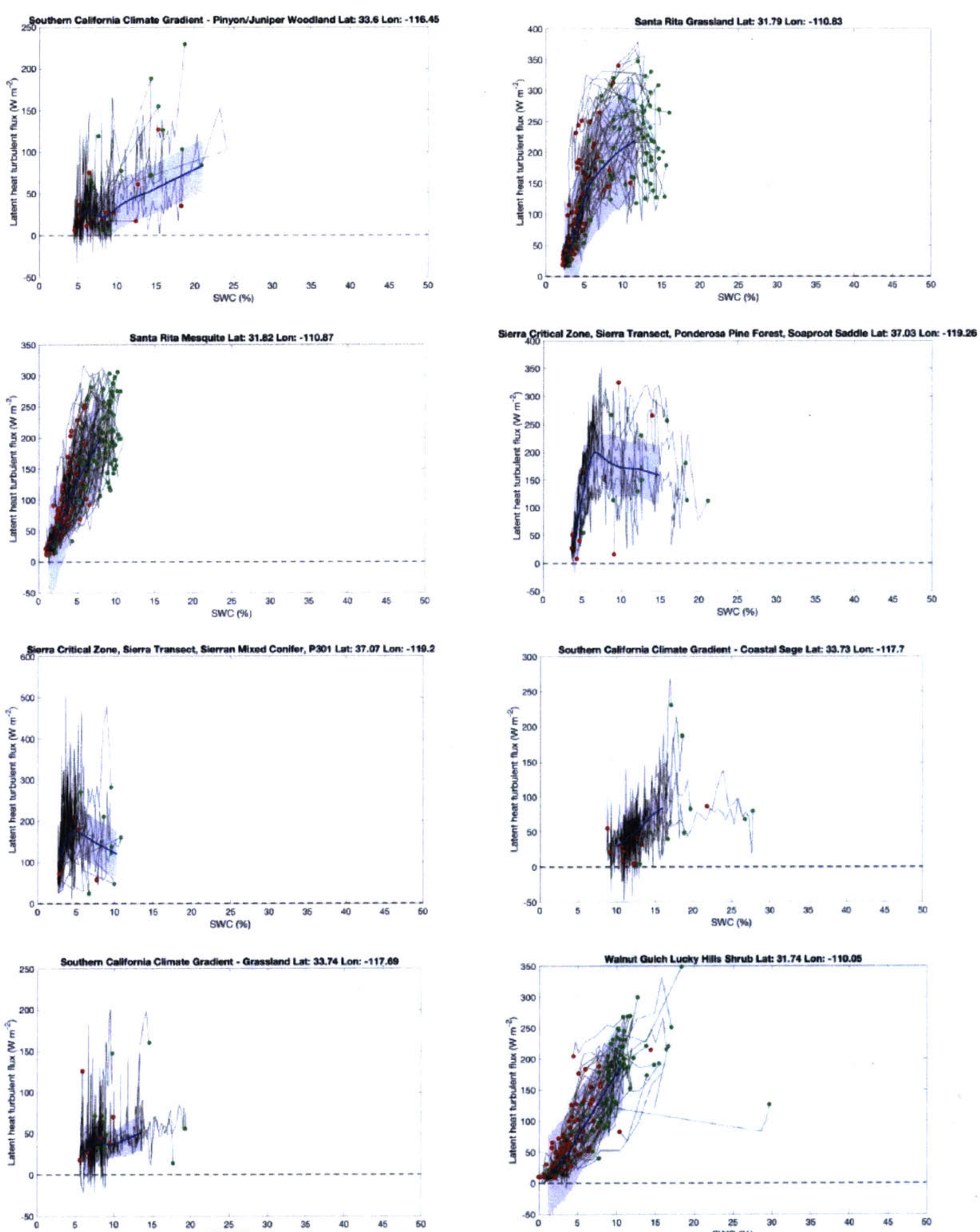


Figure 5: Phase-space plots of Soil Water Content and Latent Heat Flux relationship at all twelve AmeriFlux sites with available data.

All drydowns from all the towers are plotted on the same phase space in order to assess large-scale LE behaviour in Western United States (shown in Fig. 6). From all the towers, steep drops in LE can be observed when SWC drops below 10%. ARM milo field is still the outlier that does not share the same trend with the rest of the towers.

Similar to Fig. 4, all the drydowns in Fig. 6 are color coded by their Aridity Index (AI), where lower AI values represent less arid lands and high AI values represent more arid lands. From Figure 6, less arid sites have higher variability in LE compared to more arid sites. For both less arid and arid sites, evolution of LE is either decreasing or increasing depending on the SWC. The SWC-LE phase-space lines of all the sites in Southern California Climate Gradient still cluster together.

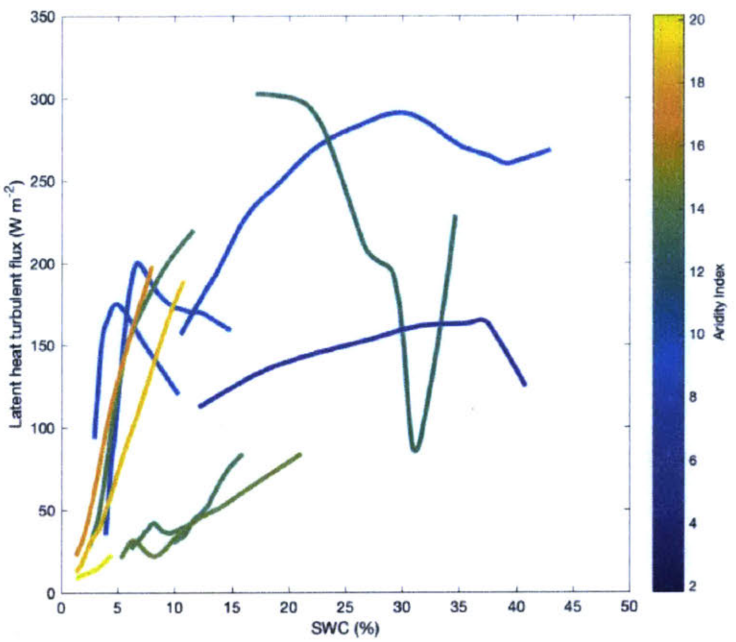
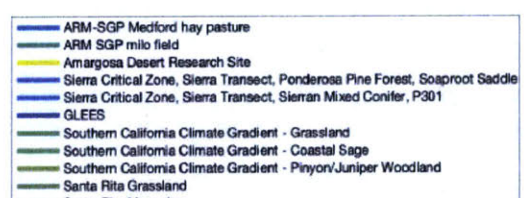
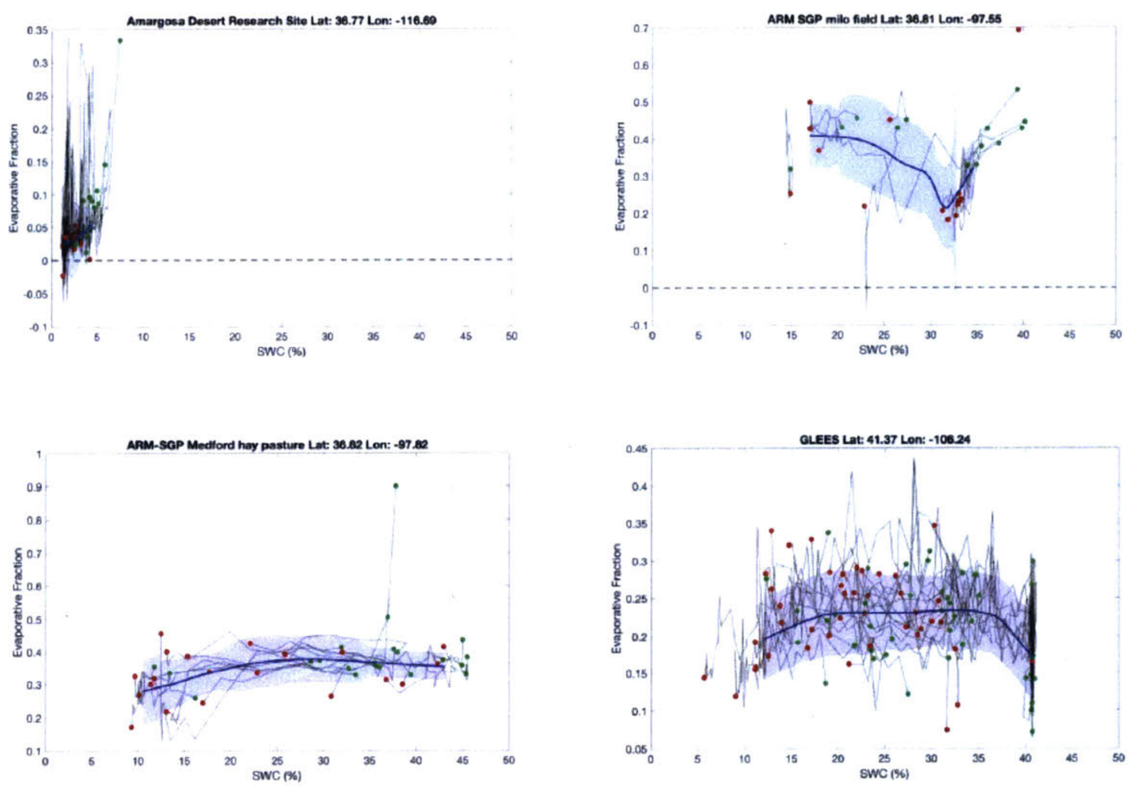


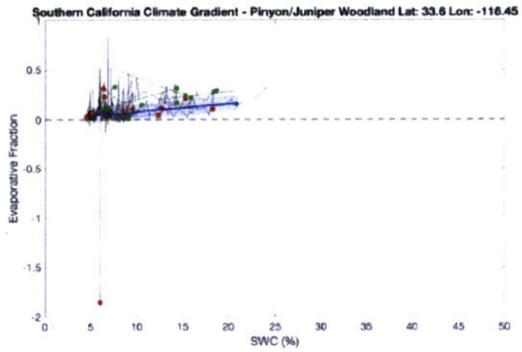
Figure 6: Summary Plot of Soil Water Content and Latent Heat Flux relationship from AmeriFlux towers of interest. Latent Heat Flux is relatively constant when Soil Water Content is above 15 - 20%. Below the threshold, Latent Heat Flux starts to decrease.

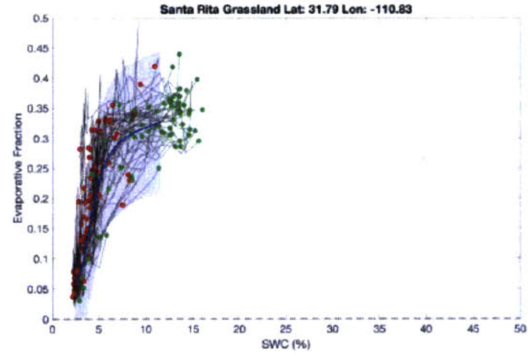


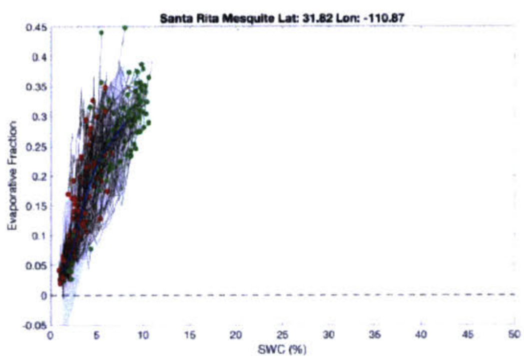
3. Soil Water Content and Evaporative Fraction

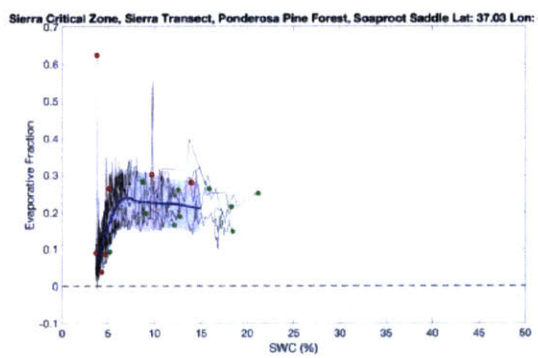
Evaporative Fraction (EF) captured the partitioning of latent heat flux, which depends on the availability of water for evaporation and net radiation in SWC-EF phase-space (shown in Fig. 7). In other words, EF represents energy available at the surface for evaporation that was normalized by summation of total sensible and latent turbulent heat fluxes. EF decreases slowly when SWC is above certain level and decreases significantly faster when SWC drops below 5 - 15% SWC depending on the towers. The shape of phase-space plots depends on the ecosystems and water availability of the towers.




Southern California Climate Gradient - Pinyon/Juniper Woodland Lat: 33.6 Lon: -116.45
Evaporative Fraction
SWC (%)


Santa Rita Grassland Lat: 31.79 Lon: -110.83
Evaporative Fraction
SWC (%)


Santa Rita Mesquite Lat: 31.82 Lon: -110.87
Evaporative Fraction
SWC (%)


Sierra Critical Zone, Sierra Transect, Ponderosa Pine Forest, Soaproot Saddle Lat: 37.03 Lon: -119.26
Evaporative Fraction
SWC (%)

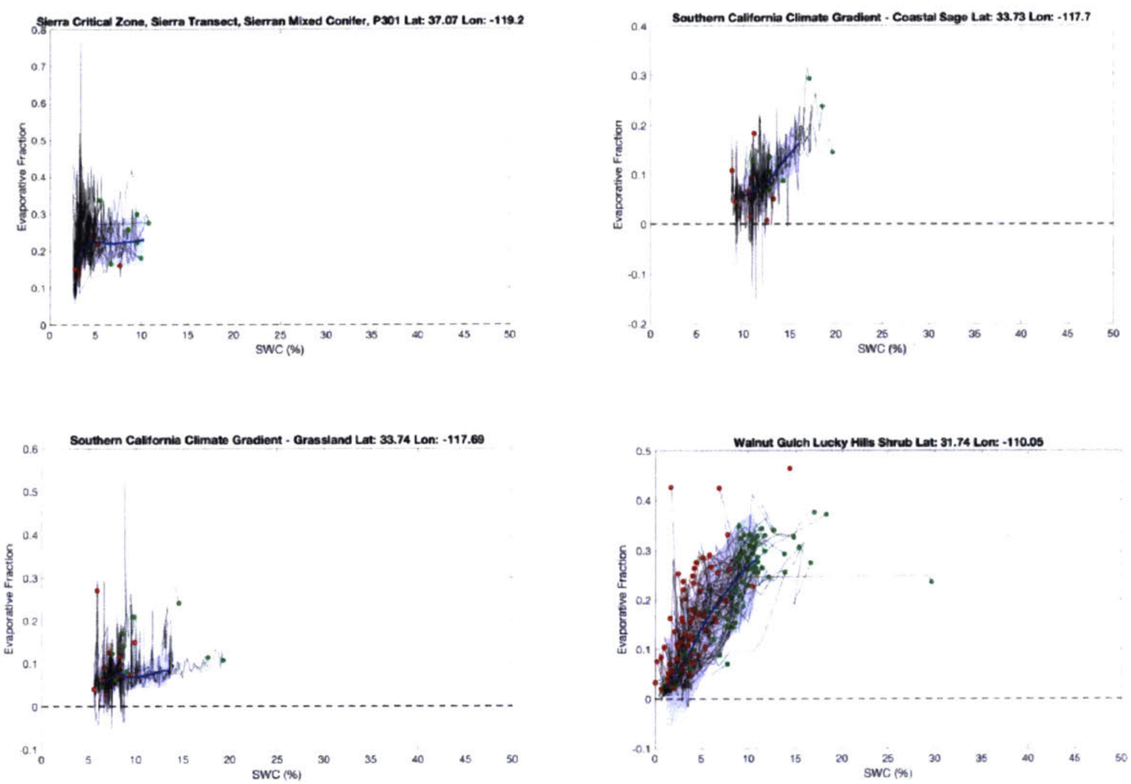


Figure 7: Phase-space plots of Soil Water Content and Evaporative Fraction relationship at all twelve AmeriFlux sites with available data.

All drydowns from all the towers are plotted on the same phase space in order to assess large-scale EF behaviour in Western United States (shown in Fig. 8). Because EF was a normalized value, all the towers seem to have similar behaviors of decreasing EF as SWC decreases except the ARM SGP milo field. One possible explanation is that the ARM SGP milo field has significantly smaller data points. Another possible explanation is that ARM SGP milo field tower is in a cropland. Agricultural activities might interfere with plant activities resulted in weird shape of the phase-space plot.

Similar to Fig. 4 and Fig. 6, all the drydowns in Fig. 8 are color coded by their Aridity Index (AI), where lower AI values represent less arid lands and high AI values represent more arid lands. From Figure

8, the variability of EF evolution is smaller compared to the evolution of FC and LE because EF is normalized by the total available energy ($LE + H$).

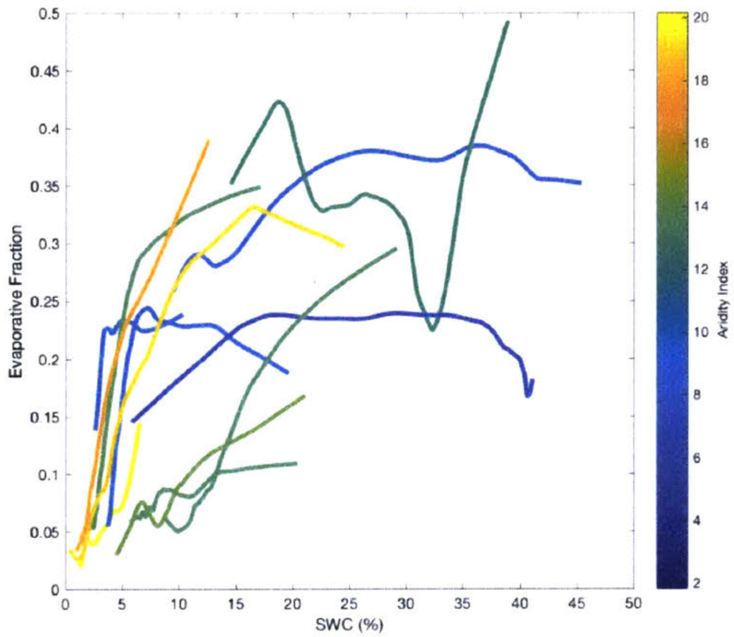
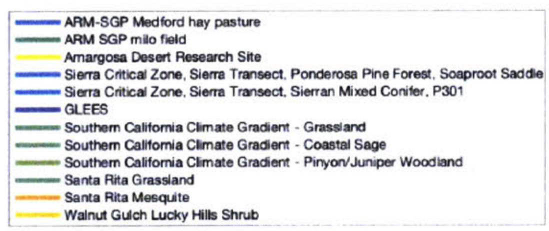
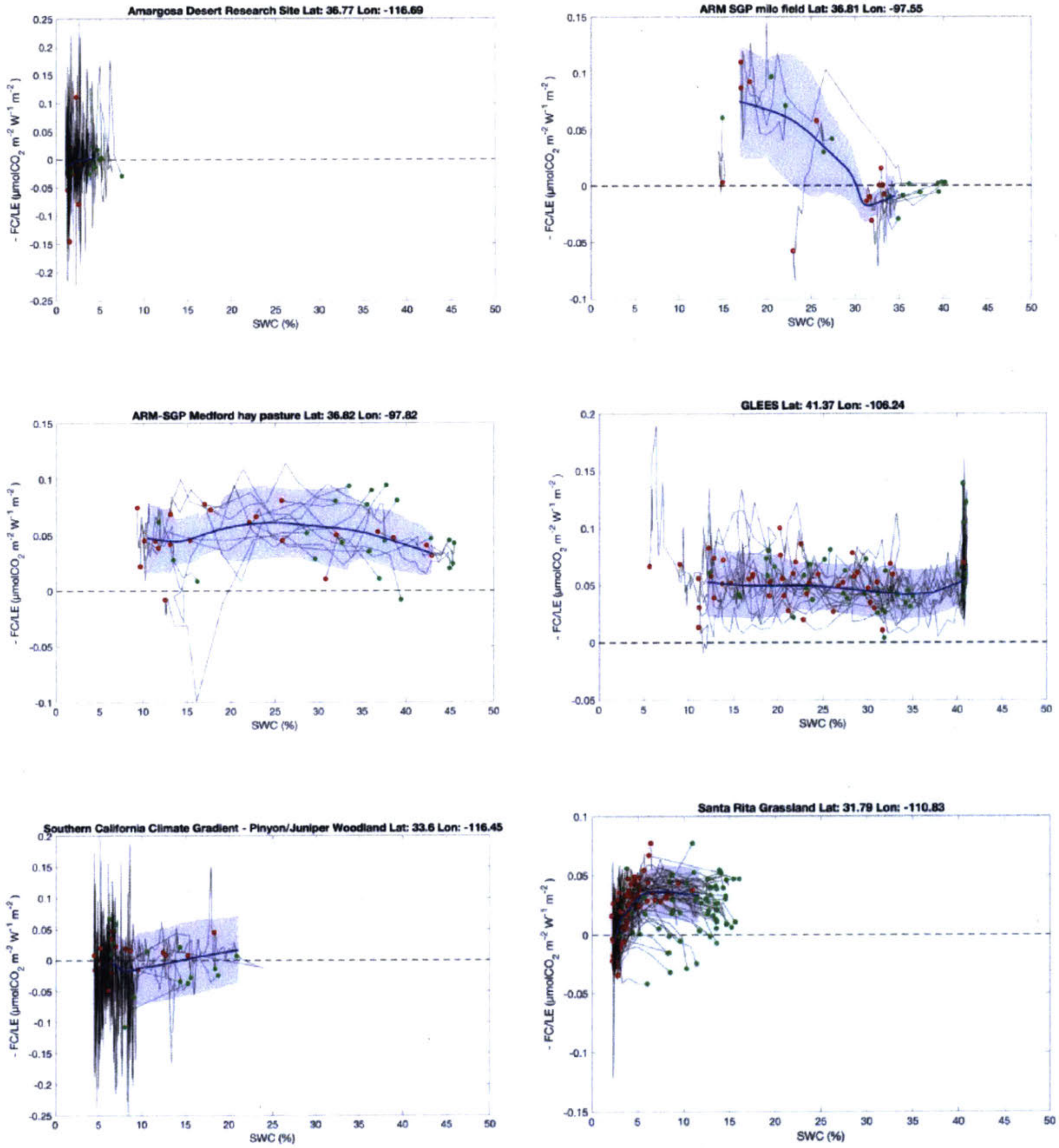


Figure 8: Summary Plot of Soil Water Content and Evaporative Fraction relationship from AmeriFlux towers of interest. Similar to Latent Heat Flux, Evaporative Fraction is relatively constant when Soil Water Content is above 15 - 20%. Below the threshold, Evaporative Fraction starts to decrease.



4. Soil Water Content and Water Use Efficiency

WUE stayed constant at the beginning of the drydowns and started to decrease when SWC dropped below 5-10% when water became limited. WUE decreases as SWC decreases because transpiration becomes more limited at low SWC, when stomata are closed in order to conserve water. When transpiration becomes small, respiration of the microbes dominates the system and increases the upward carbon flux, making WUE negative. At this limit where respiration dominates carbon flux, WUE cannot be reliably estimated. SWC-WUE phase-space plots of all towers are shown in Fig. 9.


Amargosa Desert Research Site Lat: 36.77 Lon: -116.69
ARM SGP milo field Lat: 36.81 Lon: -97.55
ARM-SGP Medford hay pasture Lat: 36.82 Lon: -97.82
GLEES Lat: 41.37 Lon: -106.24
Southern California Climate Gradient - Pinyon/Juniper Woodland Lat: 33.6 Lon: -116.45
Santa Rita Grassland Lat: 31.79 Lon: -110.83
- FC/LE (μmolCO2 m-2 W-1 m-2)
SWC (%)

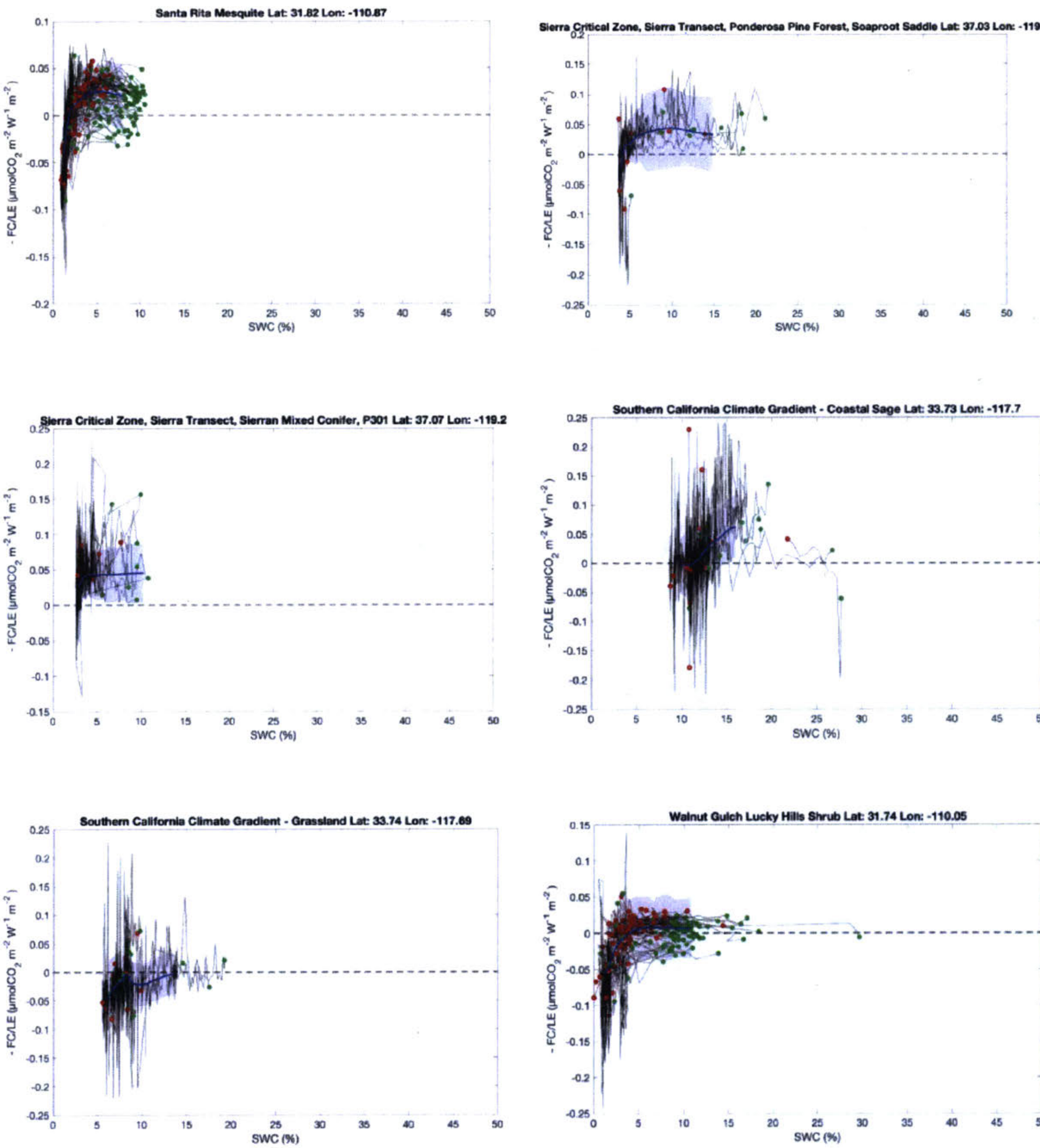


Figure 9: Phase-space plots of Soil Water Content and Water Use Efficiency relationship at all twelve AmeriFlux sites with available data.

All drydowns from all the towers are plotted on the same phase space in order to assess large-scale WUE behaviour in Western United States (shown in Fig. 10). WUE stay constant and positive across high SWC, suggesting that the landscapes uptake CO2 for plant GPP, photosynthesis, and transpiration. The uptaking rate has to be in some equilibrium with microbial respiration, which explains why the WUE is constant across ecosystems.

To investigate the pattern a little further, the definition of WUE needs to be examined. WUE is a landscape water use efficiency equivalent to carbon flux into the landscape (-FC) per water flux out of the landscape (LE). Positive WUE means carbon flux out from respiration is smaller than carbon flux landscape due to photosynthesis assimilation (Gianotti et al., 2019) Similar to energy and water-limited regimes in a low SWC region, a high SWC region represents energy-limited regime where photosynthesis, respiration, and transpiration operating in balance together yet limited by the availability of energy and resources. The equilibrium WUE value provides an estimate of 5.0 grams of carbon dioxide per 1 kilograms of water[1]. Because all the values from AmeriFlux towers are daily daytime averages, zero photosynthesis during night time can be ignored. With sufficient water, carbon flux from photosynthesis is always bigger compared to carbon flux from respiration. However, when SWC drops below 5-10%, respiration dominates the system. Both water and CO2 escape the landscape, resulting in negative WUE.

Similar to Fig. 4, Fig. 6, and Fig. 8, all the drydowns in Fig. 10 are color coded by their Aridity Index (AI), where lower AI values represent less arid lands and high AI values represent more arid lands. From Figure 8, the variability of WUE evolution is similar to the variability of EF evolution in Figure. 8. No cluster of phase-space lines is observed. All the stations, except the outlier, seem to share one WUE evolution.

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[1] 0.05 μmol CO_2/J $\cdot$ 44.01 x 10^{-6} g CO_2/μmol CO_2 $\cdot$ 2.26 x 10^6 J/kg H_2O

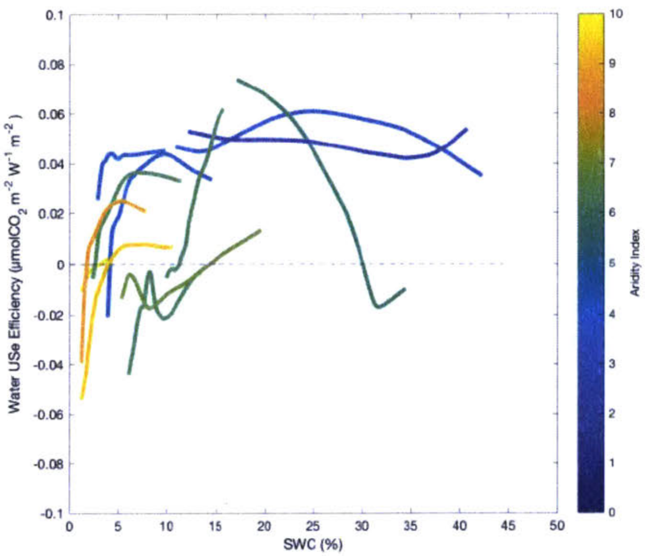
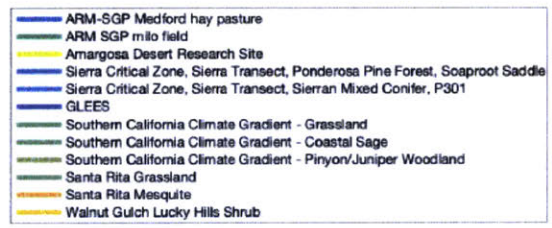
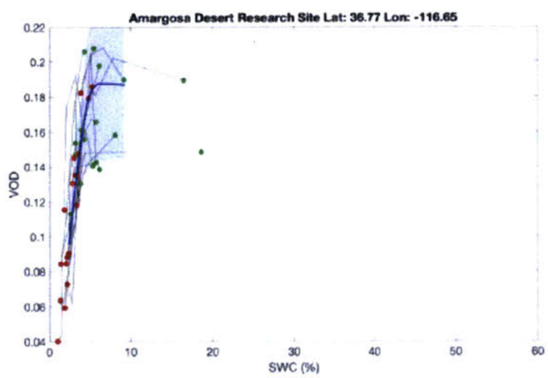


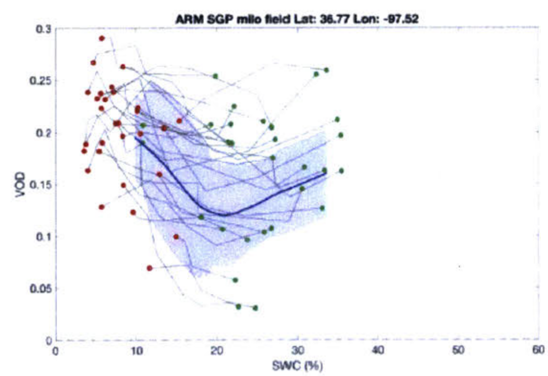
Figure 10: Summary Plot of Soil Water Content and Water Use Efficiency relationship from AmeriFlux towers of interest. Water Use Efficiency is relatively constant when Soil Water Content is above 10 - 15%. Below the threshold, Water Use Efficiency starts to decrease.

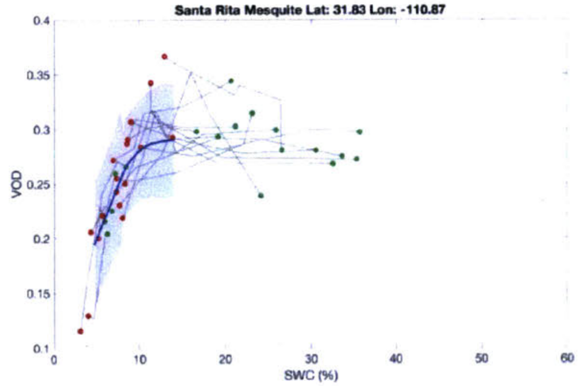


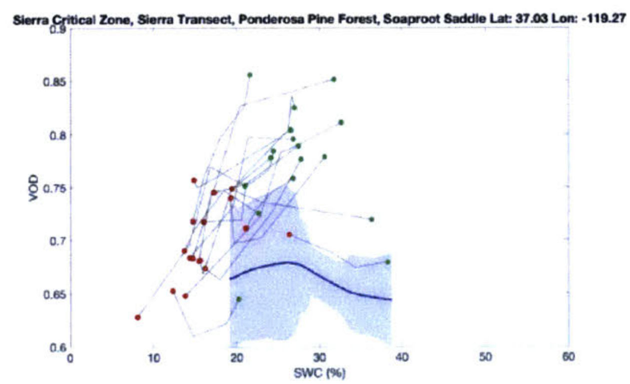
5. *Soil Water Content and Vegetation Optical Depth*

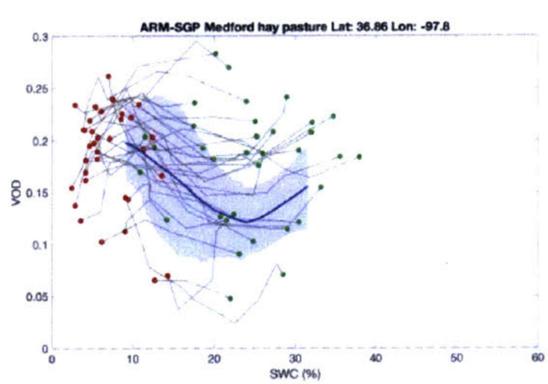
SWC-VOD phase-space plots obtained from SMAP (shown in Fig. 11) suggested a similar trend to SWC-FC phase-space plots. Although the shape of the plots was upside down compared to SWC-FC, SWC-VOD plots represent the same energy- and water-limited regimes across regions. Because VOD and FC negative correlationship to each other, VODincreases as SWC decreases until SWC drops below 10-15%

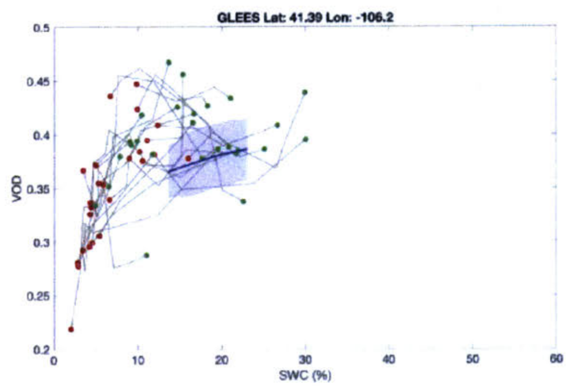

Amargosa Desert Research Site Lat: 36.77 Lon: -116.65
VOD
SWC (%)


ARM SGP milo field Lat: 36.77 Lon: -97.52
VOD
SWC (%)


Santa Rita Mesquite Lat: 31.83 Lon: -110.87
VOD
SWC (%)


Sierra Critical Zone, Sierra Transect, Ponderosa Pine Forest, Soaproot Saddle Lat: 37.03 Lon: -119.27
VOD
SWC (%)


ARM-SGP Medford hay pasture Lat: 36.86 Lon: -97.8
VOD
SWC (%)


GLEES Lat: 41.39 Lon: -106.2
VOD
SWC (%)

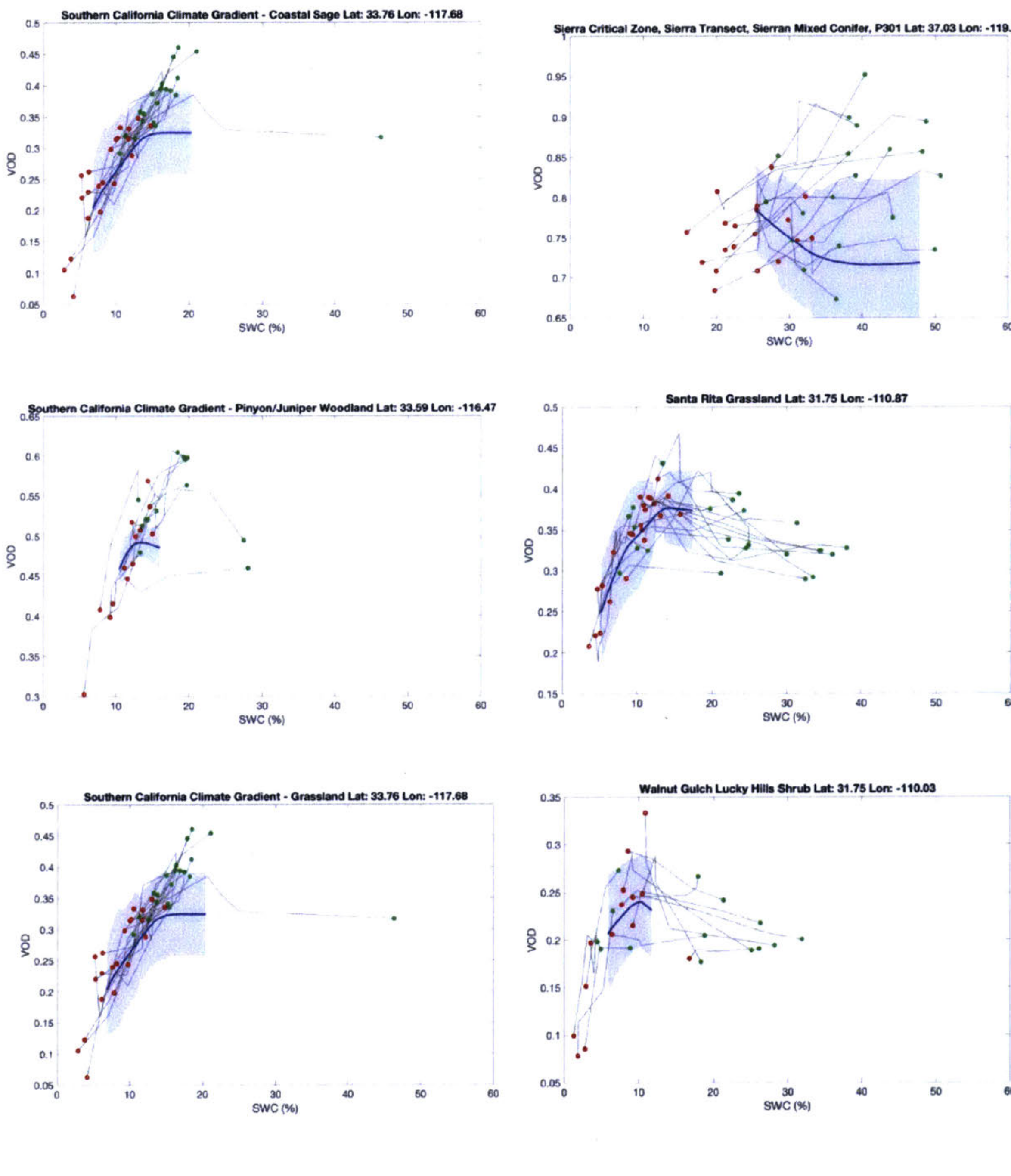


Figure 11: Phase-space plots of SWC-VOD relationship based on SMAP retrievals

All drydowns from SMAP were plotted on the same phase space in order to assess large-scale VOD behaviour in Western United States (shown in Fig. 12). Compared to Feldman et al. 2018, the shapes of the drydowns conform to Feldman's figure of the drydowns (Fig. 2 of Feldman et al.). Less arid regions are likely to stay in energy-limited regimes while more arid regions show the behaviors of both energy-limited and water-limited regimes. VOD in water-limited regions have a transition from constant VOD to decreasing VOD as SWC decrease.

All the drydowns in Fig. 12 are also color coded by their Aridity Index (AI), where lower AI values represent less arid lands and high AI values represent more arid lands. From Figure 12, the variability of VOD evolution depends on the location. Sites located near one another seem to share similar pattern. For example, all the VOD values from all the ARM SCP sites decrease and increase within the range of 0.1 to 0.2. All the VOD values from all the Sierra Critical Zone sites cluster together within the range of 0.6 to 0.8. ARM-SGP milo agricultural site is no longer an outlier because the data were average within a nine-by-nine-kilometer grid.

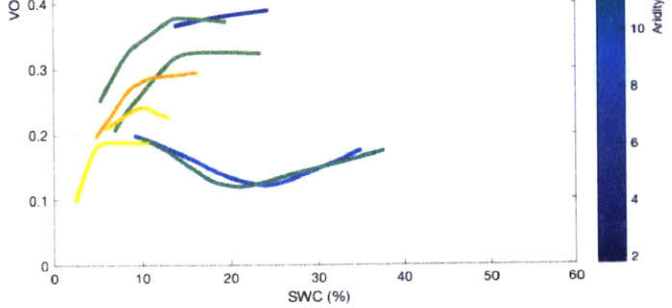
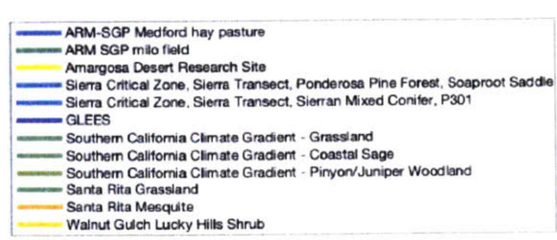


Figure 12: Summary Plot of Soil Water Content and Vegetation Optical Depth relationship from AmeriFlux towers of interest. Vegetation Optical Depth is relatively constant when Soil Water Content is above 10 - 15%. Below the threshold, Water Use Efficiency starts to decrease, which is similar to the Soil Water Content and Flux of Carbon Relationship, suggesting the possibility of correlation between Flux of Carbon from AmeriFlux Network and Vegetation Optical Depth from SMAP.

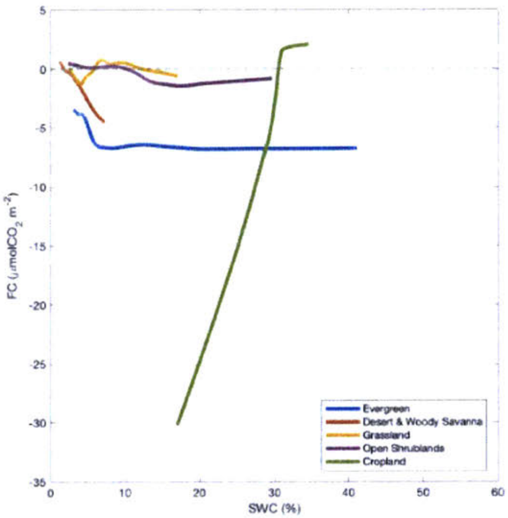


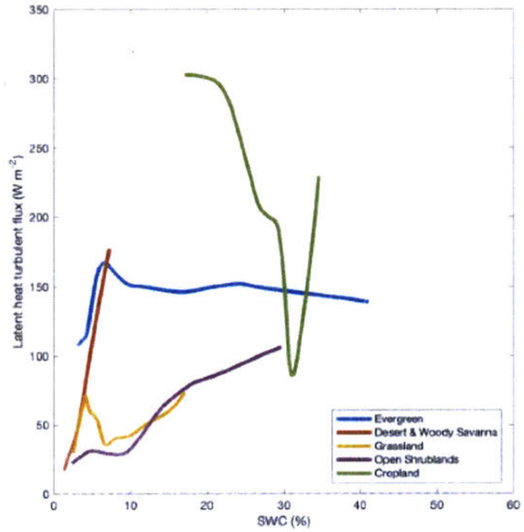
Drydowns Phase-Space Plots based on ecosystems

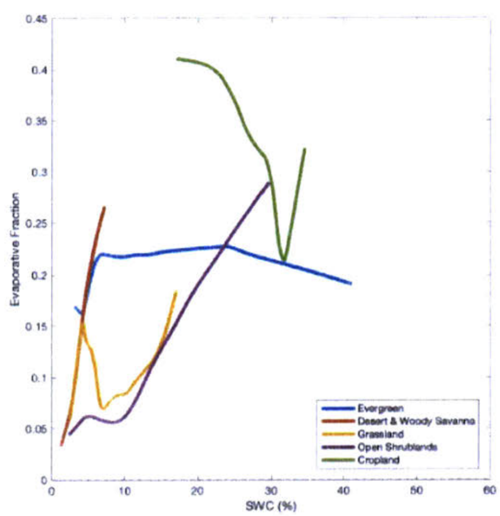
In the previous section, relationships among the plant and flux variables of interest and soil water content are captured through phase-space diagrams for all the towers of interest. In this section, drydowns from all the towers in the same ecosystems are grouped together by biomes (Table 1.) before making a phase-space line for each group. The groups used in this section are defined in the methodology section.

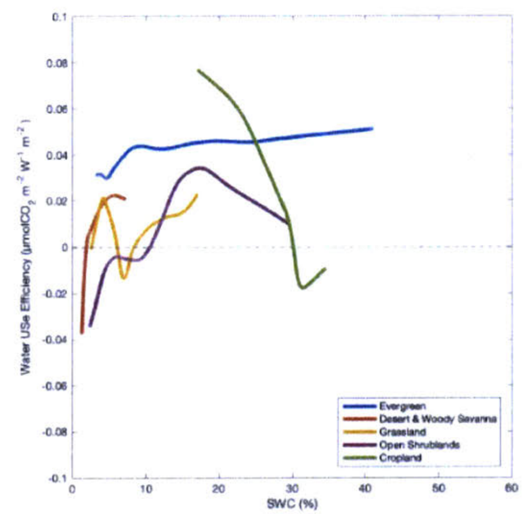
The summary plots (Fig. 13) suggests similar conclusions to the previous section. Two main observations are the characteristics of evergreen sites and cropland. The average of evergreen sites shows relatively small sensitivity to changes of SWC compared to the averages of other ecosystems while the cropland average is highly fluctuated. Pulse-reserve responses are not observed in the cropland site, suggesting highly disturbed environment due to irrigation and agriculture in the cropland.

Although analysing phase-space plots after grouping sites by their ecosystems provide similar conclusions to the phase-space plots of each site, grouping suggests potential shared behaviors within ecosystems. However, due to data limitations, shared behaviors could not be inferred based on 12 AmeriFlux towers of interest.









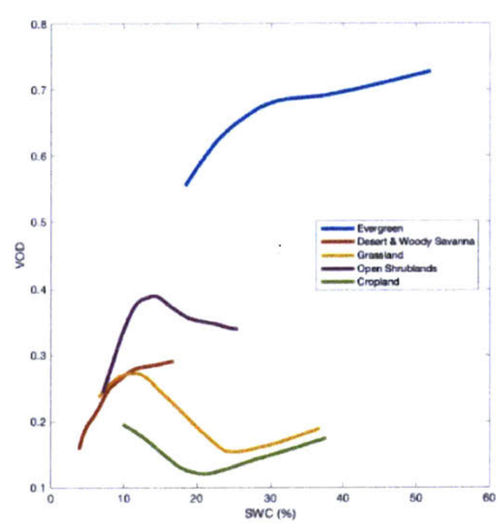


Figure 13. Summary plots of all the relationships from AmeriFlux towers of interest categorized and averaged by ecosystems

Conclusions

Based on flux tower observations, analysis of water, energy, and carbon fluxes during the evolution of interstorm soil moisture drydowns confirms moisture resource pulse-reserve ecological response of major biomes in Western United States. Croplands with extensive anthropogenic disturbance and energy-limited evergreen biomes do not show such behaviors. Transition between energy and water-limited regimes were found in all the relationship analyses. SWC-FC phase space plots suggest an increase of carbon flux as SWC decreases. SWC-LE phase-space plots suggest a decrease in latent heat flux as SWC decreases. Although EF were LE normalized by total heat fluxes, SWC-EF phase space plots suggest a similar trend to SWC-LE phase space plots of decreasing EF as SWC decreases. SWC-WUE phase space plots suggest a shared respiration and photosynthesis equilibrium among ecosystems in energy-limited regimes and decreasing in WUE in water-limited regimes. SWC-VOD phase space plot suggest a conformation of SWC-VOD relationship from Feldman et al. 2018 and the SWC-FC relationship based on AmeriFlux data. Although analyzing phase-space plots after grouping sites by their ecosystems provides similar conclusions to the phase-space plots of each site, grouping suggests potential shared behaviors within ecosystems.

In conclusion, the study provides new insights of the relationship between carbon dioxide flux and water available to vegetation during soil moisture drydowns. Specifically a pulse-reserve is evident. The patterns of fluxes during drydowns point towards a distinct pulse-response behavior. Intermittency of water availability, in contrast, to seasonal moisture availability, is responsible for episodic surge in fluxes of carbon and moisture. New research questions can be pursued for the better understanding impacts of vegetation on global carbon cycle.

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Appendices

Appendix I: AmeriFlux Time Series

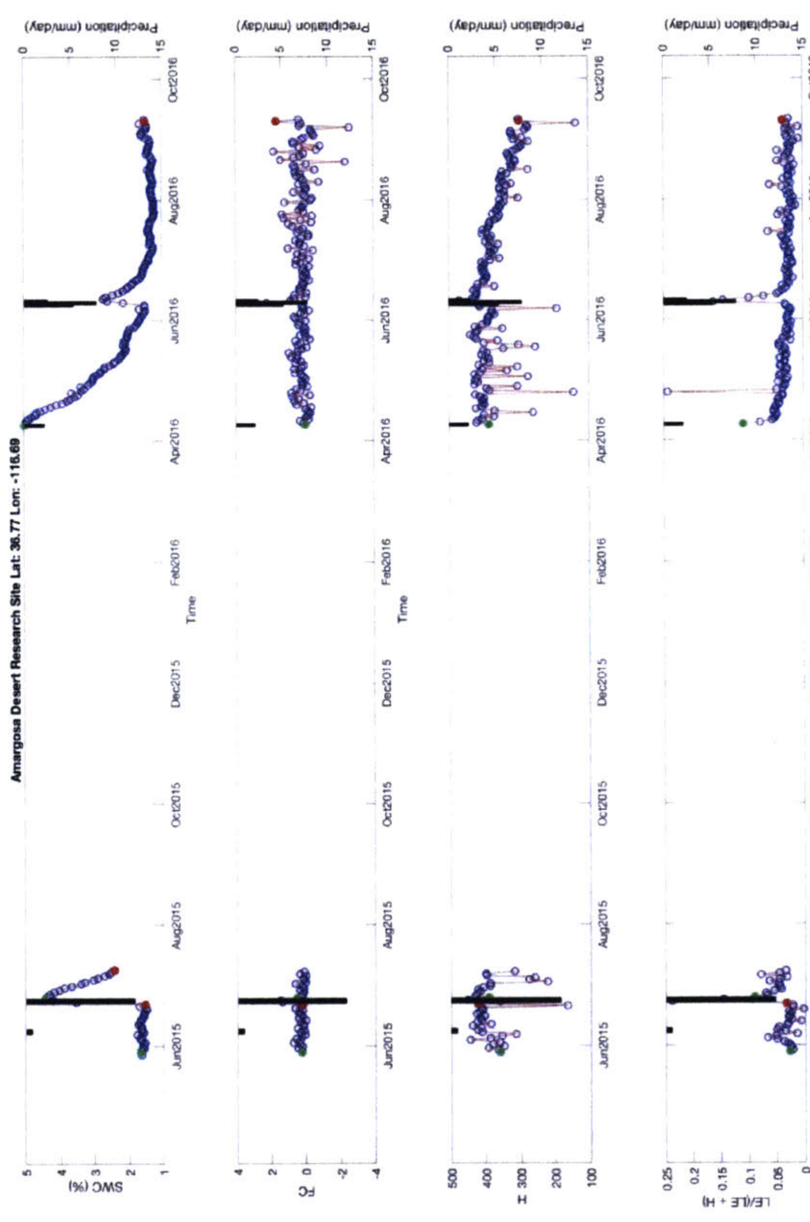

Figure a. Time series of SWC, FC, H, and WUE for Amargosa Desert Research Site between May 2015 to October 2016. The black bars represent daily precipitation.

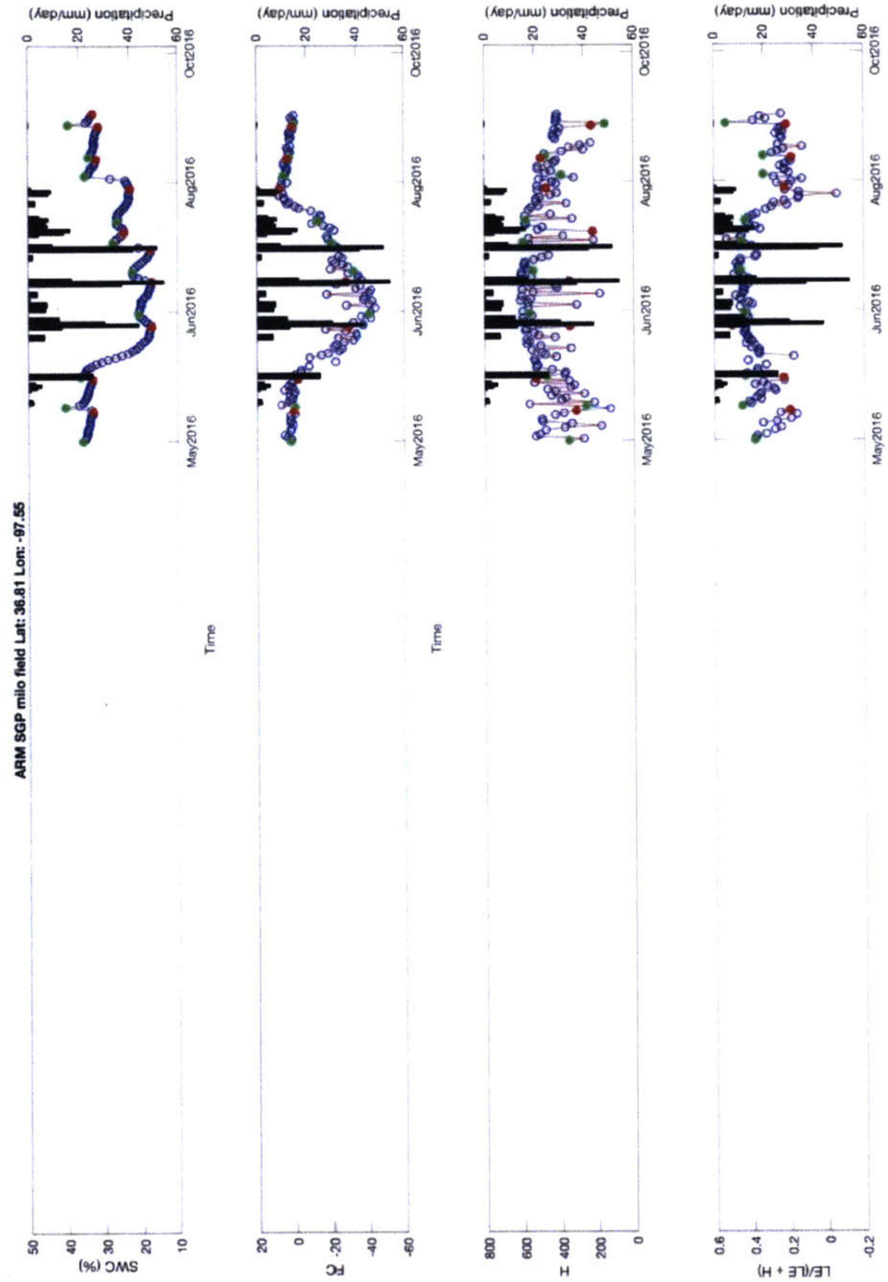

Figure b. Time series of SWC, FC, H, and WUE for ARM SGP milo agricultural field between May 2015 to October 2016. The black bars represent daily precipitation.

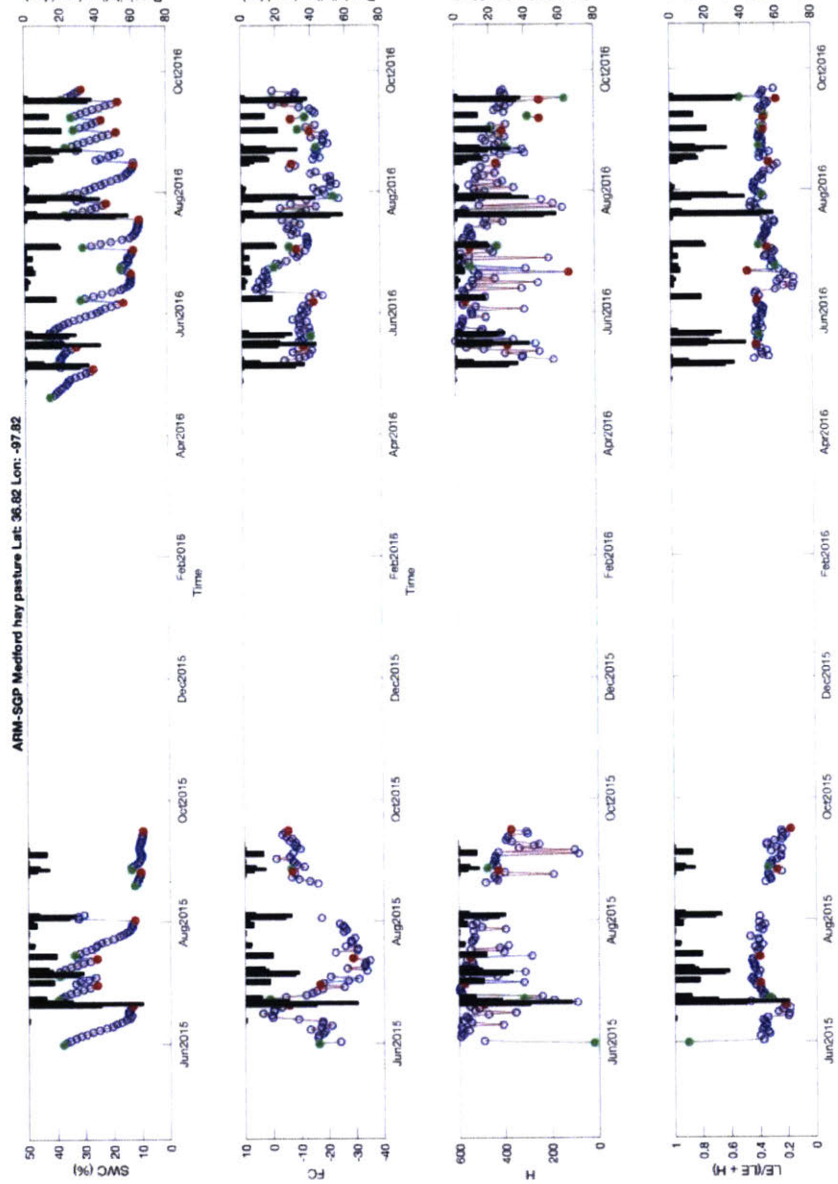

Figure c. Time series of SWC, FC, H, and WUE for ARM-SGP Medford hay pasture from May 2015 to October 2016. The black bars represent daily precipitation.

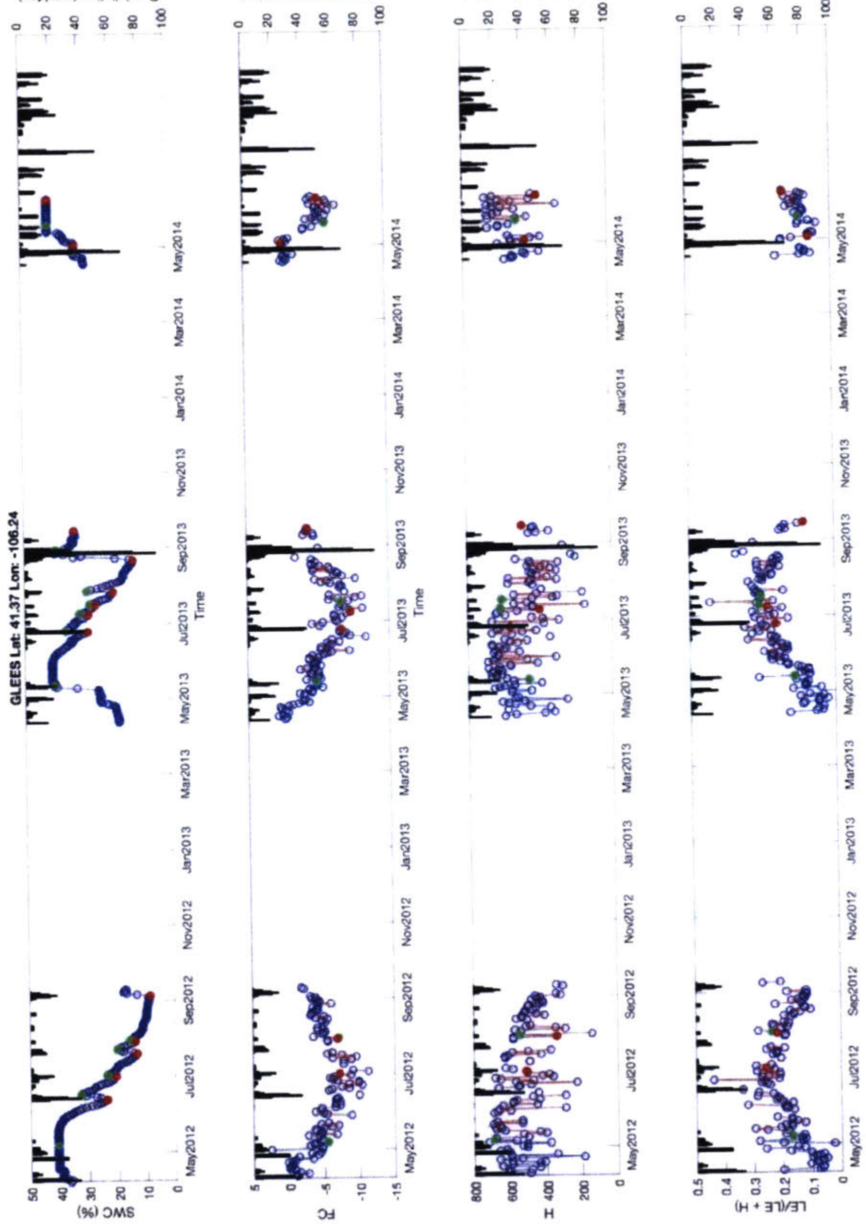

Figure d. Time series of SWC, FC, H, and WUE for GLEES from May 2012 to October 2014. The black bars represent daily precipitation.

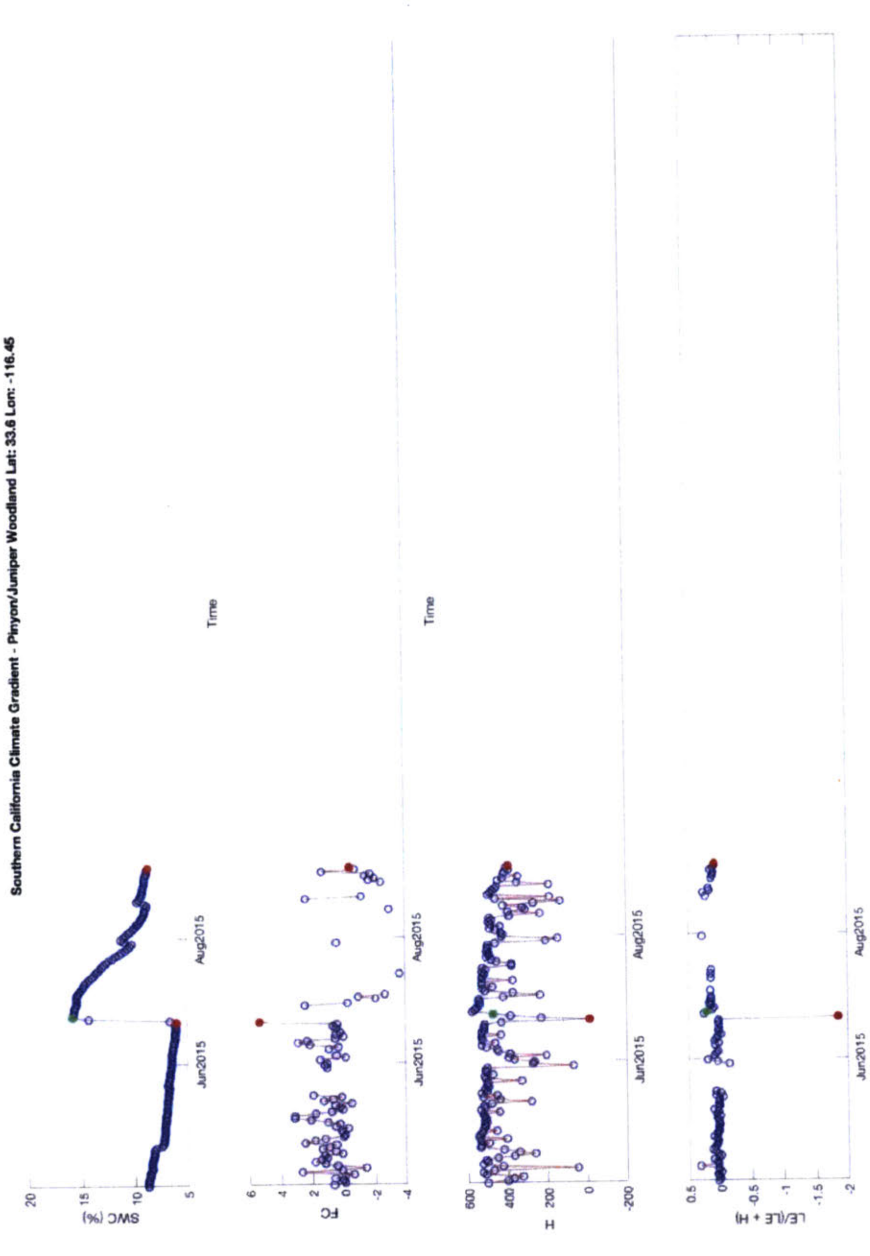

Figure e. Time series of SWC, FC, H, and WUE for Southern California Climate Gradient - Pinyon/Juniper Woodland from May 2015 to October 2016. The black bars represent daily precipitation.

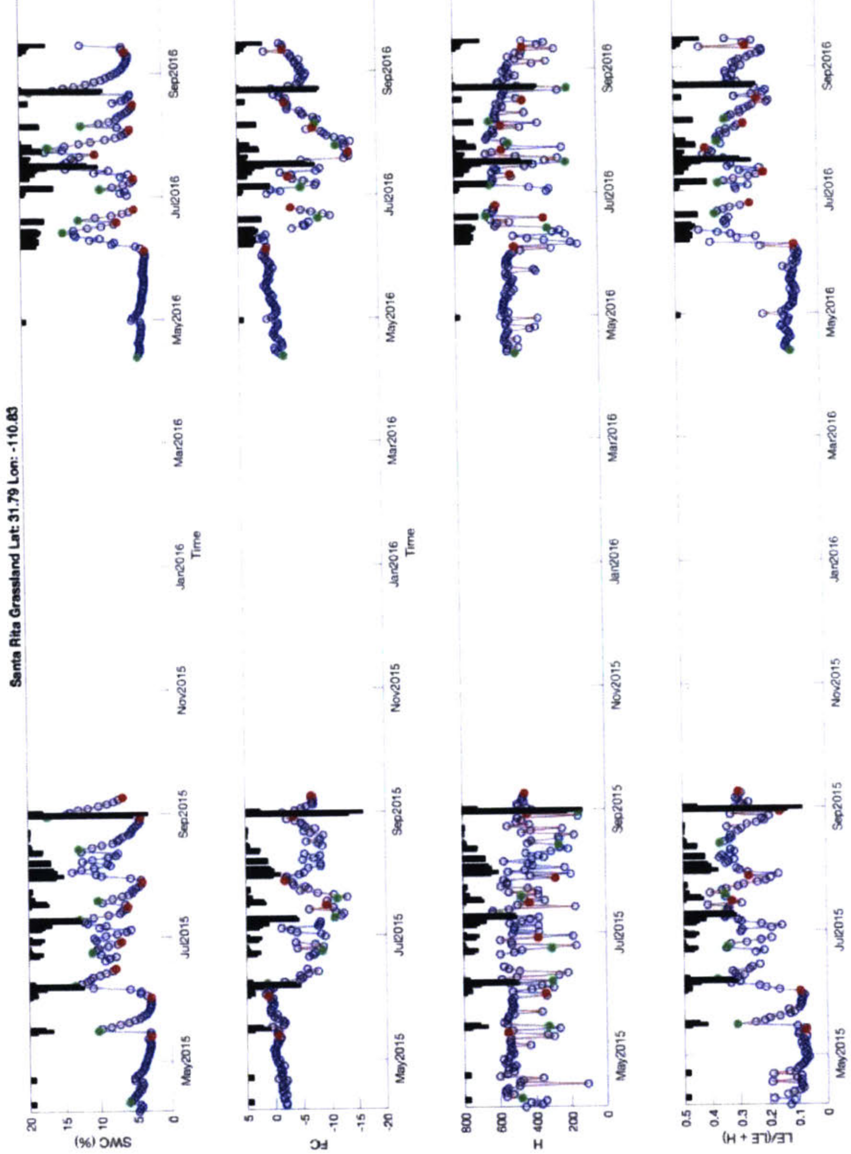

Figure f. Time series of SWC, FC, H, and WUE for Santa Rita Grassland from May 2015 to October 2016. The black bars represent daily precipitation.

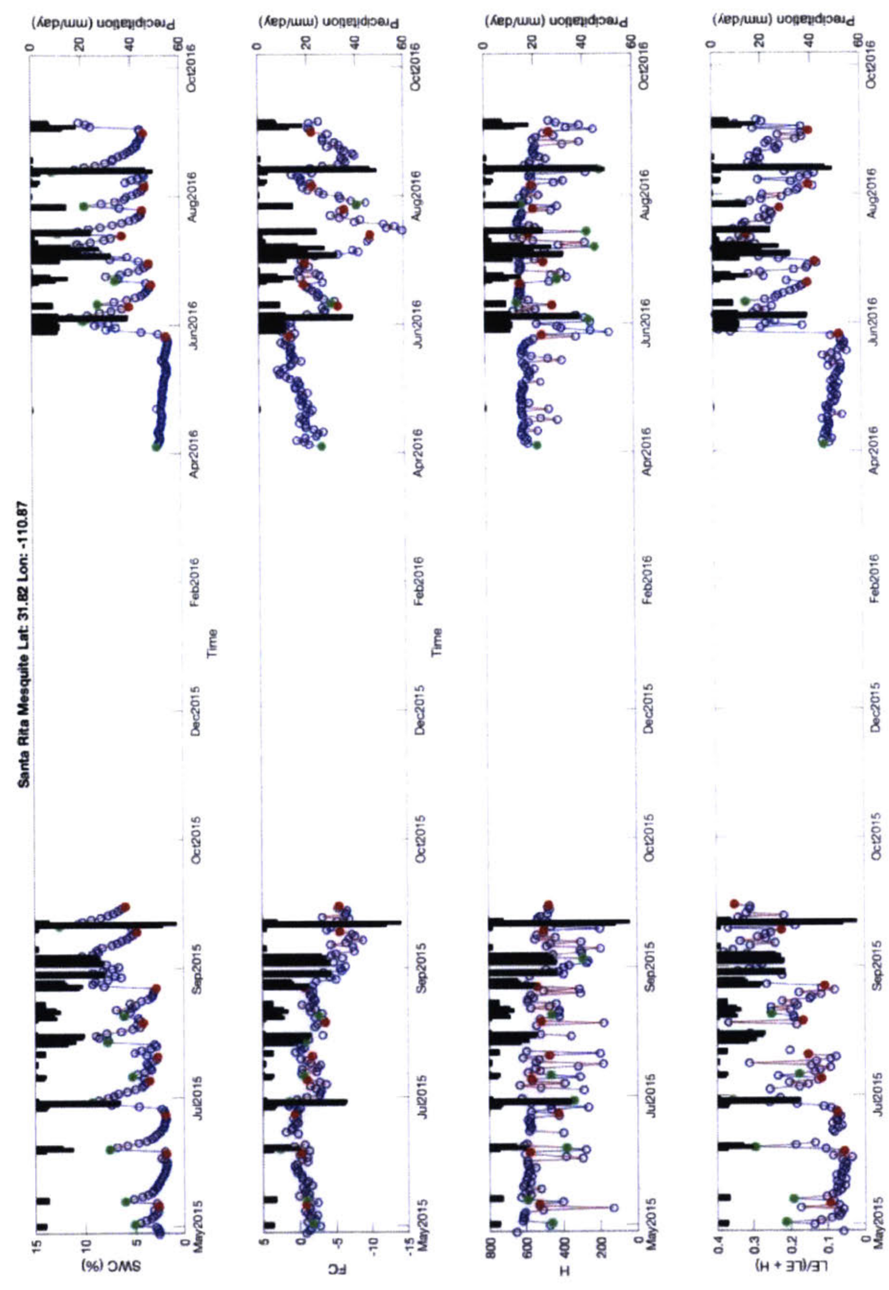

Figure g. Time series of SWC, FC, H, and WUE for Santa Rita Mesquite from May 2015 to October 2016. The black bars represent daily precipitation.

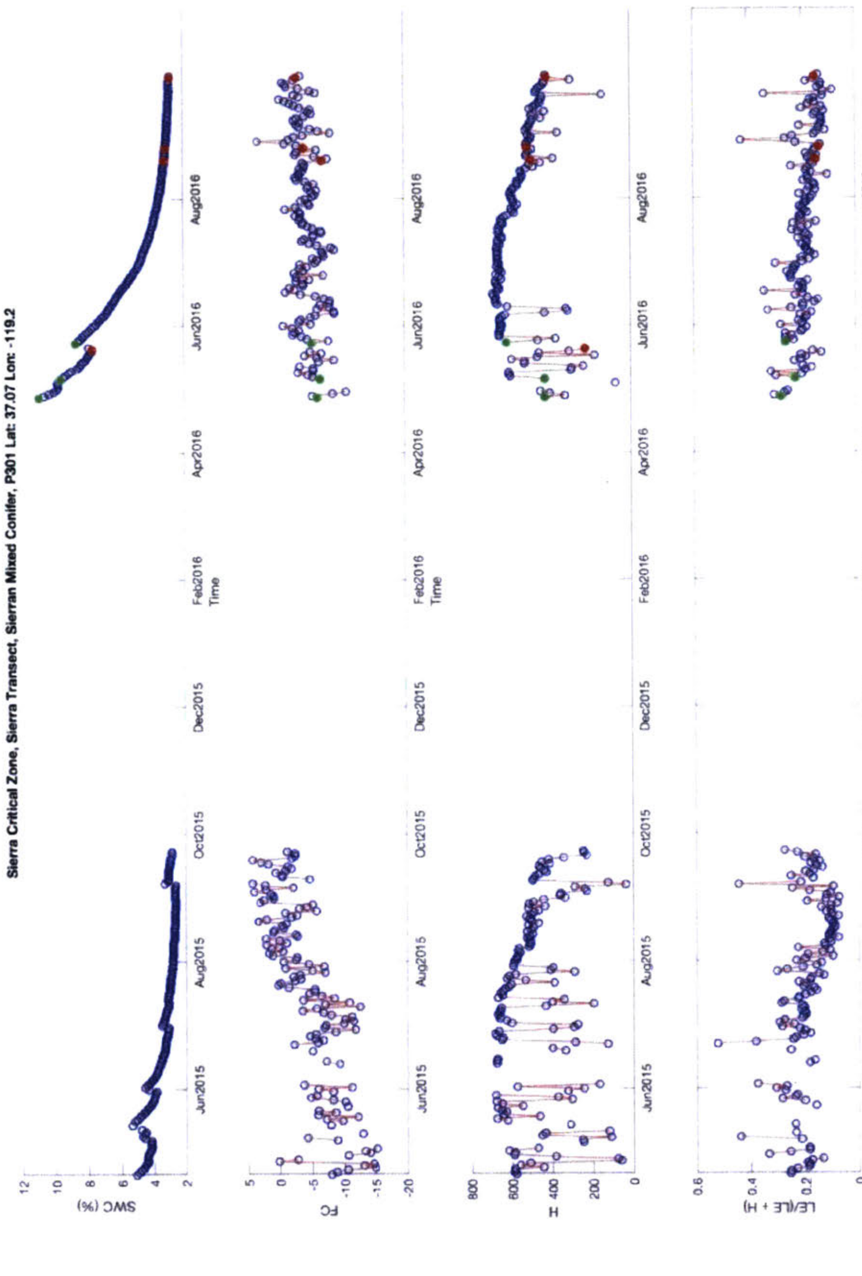

Figure h. Time series of SWC, FC, H, and WUE for Sierra Critical Zone, Sierra Transect, Sierran Mixed Conifer, P301 from May 2015 to October 2016. The black bars represent daily precipitation.

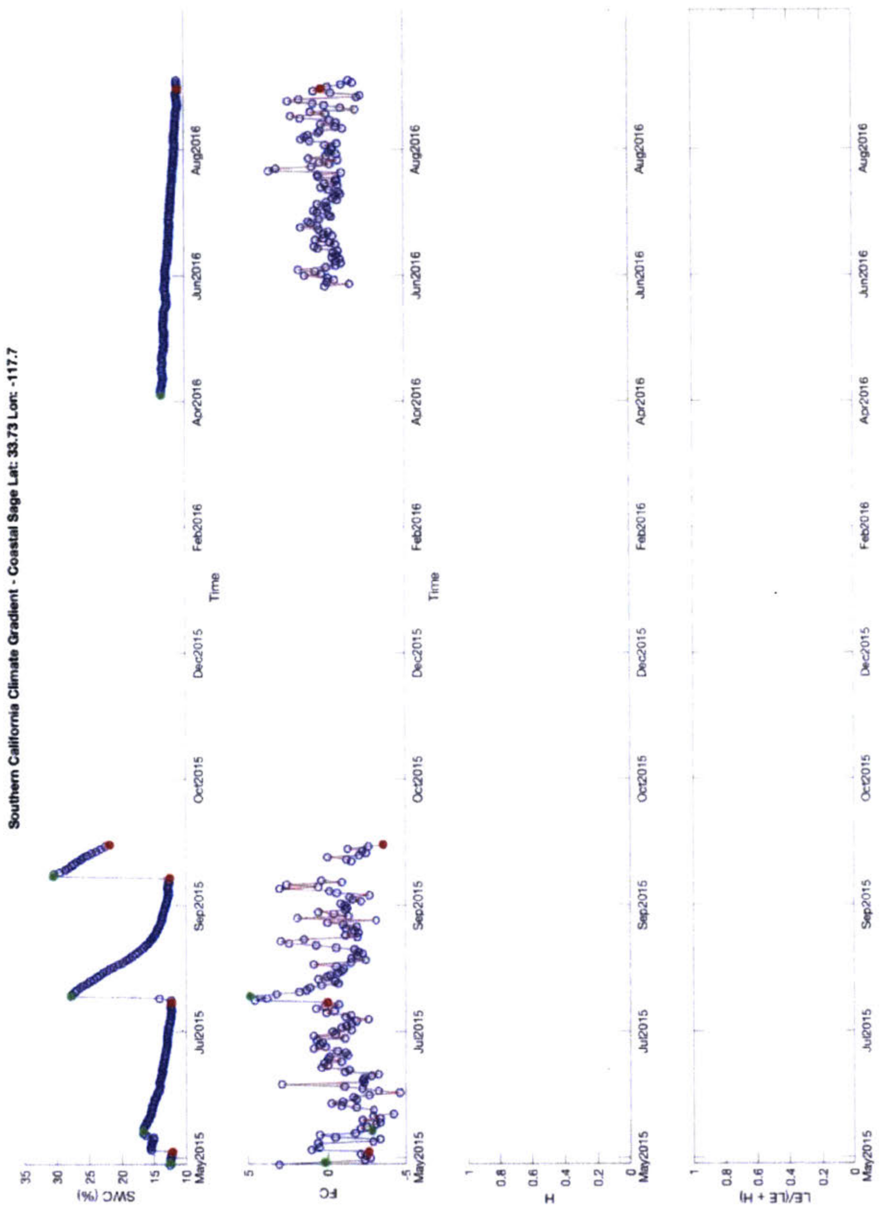

Figure i. Time series of SWC, FC for Southern California Climate Gradient - Coastal Sage from May 2015 to October 2016. H and WUE were available but not at the selected period. The black bars represent daily precipitation.

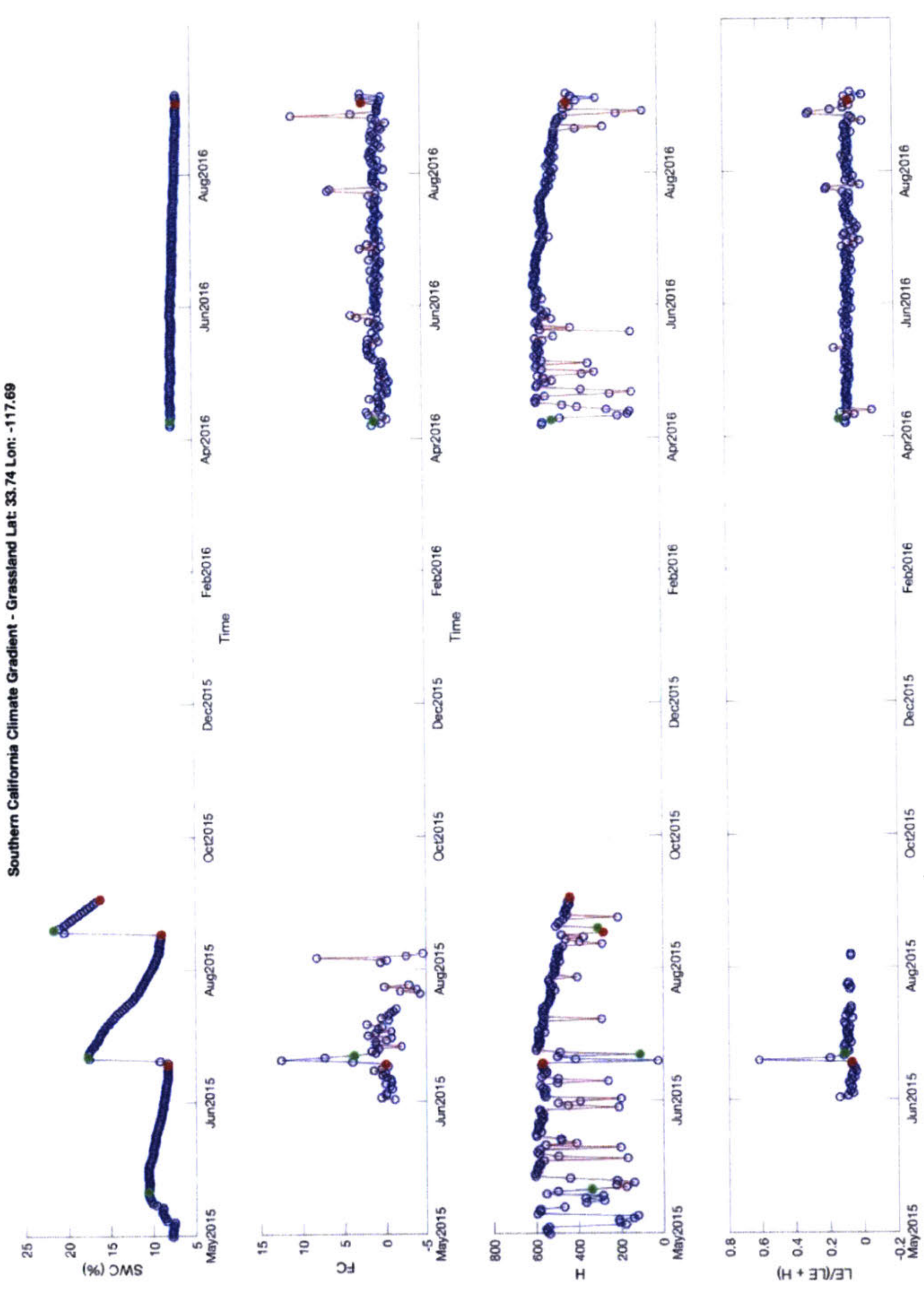

Figure j. Time series of SWC, FC, H, and WUE for Southern California Climate Gradient - Grassland from May 2015 to October 2016. The black bars represent daily precipitation.

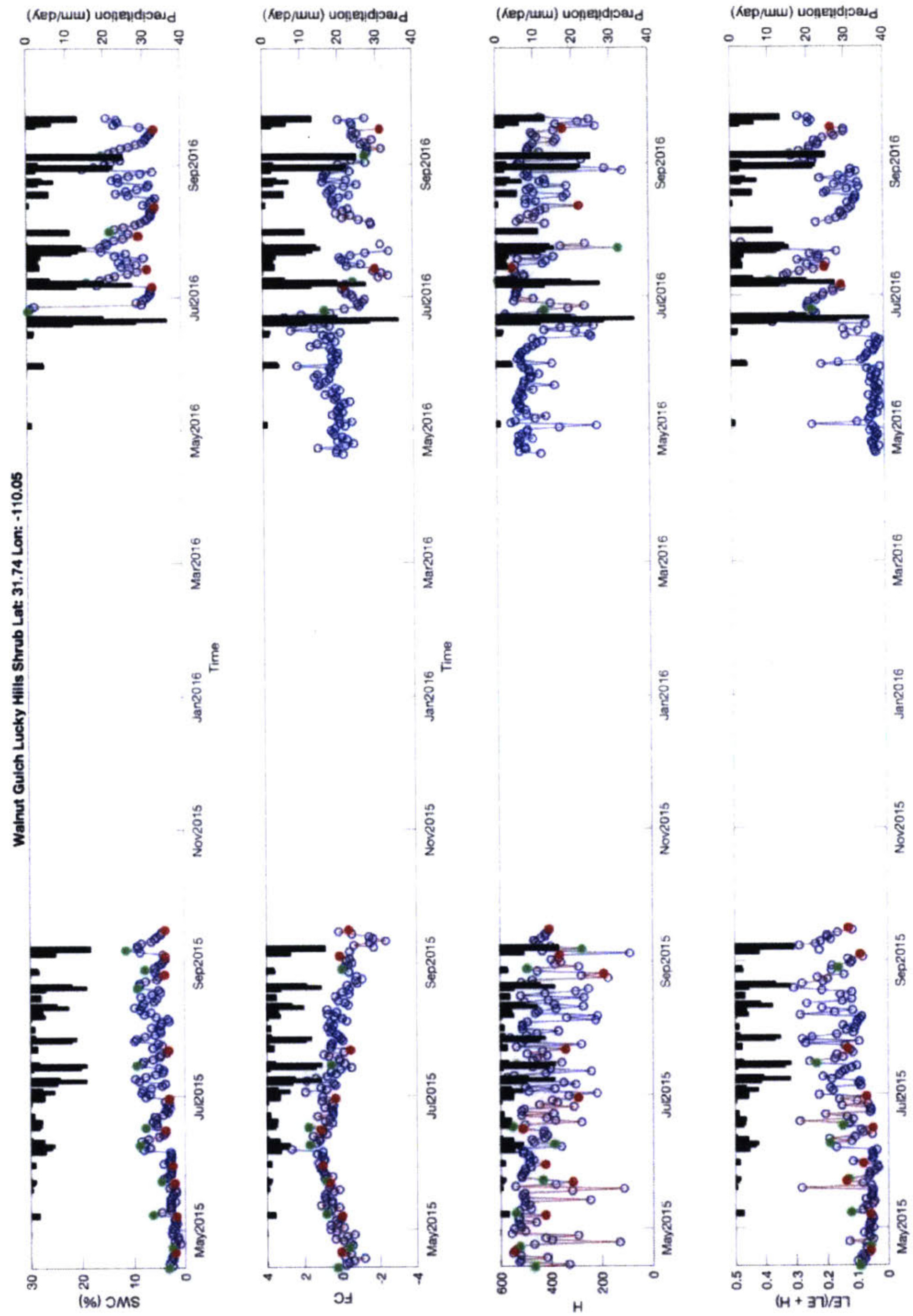

Figure k. Time series of SWC, FC, H, and WUE for Walnut Gulch Lucky Hills Shrub from May 2015 to October 2016. The black bars represent daily precipitation.

Appendix II: SMAP Time Series

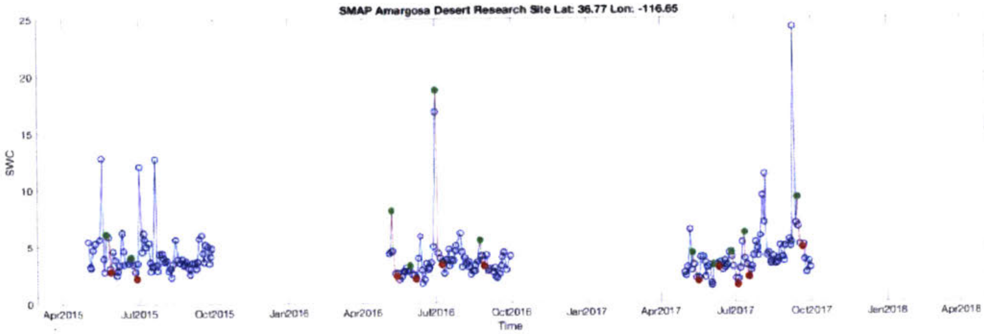

Figure l. VOD time series of the SMAP grid cell centered closest to the Amargosa Desert Research Site tower from April 2015 to October 2018.

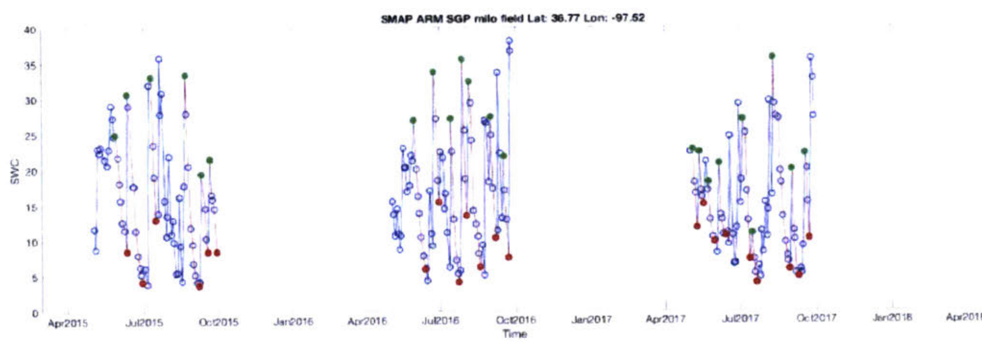

Figure m. VOD time series of the SMAP grid cell centered closest to the ARM SGP agricultural milo field tower from April 2015 to October 2018.

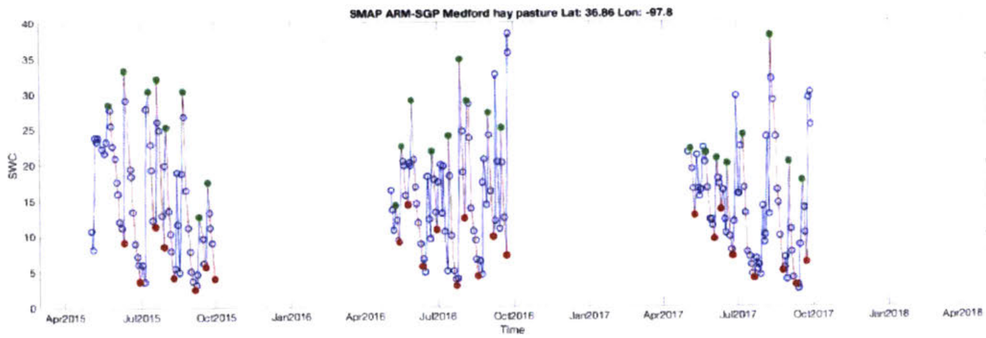

Figure. n VOD time series of the SMAP grid cell centered closest to the ARM-SGP Medford hay pasture tower from April 2015 to October 2018.

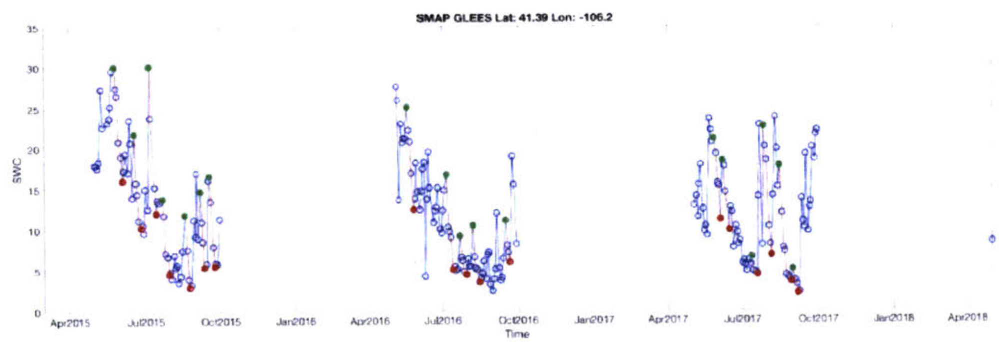

Figure. o VOD time series of the SMAP grid cell centered closest to the GLEES tower from April 2015 to October 2018.

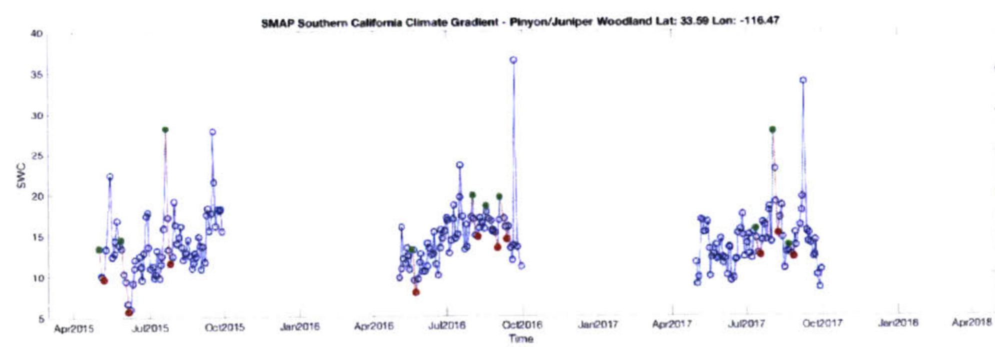

Figure. p VOD time series of the SMAP grid cell centered closest to the Southern California Climate Gradient - Pinyon/Juniper Woodland tower from April 2015 to October 2018.

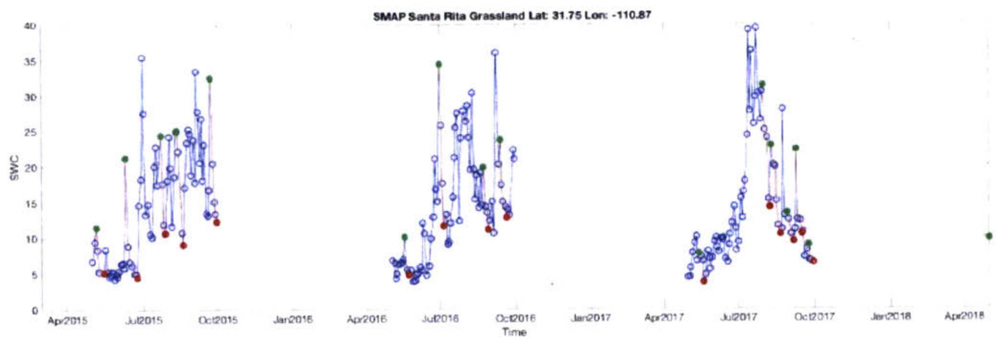

Figure. q VOD time series of the SMAP grid cell centered closest to the Santa Rita Grassland tower from April 2015 to October 2018.

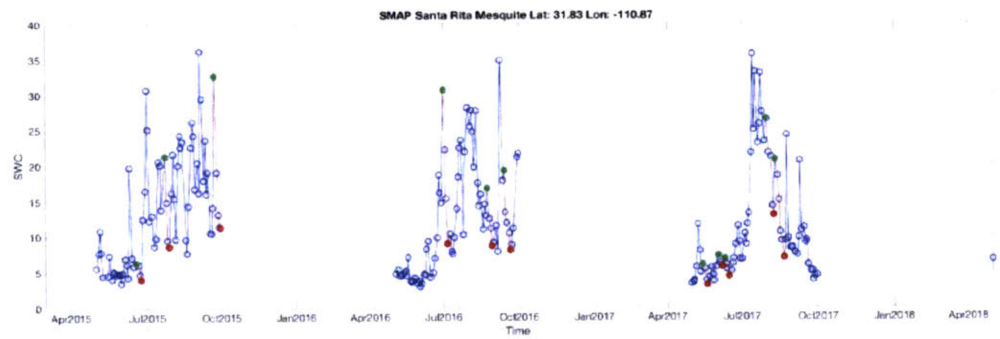

Figure. r VOD time series of the SMAP grid cell centered closest to the Santa Rita Mesquite tower from April 2015 to October 2018.

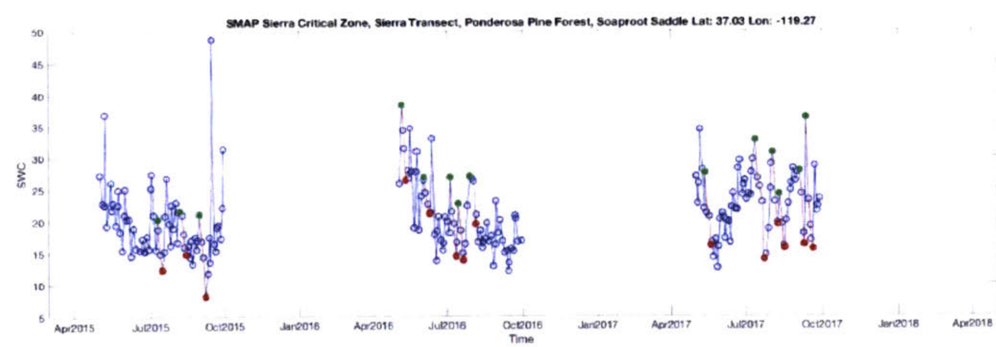

Figure. s VOD time series of the SMAP grid cell centered closest to the Sierra Critical Zone, Sierra Transect, Ponderosa Pine Forest, Soaproot Saddle tower from April 2015 to October 2018.

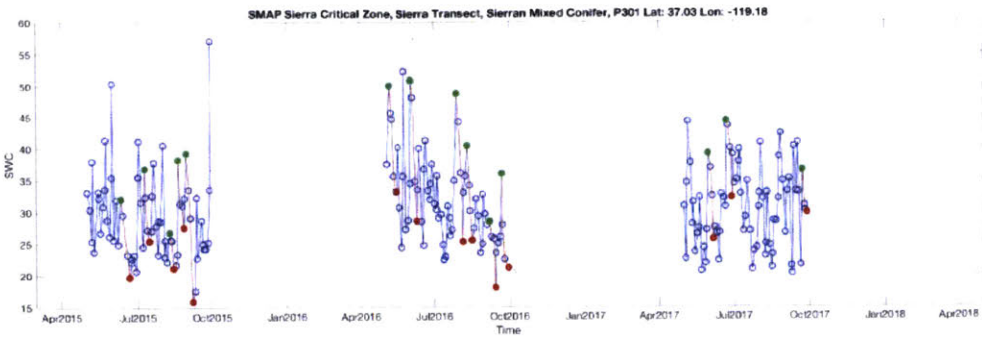

Figure. t VOD time series of the SMAP grid cell centered closest to the Sierra Critical Zone, Sierra Transect, Sierran Mixed Conifer, P301 tower from April 2015 to October 2018.

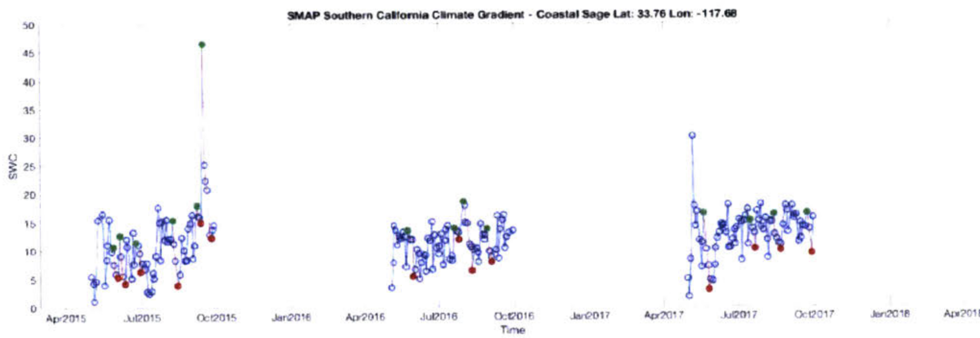

Figure. u VOD time series of the SMAP grid cell centered closest to the Southern California Climate Gradient tower from April 2015 to October 2018.

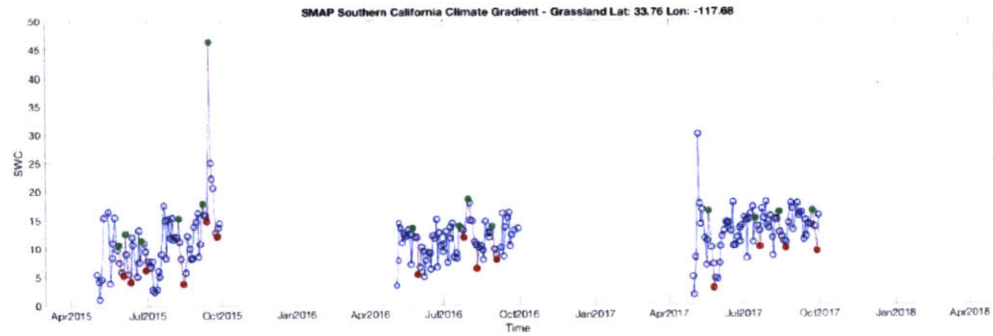

Figure. v VOD time series of the SMAP grid cell centered closest to the Amargosa Desert Research Site tower from April 2015 to October 2018.

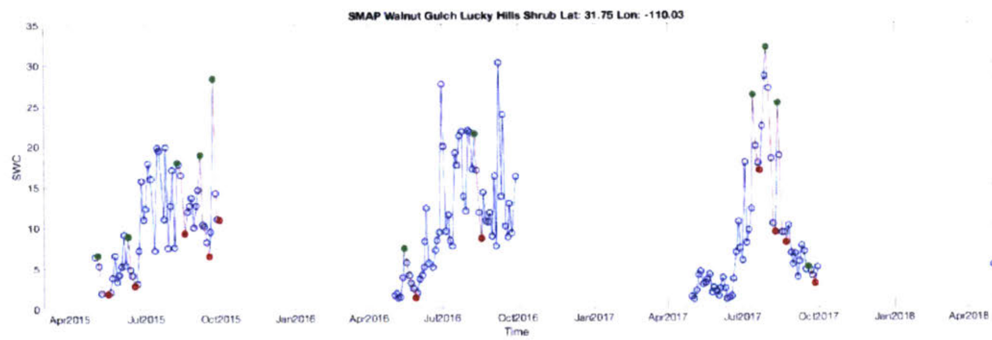

Figure. w VOD time series of the SMAP grid cell centered closest to the Amargosa Desert Research Site tower from April 2015 to October 2018.

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