Sensitivity of Forest Productivity to Trends in Snowmelt at Niwot Ridge, Colorado

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Abstract

Anthropogenic global warming caused by increased atmospheric carbon forcing is expected to cause a decrease in peak snow water equivalent (SWE), shift the timing of snowmelt to earlier in the year, and lead to slower melt rates in the mountains of the Western United States. High-elevation forests in mountainous terrain represent a critical carbon sink. Understanding the ecohydrology of subalpine forests is crucial for assessing the health of these sinks. The Niwot Ridge Long Term Ecological Research station, located at 3000 m amsl in the southern Rocky Mountains of Colorado, receives just over 1 m of annual precipitation mostly as snow, supporting a persistent seasonal snowpack in alpine and subalpine ecosystems. Previous studies show that longer growing season length is correlated with shallower snowpack, earlier spring onset and reduced net CO2 uptake. Co-located sensors provide over 20 years of continuous SWE and eddy covariance (EC) data, allowing for robust direct comparison of snow and carbon phenomena in a high-elevation catchment. Linear regression and time series analysis was performed on snowmelt, meteorological, phenological and ecosystem productivity variables. Peak productivity is correlated with peak SWE (R2=0.54) and further correlated with snowmelt disappearance (R2=0.38) and the timing of spring growth onset (R2=0.30). Timing of both peak productivity and spring growth onset are correlated with snowmelt and meteorological variables. A multivariable regression of meteorological variables, timing of spring growth onset, a temporal trend, and snowmelt rate and explains 94% of interannual variability in the timing of peak forest productivity. These results develop support and introduce new evidence for the existing studies of Niwot Ridge ecohydrology. Future work will investigate the meteorological and hydrological record extending back to 1979 and the long-term trends in snowmelt and forest productivity.

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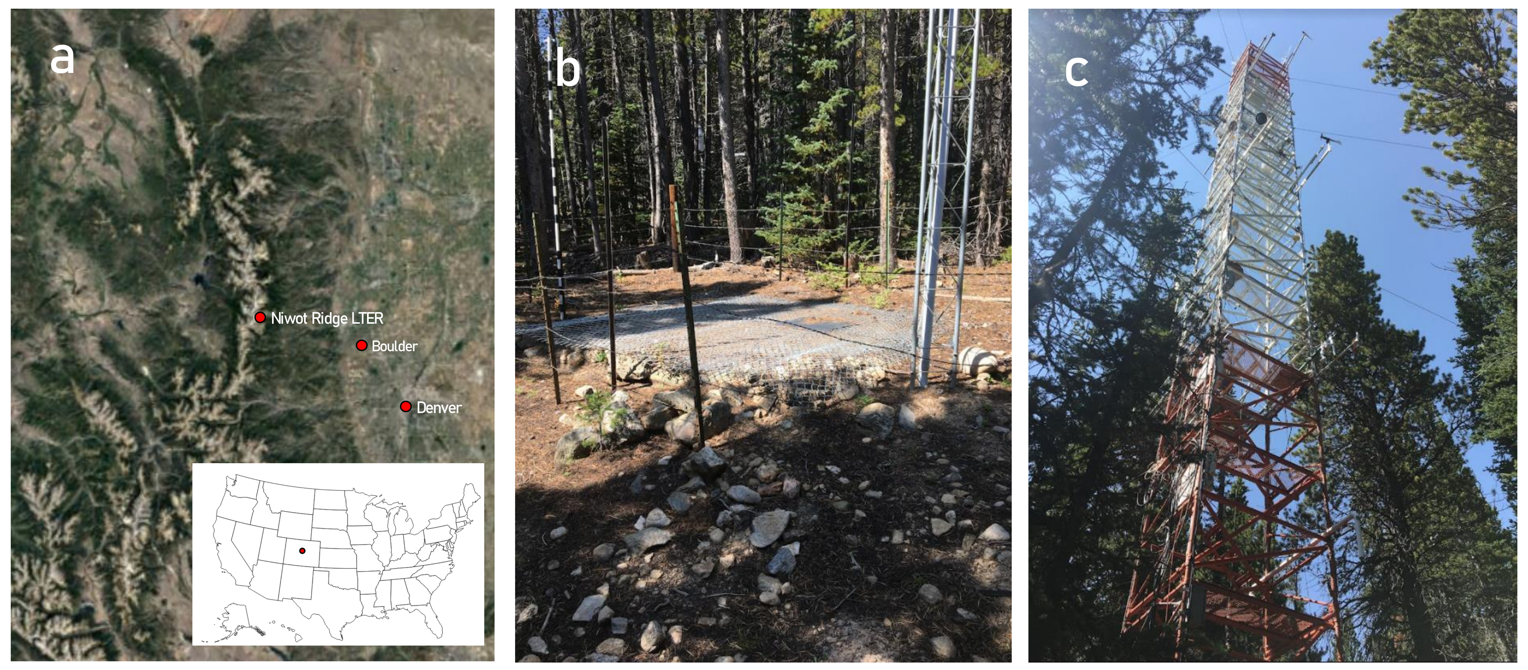
Niwot Ridge Long-Term Ecological Research Station (LTER)

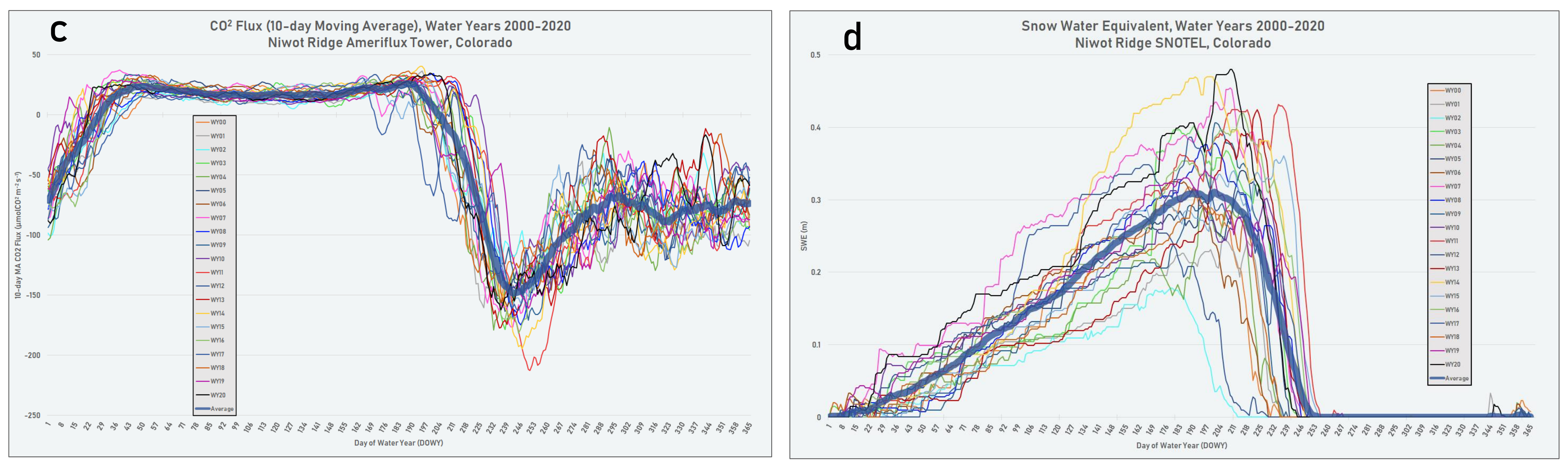
Anthropogenic global warming caused by increased atmospheric carbon forcing is expected to cause a decrease in peak snow water equivalent (SWE), shift the timing of snowmelt to earlier in the year, and lead to slower melt rates in the mountains of the Western United States[1,2].

The Niwot Ridge LTER station[3], located in the southern Rocky Mountains of Colorado, receives just over 1 m of annual precipitation mostly as snow, supporting a persistent seasonal snowpack in alpine and subalpine ecosystems[4].

Previous studies show that longer growing season length is correlated with shallower snowpack, earlier spring onset and reduced net CO^2 uptake[5,6].



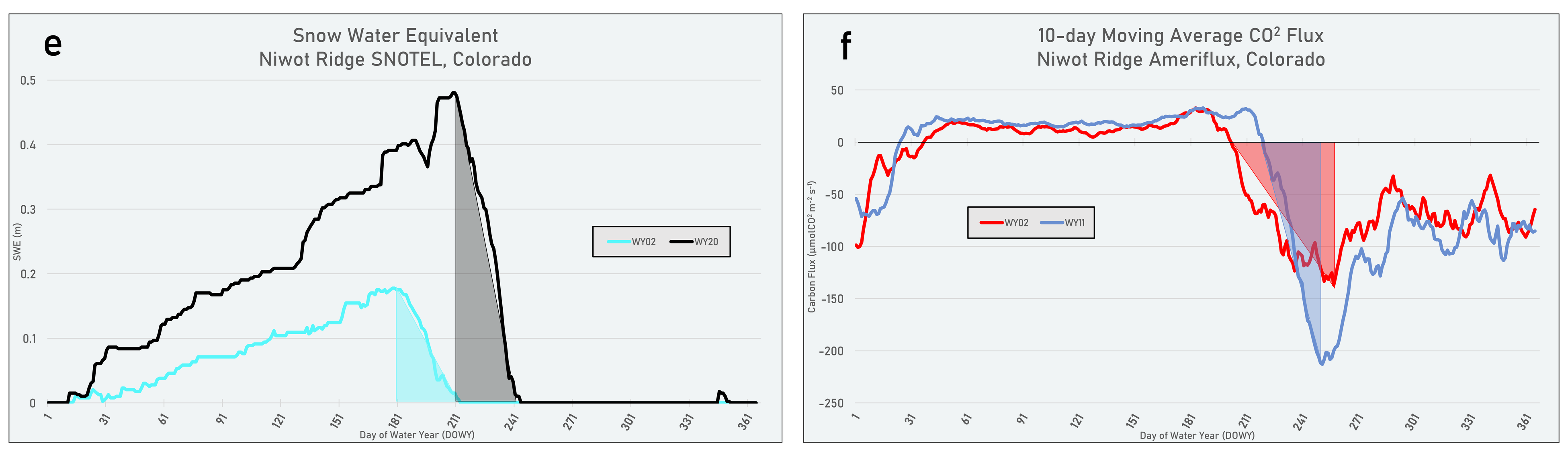
Area map (a) from Google Earth, SNOTEL site (b), and Ameriflux Tower (c) at Niwot Ridge LTER, Colorado (40.05°N, 105.6°W), located at 3000 m asl. The co-located sensors provide over 20 years of continuous SWE and eddy covariance (EC) data, allowing for robust direct comparison of snow and carbon phenomena in a high-elevation catchment.



Annual CO2 Flux (c) and SWE records (d) over Water Year (WY) 2000-2020 at Niwot Ridge. On average, peak SWE occurs on Day of Water Year (DOWY) 199, or April 17th. Spring growth onset occurs on DOWY 207, or April 25th, and both the disappearance of snow and timing of peak carbon flux occur on DOWY 241, or May 29th.

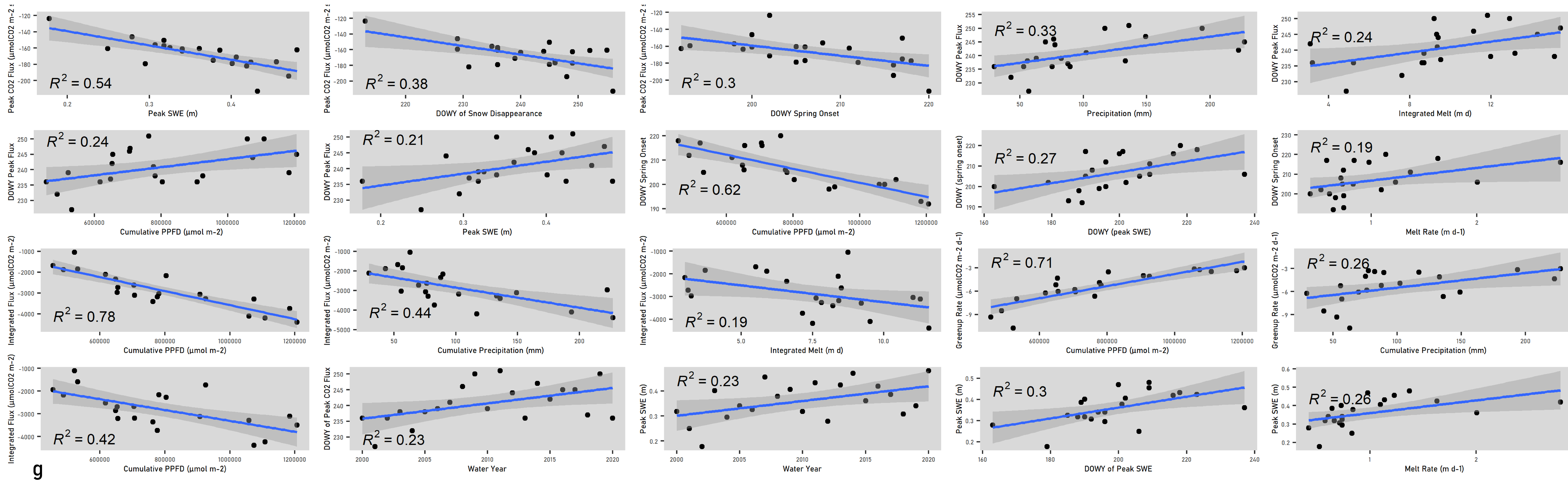
What are the snowmelt, meteorological, and phenological controls for forest productivity at Niwot Ridge and what are the time series trends?

Hypothesis: Warmer & Earlier Melt Attenuates Peak Carbon Flux



Earlier peak SWE, slower melt, and earlier DSD were hypothesized to correlate with earlier spring onset, earlier peak carbon flux, and lower peak carbon flux. Integrated melt as illustrated in (e) and integrated flux (f) were predicted to be positively correlated with each other and peak carbon flux.

Regression Analysis of Ameriflux Tower and SNOTEL data, Water Years 2000 - 2020



Peak productivity is correlated with peak SWE (R^2=0.54) and further correlated with snowmelt disappearance (R^2=0.38) and the timing of spring growth onset (R^2=0.30).

Timing of both peak productivity and spring growth onset are correlated with snowmelt and meteorological variables.

A multivariable regression of meteorological variables, timing of spring growth onset, a temporal trend, and snowmelt rate and explains 94% of interannual variability in the timing of peak forest productivity.

h

Variable	Mean	Std. Dev.	Min	Max
fluxmin	-167.2	18.269	-212.9	-123.7
dowyfluxmin	240.714	6.254	227	251
dowyonset	206.81	8.418	192	220
intgreenup	-2805.929	846.261	-4383.3	-1115.1
intgreenuptri	-2866.814	877.139	-4391.6	-1053.5
daysgreenup	34.476	10.745	14	54
rategreenup	-5.434	2.136	-10.75	-3.01
swemax	0.36	0.077	0.178	0.48
dowyswemax	199.19	16.278	163	237
dsd	240.905	10.242	213	256
daysmelt	41.714	13.081	15	66
intmelt	9.659	3.571	3.1	15.43
intmelttri	7.438	2.587	3.03	11.58
ratemelt	1.001	0.565	0.423	2.793
precip	101.976	56.435	29.7	227.195
ppfd	789269.866	229989.492	456071.755	1206379
tempavg	4.061	1.162	1.76	5.86

Regression plots for each statistically significant ($p < 0.05$) relationship in the analysis with R-squared values (g), table of summary statistics (h) and definitions for variables used in the regression analysis (i).

i

Category	Variable Name	Definition	Units
Snowmelt (SNOTEL)	swemax	Annual Maximum snow water equivalent (SWE)	m
	dowyswemax	Day of Water Year (0-365 starting October 1) of maximum SWE	
	dsd	Day of Water Year of Snow Disappearance	
	daysmelt	Length of Melt Period (dsd-dowyswemax)	d
	ratemelt	Rate of Snow Melt (swemax/daysmelt)	$m\ d^{-1}$
	intmelt	Integrated Melt (area under niviograph integrated over daysmelt)	m d
	intmelttri	Integrated Melt simplified as triangle (swemax*daysmelt/2)	m d
Carbon Flux (Ameriflux)	fluxmin	Annual Minimum CO^2 flux (10-day moving average)	$\mu molCO^2\ m^{-2}\ s^{-1}$
	dowyfluxmin	Day of Water Year of fluxmin	
	dowyonset	Day of Water Year of first negative flux (10-day MA)	
	daysgreenup	Length of "Spring Greenup" (dowyfluxmin-dowyonset)	d
	rategreenup	Rate of Greenup (fluxmin/daysgreenup)	$\mu molCO^2\ m^{-2}\ s^{-1}\ d^{-1}$
	intgreenup	Integrated Flux (area above flux curve integrated over daysgreenup)	$\mu molCO^2\ m^{-2}$
	intgreenuptri	Integrated Flux simplified as triangle (fluxmin*daysgreenup/2)	$\mu molCO^2\ m^{-2}$
Meteorology (Ameriflux)	precip	Cumulative Precipitation during Greenup	mm
	ppfd	Cumulative Photosynthetically Active Photon Density (PPFD) during Greenup	µmol m-2
	tempavg	Average Temperature during Greenup	°C
	vpdavg	Average Vapor Pressure Deficit (VPD) during Greenup	kPa

Multivariable Regression Analysis

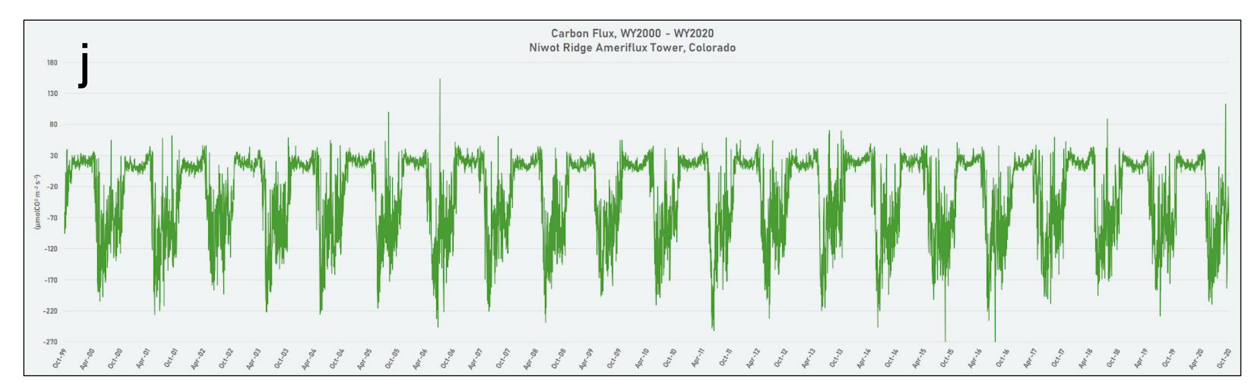
fluxmin ~ swemax + dowyonset + wy + precip + tempavg
- R-squared = 0.71

dowyfluxmin ~ ratemelt + ppfd + precip + dowyonset
- R-squared = 0.94

dowyonset ~ ppfd + swemax
- R-squared = 0.71

Implications and Future Work

These results develop support and introduce new evidence for the existing studies of Niwot Ridge ecohydrology. Future work will investigate the meteorological and hydrological record extending back to 1979 and the long-term trends in snowmelt and forest productivity.



The complete semi-hourly CO^2 flux record (j) will be further analyzed in context of additional available hydrological and ecological datasets to investigate the health of the carbon sink at Niwot Ridge.

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