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Water limitations on forest carbon cycling and conifer traits along a steep climatic gradient in the Cascade Mountains, Oregon

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Table S1. Key describing variable names, abbreviations, and units.

Category	Variable	Abbreviation	Units
Forest structure	aboveground biomass in living trees	AGB	kg C m^{-2}
	half-total surface leaf area	LAI	m^2 leaf m^{-2}
Forest growth	aboveground net primary productivity	ANPP	kg C m^{-2} yr^{-1}
	annual ring-width index	RWI	unitless
Tree characteristics	diameter at breast height	DBH	Cm
	height	H	M
	stem wood density	WD	g DM cm^{-3}
	stem wood density (ecosystem-average)	$\overline{WD}$	g DM cm^{-3}
	specific leaf area	SLA	cm^2 HSA g^{-1} C
	leaf:sapwood area ratio	LA:SA	m^2 leaf cm^{-2} sapwood
	leaf longevity	LL	years
	leaf carbon	C	% of dry weight
	leaf nitrogen	N	% of dry weight
Climate (monthly)	average, max, min temperature	T_{avg}, T_{min}, T_{max}	°C
	daily temperature range	T_{rng}	°C
	daily mean extraterrestrial radiation	R	MJ m^{-2} day^{-1}
	reference evapotranspiration	ET_0	mm $month^{-1}$
	precipitation (rain + snow)	PPT	mm $month^{-1}$
	climate moisture index (PPT-ET_0)	CMI	mm $month^{-1}$
	standardized precipitation evapotranspiration index	$SPEI$	unitless
Climate (growing-year)	e.g. CMI summed Oct. through Sept.	CMI_{gy}	mm $year^{-1}$
Climate (50-year average)	e.g. CMI_{gy} averaged annually 1964-2013	$CMI_{\overline{gy}}$	mm $year^{-1}$
Tree growth-climate response	ecosystem-average RWI-CMI correlation	$\bar{r}_{\text{RWI-}CMI}$	r
	% trees with significant positive RWI-CMI correlation	$F_{\text{RWI-}CMI}$	%

Table S2. Location and forest characteristics of 12 field sites located in the eastern Cascade Mountains, Oregon. Forest characteristics include aboveground live biomass (AGB), annual aboveground net primary productivity (ANPP), leaf area index (LAI), sapwood area, leaf:sapwood area ratio (LA:SA), maximum tree height (H_{max}), and ecosystem-average stem wood density (WD), leaf longevity (LL), specific leaf area (SLA), leaf carbon (C) and leaf nitrogen (N). Characteristics were averaged (± SE) across four subplots per plot. Stand age was calculated as the average age of the oldest 10% of trees. Sites were sampled during the summer of 2014.

Forest type	Plot	Lat.	Long.	Elev. (m)	Trees per ha	Stand Age (yrs)	AGB (kg C m^{-2})	ANPP (g C m^{-2} yr^{-1})	LAI (m^2 m^{-2})	Sapwood (cm^2 m^{-2})	LA:SA (m^2 cm^{-2})	H_{max} (m)	WD (g cm^{-3})	LL (yrs)	SLA (cm^2 g C^{-1})	C (%)	N (%)
western juniper	1	44.203	-121.368	1007	99±26	148	1.91±0.72	15±2	0.24±0.06	2.32±0.75	0.10±0.04	10.6±1.0	0.46±0.02	5.6 [c]	62±1	48.3±0.2	0.94±0.02
	2	44.247	-121.433	958	157±16	537	2.93±0.85	19±2	0.37±0.05	3.87±0.85	0.10±0.02	9.9±0.3	0.43±0.01	5.6 [c]	66±3	48.0±0.2	0.91±0.02
	3	44.297	-121.333	929	113±24	253	2.61±0.84	11±2	0.09±0.03	3.03±0.88	0.03±0.01	10.5±0.1	0.45±0.01	5.6 [c]	66±2	48.3±0.1	0.95±0.03
	4[a,b]	44.311	-121.327	908	85±18	32	0.21±0.04	15 ±3	0.32±0.04	1.36±0.33	0.24±0.07	5.7±0.7	0.45±0.01	5.6 [c]	72±3.6	47.3±0.2	1.45±0.29
	5	44.264	-121.344	975	156±19	119	2.52±0.48	18±2	0.35±0.09	4.26±0.65	0.08±0.02	11.2±0.8	0.48±0.02	5.6 [c]	60±2	48.2±0.5	0.77±0.02
ponderosa pine	1	44.326	-121.674	1124	127±20	327	16.18±2.67	143±16	1.41±0.17	13.27±1.72	0.11±0.02	35.4±0.5	0.45±0.02	4.9±0.2	96±1	47.9±0.1	1.17±0.04
	2	44.344	-121.573	978	276±74	190	7.12±1.44	124±24	1.63±0.09	16.20±3.86	0.10±0.02	26.2±1.0	0.42±0.02	3.4±0.1	94±3	48.4±0.1	1.11±0.03
	3	44.258	-121.650	1315	251±26	280	9.83±1.24	258±8	2.58±0.19	16.55±0.95	0.16±0.01	27.1±3.0	0.42±0.01	4.9±0.3	91±6	48.2±0.1	1.15±0.04
	4 (US-Me6)[a,c]	44.323	-121.605	996	165±26	23	0.71±0.05	77±7	1.21±0.09	5.70±0.75	0.21±0.03	8.43±0.3	0.43±0.02	4.8±0.3	82±3	48.9±0.1	1.21±0.04
	5 (US-Me2)[d]	44.451	-121.558	1254	334±36	106	8.57±0.66	206±23	2.04±0.21	19.63±1.73	0.10±0.01	22.9±0.7	0.44±0.02	3.9±0.3	82±3	48.3±0.1	1.05±0.02
grand fir	1	44.232	-121.670	1560	645±77	114	8.83±1.64	205±12	5.19±0.29	18.77±1.97	0.28±0.03	25.6±3.1	0.39±0.02	6.8±0.3	100±5	48.2±0.1	0.80±0.02
	2	44.241	-121.684	1519	597±76	194	21.48±2.46	311±60	6.15±1.12	23.13±1.49	0.27±0.05	35.0±1.7	0.39±0.02	9.0±0.9	104±10	47.9±0.2	0.99±0.03
	3[a]	44.302	-121.756	1429	613±212	46	11.22±2.91	340±166	5.39±1.03	17.86±2.66	0.30±0.07	25.6±2.84	0.41±0.01	7.49±1.11	89±5	48.3±0.19	1.04±0.73
	4	44.302	-121.702	1208	233±72	82	10.40±0.69	190±34	2.67±0.16	9.95±1.37	0.27±0.04	35.2±2.4	0.40±0.01	7.5±1.1	99±4	47.9±0.2	0.90±0.05
	5	44.370	-121.758	1292	205±14	182	16.68±2.11	246±18	4.16±0.04	13.01±1.27	0.32±0.03	38.5±1.4	0.41±0.01	7.7±1.1	89±3	48.0±0.2	0.94±0.10

[a] Young stands that were not included in the analysis.
[b] Western juniper leaf longevity was calculated as the ratio of foliage biomass to annual leaf fall using measurements from Runyon et al. (1994).
[c] AmeriFlux Metolius Young Pine Burn (US-Me6) flux tower. The stand was not mature and therefore was not included in the analysis.
[d] AmeriFlux Metolius Mature Pine (US-Me2) flux tower.

Table S3. Equations relating sapwood area (SA; cm^2) to diameter at breast height (DBH; cm) for three conifer species in the eastern Cascade Mountains, Oregon. Equations are of the form $SA = aDBH$, where a is the slope of the relationship.

Species	a	a [se]	r^2	RMSE (cm^2)	n
western juniper	6.096	0.343	0.85	91	56
ponderosa pine	18.135	0.615	0.93	265	65
grand fir	9.685	0.462	0.90	133	51

Table S4. Equations relating tree height (H; m) to diameter at breast height (DBH; cm) for three conifer species in the eastern Cascade Mountains, Oregon. Equations are of the form $H = 1.3 + e^{a + \frac{b}{DBH+c}}$, where *a*, *b*, and c are fitted coefficients.

Species	a	a [se]	b	b [se]	c	c [se]	r^2	RMSE (m)	n
western juniper	2.214	0.052	-14.095	2.502	2.138	1.621	0.66	1.55	225
ponderosa pine	4.015	0.054	-50.696	5.154	7.738	2.253	0.86	3.12	378
grand fir	4.081	0.079	-49.431	6.333	8.495	2.327	0.87	3.21	340

Table S5. Average (± 1 SE) growing-year climate conditions from 1964 to 2013 for sites dominated by western juniper, ponderosa pine, and grand fir in the eastern Cascade Mountains, Oregon. The growing-year extended from October of year *t-1* through September of year *t*. Climate variable include average daily temperature ($T_{\overline{gy}}$), precipitation ($PPT_{\overline{gy}}$), reference evapotranspiration ($ET_{\overline{gy}}$) and climate moisture index ($CMI_{\overline{gy}} = PPT_{\overline{gy}} - ET_{\overline{gy}}$ calculated from monthly PRISM climate data (Daly et al. 2008).

Forest type	**Plot**	$T_{\overline{gy}}$ (° C)	$PPT_{\overline{gy}}$ (mm yr^{-1})	$ET_{\overline{gy}}$ (mm yr^{-1})	$CMI_{\overline{gy}}$ (mm yr^{-1})
western juniper	1	8.25±0.11	287±11	1498±29	-1211±28
	2	8.21±0.11	311±11	1545±30	-1234±29
	3	8.60±0.11	264±10	1527±29	-1263±28
	4	8.42±0.11	273±10	1484±28	-1211±28
ponderosa pine	1	6.97±0.10	615±21	1438±28	-823±30
	2	7.72±0.11	421±15	1543±30	-1122±30
	3	6.03±0.10	749±26	1174±23	-426±30
	4	7.37±0.11	508±18	1222±24	-714±26
grand fir	1	6.03±0.10	749±26	1174±23	-426±30
	2	6.03±0.10	749±26	1174±23	-426±30
	3	6.26±0.10	901±30	1226±24	-326±33
	4	6.46±0.10	1236±38	1184±24	52±38

Table S6. Summary of tree-ring width index (RWI) correlations with a variety of climate variables for three tree species in the eastern Cascade Mountains, Oregon. Correlations between RWI and the climate variables were computed for each individual tree (n=216), with climate data averaged (temperature-related variables) or summed (water-related variable) monthly at 1- to 36-month lags. The climate response for each tree was then summarized based on the average of the top 5% of correlations, regardless of the temporal response window. The climate response for each species was the evaluated both in terms of the percent of trees that exhibited a significant (P<0.05) positive or negative correlation with the climate variable of interest and as the average strength of the correlation.

Climate variable	**Units**	**Species**	**% of trees with sig. RWI-climate correlation**				**RWI-climate correlation (r)**					
			1964 to 2013		**1994 to 2013**		**1964 to 2013**			**1994 to 2013**		
			negative	**positive**	**negative**	**positive**	**mean**	**SD**	**P**	**mean**	**SD**	**P**
T_{avg}	°C	western juniper	33.36	5.94	28.00	8.10	-0.21	0.13	0.19	-0.25	0.17	0.23
		ponderosa pine	24.89	5.59	19.95	4.30	-0.16	0.15	0.32	-0.20	0.19	0.33
		grand fir	18.11	9.23	10.81	5.55	-0.11	0.14	0.34	-0.06	0.18	0.43
T_{max}	°C	western juniper	72.05	3.6	61.17	1.80	-0.33	0.13	0.10	-0.36	0.18	0.12
		ponderosa pine	35.21	4.55	29.00	2.76	-0.2	0.16	0.26	-0.24	0.20	0.27
		grand fir	19.55	5.16	12.10	5.50	-0.14	0.14	0.32	-0.12	0.19	0.41
T_{min}	°C	western juniper	6.76	49.91	4.56	42.24	0.26	0.14	0.16	0.32	0.19	0.18
		ponderosa pine	9.48	12.69	7.20	13.50	0.06	0.14	0.43	0.14	0.20	0.40
		grand fir	10.5	12.64	7.07	9.90	0.04	0.14	0.40	0.10	0.19	0.44
VPD	kPa	western juniper	87.45	3.75	78.68	3.64	-0.41	0.15	0.07	-0.45	0.19	0.08
		ponderosa pine	46.68	4	37.33	2.22	-0.23	0.17	0.23	-0.26	0.20	0.25
		grand fir	29.41	4.06	18.39	4.82	-0.18	0.15	0.28	-0.16	0.21	0.35
Freeze	days	western juniper	45.79	4.33	40.36	2.75	-0.25	0.13	0.16	-0.32	0.18	0.18
		ponderosa pine	14.28	9.1	14.20	6.86	-0.07	0.15	0.41	-0.14	0.20	0.39
		grand fir	12.67	14.9	8.86	8.91	0.03	0.14	0.39	-0.08	0.19	0.45
CMI	mm	western juniper	2.62	90.59	2.09	89.24	0.52	0.18	0.05	0.56	0.20	0.05
		ponderosa pine	4.14	50.86	2.00	39.84	0.27	0.21	0.23	0.28	0.21	0.24
		grand fir	6.86	11.62	6.25	9.84	0.11	0.13	0.40	0.05	0.22	0.42
Deficit	mm	western juniper	89.24	3.56	87.95	1.58	-0.46	0.16	0.06	-0.52	0.20	0.07
		ponderosa pine	52.67	4	43.37	2.60	-0.26	0.17	0.19	-0.30	0.20	0.21
		grand fir	13	7.33	8.45	6.70	-0.11	0.13	0.39	-0.11	0.19	0.41
SPEI	unitless	western juniper	3.83	90.94	2.56	89.31	0.53	0.18	0.05	0.57	0.20	0.05
		ponderosa pine	4.44	51.38	2.14	40.94	0.25	0.2	0.20	0.28	0.21	0.22
		grand fir	5.86	10.6	6.31	8.78	0.11	0.12	0.44	0.05	0.21	0.42

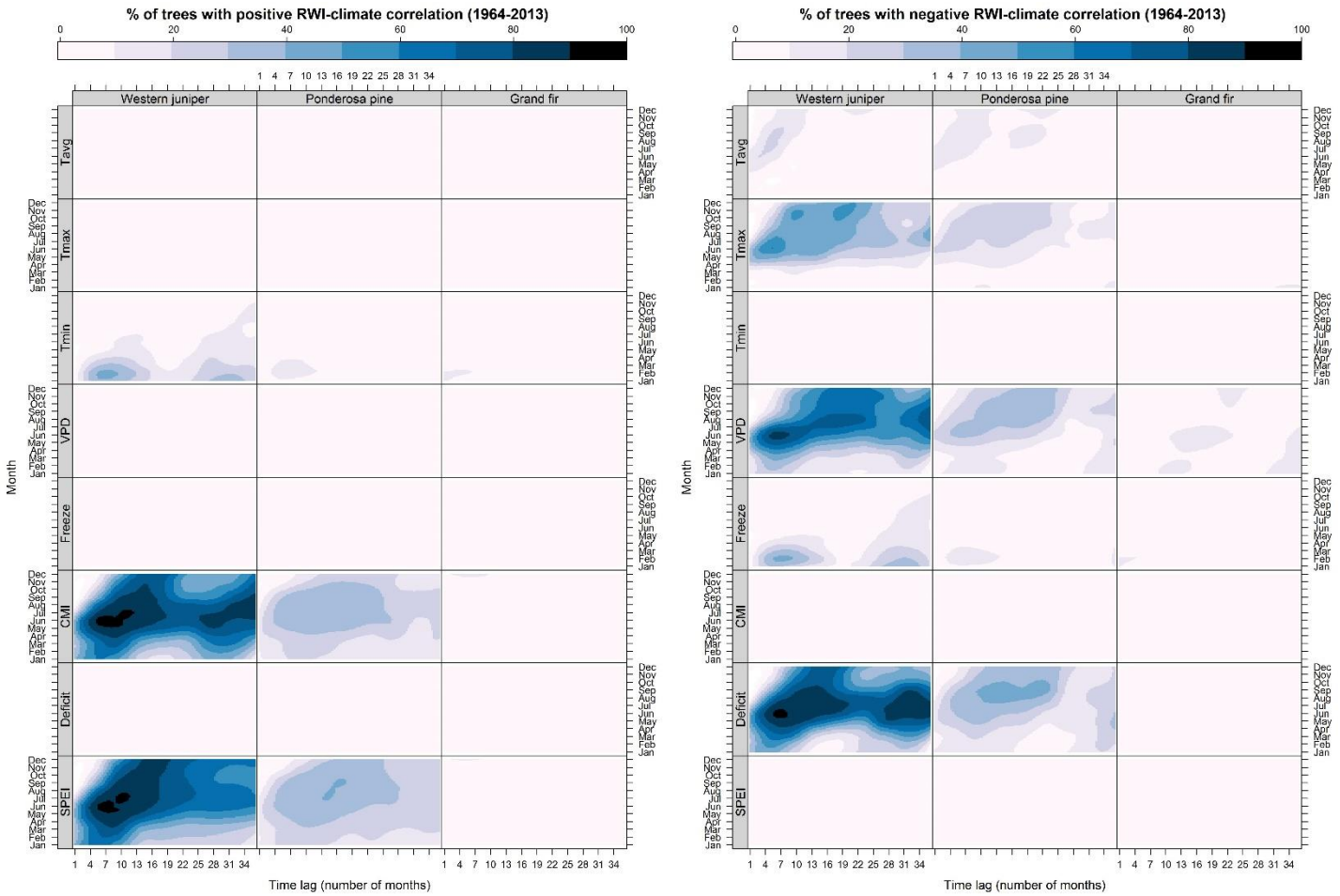
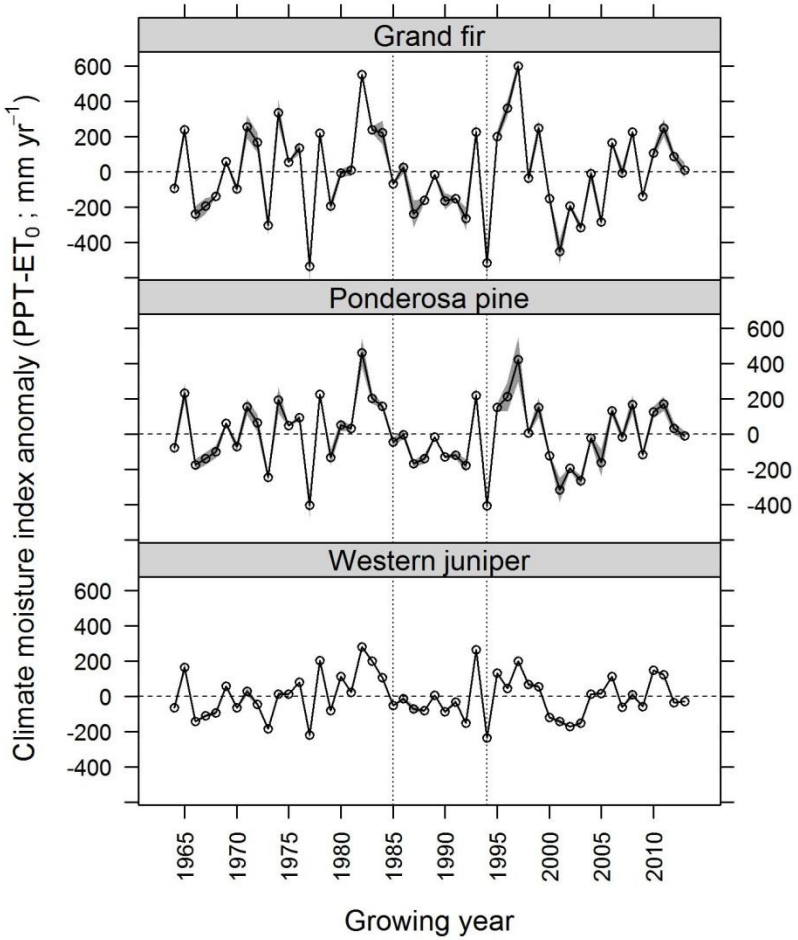


Figure S1. Proportion of trees with a significant positive (left panel) or negative (right panel) correlation between annual ring-width indices (RWI) and a variety of climate variables calculated for each month at time lags extending from 1 to 36 months. Correlations were computed for each tree (n=216) using growth and climate data from 1964 to 2013, with climate data averaged for temperature-related variables and summed for water-related variables.



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77 **Figure S2**. Growing-year climate moisture index anomalies from 1964 to 2013 for three forest types in the eastern Cascade Mountains, Oregon.

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