Berrill et al. 2016 Supplementary Materials

The following file contains:

(i) Summary of tree growth data and description of growth model formulations, and
(ii) Simulation output summary table.

Summary data and model formulations for tree size and growth

Summary data define the range of applicability of tree size and growth models. We fitted height-diameter regressions to measurements from 2678 aspen and conifer trees in nine 1 ha plots around Lake Tahoe (Table S1).

Supplementary Table 1. Summary data for aspen and conifer diameter (DBH) and height (HT) in nine stands around Lake Tahoe Basin.

Variable	Species	n	Mean	s.d.	Min.	Max.
DBH (cm)	AS	1218	27.7	14.9	10.0	81.3
	JP	102	51.0	25.4	20.1	140.6
	LP	200	43.4	19.0	20.0	9.5
	RF	255	40.2	24.1	20.3	179.4
	WF	903	44.6	20.7	20.0	140.3
HT (m)	AS	1218	17.9	6.8	4.6	34.9
	JP	102	23.9	9.5	7.8	52.9
	LP	200	23.1	7.8	5.2	43.6
	RF	255	18.6	8.0	5.7	49.3
	WF	903	22.0	8.7	4.4	49.8

Note: AS = aspen, JP = Jeffrey pine, LP = lodgepole pine, RF = red fir, WF = white fir.

We fitted basal area increment (BAI) models to conifer increment data from two consecutive repeat measurements in five 1 ha plots around Lake Tahoe (Table S2). We did not collect total height and crown height data on some trees; therefore CR data were only available for 547 trees. Dependence on CR estimates for BAI predictions necessitated development of CR prediction models. We fitted a conifer CR model to data for 547 trees in five 1 ha plots around Lake Tahoe (Table S2). Among conifer saplings measured and modeled for growth, white fir were most abundant (n = 128 out of 147 records). We developed a model of BAI for sapling aspen using repeat-measures data for small aspen 0 – 10 cm DBH. We collected these data after partial harvesting to reduce stand density in five 1 ha plots around Lake Tahoe (Table S2).

Supplementary Table 2. Summary data for basal area and diameter increment (BAI, DBHI) models in five aspen-conifer stands surrounding Lake Tahoe Basin. Conifer BAI model is for trees > 20 cm DBH, sapling conifer BAI model is for trees < 30 cm DBH, and sapling aspen diameter increment (DBHI) model is for trees < 10 cm DBH.

Model	**Variable**	**n**	**Mean**	**s.d.**	**Min.**	**Max.**
Conifer BAI	DBH (cm)	717	41.41	20.36	20.00	140.30
	HT (m)	548	21.89	7.71	6.70	45.50
	CR	547	0.69	0.14	0.23	0.94
	DBHI (cm yr^{-1})	717	0.52	0.27	0.03	2.40
	BAI (cm^2 yr^{-1})	717	34.92	24.97	1.20	166.47
Sapling conifer BAI	DBH (cm)	147	24.49	2.87	20.00	29.90
	HT (m)	147	14.18	2.73	6.70	21.60
	CR	147	0.71	0.15	0.29	0.93
	DBHI (cm yr^{-1})	147	0.50	0.27	0.03	1.37
	BAI (cm^2 yr^{-1})	147	20.08	11.84	1.27	63.22
Sapling aspen DBHI	DBH (mm)	199	30.66	23.87	1.00	100.00
	CR	199	0.65	0.12	0.21	0.95
	Percent fir BA	199	0.48	0.27	0.00	1.00
	DBHI (mm yr^{-1})	199	3.41	2.39	0.00	12.00
	BAI (cm^2 yr^{-1})	199	1.91	2.38	0.00	16.05

Note: DBH = diameter at breast height, HT = tree height, CR = crown ratio, DBHI = diameter at breast height increment, BAI = basal area increment, Percent fir BA = fir trees as proportion of BA in 0.02-ha plot centered on sample tree.

We fitted the conifer BAI model to square root transformed data $(BAI+1)^{0.5}$ to correct for skewness in BAI (cm^2 yr^{-1}). A quadratic tree size term $[(Ln\text{DBH})^{0.5} + Ln\text{DBH}]$ indicated that BA growth increased with advancing tree size, then tapered off. The best-fitting BAI model for conifer trees > 20 cm DBH included dummy variables for species and species × *Ln*(DBH) interaction, *Ln*(DBH), CR, and $SDIL^{0.5}$:

$$Jeffrey\ pine\ BAI = (-39.063 + 27.5716\ (LnDBH)^{0.5} - 2.6726\ lnDBH + 3.4357\ CR\ - 0.04205\ SDIL^{0.5})^2 - 1$$

$$Lodgepole\ pine\ BAI = (-27.2368 + 27.5716\ (LnDBH)^{0.5} - 6.2192\ lnDBH\ + 3.4357\ CR - 0.04205\ SDIL^{0.5})^2 - 1$$

$$Red\ fir\ BAI\ = (-28.9686 + 27.5716\ (LnDBH)^{0.5} - 5.3745\ lnDBH + 3.4357\ CR - 0.04205\ SDIL^{0.5})^2 - 1$$

$$White\ fir\ BAI = (-32.7465 + 27.5716\ (LnDBH)^{0.5} - 4.0763\ lnDBH + 3.4357\ CR - 0.04205\ SDIL^{0.5})^2 - 1$$

Fitting height-diameter models without an intercept to the response HT-1.37 produced models with the desirable property of predicting exactly 1.37m HT at zero DBH (Berrill et al. 2009) where: $HT = aDBH + bDBH^2 + cDBH^3 + 1.37$ (Table S3). The models indicated that up to heights of 25 m, aspen were more slender (higher height:diameter ratio) than conifers. Above 25 m, aspen height growth slowed and they rarely grew taller than 30 m, whereas large conifers over 40 m height were common.

Crown ratio did not differ between trees of different DBH or height. The best-fitting CR model included SDI to account for the impact of stand density on crown size. The model was $CR = a + bSDI^{0.5}$. We fitted the conifer BAI and CR models to data where conifers other than white fir were not well represented (Table S1). Therefore these models should only be regarded as 'preliminary models' that allowed us to simulate different aspen-conifer mixtures. These models should be validated and may need to be revised once more data are collected and the impacts of climate change become manifest and we better understand how tree crowns and growth are impacted by change such as increased soil-moisture deficit forecasted for the Sierra Nevada (www.cal-adapt.org).

We needed sapling growth models to predict BAI for smaller trees outside the range of applicable tree sizes for the conifer BAI models described above and published aspen models (Berrill and Dagley 2012). We fitted a non-linear 'sapling conifer BAI' model to BAI data for each conifer species modeling the positive relationship with CR and negative impact of SDI on BAI, and predicting zero BAI at zero DBH: $Sapling\ Conifer\ BAI = ((a^{CR} + b * lnSDI * ln(DBH + 1))^2$ (Table S3).

Supplementary Table 3. Sample size (n), parameter estimates, and root mean square error (RMSE) for models of height (m) using diameter at breast height (cm), sapling conifer basal area increment (BAI), and crown ratio for species located in nine aspen-conifer stands around the Lake Tahoe Basin.

Model	**Species**	**n**	**Parameter**			**RMSE**
			a	**b**	**c**	
Height-diameter	AS	1218	0.861	-0.0085	$2.4*10^{-5}$	3.13
	JP	102	0.514	-0.0017	−	4.10
	LP	200	0.673	-0.0033	−	4.24
	RF	255	0.521	-0.0017	−	3.06
	WF	903	0.613	-0.0025	$1.567*10^{-6}$	3.43
Sapling conifer BAI	JP	6	2.7516	-0.1614	−	0.36
	LP	8	1.9852	-0.1008	−	1.59
	RF	5	3.4313	0.1718	−	0.48
	WF	128	2.5345	0.0812	−	0.73
Crown ratio	JP	33	-0.1344	0.0061	−	0.12
	LP	56	-0.0791	0.0061	−	0.15
	RF	37	-0.0069	0.0061	−	0.10
	WF	421	0.9370	0.0061	−	0.12

Note: AS = aspen, JP = Jeffrey pine, LP = lodgepole pine, RF = red fir, WF = white fir.

The analysis of aspen sapling data revealed that aspen growth slowed in association with a greater proportion of fir trees as neighbors and was faster among larger aspen with longer crowns. The model predicts DBH increment (DBHI; mm yr^{-1}), transformed here to predict BAI cm^2 yr^{-1} from inputs of DBH (cm), CR, and proportion of neighbor tree BA in fir trees (Fir BA range 0-0.99). $Sapling\ Aspen\ BAI = \pi\big(0.5(0.1\ DBHI + DBH)\big)^2 - \pi(0.5\ DBH)^2$ where: $DBHI = (1.008 + 0.0330\ (10\ DBH)^{0.5} + 1.707\ (CR) \pm 0.527\ (FirBA)^2)^2 - 1$. The bigger impact that fir trees were having on growth of young aspen may be attributed to shading, owing to the higher leaf area density of shade-tolerant firs compared to intolerant pines and aspen (Gersonde et al. 2004). In light of greater soil-moisture deficits forecasted for the Sierra Nevada, shading may be less important than intensifying competition for limited soil moisture. Independent validation data should be collected over longer periods at more sites, and in stands experiencing fire, insects or other disturbances, to expand the range of applicability of any future models. Validation and revision of the sapling growth models is a priority for future research, especially given the importance of regeneration in our simulations of stand development and treatment longevity.

Growth simulation summary

To simulate growth in aspen-conifer stands, we used data from two of the nine sample stands as starting values. Change in stand density index (SDI) as a percent of pretreatment SDI, change in aspen as a percent of stand BA, and treatment longevity all varied between treatments with different DBH limits for conifer removal (Table S4).

Supplementary Table 4. Summary of growth model simulations for conifer removal treatments (trt) in aspen-conifer stands at Ward Creek (WA38) and Cookhouse Meadow (SSP24), Lake Tahoe Basin, California. All conifers below DBH limit were cut. Stand density index reduction (SDI cut %) as percent of pre-treatment value. Aspen (AS) as percent of stand basal area. Longevity was time taken to reach period end when SDI returned to pre-treatment level.

Pre-treatment		Treatment			Post-treatment			Period End
Site	AS (%)	Trt no.	Trt year	DBH limit (cm)	AS (%)	SDI cut (%)	Longevity (yrs)	AS (%)
WA38	14	#1	2	35	16	16	13	15
	15	#2	15	50	21	29	23	22
				60	23	38	29	25
				75	31	54	40	34
SSP24	24	#1	2	35	29	23	16	27
	27	#2	18	50	37	27	23	36
				60	45	42	36	45

References

Berrill, J-P., C.M. Dagley and V. Lyon. 2009. Monitoring Aspen Restoration Treatments in the LTBMU: Methodology and Pre-treatment Data Summary. Final Report: LTBMU Aspen Monitoring Project.

Gersonde, R.F., J.J. Battles and K.L. O'Hara. 2004. Characterizing the light environment in Sierra Nevada mixed-conifer forests using a spatially explicit light model. *Can. J. For. Res*. 34(6): 1332-1342.