SUPPLEMENT 1

The FireBGCv2 model

The Fire BGCv2 model operates across hierarchical spatial scales from 1) fixed-boundary biophysical sites, 2) dynamic stands defined by vegetation composition and structure, 3) simulation plots on which ecosystem processes are modeled for computational efficiency, 4) tree species and understory plant guilds, to 5) individual trees with attributes such as species, age, height, diameter at breast height (DBH), and leaf area. In the model climate, wildland fire, and landscape vegetation are dynamically and reciprocally linked: long-term records of daily temperature, precipitation, and radiation influence fuel production and moisture, which determine landscape ignition potential, fire frequency and size, and fire behavior. Climate and weather influence the productivity and mortality rates of individual plant species - and thus stand composition and structure - with feedbacks to the fire regime via fuel type, fuel amount, and fuel arrangement. Fire regimes in turn affect vegetation species' regeneration, composition, successional trajectories, and productivity directly through fire-caused mortality and successional patterns, and indirectly through influence on availability of light, water and other necessary resources. Required model inputs are site and stand maps, daily weather, fire frequency and size parameters, species parameters that dictate phenology, establishment, growth, and mortality, and initializing stand data for representative vegetation communities.

Wildland fire ignitions (lightning-caused) are simulated across sites using functions that relate the Keetch-Byram Drought Index (KBDI) to parameterized fire return intervals [1]. Climate and weather influences on fire ignitions are accounted for using daily deviations of site-level KBDI from an average maximum fire season KBDI, where probability of fire increases as conditions become drier. Fires spread across the simulation landscape via cell percolation following slope gradients and wind direction. Fire spread is terminated when fuels are too wet or too sparse or when cumulative annual area burned reaches an area stochastically determined from input average fire size. Potential fire sizes are scaled to KBDI – hot, dry conditions increase the occurrence probability of large fires – but actual fire sizes are constrained by fuel availability and moisture.

Individual tree mortality occurs as the result of wildfire damage, hydrologic stress, crowding, light reduction, and random mortality. Fire-caused tree mortality is modeled as a function of bark thickness (a user-defined, species-specific parameter) and scorch height, and can be used to assess fire severity where the degree of crown scorch and cambial kill depends on fire intensity and duration. Thermal limits are defined for each species in the model according to parameterized minimum, maximum, and optimal growing degree days, where temperatures outside of these limits affect trees through a reduction in the annual growth increment and eventual mortality. Tree regeneration is driven by soil moisture, litter depth, and climate-influenced cone crop production.

The LANDIS-II model

LANDIS-II models forest growth and succession of age cohorts, unlike FireBGCv2 and its tracking of individual trees. The core model simulates tree regeneration, seed dispersal, succession and mortality in individual landscape cells using species life history traits. A series of extensions developed for LANDIS-II are available to simulate additional forest processes. We incorporated the Biomass Succession extension to model forest growth, competition, succession, and individual species response to climate change [2]. The Biomass Succession extension requires species inputs for maximum aboveground net primary productivity and species establishment probability that vary according to ecoregion (environmental site conditions) and climate scenario. These values were estimated using stand scale Climate-Forest Vegetation Simulator (C-FVS) runs for each species under the varying ecoregions, climate scenarios, and time steps. C-FVS is a forest growth and simulation model that adjusts species viability and growth rates according to site specific, downscaled climate projections [3]. The C-FVS simulations were run using projected climate at 30-yr intervals (2000, 2030, 2060, 2090) to estimate maximum aboveground biomass, maximum aboveground net primary productivity, and regeneration probability inputs for LANDIS-II. Linear interpolation was used to estimate values at 10-yr intervals between the 30-yr intervals available through C-FVS. The LANDIS-II inputs supplied by C-FVS enabled individual species to respond to climate change with shifts in their growth rate and probability of establishment.

The Dynamic Fire and Fuels extension (v2.0) [4] simulated wildfire occurrence and spread according to ecoregion specific inputs of daily fire weather, ignition rates, and fire size distributions. For each individual fire event, the model selects a fire size from the fire size distribution and the associated daily fire weather values. Fire shape is then modeled with an approach adapted from Finney's minimum travel time algorithm [5], where fire spread rates and consequent fire severity respond to fuel type, fuel moisture, wind speed and slope. The fire size distribution for the Kaibab Plateau was assembled from GCNP and NKRD fire records of individual fire sizes from 1970-2012. The historical fire regime was calibrated according to historical fire frequency estimates in the literature [6-10]. We converted initial fire-size-distribution parameters to fire-duration distributions so that fire spread and consequent area burned could respond to changes in fire weather associated with the future climate projections. For example, decreases in fuel moisture under future climate projections would increase the rate of fire spread, allowing a fire to burn more area during the same fire duration period, rather than being restricted by an unchanging fire size distribution [see 4]. Management actions were implemented with the Biomass Harvest extension (v2.1) [11], which reduces the biomass of cohorts according to species and age ranges specified in management prescriptions. Thinning and prescribed burns altered fuel characteristics, converting treated cells to a post treatment fuel type with associated reductions in fire spread and fire severity potential.

We created initial forest conditions by preceding each model run with a 600-year spinup under contemporary climate conditions and historical fire frequencies, followed by 120 years of fire suppression and biomass removal to simulate 20th century logging on forest service lands. We used a 1-ha cell resolution and each extension operated at a 5-yr time step. Further details on model structure, inputs, and validation for the Kaibab Plateau study landscape are available in Flatley and Fulé 2016 [12].

Treatment parameters for FireBGCv2-Jemez and LANDIS-II-Kaibab modeling simulations

Table S1. Treatment parameters for the business-as-usual (BAU) and two intensified management factors (3xBAU, 6xBAU). Forward slashes (/) separate parameter values for BAU, 3xBAU, and 6xBAU scenarios where applicable. Values without forward slashes are held constant across model scenarios.

Treatment parameters	FireBGCv2-Jemez	LANDIS-II-Kaibab
Thinning plus prescribed fire		
Annual area treated (ha)	**BAU / 3xBAU / 6xBAU**	**BAU / 3xBAU / 6xBAU**
Ponderosa pine site	461 / 1,382 / 2,765	858 / 2,575 / 5,150
Dry mixed conifer site	120 / 361 / 722	307 / 922 / 1,844
Maximum size of individual treatments (ha)	4,097	3,231
Stand basal area minimum threshold to treat (m^2/ha) [a]		
Ponderosa pine site	4.6	Not Applicable
Dry mixed conifer site	6.9	Not Applicable
Individual tree minimum, maximum DBH (cm; FireBGCv2) [b] or minimum, maximum age (LANDIS-II)	1, 40	1, 100
Retention species [c]		
Ponderosa pine site	Ponderosa pine	Ponderosa pine
Dry mixed conifer site	Ponderosa pine, limber pine, white fir, Douglas-fir, aspen	Ponderosa pine, limber pine, white fir, Douglas-fir
Fraction of slash left on site after thinning (%)	10	Not Applicable
Prescribed fire only		
Maximum prescribed fire intensity (kW m^{-1})	30	Not Applicable
Ponderosa pine site	461 / 1,382 / 2,765	858 / 2,575 / 5,150
Dry mixed conifer site	120 / 361 / 722	307 / 922 / 1,844
Maximum size of individual treatments (ha)	4,097	3,231
Minimum, maximum stand age for treatment (yrs) [d]	100, 500	Not Applicable
Rx Fire intensity minimum, maximum (kW/m)	2, 30	Not Applicable

[a] Only stands with basal area above the minimum threshold are eligible for treatment
[b] All eligible trees within the minimum-maximum diameter range are removed from stands
[c] Retention species are not removed from stands
[d] Only stands older than the minimum age and younger than the maximum age are eligible for treatment (because stands are dynamically created following disturbance these inputs correspond to time since last wildfire).

Widlfire area burned results for FireBGCv2-Jemez and LANDIS-II-Kaibab modeling simulations

Table S2. FireBGCv2-Jemez wildfire area burned annually (median area and 25th and 75th percentiles, ha) combined for ponderosa pine and dry mixed conifer sites in wildfires of all types and high severity wildfires (tree mortality > 70%) for climate-management scenarios. The combined area of ponderosa pine and dry mixed conifer sites is 77,489 ha.

Climate factor	Management factor	Annual area burned (ha), All wildfires			Annual area burned (ha), High severity wildfires		
		Median	*25th*	*75th*	*Median*	*25th*	*75th*
Contemporary	Suppression Only	945	58	3247	123	3	1689
Contemporary	BAU	812	119	4453	297	13	846
Contemporary	3xBAU	389	49	8161	122	11	1468
Contemporary	6xBAU	900	67	4889	153	8	964
Warm-Dry	Suppression Only	1734	236	6975	210	2	935
Warm-Dry	BAU	1207	102	8692	305	10	1880
Warm-Dry	3xBAU	2644	149	13221	349	6	2377
Warm-Dry	6xBAU	510	153	5960	493	11	1741
Hot-Arid	Suppression Only	1778	153	14873	467	47	5212
Hot-Arid	BAU	2039	228	12084	485	24	3027
Hot-Arid	3xBAU	1419	259	9190	629	119	2624
Hot-Arid	6xBAU	1959	106	6141	501	93	1967

Table S3. LANDIS-II-Kaibab wildfire area burned annually (median area and 25th and 75th percentiles, ha) in ponderosa pine and dry mixed conifer sites in wildfires of all types and high severity wildfires (> 50% crown burned) for climate-management scenarios. The combined area of ponderosa pine and dry mixed conifer sites is 155,439 ha.

Climate factor	**Management factor**	**Annual area burned (ha), All fires**			**Annual area burned (ha), High severity fire**		
		Median	*25th*	*75th*	*Median*	*25th*	*75th*
Contemporary	Suppression Only	3719	2821	5180	1647	1015	2535
Contemporary	BAU	3056	2236	4201	1444	659	1760
Contemporary	3xBAU	663	529	1072	112	72	211
Contemporary	6xBAU	724	412	929	81	35	145
Warm-Dry	Suppression Only	3656	2402	4936	1095	595	1451
Warm-Dry	BAU	2180	1401	3498	462	374	1040
Warm-Dry	3xBAU	600	394	881	91	54	162
Warm-Dry	6xBAU	510	337	759	36	18	80
Hot-Arid	Suppression Only	3547	2761	4456	1127	698	1750
Hot-Arid	BAU	2700	1524	3839	734	341	1067
Hot-Arid	3xBAU	931	622	1242	125	69	233
Hot-Arid	6xBAU	447	252	642	32	16	69

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