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Supplementary material

Non-additive effects of alternative stable states on landscape flammability in NW Patagonia: fire history and simulation modelling evidence

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Supplementary material 1. Fire-history maps

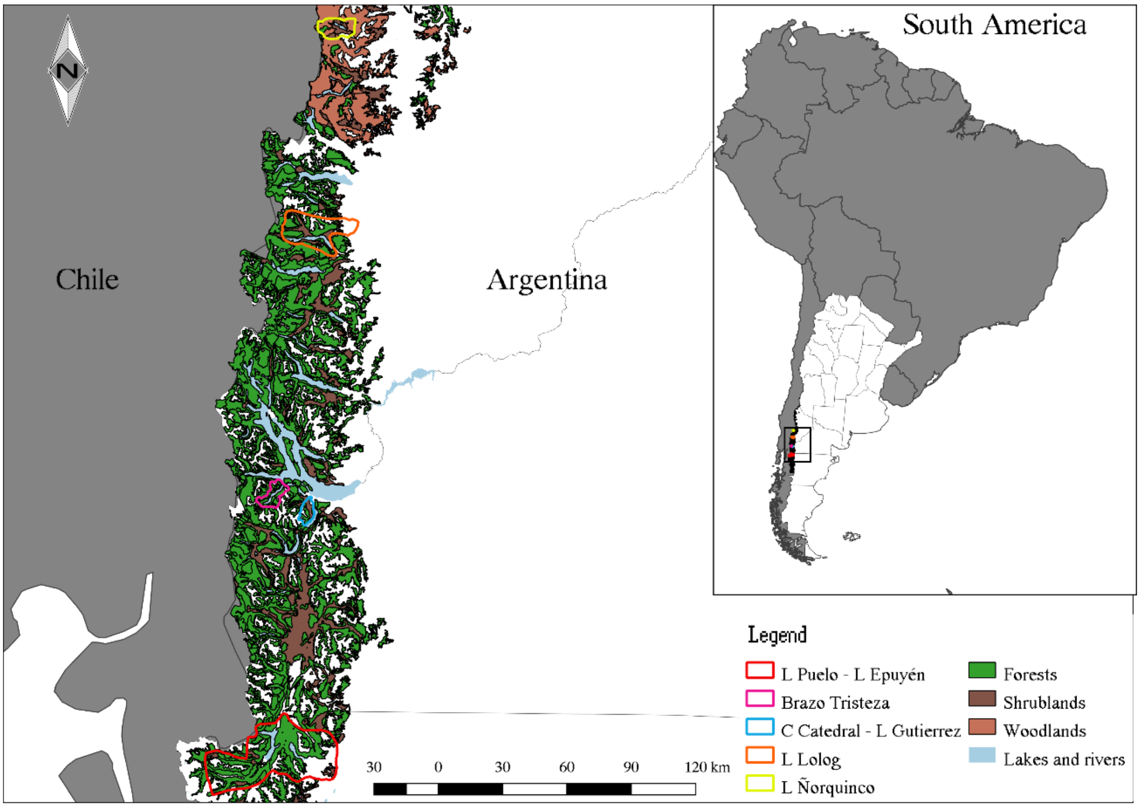

Fig. S1. Map representing the location of the five fire-history maps. On the right side, there is a map of South America, and the black rectangle represents the study area, which is represented on a broader scale on the left side.

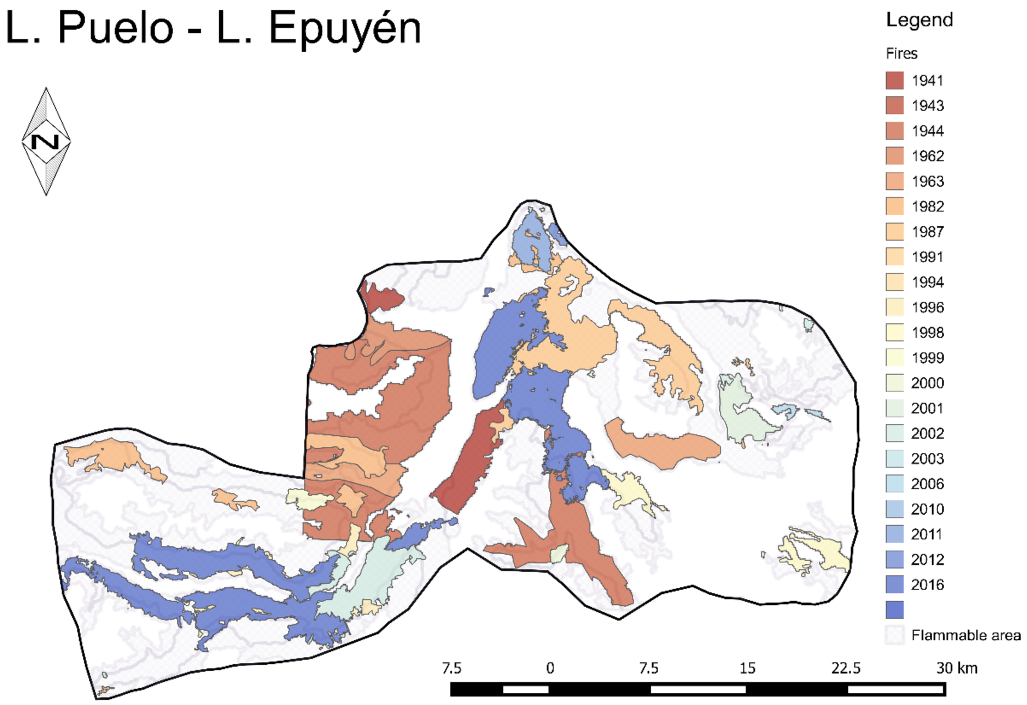

Fig. S2. Lago Puelo–Lago Epuyén fire-history map.

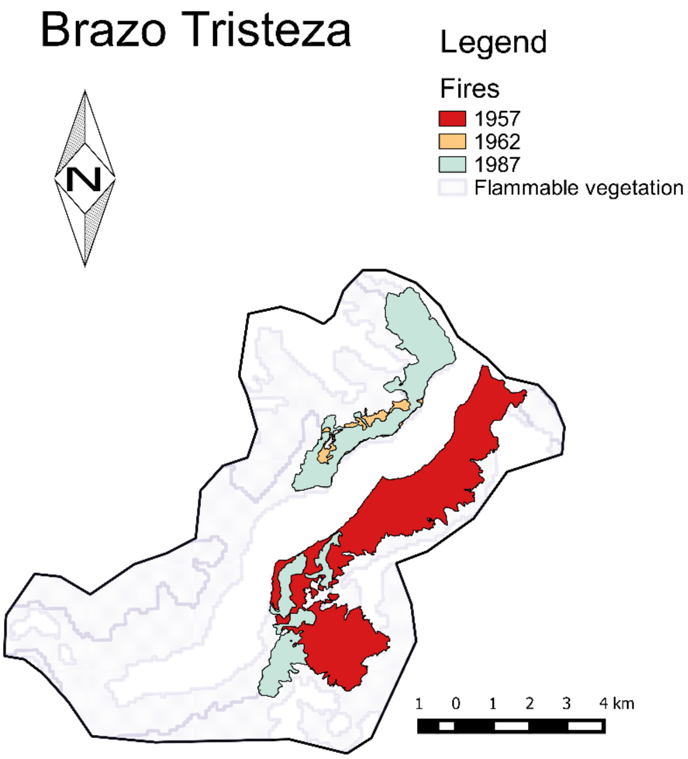

Fig. S3. Brazo Tristeza fire-history map.

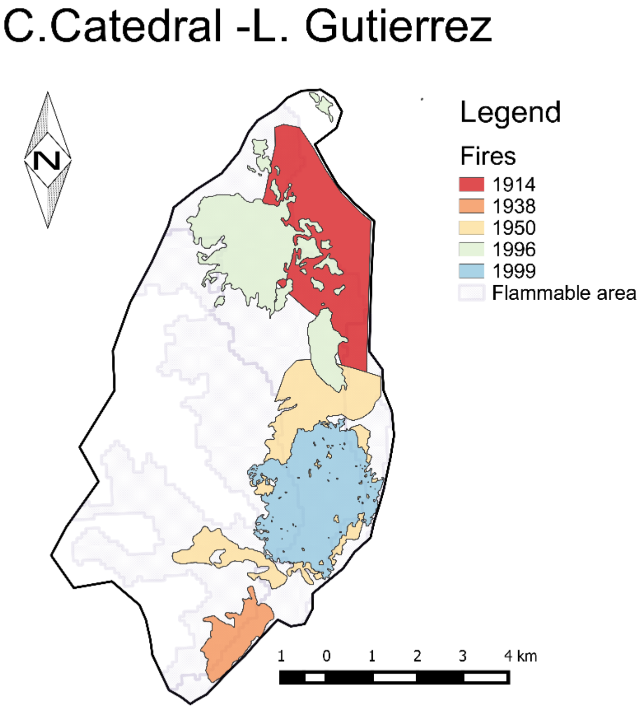

Fig. S4. Cerro Catedral– Lago Gutierrez fire-history map.

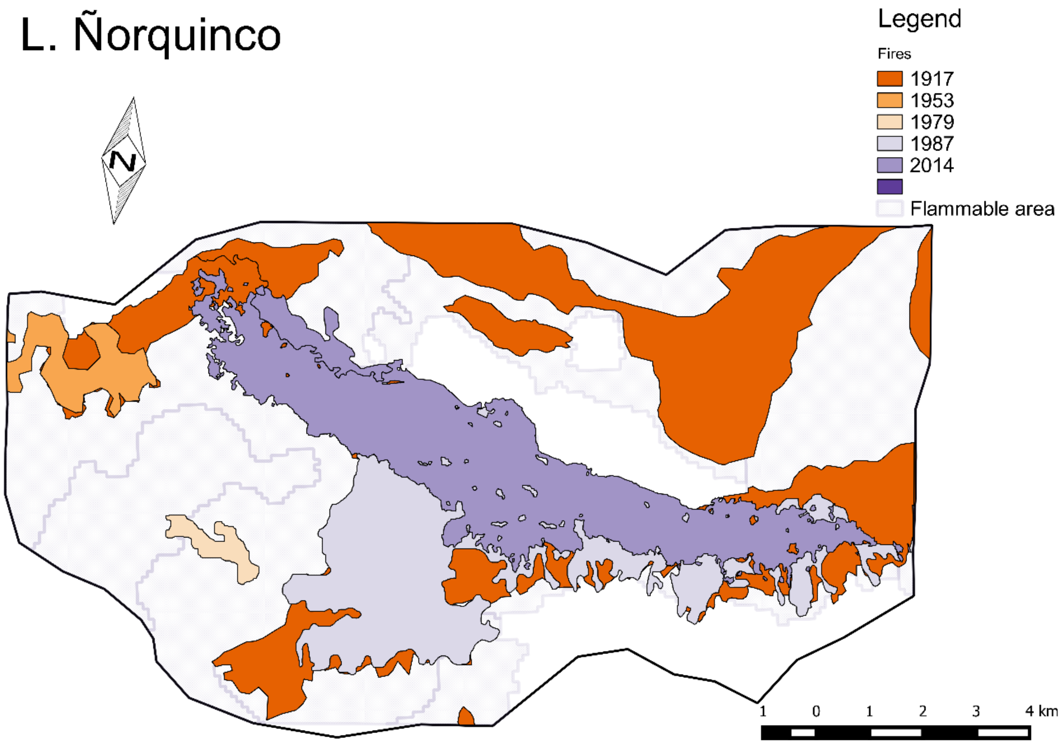

Fig. S5. Lago Ñorquinco fire-history map.

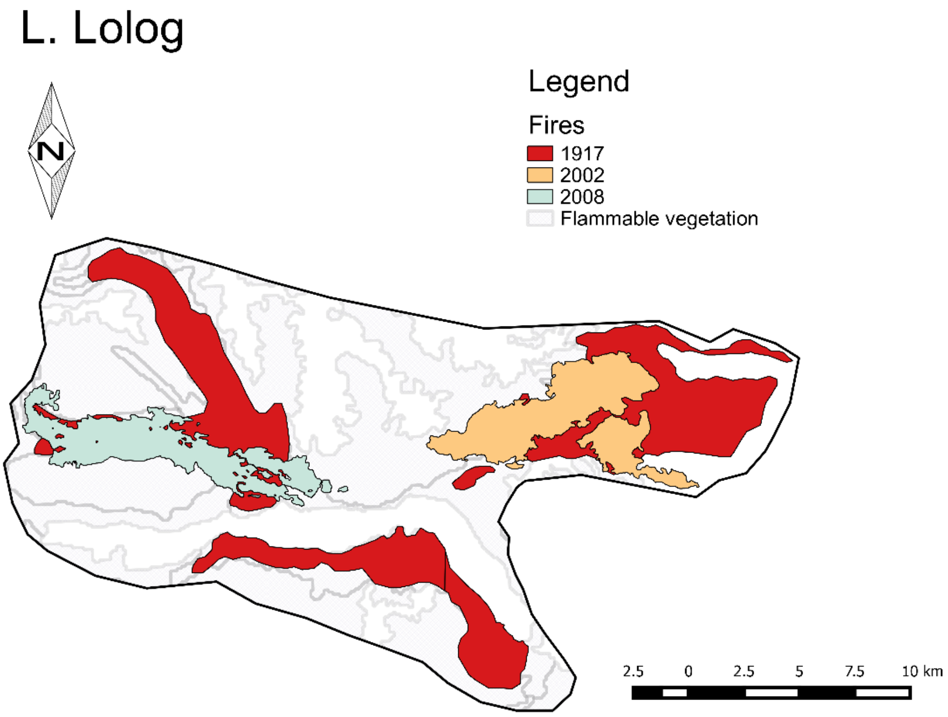

Fig. S6. Lago Lolog fire-history map.

Supplementary material 2. Simulation model, overview and results

To explore how time since fire (TSF) interval distributions respond to variations in landscapes' vegetation composition and fire frequencies we build a spatially explicit toy model implemented in SELES (SELES; Fall and Fall 2001). The model comprises two hierarchical levels: cells and landscape. There are two processes that take place: fire and succession. Cells have a 30 × 30-m resolution (0.09 ha) and the landscape is a 3600-ha square grid (200 × 200 cells) that varies in vegetation composition and TSF. The model simulates fires and regeneration in annual time steps and simulation runs comprise 1000 years.

Landscape variables

Fuel desiccation weather factor (*w*): every year a value of *w* is sampled from a truncated normal distribution (mean =1, s.d. = 0.08). Values of 1 denote normal years whereas numbers <1 denote drier years and values >1 denote moister years. This factor modules both fire spread and forest propagule dispersal.

Cell variables

Fuel type: every cell in the landscape has one of two fuel types: pyrophytic (resprouting shrubland) or pyrophobic (coloniser forest).

TSF: time since the last fire in years. After a cell burns its TSF turns to 0. TSF increases 1 year every year the cell does not burn and ranges from 0 to *N* years.

Time since regeneration: time since seed establishment in years, it ranges from 0 to *N* years. After a cell burns, time since establishment turns to 0. If a forest propagule establishes in a shrubland cell its time since establishment turns into 1 and every year without a new fire it increases by 1 year.

Model overview and scheduling

All stochastic process in the model occur at cell level as described below:

Each year a unique value for w is randomly sampled from a normal distribution (Fig. 1). Once this value is set Fire and Regeneration take place.

Fire module

The fire model comprises two processes: ignition and fire propagation. Fire starts from an ignition cell and spreads to its eight neighbours given a fire spread probability (Pbase) that depends on the cell's TSF. After a fire occurs vegetation turns always to shrubland. A cell cannot burn twice per year.

Fire spread probability is a function of the time since the last fire (Pbase, Fig. 1*a*) of the focal cell but modified by the current year fuel desiccation weather factor (w) following Kitzberger *et al.* (2012).

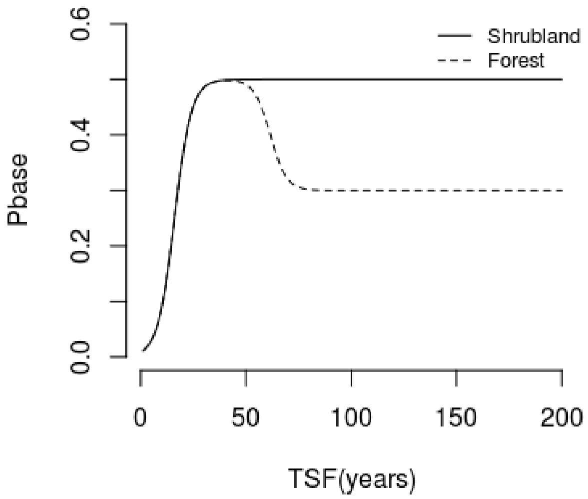

Fig. S7. Fire spread probability (Pbase) relationships with time since fire for forest and shrublands.

Succession module

Each forest cell produces and disperses seeds to adjacent shrubland cells every year but the distance seeds may reach depends on *w*. Seed dispersal probability in normal years ($w = 1$) occurs only in adjacent cells whereas in moister years in may reach cells to up to 60 m (two cells). If a seed reaches a cell, time since regeneration turns to 1. When time since regeneration is 80 shrubland cells turn to forest and are able to disperse seeds.

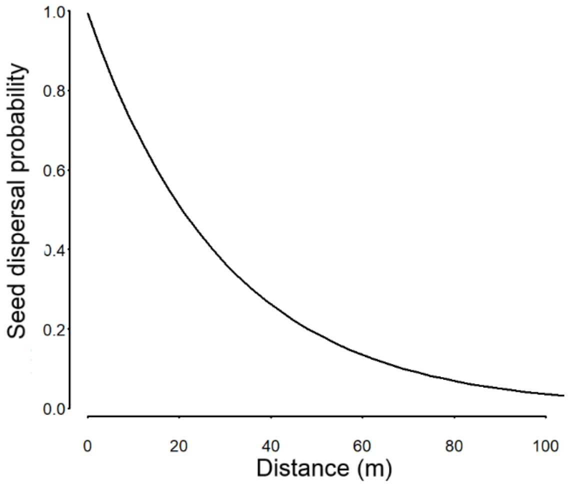

Fig. S8. Seed dispersal probability decreases with distance to the remnant patch.

Simulation scenarios

We simulated six vegetation composition scenarios (Fig. 3*a*) with different proportions of shrubland and forest, with three different fire frequencies, two ignitions per year, one ignition per year and one ignition every 10 years. We ran 10 repetitions of 1000 years per scenario.

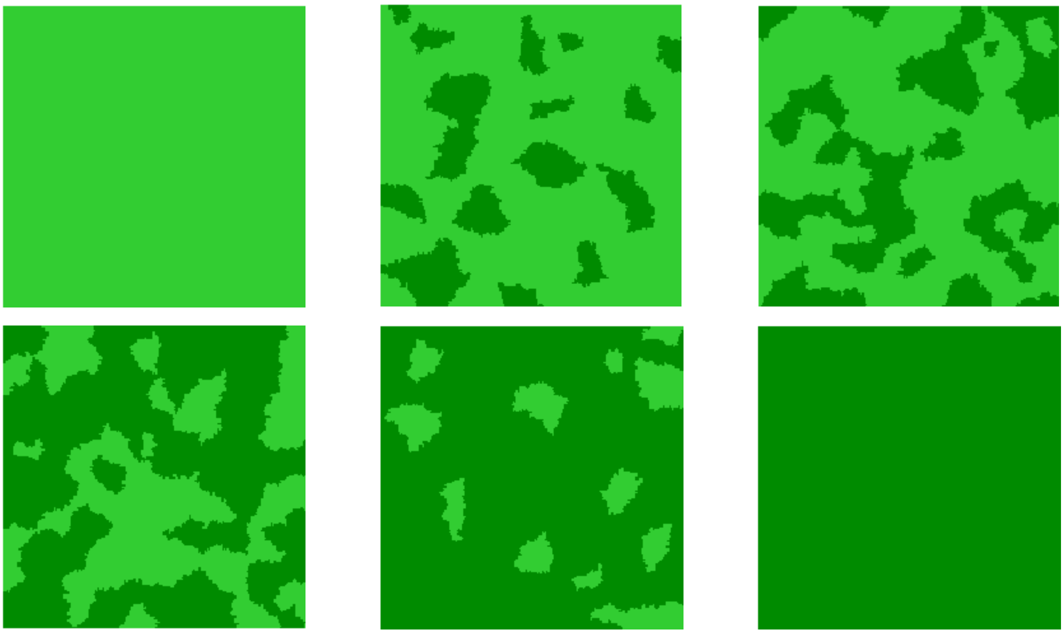

Fig. S9. Simulated landscapes with different shrubland (light green) and forest (dark green) proportion. 0% forest top left, 20% forest top centre, 40% forest top right, 60% forest bottom left, 80% forest bottom centre, 100% forest bottom right.

With the simulated fire data, we calculated some summary statistics at the landscape level. The percentage of all the ignitions simulated in that landscape that propagated (ignitions that propagated, %). The percentage of all fires simulated in the landscape 1000-year simulations that were >5 ha (fires larger than 5 ha). These fires are the ones used to fit the fire interval distributions. The proportion of area burned in the landscape that corresponds to shrubland (shrubland AB ÷ total AB). Finally, the percentage of the landscape covered at the end of the 1000-year simulation (final forest cover, %).

Results

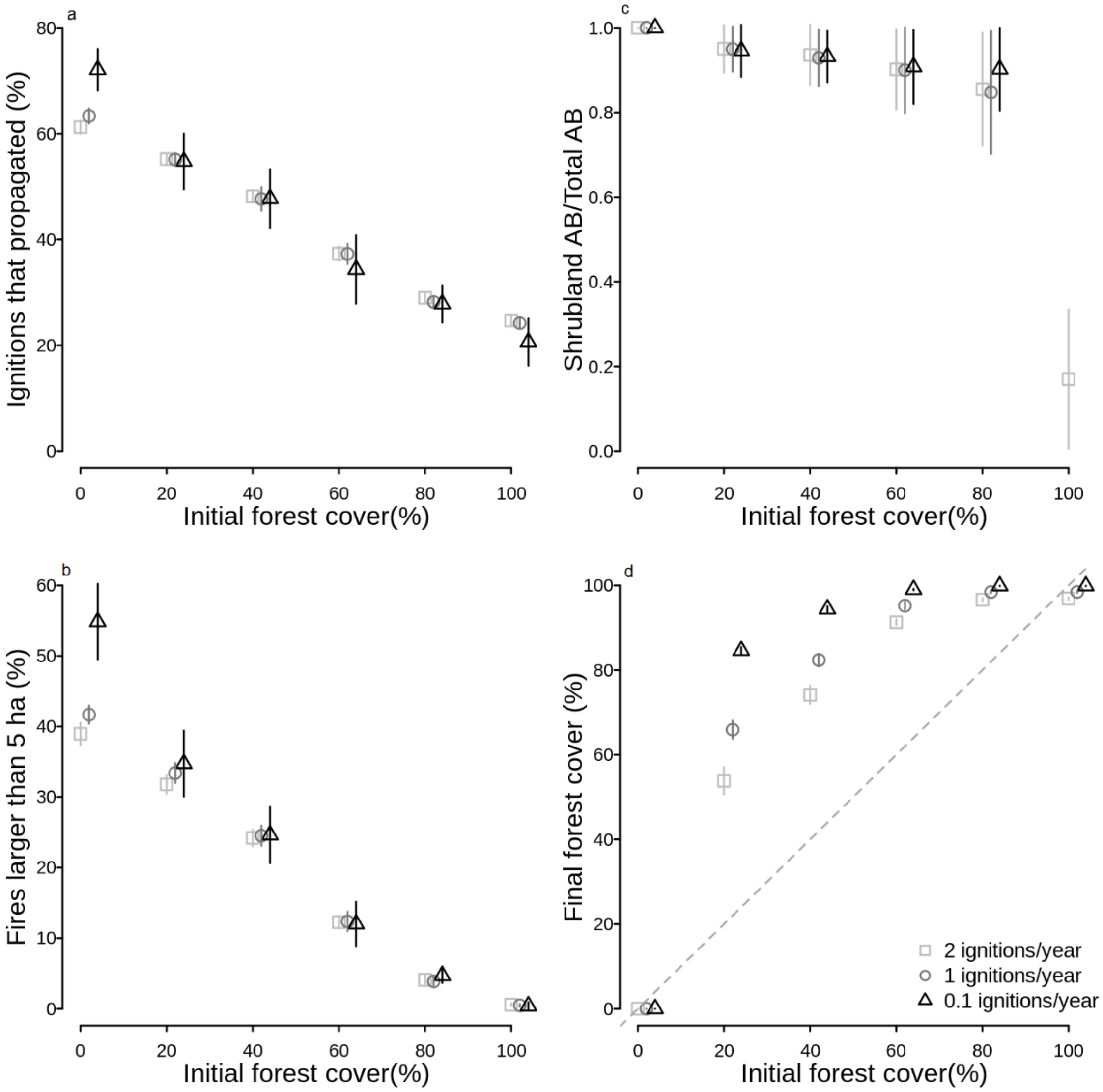

Fig. S10. Proportion of ignitions that propagated (*a*) and the fires larger than 5 ha (*b*) decreases with forest cover. The proportion of the burned area that corresponds to shrubland is always greater than forest but in the scenario, that is 100% forest cover (*c*). Final forest cover increases compared with the initial forest cover in every scenario but the one that had no forest cover (*d*).

Model selection

Table S1. Difference in Watanabe Information Criterion (ΔWAIC) values for the alternative models

Forest (%)	Frequency (ignitions per year)	ΔWAIC			
		Moisture	Weibull	Olson	Logistic
20	2	221.059	408.21	408.21	0
20	2	180.574	353.74	353.74	0
20	2	159.388	347.376	347.376	0
20	2	226.66	475.425	475.425	0
20	2	200.132	400.506	400.506	0
20	2	196.379	335.509	335.509	0
20	2	201.995	384.632	384.632	0
20	2	202.778	401.968	401.968	0

20	2	263.63	501.214	501.214	0
20	2	252.279	492.288	492.288	0
20	0.1	0.866	0	0	2.873
20	0.1	0	4.695	4.695	1.192
20	0.1	10.245	20.463	20.463	0
20	0.1	1.808	7.645	7.645	0
20	0.1	0	0.752	0.752	1.498
20	0.1	1.201	0	0	1.783
20	0.1	4.184	0	0	2.084
20	0.1	8.859	22.47	22.47	0
20	0.1	3.47	8.934	8.934	0
20	0.1	5.607	12.833	12.833	0
20	1	99.667	217.086	217.086	0
20	1	93.683	171.956	171.956	0
20	1	119.041	242.581	242.581	0
20	1	133.36	296.428	296.428	0
20	1	81.585	174.81	174.81	0
20	1	114.06	217.683	217.683	0
20	1	98.883	214.261	214.261	0
20	1	119.002	225.491	225.491	0
20	1	117.503	234.987	234.987	0
20	1	96.338	209.403	209.403	0
40	2	106.31	238.616	238.616	0
40	2	72.827	164.993	164.993	0
40	2	121.407	258.527	258.527	0
40	2	84.624	156.142	156.142	0
40	2	129.413	256.438	256.438	0
40	2	94.682	212.413	212.413	0
40	2	127.731	272.287	272.287	0
40	2	101.399	212.634	212.634	0
40	2	118.158	272.164	272.164	0
40	2	125.11	277.499	277.499	0
40	0.1	0.864	1.558	1.558	0
40	0.1	0	1.614	1.614	3.089
40	0.1	0.55	0	0	4.953
40	0.1	1.82	3.298	3.298	0
40	0.1	2.063	1.516	1.516	0
40	0.1	1.608	0	0	2.991
40	0.1	1.995	2.856	2.856	0
40	0.1	0.623	2.067	2.067	0
40	0.1	0.395	0	0	6.206
40	0.1	1.499	0	0	5.839
40	1	58.284	127.148	127.148	0
40	1	38.335	87.443	87.443	0
40	1	44.593	110.905	110.905	0
40	1	42.595	87.563	87.563	0
40	1	63.567	124.252	124.252	0
40	1	45.107	89.973	89.973	0
40	1	37.122	72.764	72.764	0
40	1	24.259	55.953	55.953	0
40	1	41.892	94.974	94.974	0
40	1	47.322	95.156	95.156	0
60	2	24.848	52.384	52.384	0
60	2	20.272	41.016	41.016	0
60	2	29.747	75.767	75.767	0
60	2	30.229	68.173	68.173	0
60	2	22.447	46.612	46.612	0
60	2	18.743	40.446	40.446	0
60	2	25.468	63.745	63.745	0
60	2	16.9	62.315	62.315	0

60	2	30.426	69.916	69.916	0
60	2	15.918	28.854	28.854	0
60	0.1	0.77	0	1.082	1.974
60	1	5.759	13.008	13.008	0
60	1	19.719	40.396	40.396	0
60	1	4.76	14.502	14.502	0
60	1	14.67	36.124	36.124	0
60	1	7.706	14.71	14.71	0
60	1	11.928	25.081	25.081	0
60	1	9.618	20.859	20.859	0
60	1	8.592	22.204	22.204	0
60	1	9.071	18.509	18.509	0
60	1	18.215	41.065	41.065	0
80	2	0	8.318	8.318	2.295
80	2	0	7.662	7.662	10.205
80	2	0	4.809	4.809	3.241
80	2	0	8.419	8.419	4.752
80	2	0	4.512	4.512	1.826
80	2	0	25.594	25.594	7.508
80	2	0	7.197	7.197	5.416
80	2	0	12.792	12.792	7.023
80	2	0	12.226	12.226	2.606
80	2	0	2.443	2.443	4.218
80	1	0	4.407	4.407	3.692
80	1	0	3.746	3.746	3.465
80	1	0	7.194	7.194	4.097
80	1	0	6.473	6.473	5.232
80	1	0	8.156	8.156	4.674
80	1	0	5.843	5.843	4.948
80	1	0	6.341	6.341	7.754
80	1	0	4.787	4.787	9.172
80	1	0	4.438	4.438	3.008
0	2	730.185	941.458	941.458	0
0	2	725.093	990.745	990.745	0
0	2	787.666	1042.819	1042.819	0
0	2	718.901	941.494	941.494	0
0	2	713.016	980.526	980.526	0
0	2	620.967	824.308	824.308	0
0	2	664.41	892.202	892.202	0
0	2	754.04	1005.614	1005.614	0
0	2	696.582	907.899	907.899	0
0	2	806.253	1054.512	1054.512	0
0	0.1	167.711	253.792	253.792	0
0	0.1	339.953	605.22	605.22	0
0	0.1	215.767	370.882	370.882	0
0	0.1	252.298	421.532	421.532	0
0	0.1	322.473	482.924	482.924	0
0	0.1	283.72	427.656	427.656	0
0	0.1	302.979	475.26	475.26	0
0	0.1	204.579	352.773	352.773	0
0	0.1	173.426	306.837	306.837	0
0	0.1	320.062	539.783	539.783	0
0	1	722.973	969.048	969.048	0
0	1	801.603	1090.725	1090.725	0
0	1	669.331	908.942	908.942	0
0	1	645.4	863.657	863.657	0
0	1	628.581	916.554	916.554	0
0	1	734.336	968.828	968.828	0
0	1	585.238	803.262	803.262	0
0	1	558.115	755.375	755.375	0

0	1	722.136	974.092	974.092	0
0	1	612.665	904.709	904.709	0

Supplementary material 3. Alternative models and priors

We gave an identifying number for censoring to every cell: 1 if right censored and 0 if not censored (between-fire intervals, BFI) (see Moritz *et al.* 2009). In order to fit fire interval distributions to the simulated fire histories we point sampled the landscapes every 400 m and used only BFI. All calculations were performed in *R* (R Foundation for Statistical Computing, Vienna, Austria). With these data we fitted four alternative models where the likelihood of every fire interval was:

$$L_i \begin{cases} f(t_i) \ \mathit{if} \ \delta_i = 0 \\ A(t_i) \ \mathit{if} \ \delta_i = 1 \end{cases}$$

where L_i is the likelihood of having an interval like t_i and δ_i identifies if the interval was censored (δ_i = 1 or not δ_i = 0). If the interval is censored the likelihood is the cumulative function ($A(t)$ probability of surviving until time t or probability of remaining unburnt until time t). If the interval is not censored the likelihood is the probability density function ($f(t)$ probability of burning at time t).

Weibull model

$$h(t_i) = \frac{c \times t_i^{c-1}}{b^c}$$

Here b is the scale parameter that gives the 63.2 percentile of fire intervals and c the shape parameter. If $c = 0$, flammability does not change with TSF; if $c > 0$, flammability increases with TSF; and finally, if $c < 0$, flammability decreases with TSF.

Logistic model

$$h(t_i) = \frac{h}{1 + \left(c \times e^{-r \times t_i}\right)}$$

Here flammability increases at a rate r until reaching an asymptote h and $h \div (c + 1)$ is the flammability at $t = 0$.

Olson model

$$h(t_i) = h\left(1 - e^{-k \times t_i}\right)$$

Here flammability grows at a rate k as it approaches an asymptote h.

Moisture model

$$h(t_i) = h\left(1 - e^{-k\times t}\right)\times\left(r + e^{-m\times t_i}\right)$$

This model is a variation of the Olson model where flammability eventually declines to a level equal to *rh* at a rate defined by *m*.

Find here details on the probability density function and the cumulative density function for the four models proposed.

Probability density function

$$f(t_i) = h(t_i)\times\ e^{-H(t_i)}$$

Cumulative function – survivorship function

$$A(t_i) = e^{-H(t_i)}$$

where $h(t_i)$ is the hazard function and $H(t_i)$ is the integral of the hazard function and t is the fire interval.

Weibull model

$$h(t_i) = \frac{c\times t_i^{c-1}}{b^c}$$

$$H(t_i) = \left(\frac{t_i}{\mathrm{b}}\right)^c$$

Here *b* is the scale parameter that gives the 63.2 percentile of fire intervals and *c* the shape parameter. If $c = 0$, flammability does not change with TSF; if $c > 0$, flammability increases with TSF and finally; and if $c < 0$, flammability decreases with TSF. We used weakly informative priors for all of these parameters a truncated normal distribution (mean = 0, standard deviation = 1000).

Logistic model

$$h(t_i) = \frac{h}{1 + \left(c\times e^{-r\times t_i}\right)}$$

$$H(t_i) = \frac{h\times\ln\left(\dfrac{e^{r\times t_i} + c}{1 + c}\right)}{r}$$

Here flammability increases at a rate *r* until reaching an asymptote *h* and $h \div (c + 1)$ is the flammability at $t = 0$. We used weakly informative priors for all of these parameters, a beta distribution (shape1 = 1, shape2 = 1) for h and r and a truncated normal distribution (mean = 0, standard deviation = 1000) for *c*.

Olson model

$$h\left(t_i\right) = h\left(1 - e^{-k\times t_i}\right)$$

$$H\left(t_i\right) = h \times \left(t_i + \frac{e^{-k\times t_i}}{k} - \frac{1}{k}\right)$$

Here flammability grows at a rate k as it approaches an asymptote h. We used weakly informative priors for all of these parameters a beta distribution (shape1 = 1, shape2 = 1).

Moisture model

$$h\left(t_i\right) = h\left(1 - e^{-k\times t_i}\right)\times\left(r + e^{-m\times t_i}\right)$$

$$H\left(t_i\right) = h \times \left(r\times t_i + \frac{r\times e^{-k\times t_i}}{k} - \frac{e^{-m\times t_i}}{m} + \frac{e^{-(m+k)\times t_i}}{m+k} - \frac{r}{k} + \frac{1}{m} - \frac{1}{m+k}\right)$$

This model is a variation of the Olson model where flammability eventually declines to a level equal to rh at a rate defined by m. We used weakly informative priors for all of these parameters a beta distribution (shape1 = 1, shape2 = 1).

Supplementary material 4. Parameter estimations and model selection

In order to select among the different models we used the Watanabe Information Criterion (WAIC, Watanabe 2012) and performed a posterior predictive check. For every set of models we calculated weights which is an estimate of the probability that the model will make the best predictions on new data, conditional on the set of models considered. The Moisture model showed the lowest WIAC and the greatest weight for Lago Puelo–Lago Epuyén and the Brazo Tristeza sites, the Logistic model for Cerro Catedral–Lago Gutierrez and Lago Ñorquinco, and the Weibull model for Lago Lolog (Table A2).

Table S2. Watanabe Information Criterion (WAIC) for every model and every site

ΔWAIC, Difference in Watanabe Information Criterion;

Site	Model	WAIC	ΔWAIC	Weight
Lago Puelo–Lago Epuyén	Weibull	14333.255	66.229	0
	Logistic	14694.129	427.103	0
	Olson	14860.819	593.793	0
	Moisture	**14267.026**	**0.000**	**1**
Brazo Tristeza	Weibull	271.110	9.122	0.009
	Logistic	266.191	4.203	0.103
	Olson	267.875	5.887	0.044
	Moisture	**261.988**	**0.000**	**0.844**
Cerro Catedral–Lago Gutierrez	Weibull	645.375	12.627	0.002
	Logistic	**632.748**	**0.000**	0.985
	Olson	641.425	8.677	0.013
	Moisture	674.953	42.205	0
Lago Ñorquinco	Weibull	2317.433	2.379	0.233
	Logistic	**2315.054**	**0.000**	**0.767**

	Olson	2343.858	28.804	0
	Moisture	2515.480	200.426	0
Lago Lolog	**Weibull**	**2175.092**	**0.000**	**1**
	Logistic	2339.248	164.156	0
	Olson	2433.921	258.829	0
	Moisture	2689.287	514.195	0

Table S3. Parameter estimations for the selected models

Mean, Mean of the posterior distributions; HPD, high posterior density; Rhat, successful convergence if Rhat ≤ 1.1; n.eff, effective sample size

Site	Model	Paremeter	Mean	HPD interval	Rhat	n.eff
Lago Puelo–Lago Epuyén	Moisture	h	0.05	0.04; 0.05	1.00	2533
		k	0.99	0.96; 1	1.00	42282
		m	0.97	0.94; 1	1.00	180000
		r	0.04	0.03; 0.04	1.00	3022
Brazo Tristeza (PN NH)	Moisture	h	0.01	0; 0.01	1.00	4321316
		k	0.04	0.01; 0.07	1.00	1405089
		m	0.03	0.01; 0.06	1.00	1200000
		r	0.01	0; 0.01	1.00	11917417
Cerro Catedral–Lago Gutierrez	Logistic	h	0.002	0.001; 0.003	1.00	120000
		c	17.792	5.43; 30.389	1.00	11138
		r	0.111	0.068; 0.158	1.01	69668
Lago Ñorquinco	Logistic	h	0.004	0.003; 0.006	1.00	73870
		c	32.618	20.713; 45.142	1.00	16871
		r	0.063	0.051; 0.076	1.00	13175
Lago Lolog	Weibull	c	9.43	8.02; 10.84	1.00	2083
		b	127.65	122.39; 133.16	1.00	1924

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