

Supporting Information for: **Improving the representation of drought-induced tree mortality in LPJmL-5**

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Contents of this file

- S1: Annual to monthly background mortality
- S2: Optuna multi-objective optimisation
- S3: Sensitivity of drought mortality to VPD and phenology

5 S1 Annual to monthly background and heat-stress mortality

To enable drought-induced mortality to be calculated at a monthly timescale, the existing annual background and heat stress mortality were first converted to a monthly timescale. This step ensures that all mortality processes operate on the same monthly timescale without changing total annual mortality for each PFT.

In the baseline model, mortality is applied once per year as a single annual event. For the monthly version, annual mortality is redistributed over the twelve months of the following year using:

$$mort_{monthly} = 1.0 - (1.0 - mort_{annual})^{1/12}. \quad (S1)$$

This relationship preserves the total annual mortality while providing a monthly resolution. This redistribution introduces a one-year shift in timing, but allows the number of individuals to be updated monthly, which is needed to capture seasonal drought effects.

Figure S1 shows this redistribution for eight calibration locations with different dominant PFTs. The left column compares mortality in the baseline model and the new monthly mortality implementation (MM), where the baseline shows a sharp annual peak and the MM version is smoother across months. The right column shows that the yearly sum of monthly mortality matches the baseline annual totals for each PFT (with a one-year shift), so the overall magnitude stays the same despite the redistribution.

Figures S2 and S3 further show that FPC and GPP are largely unchanged in the MM model. The main difference is a smoother tree FPC over the year, since mortality is applied monthly rather than as a single event. Small differences in FPC and GPP arise from the one-year shift in mortality timing, but these are minor and do not affect overall vegetation dynamics.

In summary, converting background and heat stress mortality to a monthly timescale is an intermediate but necessary step. It preserves total annual mortality while allowing the new drought-induced mortality to operate at a monthly time scale, capturing seasonal differences in drought stress.

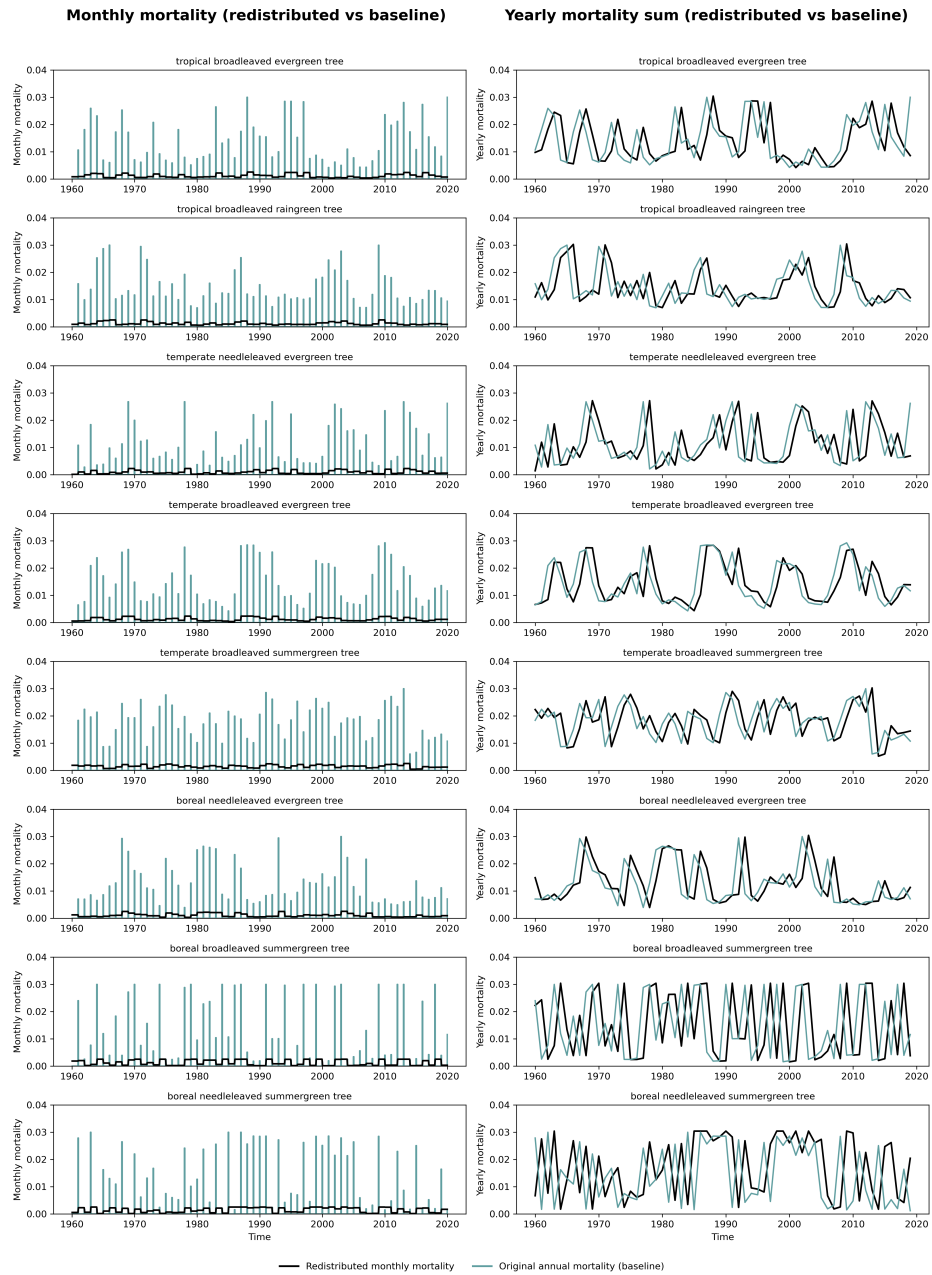


Figure S1. Monthly redistribution of background mortality in the MM model for eight calibration locations. The left column compares monthly mortality in the baseline and the MM model. The right column shows yearly totals, indicating that overall mortality is conserved apart from a one-year shift.

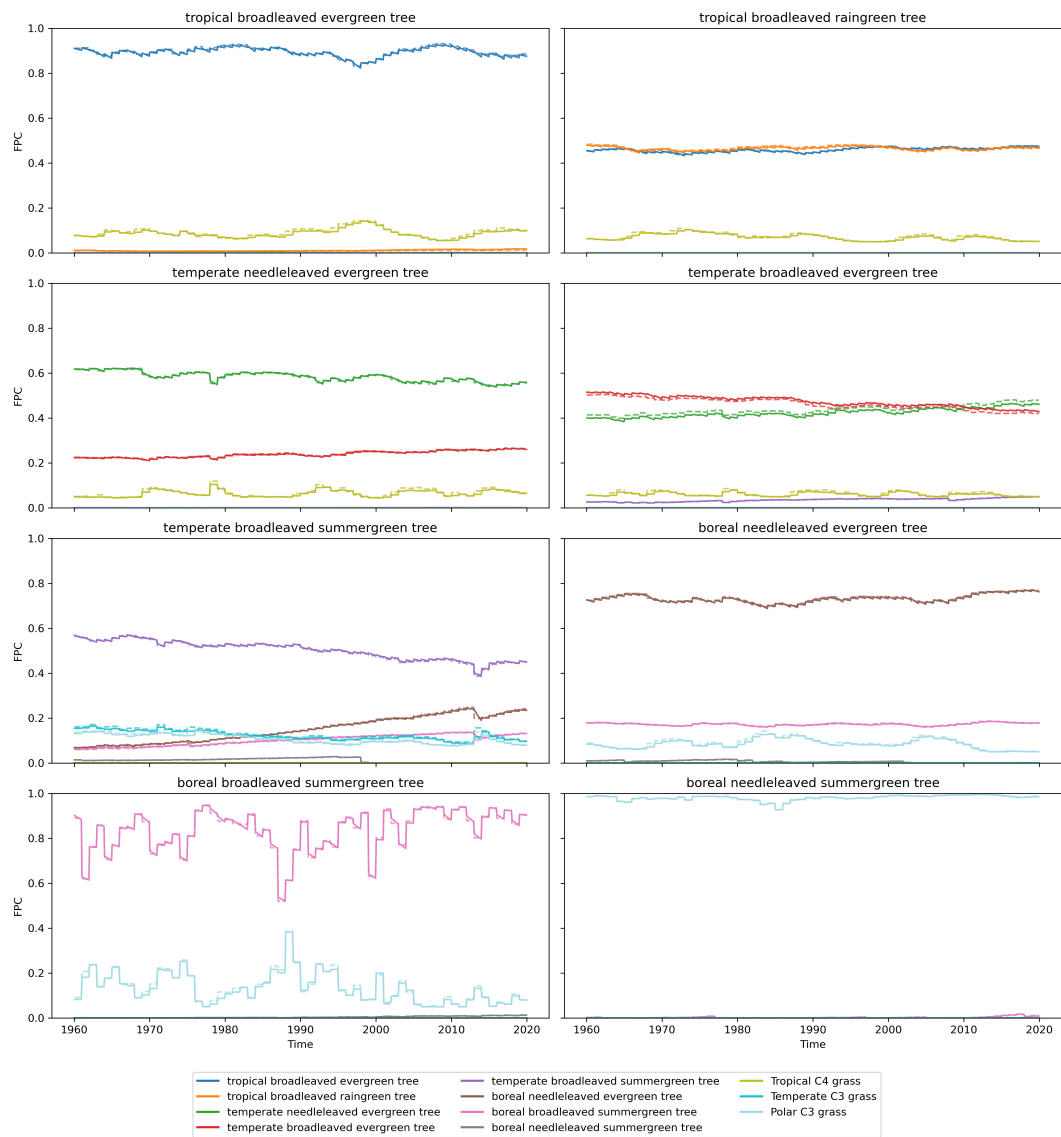


Figure S2. FPC at eight calibration locations for the baseline and MM models. Dashed lines indicate the baseline model, while solid lines indicate the MM model.

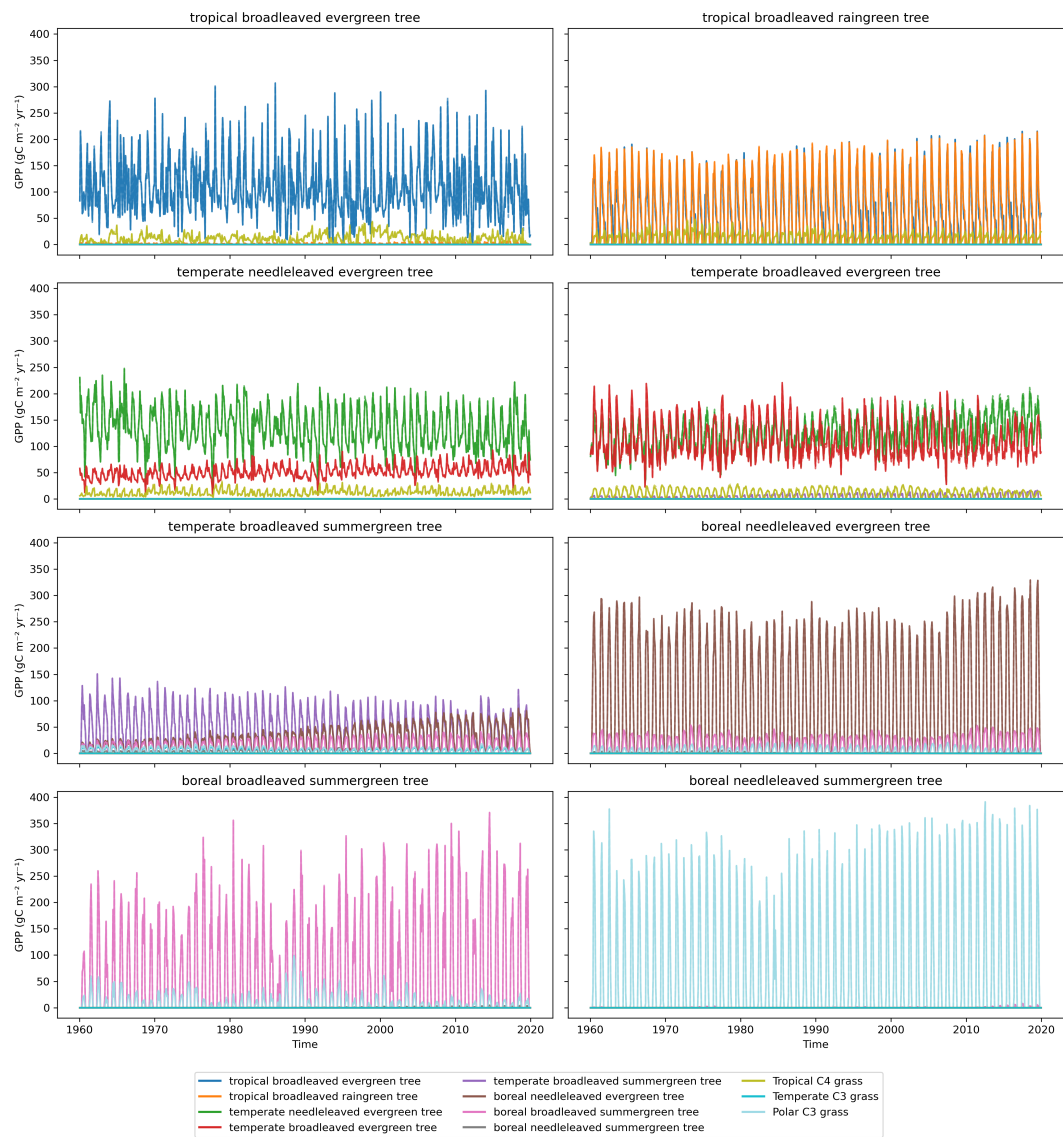


Figure S3. GPP at eight calibration locations for the baseline and MM models. Dashed lines indicate the baseline model, while solid lines indicate the MM model.

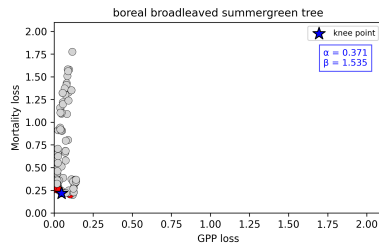
S2 Optuna multi-objective optimisation

S2.1 Pareto fronts

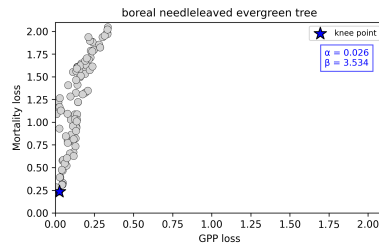
Figure S4 shows the Pareto fronts from the Optuna multi-objective optimisation for each tree PFT. Each point represents one parameter combination (α, β) , with GPP loss on the x-axis and mortality loss on the y-axis. Red points show the Pareto-optimal solutions, while grey points show all other trials. The blue star marks the parameter set used in the final DM simulations.

For most PFTs, mortality loss varies much more than GPP loss. This means mortality can often be improved substantially with only small changes in the GPP loss. As a result, the optimisation is mainly driven by mortality, while GPP is relatively insensitive to changes in α and β .

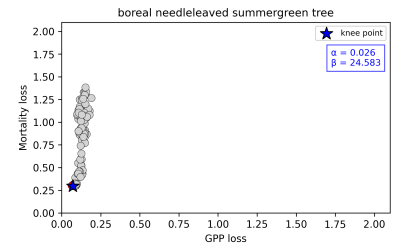
In most cases, the final parameter set was chosen as the Pareto-optimal solution with the shortest distance to the origin. For temperate needleleaved evergreen trees, however, trial 35 was selected instead of trial 36. Although trial 36 had a slightly smaller distance to the origin (0.259 vs 0.264), looking at the time series showed that trial 35 behaved more realistically. Because the difference was very small, trial 35 was used in the final simulations.



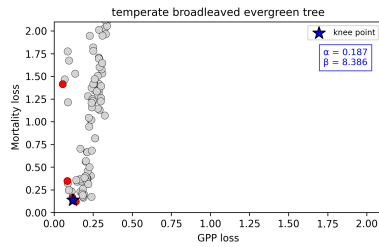
Trial	GPP	Mort	α	β
57.0	0.019	0.321	0.425	4.61
65.0	0.02	0.258	0.376	3.205
94.0	0.075	0.246	0.290	14.128
20.0	0.048	0.217	0.371	1.535
56.0	0.103	0.204	0.231	10.29
13.0	0.119	0.199	0.257	3.537



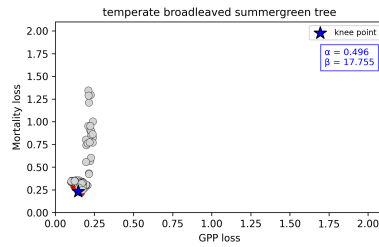
Trial	GPP	Mort	α	β
30.0	0.007	0.28	0.013	0.435
52.0	0.01	0.268	0.073	4.807
22.0	0.018	0.248	0.022	22.142
42.0	0.026	0.237	0.026	3.534



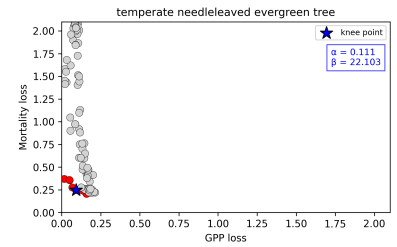
Trial	GPP	Mort	α	β
93.0	0.064	0.3	0.135	0.056
92.0	0.068	0.298	0.026	24.583
37.0	0.071	0.295	0.026	24.583



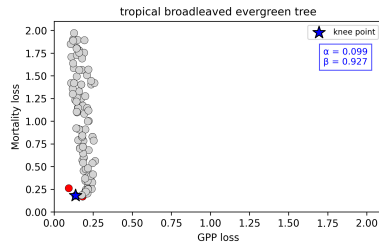
Trial	GPP	Mort	α	β
69.0	0.056	1.413	0.542	11.252
71.0	0.086	0.346	0.018	14.057
32.0	0.089	0.32	0.107	0.612
15.0	0.096	0.245	0.121	1.63
10.0	0.112	0.229	0.109	11.629
46.0	0.118	0.162	0.139	5.787
90.0	0.118	0.162	0.139	5.787
97.0	0.121	0.136	0.187	8.386
41.0	0.14	0.121	0.187	8.386



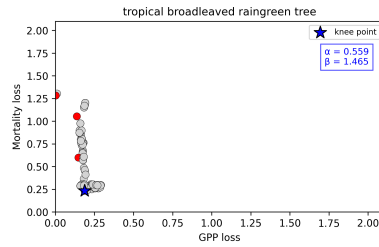
Trial	GPP	Mort	α	β
24.0	0.101	0.335	0.166	12.546
23.0	0.121	0.289	0.253	19.562
63.0	0.136	0.267	0.332	22.857
89.0	0.146	0.231	0.496	17.755
18.0	0.161	0.222	0.365	17.293
66.0	0.165	0.219	0.565	22.788



Trial	GPP	Mort	α	β
14.0	0.017	0.369	0.022	8.526
59.0	0.05	0.358	0.084	4.815
4.0	0.051	0.355	0.084	4.815
84.0	0.069	0.275	0.111	6.573
35.0	0.092	0.247	0.111	22.103
49.0	0.132	0.243	0.206	1.199
34.0	0.144	0.235	0.182	20.959
18.0	0.156	0.222	0.376	10.279
36.0	0.159	0.204	0.233	22.782



Trial	GPP	Mort	α	β
40.0	0.094	0.261	0.012	22.562
80.0	0.137	0.18	0.099	0.927
34.0	0.138	0.18	0.099	0.927
2.0	0.183	0.17	0.079	7.341
61.0	0.183	0.17	0.079	7.341



Trial	GPP	Mort	α	β
96.0	0.003	1.282	0.532	14.35
9.0	0.138	1.053	0.67	21.814
55.0	0.148	0.598	0.503	2.292
33.0	0.16	0.287	0.186	21.347
58.0	0.175	0.274	0.393	0.796
27.0	0.176	0.274	0.393	0.796
24.0	0.185	0.273	0.512	18.173
79.0	0.187	0.234	0.559	1.465

Figure S4. Pareto fronts for the 100 Optuna trials of each tree PFT. Each point represents one parameter combination (α , β). Grey points show all evaluated trials, red points indicate Pareto-optimal solutions, and the blue star marks the selected parameter set used in the final DM simulations.

S2.2 SPEI–GPP and SPEI–mortality relationships

Figure S5 shows the SPEI–GPP and SPEI–mortality relationships for the baseline, MM, and selected DM simulations, together with the corresponding objective functions for each tree PFT. The DM simulation uses the α and β values from the selected Pareto-optimal point on the Pareto front. Points show the data, while the lines show the fitted relationships. The dashed black lines indicate the mortality and GPP objective functions. The losses shown in Figure 5 of the manuscript was calculated as the RMSE between the fitted model relationships and the corresponding objective functions.

The biggest changes are in the mortality relationships. For most tropical and temperate PFTs, the DM simulation produces slopes that are much closer to the mortality objective than either the baseline or MM simulations. The boreal PFTs show smaller changes.

Differences in the GPP relationships are generally small. For most PFTs, the DM simulation stays close to the baseline and MM results, suggesting that the optimisation mainly affects mortality. For tropical broadleaved evergreen trees, there is a small drop in GPP performance, but this comes with a much larger improvement in the mortality relationship. Overall, the reduction in mortality loss outweighs the increase in GPP loss, leading to a better overall fit to the objective functions.

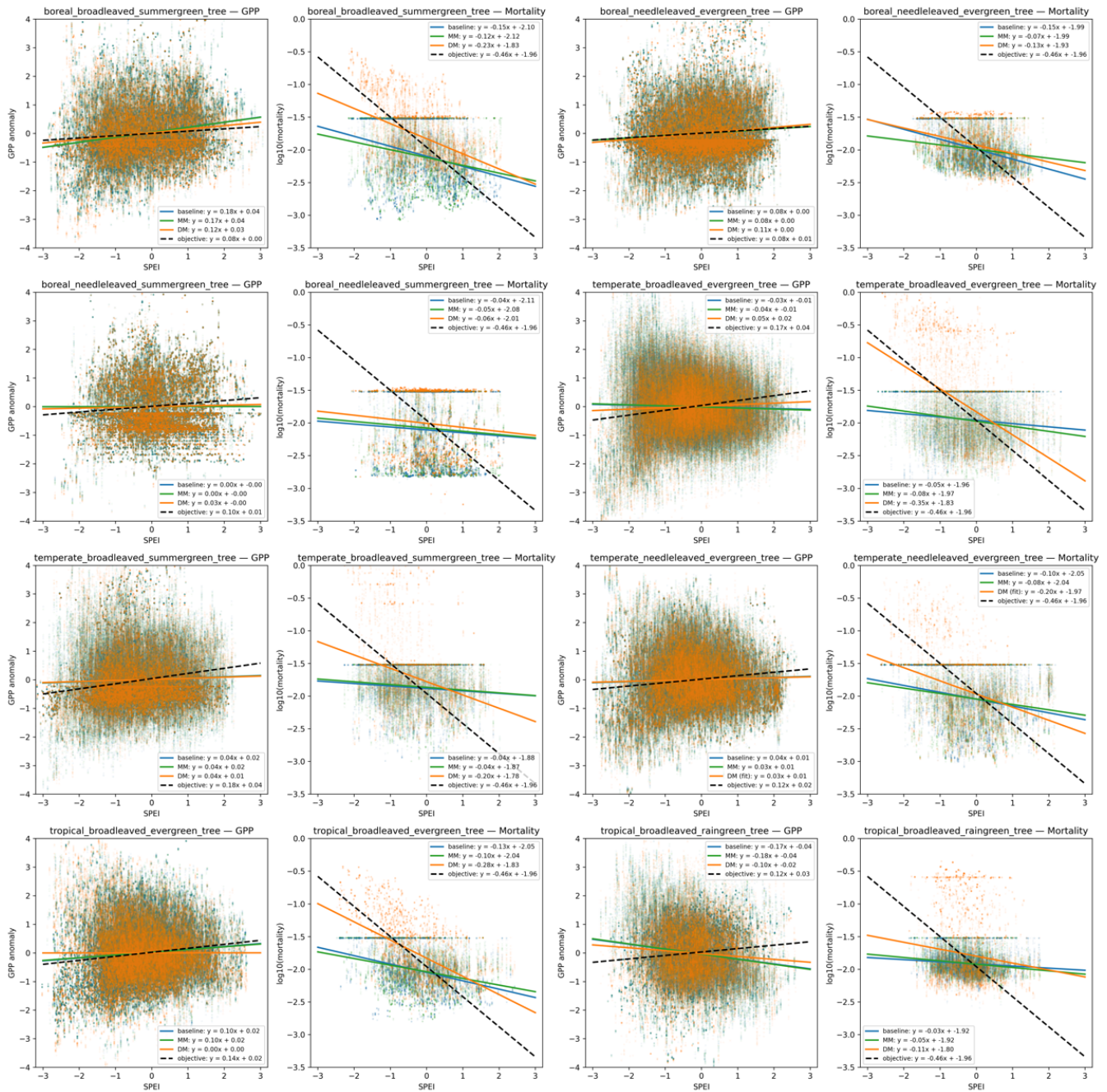


Figure S5. SPEI–GPP and SPEI–mortality relationships for each tree PFT. Blue, green, and orange points and lines show the baseline, MM, and selected DM simulations, respectively. Dashed black lines indicate the mortality and GPP objective functions used during calibration. The DM simulation generally produces mortality responses that are closer to the objective functions, particularly for tropical and temperate PFTs, while changes in GPP responses are relatively small.

S2.2.1 Parameter sensitivity across PFTs

Figures S6 and S7 show how mortality and GPP losses vary for the Optuna trials for each tree PFT as a function of α and β . Each figure contains three panels per PFT: loss versus α , loss versus β , and α vs β . Each point represents one trial, with darker colours indicating lower loss.

55 For mortality, most PFTs show a clear dependence on α . In general, low to intermediate values of α tend to give the lowest loss, while higher values lead to a strong increase in mortality loss. The relationship with β is more scattered, with no consistent optimum across PFTs. This suggests that α has a stronger influence on the mortality response than β in the calibration.

For GPP, loss values are generally lower and less variable than for mortality. The dependence on α is weaker, and most PFTs do not show a clear minimum. The relationship with β also shows no clear pattern, indicating that GPP loss is only weakly
60 sensitive to α and β .

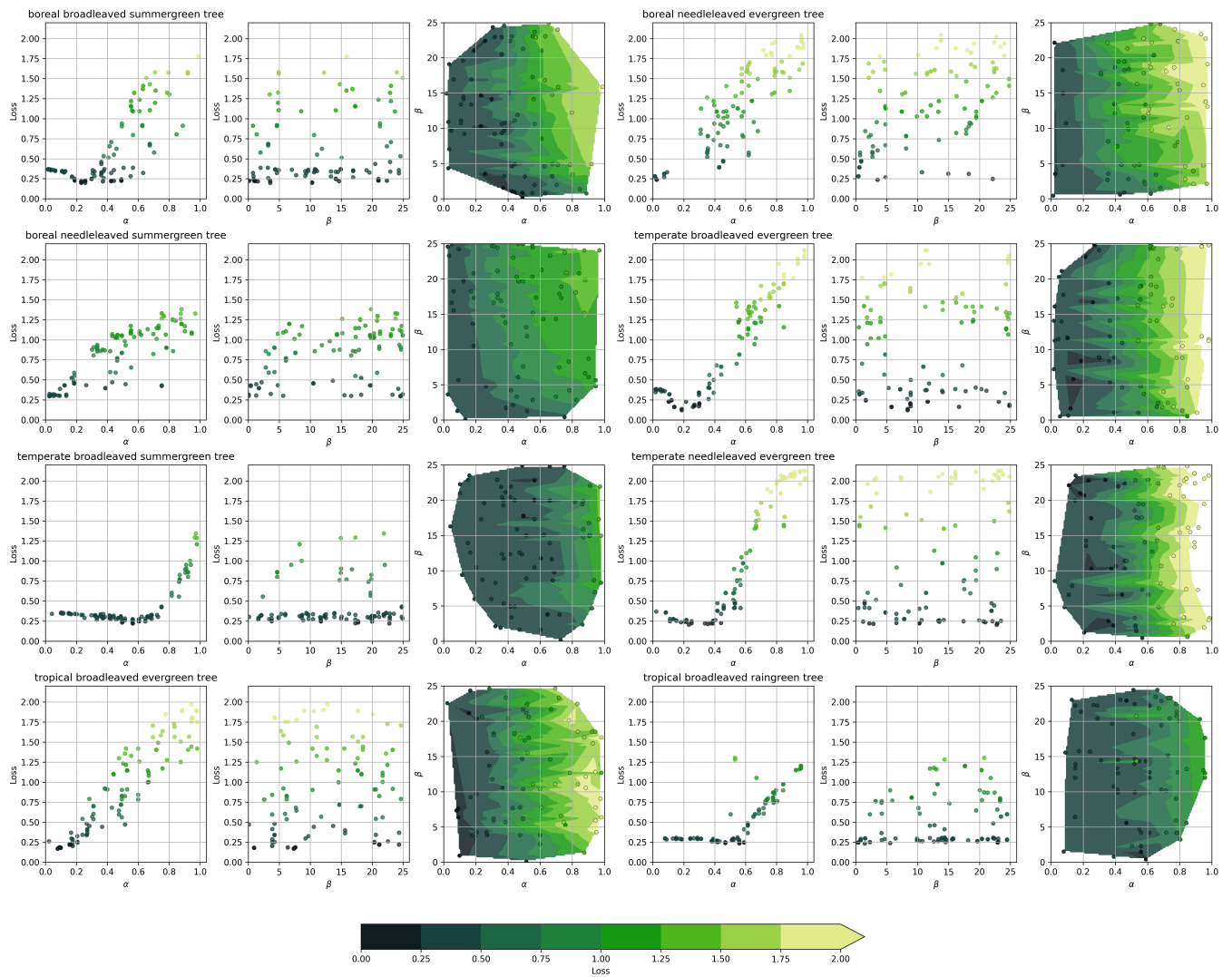


Figure S6. Mortality loss across Optuna trials for each tree PFT. Each panel shows loss versus α , loss versus β , and α vs β . Points represent individual trials, with darker colours indicating lower loss.

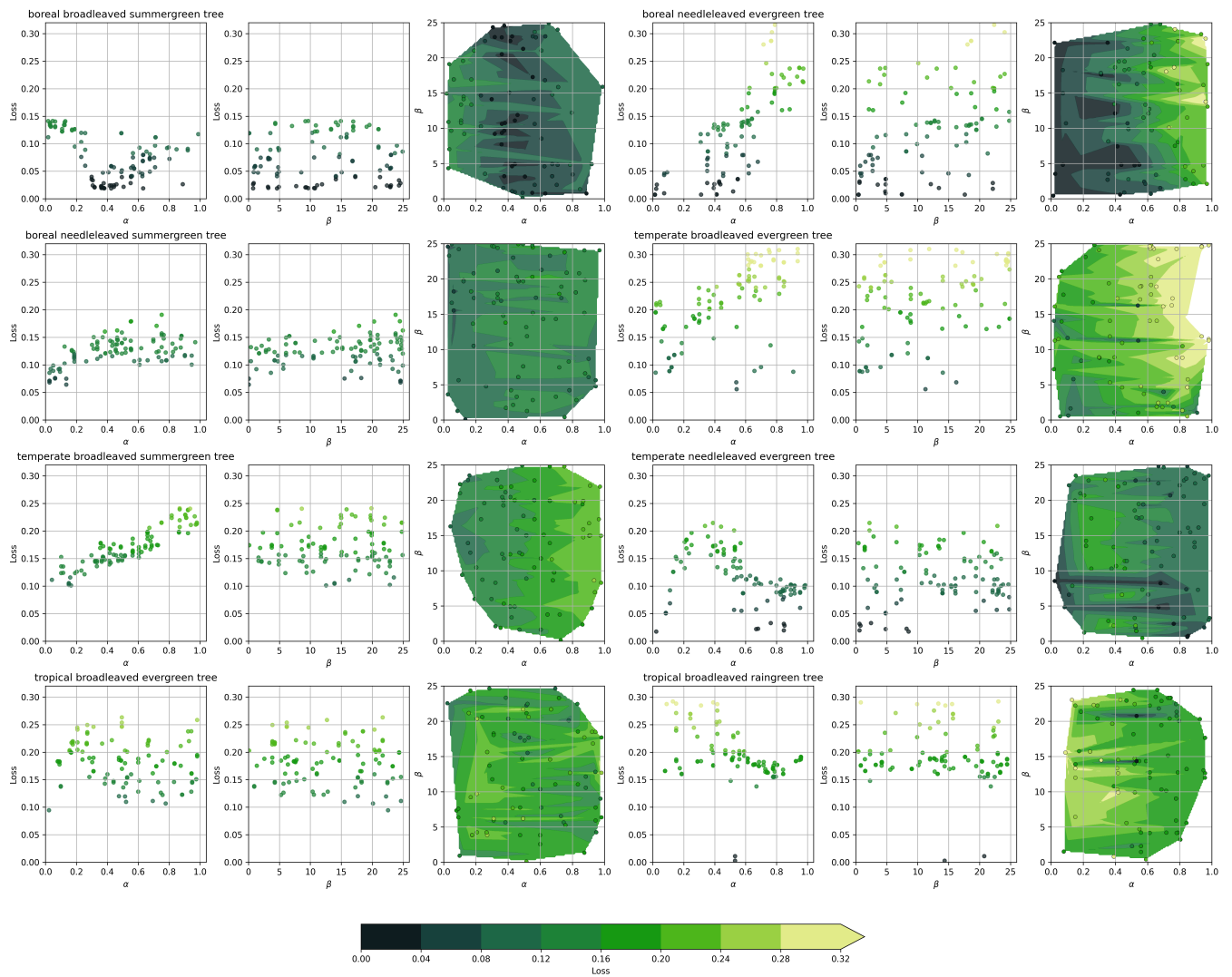


Figure S7. GPP loss across Optuna trials for each tree PFT. Panel structure is identical to Figure S6. Colours indicate GPP loss, with darker values showing lower loss. Note the different colorbar range.

S3 Sensitivity of drought mortality to VPD and phenology

To test how the drought mortality changes with VPD and phenology, we repeated the curves from Figure 6 in the manuscript while varying both variables (Figures S8 and S9). Increasing VPD generally leads to higher mortality rates for all PFTs. When VPD is low, mortality can stay limited even under strong water stress, whereas higher VPD leads to a much steeper increase in mortality once the threshold is crossed. Phenology acts as a limiting factor for when drought mortality can occur. Lower phenology values reduce overall mortality because the response is scaled down when leaf activity is low. When phenology is zero, drought mortality is also zero, since no active vegetation is present.

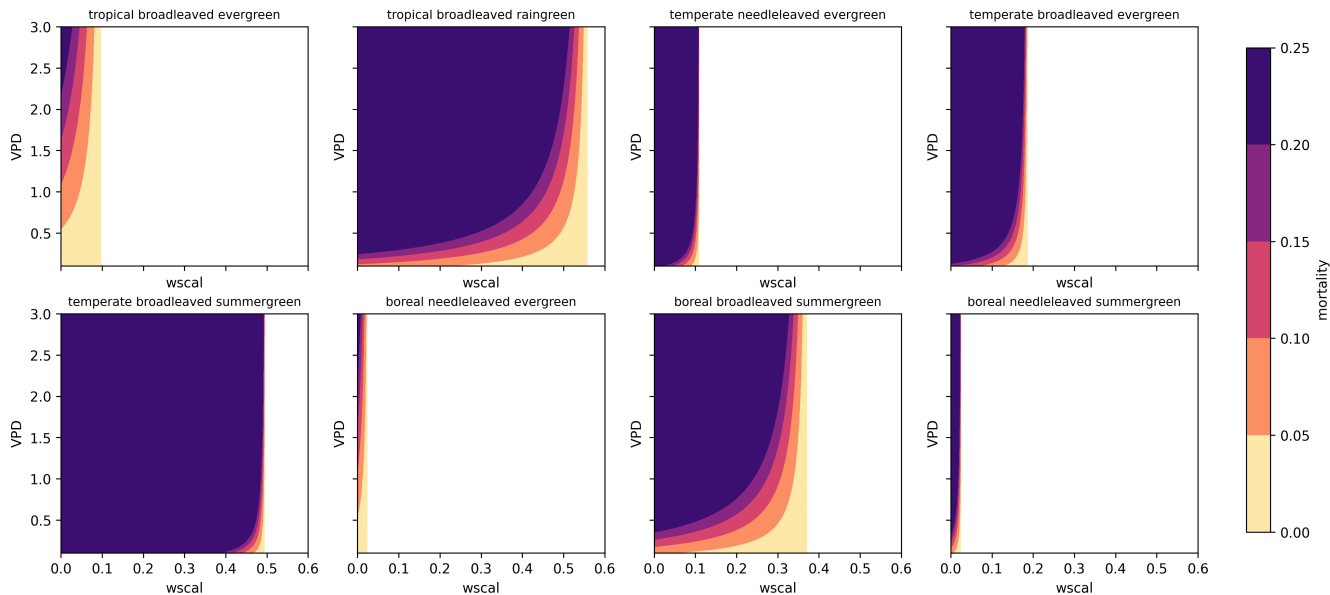


Figure S8. Drought mortality as a function of water stress (*wscal*) and vapour pressure deficit (VPD). Mortality increases with increasing VPD due to higher atmospheric demand. Values where mortality is zero are masked out.

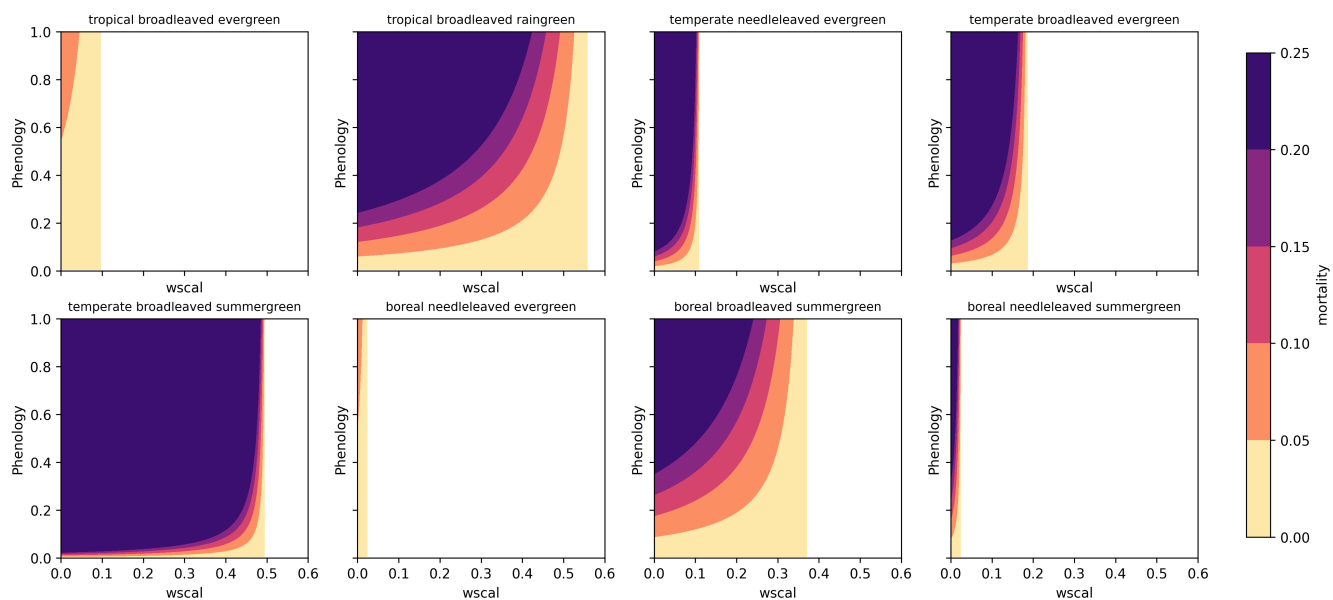


Figure S9. Drought mortality as a function of water stress ($wscal$) and phenology. Lower phenology reduces drought mortality, and when phenology is zero, drought mortality is zero. Values where mortality is zero are masked out.