No drought steeling in 1,175 tree-ring sites

A preregistered test of whether a moderate earlier drought makes trees more resilient to a later severe one, with time-shift, permutation and placebo controls and a rerun on gridded drought data

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Version 1.0, 9 November 2026. Finding F63 in the findings ledger, Test A. Honest null (tier D).

Abstract

A common intuition holds that stress hardens: a tree that came through a dry spell should cope better with the next one. We tested that idea on 1,175 tree-ring sites in the contiguous United States, 65 species and 3,780 site-drought events, with the test written down and hash-locked before the run. A moderate drought four to eleven years earlier moved log resilience to a later severe drought by +0.039 (95% interval -0.011 to +0.090), inside a time-shift null whose 95th percentile was 0.065 (p 0.18). The preregistered steeling test failed. A severe prior drought lowered growth in the drought year (resistance -0.087, p 0.006) and raised recovery after it by +0.096, so resilience barely moved. Part of that recovery gain follows from how the indices are built. A rerun with drought taken from 0.5 degree gridded data on 1,097 sites gave +0.025 (-0.009 to +0.059), below its own time-shift 95th percentile of 0.038 (p 0.14). The interval still allows a gain of up to about 9 percent in resilience, so small conditioning effects are not ruled out.

1 What this means for a reader

If someone tells you that forests exposed to drought become hardened against the next one, ask for the test against a version of the drought record moved in time. Across a large public archive of tree rings, trees that had lived through an earlier drought grew less in the severe drought year and bounced back more afterwards, and the two roughly cancelled. At this scale, drought "priming" of trees is not shown.

2 Introduction

The question comes from a broad idea about stress and adaptation: that a moderate earlier stress leaves an organism better prepared for a harder one. Applied to trees, we call this steeling. Trees make a good test, because each annual ring records growth, and public archives hold thousands of sites with records over a century long.

Forest ecology points mostly the other way. Anderegg and colleagues [1] examined stem growth after severe drought at 1,338 forest sites worldwide and reported a widespread drought legacy: growth stayed low for one to four years after the drought, most often in dry ecosystems and in the pine family. Anderegg and colleagues [2] later asked whether forests acclimate to repeated droughts or become more vulnerable, and concluded that successive droughts are generally more damaging, with conifers the most affected. We read that paper at the level of its publisher page and press coverage.

The usual measures of drought response come from Lloret, Keeling and Sala [3], who proposed resistance, recovery and resilience indices from ring growth around a low-growth episode in ponderosa pine. Schwarz and colleagues [4] reviewed 82 studies that used these indices and listed cases where they mislead: a lagged growth minimum, depressed growth in the reference years before the drought, and repeated droughts. Their review bears on our result, because resilience equals resistance times recovery, so a weak drought-year ring raises recovery by arithmetic alone.

Our searches, run on 9 November 2026, found these and related studies on legacies and repeated drought. We did not find a study of this exact contrast, moderate earlier drought against later resilience, scored against a time-shifted drought record. That is a search result, not proof that none exists.

3 Preregistration and design

The design was written as a preregistration and hash-locked on 29 October 2026 at 22:54 UTC, before any hypothesis value was computed. A smoke run at small sizes before the lock printed design counts only: 1,175 sites, 3,780 events, 65 species, 177 climate divisions, and the prior-drought group sizes. No coefficient was printed or read.

The locked file covers four tests, A to D. Tests B to D are simulations of a loaded rod, a small neural network and a Bayesian learner, and they say nothing about trees. This paper reports Test A, the only test on real data. Across all four tests the run returned 22 verdicts, 10 passing and 12 failing.

Test A had four preregistered predictions, each a set of rules that must all hold:

- A1, steeling: the moderate-drought coefficient is above 0, its Benjamini-Hochberg adjusted q is below 0.05, and it is above the 95th percentile of both nulls.
- A2: the moderate-drought coefficient exceeds the severe-drought coefficient, with q below 0.05.
- A3: resilience rises and then falls with drought dose, by the two-lines test, with a statistic above 1.96 and above its shuffle 95th percentile.
- A placebo: grouping by a window after the event must not predict resilience (p at or above 0.05).

The forecast written before the run: A1 weak or null, A2 likely positive because severe drought leaves legacies, and A3 failing.

4 Data and provenance

Rings: standard chronologies for the contiguous United States from the International Tree-Ring Data Bank [5], held by NOAA's National Centers for Environmental Information as public data with a request to cite the contributors. Ring width only. Years from 1896 with at least 5 samples where a sample count exists; index values at or below 0 dropped.

Drought, main test: NOAA nClimDiv divisional Palmer Drought Severity Index, version 1.0.0 built on 6 October 2026 [6], US federal data with no restriction on use. Each site was placed in its climate division by its coordinates, and the yearly drought value is the June to August mean of that division. The final sample is 1,175 sites, 65 species and 177 divisions, with 579 division drought years and 3,780 site-drought events.

Drought, rerun: the self-calibrating PDSI from CRU TS 4.10 at 0.5 degree, 1903 to 2025 [7] [8], released under the Open Database License 1.0 with attribution to the Climatic Research Unit, University of East Anglia. Each site takes the nearest cell with complete June to August data in at least 60 years, within 1 degree. This gave 1,097 sites, 64 species, 505 cells and 2,549 events.

A division averages over a large area, and a site sits at one point in it. The rerun exists to pay that debt. A 0.5 degree cell is closer to the site and is still not a station.

5 Methods

Events

A focal year t is a division year with June to August PDSI at or below -3. An event needs ring growth in years $t-3$ to $t+3$, no other severe year in $t-3$ to $t-1$ or $t+1$ to $t+3$, and drought data for the exposure window $t-11$ to $t-4$.

The Lloret indices

With g_t the ring index in the drought year, G_{pre} the mean of the three years before and G_{post} the mean of the three years after, the Lloret indices are resistance, recovery and resilience:

$$R_t = \frac{g_t}{G_{pre}}, R_c = \frac{G_{post}}{g_t}, R_s = \frac{G_{post}}{G_{pre}} = R_t \cdot R_c \quad (1)$$

All three are analysed as natural logarithms. The product in eq. 1 matters later: a lower drought-year ring lowers R_t and raises R_c by the same factor.

Exposure groups

The exposure is the lowest June to August PDSI in years $t - 11$ to $t - 4$. An event is in the none group if that minimum is above -2, moderate if it lies above -3 and at or below -2, and severe if it is at or below -3. The groups held 986, 941 and 1,853 events. The dose is the larger of 0 and minus that minimum.

The model

For event i at site s in year t:

$$\ln R_s = \beta_m M_i + \beta_s S_i + \gamma_1 D_t + \gamma_2 D_{pre} + \gamma_3 D_{post} + \alpha_s + \tau_t + \varepsilon_i \quad (2)$$

where M_i and S_i mark the moderate and severe groups, D_t, D_{pre} and D_{post} are the drought-year PDSI and the mean PDSI of the three years before and after, and α_s and τ_t are site and year fixed effects. Species are constant within a site, so site effects absorb them; a model with species and year effects was reported as secondary. Standard errors are clustered by climate division. Resistance and recovery were fitted with the same model as secondary outcomes. The coefficient under test is β_m.

In the rerun, the preregistered primary model used species and year effects in place of site effects, with the same covariates and the same clustering by division.

Shape in dose

For prediction A3, resilience with site, year and covariate effects removed and no group terms was set against the dose, and the two-lines test was applied. Its statistic is the smaller of the rising line's z and minus the falling line's z, so a large positive value means a rise and then a fall.

6 Controls and planted checks

Test A had no planted check: no synthetic forest with a known steeling effect was built and run through the model. The placebo window serves as the design check, together with three controls.

- The time-shift null moves each division's PDSI record by a random offset of at least 20 years, wraps it, and rebuilds every event and group. It keeps each record's pattern of droughts and breaks its link with the rings. 200 draws. This is the null the preregistered rule binds.
- The label-permutation null shuffles the prior-drought labels among each site's own events, 500 draws. It keeps every drought date in place, so it is the weaker comparison.
- The dose shuffle permutes residual resilience across dose for the two-lines test, 200 draws.
- The placebo window groups each event by drought in years $t + 5$ to $t + 12$, after the event.

Each p value from draws is the share of draws at or above the real value, with one added to the count and to the number of draws:

$$p = \frac{k + 1}{n + 1} \quad (3)$$

where k is the number of draws at or above the real value and n the number of draws. The real value is

compared with the null distribution's 95th percentile. The rerun used the same time-shift null on each grid cell's record, 200 draws.

7 Results

Table 1 gives the estimates, and Figure 1 draws the main ones. A moderate drought four to eleven years earlier moved log resilience to a later severe drought by +0.039 (95% interval -0.011 to +0.090), inside a time-shift null whose 95th percentile was 0.065 (p 0.18). Its raw p was 0.128 and its adjusted q 0.166. A severe prior drought gave +0.009 (-0.039 to +0.057). Moderate minus severe was +0.030 (-0.014 to +0.074, q 0.214).

Table 1. Estimates on the log Lloret index, division PDSI, with 95% intervals clustered by climate division. Site and year effects unless stated.

Outcome and term	Estimate	95% interval	p	Events
Resilience, moderate prior	+0.039	-0.011 to +0.090	0.128	3,780
Resilience, severe prior	+0.009	-0.039 to +0.057	0.71	3,780
Resilience, moderate minus severe	+0.030	-0.014 to +0.074	0.18	3,780
Placebo window, moderate	+0.006	-0.059 to +0.070	0.86	3,976
Species effects, moderate	+0.037	0.000 to +0.074	0.047	3,780
Species effects, severe	+0.035	-0.005 to +0.076	0.089	3,780
Resistance, moderate prior	-0.063	-0.155 to +0.028	0.18	3,780
Resistance, severe prior	-0.087	-0.149 to -0.025	0.006	3,780
Recovery, moderate prior	+0.103	+0.025 to +0.180	0.010	3,780
Recovery, severe prior	+0.096	+0.035 to +0.158	0.002	3,780

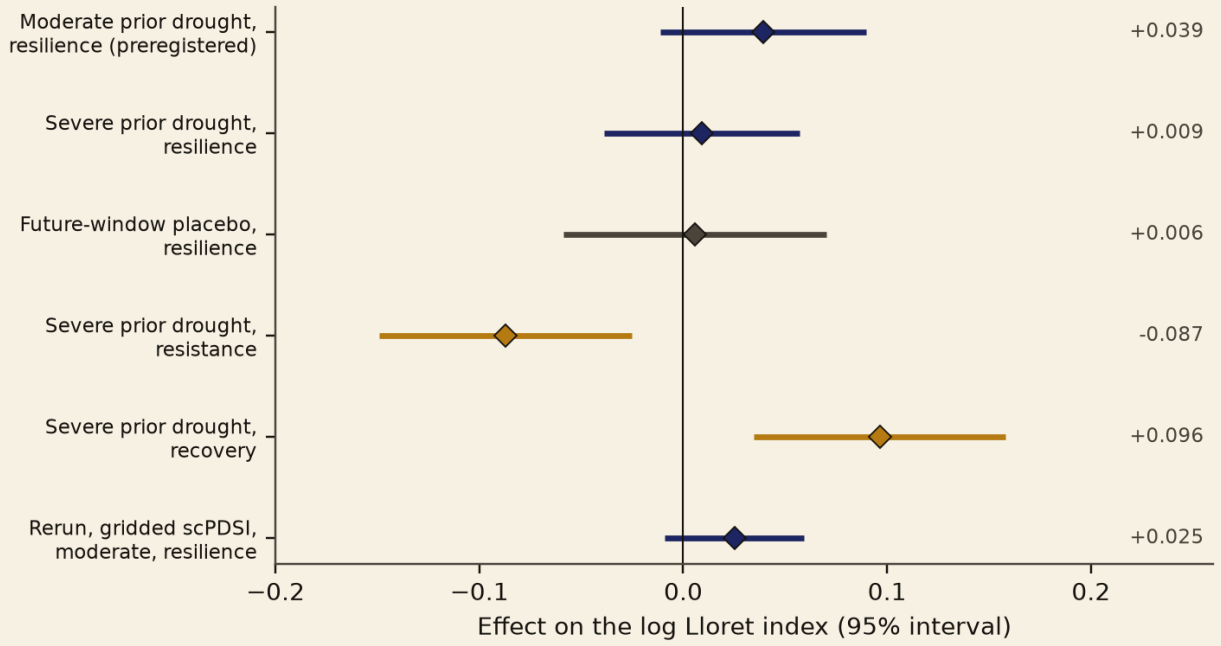


Figure 1. Estimates with 95% intervals. Navy: resilience under the preregistered model and the rerun. Grey: the placebo window. Ochre: the two components after a severe prior drought. Drawn from the two runs' result files.

Figure 2 sets the moderate-drought estimate against the three null ranges. It sits inside the time-shift range in both runs and above the label-permutation range (95th percentile 0.020, p 0.004). The label permutation keeps each site's drought timing, so beating it says less, and the preregistered rule used the time shift.

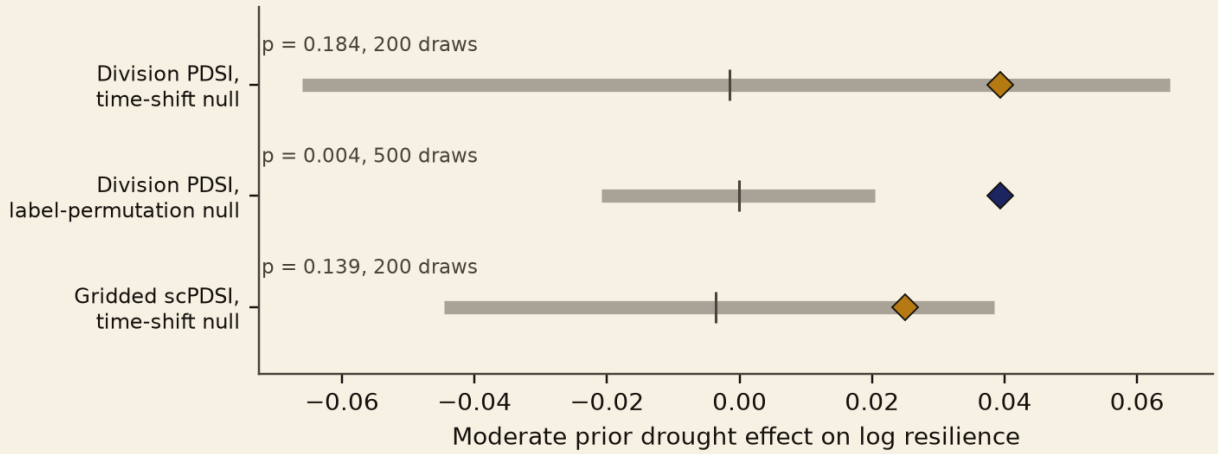


Figure 2. The moderate prior drought estimate (diamond) against the 5th to 95th percentile range (bar) and mean (tick) of each null. Ochre marks an estimate inside the range, navy one above it.

The components explain the null in resilience. A severe prior drought lowered growth in the drought year (resistance -0.087, p 0.006) and raised recovery after it by +0.096, so resilience barely moved. By eq. 1, a lower drought-year ring raises recovery by the same factor it lowers resistance, so the recovery gain is partly arithmetic and is not evidence of conditioning.

The placebo window was clean: drought after the event gave +0.006 (p 0.86). No rise-then-fall shape appeared with dose. The two lines fell and then rose, neither significantly (z -0.89 and +0.81), and the statistic of -0.89 sat below its shuffle 95th percentile of 1.26. The mean residual resilience by number of moderate-drought years in the window was -0.007 for none (1,705 events), +0.005 for one (1,268), +0.008 for two (643), -0.019 for three (103) and +0.059 for four (44).

With species and year effects in place of site effects, the moderate prior drought gave +0.037 (0.000 to +0.074, p 0.047), and severe +0.035 (p 0.089). The two did not differ (+0.002), so under that model any prior drought went with slightly higher resilience, with no edge for a moderate one. The rerun tested that sign.

The rerun on gridded drought

The rerun, preregistered and locked on 30 October 2026 at 03:20 UTC, took drought from the nearest 0.5 degree cell of the CRU self-calibrating PDSI. Its kill condition fires when the 95% interval of the species-effects estimate includes 0 or the estimate sits at or below the time-shift 95th percentile. Table 2 gives its estimates.

Table 2. Rerun on gridded scPDSI, 1,097 sites. Species and year effects unless stated; 95% intervals clustered by climate division.

Outcome and term	Estimate	95% interval	p	Events
Resilience, moderate prior	+0.025	-0.009 to +0.059	0.15	2,549
Resilience, severe prior	+0.018	-0.022 to +0.058	0.37	2,549
Site effects, moderate prior	+0.049	-0.002 to +0.101	0.062	2,549
Site effects, severe prior	+0.064	+0.009 to +0.118	0.022	2,549
Resistance, moderate prior	-0.046	-0.110 to +0.017	0.15	2,549
Recovery, moderate prior	+0.072	+0.009 to +0.134	0.024	2,549
Placebo window, moderate	-0.010	-0.041 to +0.022	0.55	2,803

A rerun with drought taken from 0.5 degree gridded data on 1,097 sites gave +0.025 (-0.009 to +0.059), below its own time-shift 95th percentile of 0.038 (p 0.14). The kill condition fired on both of its rules, and the adjusted q was 0.174. The small positive sign under division drought with species effects did not survive the finer drought

data. Resistance fell and recovery rose, as in the main run.

Table 3 sets the forecasts written before the main run against the outcomes.

Table 3. Forecasts fixed in the preregistration against what the run gave.

Prediction	Forecast	Outcome
A1 steeling	weak or null	fail, null
A2 moderate beats severe	likely positive	fail, +0.030 with q 0.214
A3 rise then fall in dose	fail	fail
Placebo window	clean	clean

8 Discussion

The test asked whether moderate drought conditions trees for a later severe one. It found no effect beyond what a drought record moved in time also produces, in two runs with two drought products. That is an honest null: a working test, a clean placebo, and an estimate inside its null.

The result fits the direction of Anderegg and colleagues [2], who reported that repeated droughts tend to hurt more. Our severe-prior estimates of resistance fit the legacy picture of Anderegg and colleagues [1]: a tree that has been through a severe drought lays down a narrower ring in the next one.

The recovery gain is where a careless reading would find steeling. Recovery rose by about as much as resistance fell. Schwarz and colleagues [4] warned that Lloret's indices mislead when growth in the reference years is depressed or droughts repeat, and eq. 1 shows the simplest version of the problem. A study that reported recovery alone would see trees "bouncing back" better after earlier drought. The resilience ratio, which cancels the drought-year ring, shows no net gain.

The label-permutation null is the trap on the other side. The estimate beat it with p 0.004. That null keeps every drought date in place, so it compares events within a site's own history and does not remove effects tied to when droughts fell. We fixed the time-shift null as binding before the run, and it was not beaten.

9 Limitations

- The 95% interval reaches +0.090 in log resilience, a gain of about 9 percent. Small conditioning effects are not ruled out.
- No planted forest with a known steeling effect was run through the model, so the design's ability to detect an effect is shown only by the width of its interval.
- No autocorrelation baseline for growth memory was fitted, so part of any legacy could be the persistence of the ring series itself.
- The recovery gain is partly mechanical, by eq. 1.
- Division drought is coarse. The rerun's 0.5 degree cells are closer to the sites and are still gridded estimates, not station data.
- In the rerun with site effects in place of species effects, a severe prior drought gave +0.064 (+0.009 to +0.118, uncorrected p 0.022). That model was not the preregistered test there. We read it as a lead for a new locked study.
- Sites are in the contiguous United States and the record is ring width only.
- Scoring was done by our own code and was not blind.

10 Verified

Verified: on 9 November 2026 the counts (1,175 sites, 65 species, 177 divisions, 579 division droughts, 3,780

events and the three group sizes), every estimate, interval and p value in Table 1, the adjusted q values, the time-shift and label-permutation null percentiles and p values, the two-lines statistics and the residuals by number of moderate years were re-read from the main run's result file. The rerun's counts and every value in Table 2, its null percentile, p and q, and its kill verdict were re-read from its own result file. All tree values match the findings ledger. The SHA-256 of each preregistration matches the hash recorded in its result file. Both figures were drawn by a script that reads only the two result files. The verdict count across all four tests, 10 passing and 12 failing, was counted from the main result file and differs from the ledger headline; see Corrections. The study was not re-run for this paper. The literature was found by searches run on 9 November 2026 and read at the level of abstracts, publisher pages, press coverage and search summaries; the full texts were not read.

11 Corrections

- 30 October 2026: the gridded rerun found that the positive sign under division drought with species effects (+0.037, p 0.047) did not survive site-scale drought (+0.025, below the time-shift 95th percentile of 0.038). Forest and stress models keep no steeling as the default. This paper reports both.
- 9 November 2026: the findings ledger headline and the run's own summary gave 9 passing and 13 failing verdicts across Tests A to D. The result file and the ledger entry's own list of names give 10 passing and 12 failing. No tree value changes.
- 9 November 2026: first published version.

12 Reproduction

- Data: ITRDB standard ring-width chronologies for the contiguous United States; NOAA nClimDiv divisional PDSI; for the rerun, CRU TS 4.10 scPDSI at 0.5 degree.
- Place each site in its climate division and take the June to August mean PDSI. Mark severe drought years at -3 or below and build events and exposure groups as in the methods.
- Compute eq. 1 as logarithms and fit eq. 2 with site and year effects and division-clustered errors.
- Repeat with each division's PDSI record shifted by a random offset of 20 years or more, 200 times, and compute eq. 3. Run the label permutation 500 times and the placebo window once.
- Rerun with the nearest scPDSI cell for each site, species and year effects, and 200 shifts of each cell's record.
- Main run: preregistration SHA-256 1e7230973641a2c07fe5eb1b44bc6874eff80c7b85ff081920c22d21ee93ca7c. Plan SHA-256 99b4edfab5def0ab554b7188acd68254cc4d5fc80d9bcd5b07625c1c9ff583ce. Run 20261029T225453Z. Result file SHA-256 0ef775ca981f2cdaca7b4df602b1c6514daba73ccb3035def7f36ef15d3c6828.
- Rerun: preregistration SHA-256 aabf64d9ea802d33515d9cf768a30fabaf9e9d61587b0431b72fd495147938c8. Plan SHA-256 ec3e804546d9bc3654c41c19e1b781d5b95aded086f8f1bbf2aed72f49688d6c. Run 20261030T033057Z. Result file SHA-256 fbfc39401773f4e60332c386f7672bf077eb41b0438317cfc61aa9dd028ce53f.
- Cost: the main run took about ten minutes on one desktop CPU for all four tests, 132.4 kJ measured at the machine; Test A's model took 2.3 seconds and its time-shift null 132 seconds. The rerun's tree test took 18 seconds.

13 Appendix A. The preregistered verdicts

Each verdict is a set of rules written before the run. A verdict passes only when every rule holds. Values are read from the result files.

Table 4. Preregistered verdicts for Test A and the rerun, and the rules that decided them.

Verdict	Deciding rule	Value	Holds
A1 steeling	moderate estimate above 0; q below 0.05; above time-shift 95th percentile (0.065); above permutation 95th percentile (0.020)	0.039; 0.166; 0.039; 0.039	no
A2 moderate beats severe	difference above 0; q below 0.05	0.030; 0.214	no
A3 rise then fall	two-lines statistic above 1.96 and above its shuffle 95th percentile (1.26)	-0.89	no
Placebo clean	placebo p at or above 0.05	0.86	yes
Rerun, steeling holds	kill condition not met: interval excludes 0 and estimate above time-shift 95th percentile (0.038)	-0.009 to +0.059; 0.025	no

14 Glossary

Each term is defined where it is first used in the text. The same definitions, with the field each comes from and what each excludes, are collected here.

- **steeling**. The idea that a moderate earlier stress leaves an organism better able to cope with a later, harder one; here, that a tree which lived through a moderate drought loses less growth to a later severe drought. Field: psychology and stress biology, here applied to trees. Excludes recovery from the same drought, and any gain that follows only from how the growth indices are computed.
- **drought legacy**. Growth that stays below its expected level for one or more years after a drought ends. Field: forest ecology. Excludes the loss of growth in the drought year itself.
- **preregistration**. A dated written plan for a study, fixed and hash-locked before any result is seen: the question, the data, the statistic, the controls, the forecasts and the kill conditions. Field: research method (metascience). Excludes a plan revised after looking at the outcome, and a protocol written only for the record after the run.
- **verdict**. The pass or fail of one preregistered rule set against the run's numbers, read off by code. Field: research method (our usage). Excludes an interpretation written after reading the numbers.
- **Benjamini-Hochberg correction**. A rule that adjusts a set of p values so that, among the tests called significant, the expected share of false calls stays at or below a chosen rate, here 0.05; the adjusted value is called q. Field: statistics, multiple testing. Excludes the stricter Bonferroni rule, which bounds the chance of any false call.
- **two-lines test**. A test for a rise-then-fall shape that fits one straight line on each side of a data-chosen break point and asks whether the first rises and the second falls, both significantly. Field: statistics (Simonsohn 2018). Excludes a quadratic fit, which can report a peak where none exists.
- **standard chronology**. One yearly ring-width index for a site, made by removing each tree's age trend and averaging the trees, scaled so that an ordinary year is near 1. Field: dendrochronology. Excludes raw ring widths of single trees, and density or isotope records.
- **Palmer Drought Severity Index (PDSI)**. A monthly index of soil-moisture supply against demand built from temperature and precipitation; 0 is normal, -2 is moderate drought and -3 or lower is severe drought. Field: climatology and hydrology. Excludes a direct measurement of soil water, and drought indices built on precipitation alone.
- **climate division**. One of the regions into which NOAA splits the contiguous United States for climate records, each with one averaged monthly series per variable. Field: US climatology (NOAA). Excludes a single weather station, and a regular grid cell.
- **self-calibrating PDSI (scPDSI)**. A version of the Palmer index whose constants are fitted to each location's own climate, so that the thresholds mean similar rarity everywhere; here taken from the CRU TS gridded

product at 0.5 degree. Field: climatology. Excludes the original Palmer index with fixed constants, and station measurements.

- **Lloret indices**. Three ratios of ring growth around a drought year: resistance is the drought-year growth over the mean of the three years before, recovery is the mean of the three years after over the drought-year growth, and resilience is the mean after over the mean before. Field: dendroecology. Excludes measures of tree death, and growth responses that unfold over more than three years.
- **fixed effects**. One free constant per site (or species) and one per calendar year in a regression, so that differences between sites and between years cannot be mistaken for the effect of the variable under test. Field: econometrics and statistics. Excludes random effects, which treat those constants as draws from one distribution.
- **clustered standard errors**. Standard errors computed so that events in the same climate division may be correlated with each other, which widens the interval when they are. Field: econometrics. Excludes ordinary standard errors that treat every event as independent.
- **planted check**. Data built so that the right answer is known, run through the same analysis before the real data, to show that the analysis can see the effect when it is there. Field: research method; called a positive control in experimental science. Excludes any check made on the real data, which cannot show what the analysis misses.
- **control**. A version of the data with the structure under test removed (for example shuffled or pooled), scored the same way as the real data, so the real score has something to beat. Field: statistics and experimental design. Excludes a comparison with a different dataset or with a published number.
- **time-shift null**. A control in which each drought record is moved in time by a random offset of 20 years or more, with the end wrapped round to the start, and the events rebuilt; it keeps each record's own pattern of droughts and breaks its timing against the rings. Field: time-series statistics, surrogate data. Excludes shuffling single years, which also destroys the drought record's own pattern.
- **label-permutation null**. A control in which the prior-drought labels are shuffled among each site's own events, keeping every drought date in place. Field: statistics. Excludes a null that moves the droughts themselves.
- **placebo window**. The same test run with the exposure window placed after the event, years 5 to 12 later, where no causal effect is possible, so that any effect found there points to a flaw in the design. Field: statistics and econometrics. Excludes a control on the outcome data.
- **null distribution**. The spread of scores a control gives over many random draws; its 95th percentile is the bar a real score must clear. Field: statistics. Excludes a theoretical distribution assumed rather than drawn from the data.
- **kill condition**. A rule written in the preregistration that, when met, decides against the claim with no room for judgement after the run. Field: research method (our usage, after Popper's falsification). Excludes reasons found after the run for setting a result aside.
- **honest null**. A working test that found no effect beyond a stated bound, a forecast that failed, or an error of our own found and fixed, reported with the same weight as a positive result. Field: research method (our usage). Excludes a void run, and a result left unpublished because it was negative.

15 References

[1] Anderegg, W. R. L., Schwalm, C., Biondi, F., Camarero, J. J., Koch, G., Litvak, M., Ogle, K., Shaw, J. D., Shevliakova, E., Williams, A. P., Wolf, A., Ziaco, E. and Pacala, S. (2015). Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. Science 349, 528-532. doi:10.1126/science.aab1833

[2] Anderegg, W. R. L., Trugman, A. T., Badgley, G., Konings, A. and Shaw, J. (2020). Divergent forest sensitivity to repeated extreme droughts. Nature Climate Change 10, 1091-1095. doi:10.1038/s41558-020-00919-1

[3] Lloret, F., Keeling, E. G. and Sala, A. (2011). Components of tree resilience: effects of successive low-growth episodes in

old ponderosa pine forests. Oikos 120, 1909-1920. doi:10.1111/j.1600-0706.2011.19372.x

[4] Schwarz, J., Skiadaresis, G., Kohler, M., Kunz, J., Schnabel, F., Vitali, V. and Bauhus, J. (2020). Quantifying growth responses of trees to drought: a critique of commonly used resilience indices and recommendations for future studies. Current Forestry Reports 6, 185-200. doi:10.1007/s40725-020-00119-2

[5] International Tree-Ring Data Bank. NOAA National Centers for Environmental Information, World Data Service for Paleoclimatology. Standard chronologies, North America. https://www.ncei.noaa.gov/pub/data/paleo/treering/

[6] NOAA National Centers for Environmental Information. nClimDiv climate division data, Palmer Drought Severity Index, version 1.0.0, build of 6 October 2026, with the contiguous US climate division boundaries. Retrieved 29 October 2026.

[7] Harris, I., Osborn, T. J., Jones, P. and Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Scientific Data 7, 109. doi:10.1038/s41597-020-0453-3

[8] Climatic Research Unit, University of East Anglia. CRU TS 4.10 self-calibrating Palmer Drought Severity Index, 0.5 degree, 1903 to 2025. Open Database License 1.0. https://crudata.uea.ac.uk/cru/data/hrg/