Evaluating Chronological Hypotheses by Simulating Radiocarbon Datasets

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Problem

- Evaluating precise chronological hypotheses with ^{14}C datasets can be challenging[1].
- Measurement error[2], uncertainty in the ^{14}C calibration curve[3], mismatches between the event dated and the event of interest (old wood issues)[4, 5], inter- and intra-annual ^{14}C variability[6], and variability between labs[7, 8] can impact measurements.
- Good chronometric hygiene is a potential solution, but is incompatible with many legacy datasets.

Solution

- **Simulate** ^{14}C datasets under a specific chronological hypothesis to develop **expectations** of a dataset if the hypothesis were correct.
- **Compare** the results of the simulation to the **observed** datasets.

Applications

- **Known** synchronous event – **Laacher See** volcanic eruption ~12.9 kya[9].
- **Hypothesized** synchronous event - extraterrestrial impact at the onset of the **Younger Dryas** ~12.8 kya[10, 11].

Results

- Simulations generate variability **consistent** with the observed Laacher See Tephra **(LST)** dataset.
- Simulations generate **significantly less variability** than observed Younger Dryas Boundary impact hypothesis **(YDB)** dataset; **assuming a synchronous event, the observed YDB dataset is extremely improbable.**

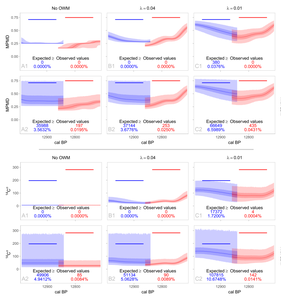


Figure 1. Mean Pairwise Manhattan Distance (MPMD) distributions for simulated LST (blue) and YDB (red) datasets. Bands represent 50% and 95% highest density intervals and thin lines represent the mode of the distribution. Solid horizontal lines represent MPMD calculated from the observed LST and YDB datasets. Higher MPMD values indicate more variability within a given set of ^{14}C measurements. Simulations incorporating a lab bias and repeatability model (bottom row) are consistent with the observed LST dataset. No model is consistent with the observed YDB dataset.

Figure 2. As with figure 1, but measuring the mean of the standard deviations of the simulated ^{14}C measurements ($^{14}C^{\sigma}$).

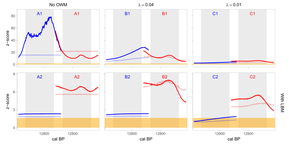
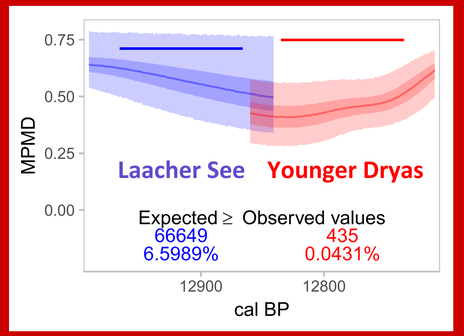
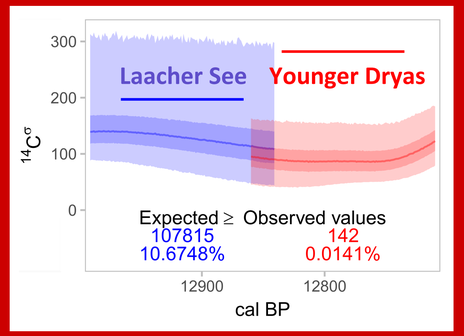


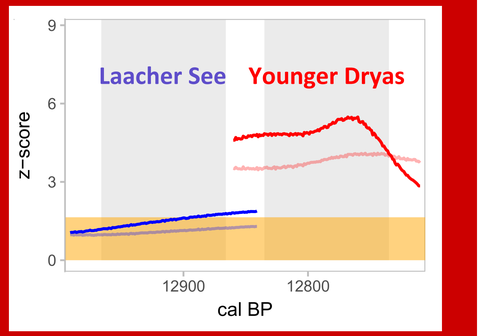
Figure 3. Distance, in z-scores, of the observed MPMD (solid lines) and observed $^{14}C^{\sigma}$ (transparent lines) from the mean of each simulated MPMD and $^{14}C^{\sigma}$ distribution. Gold regions mark the lower 95% of each simulated distribution. Observed values above the gold region are inconsistent with the simulated distributions. Observed values many z-scores above the simulated distributions indicate values that are very improbable, given a synchronous event.

Hypothesized **extraterrestrial impact** event at **Younger Dryas Boundary *inconsistent*** with **simulated synchronous** ^{14}C dates.

Laacher See volcanic eruption ***is consistent*** with **simulated synchronous** ^{14}C dates.







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Works Cited:

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Datasets

Laacher See Tephra dates[8]

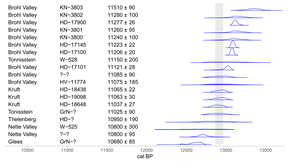

Figure 5. LST samples by location, ^{14}C measurements, and calibrated age distributions. Vertical grey bar represents range over which simulation was performed, 12,966 – 12,866 cal bp. Open age densities correspond to samples with potential "old wood" effects. All LST dates are non-AMS.

Younger Dryas Boundary dates[10]

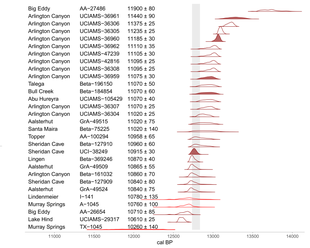

Figure 6. YDB samples by location, ^{14}C measurements, and calibrated age distributions. Vertical grey bar represents range over which simulation was performed, 12,835 – 12,735 cal bp. Open age densities correspond to samples with potential "old wood" effects. All but three are AMS.

	LST (n = 19)	YDB (n = 30)
n sites	6	13
n AMS measurements	0 (0.0%)	27 (90.0%)
n unique laboratories	6	8
n "old wood" measurements	18 (94.7%)	24 (80.0%)
Average ^{14}C measurement error	94.47	59.00
$^{14}C^{\sigma}$	196.94	282.02
MPMD	0.71	0.75

Table 1. Features of the LST and YDB datasets

Figure 4. Map of YDB (red) and LST (blue) sites.

How the simulation works

1. Generate vector *C* of *n* **identical** calendar ages, where *n* matches the number of measurements in an observed ^{14}C dataset.
2. For each of *k* ^{14}C measurements in the observed dataset potentially subject to an *"old wood"* effect, apply random offsets drawn from exponential distribution to *k* calendar ages in vector *C*.
3. **Uncalibrate** vector *C*, generating vector of **target mean atmospheric ^{14}C values**.
4. Offset **target** ^{14}C values to account for slight **interannual variability**[5] in atmospheric radiocarbon; offsets drawn from **beta distribution** of possible interannual variability.
5. Apply offsets drawn randomly from **Laboratory Bias and Repeatability Model (LBM)** to target mean atmospheric ^{14}C values. LBM is a Bayesian multi-level model fitted with data from the **Fifth International Radiocarbon Intercomparison (VIRI)**[12, 13] that accounts for inter- and intra- laboratory variability based on the number and type of labs (AMS vs. GPC/LSC) in the observed dataset.
6. Steps 1-5 produce a vector of ^{14}C measurements of length *n*. Calculate the **standard deviation** of this vector of ^{14}C measurements ($^{14}C^{\sigma}$).
7. **Calibrate** vector of ^{14}C measurements incorporating measurement error values from observed dataset using **IntCal13**[3] calibration curve. This step produces *n* calendar age probability distributions.
8. For each pair of calendar ages, calculate **Manhattan Distance** between probability distributions. Take the **mean** of the $\frac{n^2-n}{2}$ **pairwise** Manhattan Distances **(MPMD)**.
9. Repeat 10,000 times to generate robust distributions of **SD** and **MPMD**.
10. Repeat steps 1 – 9 for each hypothesized possible calendar age
11. Compare simulated $^{14}C^{\sigma}$ and **MPMD** distributions to $^{14}C^{\sigma}$ and **MPMD** values calculated for observed dataset.

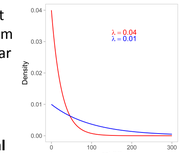

Figure 7. Exponential distributions from which "old wood" offsets are drawn.

Simulation was coded in R using the packages **Rstan**, **rcarbon**, **ggplot2**, **parallel**, **reshape2**, **matrixStats**, **patchwork**, and **rethinking**. Simulations run on SMU's **ManeFrame II** cluster.