Package 'ErrorTracer'

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Type Package

Title Bayesian Error Propagation and Forecast Uncertainty Decomposition

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Description Provides a full pipeline from regularized or standard regression models (elastic net, linear models, generalized linear models, random forests) to informed Bayesian priors, or accepts an existing 'brms' fit directly, for structured forecast uncertainty decomposition (parameter / environmental / residual, plus group-level variance for new random-effect levels and a temporal component under autocorrelation, alongside global Sobol indices), forecast shelf life analysis (quantifying when a forecast becomes uninformative, with Kaplan-Meier pooling across forecast origins), null-model skill scoring, and calibration diagnostics. Designed for ecological and genomic forecasting with climate or environmental covariates. Methods build on Bürkner (2017) <doi:10.18637/jss.v080.i01> for Bayesian regression via 'Stan', Friedman, Hastie, and Tibshirani (2010) <doi:10.18637/jss.v033.i01> for elastic net regularization, Wright and Ziegler (2017) <doi:10.18637/jss.v077.i01> for random forests, and Vehtari, Gelman, and Gabry (2017) <doi:10.1007/s11222-016-9696-4> for leave-one-out cross-validation.

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`decompose_uncertainty` *Extract or recompute uncertainty decomposition*

Description

Returns a `data.frame` with the uncertainty decomposition stored inside an `et_prediction` object:

param_var Variance of the posterior linear predictor (on the response scale) — captures uncertainty in fitted regression coefficients.

group_var (Only present when predicting for a *new* level of a random effect.) Between-group variance integrated from the fitted group-level distribution. When predicting for a group the fit has seen, its estimated effect is part of `param_var` and this column is absent.

env_var Variance arising from measurement or prediction uncertainty in the predictor values (estimated via perturbation in `et_predict`). A genuine sub-share of `total_var` (see below), not an add-on. Zero when `env_noise = NULL`.

v_env_mcse Monte Carlo standard error of `env_var`.

residual_var Posterior mean of σ^2 (or its family-specific analogue) — biological process noise, unmeasured drivers, and drift. For autocorrelation models this is the *innovation* variance, not the stationary marginal variance; the autocorrelated accumulation is reported separately in `temporal_var`. For a non-identity link it is evaluated at the *perturbed* mean, $E_s[V(\mu^{\text{env}})]$, because that is the mean the predictive draws are generated at; it therefore depends on `env_noise` through the variance function. For Gaussian, $V(\mu) = \sigma^2$ is independent of the mean and the distinction does not arise.

temporal_var (Only present when the model formula contains an autocorrelation term such as `ar()`, `ma()`, `arma()`, `cosy()`, `unstr()`, `sar()`, or `car()`.) Variance attributable to residual temporal or spatial dependence beyond the named components, computed as the signed remainder `total_var - (param_var + env_var + residual_var)` (minus `group_var` when present). This captures the AR/MA/ARMA innovation accumulation that a single-innovation `residual_var` cannot represent. It is **signed**: a negative value means autocorrelated errors *reduce* predictive variance relative to the independent-innovation baseline, which is a real possibility for a covariance term. Being a remainder, it also absorbs Monte Carlo error from the other components, so read a `temporal_var` of the same order as `v_env_mcse` as noise.

closure_gap (Only present for iid models.) `total_var - (param_var + env_var + residual_var)` (minus `group_var` when present): how far the named components fall short of the measured posterior predictive variance. For a correctly specified iid model it is Monte Carlo error with mean zero, but it is *not* of the order of `v_env_mcse`: its scale is the sampling error of a variance estimated from `n_draws` draws, roughly $\sqrt{2/n_{\text{draws}}}$ in relative terms, so single observations commonly sit several per cent and occasionally over ten per cent away from zero. Judge it by its *mean across observations*, which should be indistinguishable from zero; a mean that is not means a component is mis-estimated.

total_var Total predictive variance: the **sampled variance of the environmentally inclusive posterior predictive draws**, which is the distribution the reported credible interval is drawn from. The driver perturbation is applied *before* the predictive draw, so `env_var` is a genuine share of this total.

Usage

```
decompose_uncertainty(predictions, ...)
```

Arguments

predictions	An et_prediction object from et_predict, or an et_prediction_list (grouped).
...	Unused.

Details

Changed in 1.4.0. total_var used to be *defined* as the sum of the other components, which made the shares reconcile to 100% by construction and made env_var an add-on to a predictive variance that did not contain it. It is now measured, and the sum is recovered as a *result*: the components add up to total_var exactly for autocorrelation models (where temporal_var is the remainder) and up to Monte Carlo error for iid models (reported as closure_gap). param_var, env_var and residual_var remain non-negative; temporal_var and closure_gap are signed.

Value

A data.frame with columns obs_id, total_var, param_var, env_var, v_env_mcse, residual_var (plus group_var when predicting for new random-effect levels, temporal_var for autocorrelation models or closure_gap for iid ones, and a leading group column for grouped predictions).

Examples

```
set.seed(1)
df  <- data.frame(y = rnorm(20), x1 = rnorm(20))
fit <- et_fit(y ~ x1, data = df,
              chains = 1, iter = 500, warmup = 250,
              cores = 1, refresh = 0)
new_df <- data.frame(x1 = rnorm(5))
pred   <- et_predict(fit, newdata = new_df,
                     env_noise = list(x1 = 0.2),
                     n_draws = 200)
decomp <- decompose_uncertainty(pred)
head(decomp)
```

---

et_calibrate *Assess calibration of posterior predictive intervals*

Description

Computes observed coverage probability at multiple nominal CI levels. A well-calibrated Bayesian model should produce 90% CIs that contain the true value 90% of the time, etc.

Usage

```
et_calibrate(predictions, observed, response_col = NULL, ci_levels = NULL, ...)
```

Arguments

predictions	An et_prediction or et_prediction_list.
observed	A data.frame with true response values. Must have the same number of rows as predictions$newdata (rows are matched positionally) and a column with the true response values.
response_col	Character. Name of the response column in observed. Defaults to the left-hand side of the model formula if it can be inferred, otherwise must be specified.
ci_levels	Numeric vector. CI levels to assess. Defaults to all levels present in the et_prediction object.
...	Unused.

Value

A data.frame with columns:

ci_level Nominal CI level.

nominal Same as ci_level.

observed_coverage Fraction of true values falling inside the CI.

n_obs Number of observations used.

calibration_error Signed difference: observed - nominal. Positive = over-coverage (CIs too wide / conservative). Negative = under-coverage (CIs too narrow / overconfident).

sharpness Mean CI width across observations. Sharpness and calibration are complementary: a model can be calibrated but useless if sharpness is poor (very wide CIs).

For grouped predictions, a group column is prepended.

Examples

```
set.seed(1)
df  <- data.frame(y = rnorm(20), x1 = rnorm(20))
fit <- et_fit(y ~ x1, data = df,
              chains = 1, iter = 500, warmup = 250,
              cores = 1, refresh = 0)
valid_df <- data.frame(y = rnorm(5), x1 = rnorm(5))
pred <- et_predict(fit, newdata = valid_df,
                   n_draws = 200)
cal <- et_calibrate(pred, observed = valid_df, response_col = "y")
print(cal)
```

et_diagnose *Diagnose a fitted ErrorTracer model*

Description

Computes Rhat, effective sample size ratios, divergent transitions, and leave-one-out cross-validation (LOO-CV) for a fitted `et_model`.

Usage

```
et_diagnose(model, loo = TRUE, ...)
```

Arguments

`model`	An `et_model`, `et_model_list`, or `brmsfit` object.
`loo`	Logical. Whether to run LOO-CV (can be slow; default `TRUE`).
`...`	Unused.

Value

A list with elements:

convergence List: `rhat_max`, `rhat_all_ok`, `neff_min`, `neff_all_ok`, `n_divergences`.

loo List or `NULL`: `elpd_loo`, `p_loo`, `looic`, `n_bad_pareto_k`, `loo_object`.

summary Printed summary from `brms::summary()`.

For `et_model_list`, a named list of per-group diagnostic lists plus an aggregated `summary` data.frame.

et_diagnose.brmsfit *Use a model fitted outside ErrorTracer*

Description

Wraps an existing `brms` fit in the `et_model` structure that `et_fit` returns, so a model fitted elsewhere — by hand, by a colleague, or in an earlier script — is carried through `et_predict`, `decompose_uncertainty`, `shelf_life` and the calibration diagnostics without being refitted. Stages 1 and 2 of the pipeline are therefore optional: the prior-extraction step is a convenience for workflows that begin with a penalized fit, not a requirement for the accounting that follows it.

Usage

```
## S3 method for class 'brmsfit'
et_diagnose(model, loo = TRUE, ...)

as_et_model(fit, data = NULL, prior_spec = NULL, seed = NULL)

## S3 method for class 'brmsfit'
et_predict(model, newdata, ...)
```

Arguments

model	A brmsfit, when et_predict() or et_diagnose() is called on one directly. It is passed through as_et_model() first.
loo	Logical. Whether et_diagnose computes LOO-CV.
...	Further arguments forwarded to et_predict or et_diagnose.
fit	A fitted brmsfit.
data	Training data. Defaults to the model frame stored on the fit (fit$data), which carries every column the formula used and is what the later stages need; supply the original data frame when a later stage must see a column the formula did not.
prior_spec	Optional et_prior_spec from extract_priors, when the fit was given informed priors. Only the prior-versus-posterior plots read it; anything else is ignored.
seed	Integer seed recorded on the model and used as the default for et_predict(). Defaults to the seed the fit was sampled with, when that can be recovered from the back end, and is otherwise NULL, which leaves predictions drawing from the ambient stream unless et_predict(seed =) supplies one.
newdata	Data frame of covariate values to forecast at, forwarded to et_predict.

Details

et_predict() and et_diagnose() accept a brmsfit directly and call this function themselves, so the wrapper is only needed when you want the et_model object itself — to inspect it, to attach a prior specification, or to override the training data.

Value

An et_model object, identical in structure to what et_fit returns.

What the pipeline reads off the fit

Four things: the posterior draws; the response family, for the variance function of the residual component; the model formula, to find the response column and to detect an ar()-family term; and the training data, to continue an autocorrelated series forward and to set the default response_scale in shelf_life. A brmsfit carries all four.

A bare stanfit or CmdStanMCMC carries none of them, and is rejected with a pointer to brms::brm(empty = TRUE), which is the supported route for draws from a hand-written Stan program: it builds the brmsfit scaffolding around a formula, family and data set, and the external draws are attached to it.

Examples

```
set.seed(1)
d   <- data.frame(y = rnorm(30), x = rnorm(30))
fit <- brms::brm(y ~ x, data = d, chains = 1, iter = 500, refresh = 0)
m    <- as_et_model(fit)
pred <- et_predict(m, newdata = d[1:5, ], env_noise = list(x = 0.1))
```

```
# Equivalently, straight from the fit:
pred <- et_predict(fit, newdata = d[1:5, ], env_noise = list(x = 0.1))
```

`et_fit` *Fit a Bayesian regression model with informed priors*

Description

Wraps `brms::brm()` and attaches the prior specification, training data reference, and configuration for downstream uncertainty decomposition. Pass `priors` from `extract_priors` to use regularized-model coefficients to set the prior scale (and, with `shrinkage = "estimate"`, the prior mean); omit it for default (weakly informative) priors.

Usage

```
et_fit(
  formula,
  data,
  priors = NULL,
  chains = 4L,
  iter = 2000L,
  warmup = floor(iter/2),
  cores = min(chains, parallel::detectCores()),
  seed = 42L,
  adapt_delta = 0.95,
  max_treedepth = 12L,
  grouping = NULL,
  eiv = NULL,
  ar_prior = c("weakly_informative", "stationary", "flat"),
  silent = 2L,
  ...
)
```

Arguments

`formula`	An R formula, e.g.\ `response ~ .` or `y ~ x1 + x2`.
`data`	A `data.frame` with all predictors and the response.
`priors`	An `et_prior_spec` object from `extract_priors`, or a `brmsprior` object, or `NULL` for brms defaults.
`chains`	Integer. Number of MCMC chains (default 4).
`iter`	Integer. Total iterations per chain, including warmup (default 2000).
`warmup`	Integer. Warmup iterations per chain (default `floor(iter / 2)`).
`cores`	Integer. Parallel cores (default `min(chains, parallel::detectCores())`).

`seed` Integer. Random seed for reproducibility (default 42).

`adapt_delta` Numeric. Target acceptance probability for HMC (default 0.95).

`max_treedepth` Integer. Maximum tree depth (default 12).

`grouping` Character. Name of a column in `data` to use for grouping. If non-`NULL`, one model is fitted per unique group value and an `et_model_list` is returned.

`eiv` Optional errors-in-variables specification. A named list / vector mapping predictor names to either a scalar SD or a vector of per-row SDs (length `nrow(data)`). For each entry, the formula term for that predictor is rewritten as `brms::me(pred, se_pred)` (an auxiliary `se_<pred>` column is appended to `data`), so the posterior reflects measurement error in the predictor as well as coefficient uncertainty. The beta posteriors widen accordingly, which partially absorbs what ErrorTracer's downstream `env_var` component would otherwise report. When `eiv` is supplied together with an `et_prior_spec` from `extract_priors`, the informed priors are *dropped* because they target `class = "b"` terms and `me()` terms live under `class = "bsp"`; brms defaults are used instead (and a warning is logged).

`ar_prior` Character. Prior on autocorrelation parameters (`class = "ar"` / `"ma"`) when the formula carries an `ar()` / `ma()` / `arma()` term. `brms`'s own default is *flat and unbounded*, which on a short series lets the posterior straddle the unit root; the k-step forecast variance $\sigma^2(1-\phi^{2k})/(1-\phi^2)$ then diverges, and `temporal_var` and `shelf_life` become uninterpretable. Options:

- `"weakly_informative"` (default) `normal(0, 0.5)` — about 95% of the prior mass lies inside $(-1, 1)$, but the parameter is not hard-bounded, so a genuinely non-stationary series can still say so.
- `"stationary"` The same prior truncated to $(-1, 1)$. For AR(1) this is exactly the stationarity region; for higher orders it is necessary but not sufficient, and a warning says so.
- `"flat"` `brms`'s unbounded default.

A prior the caller supplies for these classes is never overridden. Regardless of the setting, `et_fit()` warns after fitting when more than 5% of the posterior sits at $|\phi| \geq 1$.

Families and autocorrelation. `brms` represents an autocorrelation term in two ways, and only one of them can be forecast from. For `gaussian` and `student` it uses the response residuals ($\varepsilon = y - \mu$) and iterates the fitted process onto new rows, which is what `et_predict` needs. For any other family with `brms`'s default `cov = FALSE` the term becomes a vector of *latent* residuals that `brms` cannot extend beyond the training rows, so `et_fit()` stops with an explanation rather than letting the fit succeed and the prediction fail. Write such a term as `ar(time = year, p = 1, cov = TRUE)`. Because the covariance formulation exists at order one only, a non-Gaussian family cannot carry an autocorrelation term beyond lag 1 in `brms` at all.

`silent` Integer passed to `brms::brm()` (default 2, no Stan output).

`...` Additional arguments passed to `brms::brm()`.

Value

An `et_model` object (or an `et_model_list` if `grouping` is specified).

Scope and limitations

`et_fit()` is deliberately a **thin wrapper around** `brms`: the formula, family, and any autocorrelation term (`ar()`/`ma()`/ `arma()`/...) are passed straight through, so ErrorTracer inherits `brms`'s modelling scope and its Stan back-end. The added value is the prior pipeline, the structured uncertainty decomposition, forecast skill / shelf life, and calibration diagnostics — not new model classes.

Two boundaries to keep in mind:

- **Hierarchical / random-effects models** fit through the formula (`y ~ x + (x | group)`) and are decomposed correctly, with the in-sample / out-of-sample distinction handled explicitly. Predicting for a group the fit has *seen* uses that group's estimated effect: the effect is a parameter, its posterior uncertainty is part of `param_var`, and there is no separate group component (conditioning on a known group *reduces* predictive variance relative to the population level). Predicting for a *new* level integrates over the group-level distribution and adds a `group_var` component carrying the between-group variance; `et_predict` detects new levels automatically. The `grouping` argument here is a *separate* device: it fits one independent model per group (no pooling), not a single multilevel model.
- **Convergence is your responsibility.** `et_fit()` emits a warning on high Rhat or divergent transitions, but you should inspect `et_diagnose` before predicting; the defaults (`iter = 2000`, 4 chains) are a starting point, not a guarantee.

Examples

```
set.seed(1)
df  <- data.frame(y = rnorm(20), x1 = rnorm(20), x2 = rnorm(20))
ps  <- extract_priors(lm(y ~ x1 + x2, data = df))
fit <- et_fit(y ~ x1 + x2, data = df, priors = ps,
              chains = 1, iter = 500, warmup = 250,
              cores = 1, refresh = 0)
print(fit)
```

---

et_pit *Probability integral transform (PIT) for calibration diagnostics*

Description

Computes the probability integral transform of held-out observations under the (reported) posterior predictive distribution — the same distribution the credible intervals and `et_calibrate` coverage are built from, including environmental uncertainty when it was folded in. For a well-calibrated model the PIT values are $\mathrm{Uniform}(0, 1)$. Systematic departures diagnose *how* the model is miscalibrated, which interval coverage alone cannot: a **U-shape** means the predictive is too narrow (overconfident), a central **hump** means it is too wide (underconfident), and a **slope / shift** means it is biased. Visualise with `et_plot_pit` (a PIT / rank histogram).

Usage

```
et_pit(predictions, observed, response_col = NULL, randomize = TRUE, ...)
```

Arguments

predictions	An et_prediction or et_prediction_list.
observed	A data.frame of true responses, positionally matched to predictions$newdata (and containing the grouping column for a grouped prediction).
response_col	Character. Response column name; inferred from the model formula when NULL.
randomize	Logical. Use the *randomized* PIT (default TRUE), which spreads the probability mass at ties so the values are uniform under calibration for **discrete** predictions (counts, binary). It is a no-op for continuous predictions, where exact ties have probability ~0. Set FALSE for the non-randomized $P(Y \leq y)$.
...	Unused.

Value

A data.frame with columns obs_id and pit (plus a leading group column for grouped predictions).

See Also

et_plot_pit, et_calibrate

---

et_plot_calibration *Plot calibration: observed vs nominal coverage*

Description

A well-calibrated model produces points along the 1:1 diagonal. Points above the diagonal indicate over-coverage (conservative); below indicates under-coverage (anti-conservative).

Usage

```
et_plot_calibration(cal, group_col = NULL)
```

Arguments

cal	A data.frame from et_calibrate.
group_col	Optional character. Name of a column in cal that identifies sub-groups (e.g.\ "species", "cluster_id"). When NULL (default), et_plot_calibration uses the group column if present; otherwise it auto-detects any single non-canonical column with more than one unique value and treats it as the grouping. Set to NA to force a single un-grouped series.

Value

A ggplot2 object.

et_plot_coefficients *Forest plot of regression coefficients*

Description

Compares Bayesian posterior estimates (95% CI) with the regularized or first-stage coefficient estimates stored in the prior specification (shown as crosses).

Usage

```
et_plot_coefficients(model)
```

Arguments

model	An et_model or et_model_list.

Value

A ggplot2 object.

et_plot_decomposition *Plot uncertainty decomposition*

Description

Produces a stacked bar chart showing the relative contributions of parameter, environmental, and residual variance for each observation, plus a temporal-autocorrelation component and a group component when those are present in decomp (see decompose_uncertainty). The iid closure_gap is deliberately *not* drawn: it is a diagnostic rather than a source of variance, and a grey remainder bar makes the figure harder to read for no interpretive gain.

Usage

```
et_plot_decomposition(decomp, proportional = TRUE, group_col = NULL)
```

Arguments

decomp	A data.frame from decompose_uncertainty or directly the $decomposition slot of an et_prediction.
proportional	Logical. If TRUE (default), each component is shown as a share of the components drawn, so every bar sums to exactly 1 and the y axis is a true proportion (labelled as a percentage). For an autocorrelation model that denominator *is* total_var, because temporal_var is the remainder against it. For an iid model the named components fall short of total_var by closure_gap, so the bars are shares of the decomposed variance rather than of the measured total;

the gap is reported in the decomposition and by `print()`, and a material one raises an informational message naming its mean and maximum. Normalising by `total_var` instead would leave iid bars visibly short of 1 on an axis labelled "share", which reads as a plotting fault. If `FALSE`, raw variances are shown. `temporal_var` is signed, so a negative component is drawn below the zero line rather than silently clamped.

`group_col` Character. Optional name of a grouping column in `decomp` (present for grouped predictions). One bar is drawn per group: the components are summed over the group's observations and divided by the summed `total_var`, so the bar still sums to 1. That is a variance-weighted share, equal to `mean(component) / mean(total_var)`, and it is the quantity to quote alongside the figure. It is not the mean of the per-observation shares, which would weight a low-variance lead equally with a high-variance one; for an autocorrelation model, where predictive variance grows with lead time, the two can differ by tens of percentage points.

Value

A `ggplot2` object.

`et_plot_forecast` *Plot posterior predictive fan chart*

Description

Overlays nested credible interval ribbons on the median forecast, with optional observed values for calibration assessment.

Usage

```
et_plot_forecast(
  predictions,
  observed = NULL,
  response_col = NULL,
  time_col = NULL
)
```

Arguments

`predictions`	An `et_prediction` object.
`observed`	Optional `data.frame` with true response values. If provided, points are overlaid.
`response_col`	Character. Name of the response column in `observed`.
`time_col`	Character. Column in `predictions$newdata` used as the x-axis. Defaults to observation index.

Value

A `ggplot2` object.

et_plot_pit *Plot a PIT / rank histogram for calibration*

Description

Histogram of the probability-integral-transform values from `et_pit`. Bars level with the dashed uniform reference line indicate calibration; a **U-shape** means overconfident (too-narrow) intervals, a central **hump** means underconfident (too-wide), and a **tilt** means bias. The shaded band is an approximate 95% consistency region for the bar heights under uniformity. When `pit` carries a `group` column the reference line and band are computed separately for each panel, so panels holding different numbers of observations remain comparable.

Usage

```
et_plot_pit(pit, bins = 10L)
```

Arguments

`pit`	A `data.frame` from `et_pit` (a `pit` column, optionally `group`), or a bare numeric vector of PIT values.
`bins`	Integer. Number of histogram bins (default 10).

Value

A `ggplot` object.

See Also

`et_pit`, `et_plot_calibration`

et_plot_prior_posterior *Plot prior vs posterior distributions for model coefficients*

Description

Overlays prior and posterior density for each predictor coefficient, visualising how much the data update the priors.

Usage

```
et_plot_prior_posterior(model, max_preds = 8L, n_prior_draws = 4000L)
```

Arguments

model	An et_model object with a non-NULL prior_spec (from et_fit or as_et_model).
max_preds	Integer. Maximum number of predictors to show (default 8). Predictors are shown in the order they appear in the prior specification.
n_prior_draws	Integer. Number of random draws for the prior density (default 4000).

Value

A ggplot2 object.

---

et_plot_sensitivity *Plot a sensitivity profile*

Description

Visualises the output of et_sensitivity_profile: for each noise grid point, shows how the **environmental share** of total variance and the **forecast horizon** respond. Observed horizons are drawn as solid points; projected horizons are hollow points; lower-bound rows are drawn as upward arrows at the last informative time.

Usage

```
et_plot_sensitivity(sens, show = c("horizon", "env_share", "ratio"))
```

Arguments

sens	An et_sensitivity object from et_sensitivity_profile.
show	"horizon" (default) shows the shelf-life horizon; "env_share" shows env_var / total_var; "ratio" shows the mean CI width / plausible range.

Details

The x-axis is the noise fraction (when the grid was built from fraction_grid) or the grid step label otherwise. When both a numeric fraction and a descriptive label exist, the fraction is preferred for continuous x-positioning.

Value

A ggplot2 object.

See Also

et_sensitivity_profile

et_plot_shelf_life *Plot forecast shelf life*

Description

Shows how credible interval width grows over the forecast horizon and marks the threshold beyond which the forecast is uninformative.

Usage

```
et_plot_shelf_life(sl, show_ratio = TRUE, max_ratio = NULL)
```

Arguments

sl	An et_shelf_life object from shelf_life.
show_ratio	Logical. If TRUE (default), plots the ratio (CI width / plausible range) rather than raw CI width.
max_ratio	Numeric. Optional upper limit for the y axis, applied as a zoom (coord_cartesian) rather than a filter, so nothing is dropped and a trace that exceeds it runs off the top of the panel. Use it when one series sits an order of magnitude above the rest and compresses them against the axis; say in the caption that the panel is capped. NULL (default) fits all of the data.

Value

A ggplot2 object.

et_predict *Posterior prediction with uncertainty decomposition*

Description

Generates posterior predictive draws for new observations, propagates environmental measurement uncertainty through the model, and computes credible intervals. The resulting et_prediction object is the input to decompose_uncertainty, shelf_life, and the plotting functions.

Usage

```
et_predict(
  model,
  newdata,
  env_noise = NULL,
  env_cov = NULL,
  env_dist = NULL,
  env_ensemble = NULL,
```

```
  n_draws = NULL,
  ci_levels = c(0.5, 0.8, 0.9, 0.95),
  n_perturb = NULL,
  n_env_draws = 1L,
  interval_type = c("predictive", "linpred"),
  include_env_in_ci = NULL,
  var_trim = 0,
  seed = NULL,
  ...
)
```

Arguments

model	An et_model or et_model_list object from et_fit, or a brmsfit object (which is passed through as_et_model).
newdata	A data.frame containing the predictor columns named in the model formula. For grouped models, must also contain the grouping column.
env_noise	Environmental measurement / prediction uncertainty. Can be: • NULL (default): no environmental noise. • A single numeric: applied as a fraction of each predictor's empirical SD in newdata (e.g.\ 0.1 means 10% noise, constant across all observations). • A named list or named numeric vector with one scalar per predictor: constant absolute noise SD per predictor, e.g.\ list(Tmean = 0.5, PPT = 10). • A named list where each entry is a **numeric vector of length** nrow(newdata): *time-varying* (per-row) noise SDs. Use this when predictor uncertainty grows with forecast horizon, e.g.\ from a GCM ensemble spread that increases over time: list(Tmean = 0.30 + 0.01 * (years - base_year)). Entries not supplied default to zero (no noise for that predictor).
env_cov	Correlation structure of the environmental noise. The *magnitudes* of the noise come from env_noise; env_cov supplies the *correlation* between predictors, so that a perturbation on row i is drawn from $\mathcal{N}(0,\ D_i R D_i)$ with $D_i = \mathrm{diag}(\sigma_{i1}, \ldots, \sigma_{ip})$ and R = the correlation matrix. One of: • NULL (default): independent noise, $R = I$ — equivalent to ErrorTracer behaviour prior to this feature and the right choice when predictor measurement errors are genuinely independent (e.g.\ separate instruments on unrelated variables). • "empirical": compute the correlation of the predictor columns in the **training data** (model$data). Use this when predictor *errors* are expected to inherit the correlation structure of the predictors themselves — e.g.\ temperature and humidity that co-vary in the underlying climate system. • "newdata": compute the correlation of the predictor columns in newdata. Useful when the forecast window has a different covariance structure than training (e.g.\ scenario runs). • A numeric $p \times p$ matrix with dimnames matching the model's predictors. Entries with an off-diagonal exceeding 1 are rescaled to a correlation matrix. Use this to supply an independent estimate of the *error* correlation structure (e.g.\ from a reanalysis product or a sensor covariance report).

A correlation derived from training data is a working assumption: the structure of the *errors* is assumed to mirror the structure of the *values*. When this is implausible, pass a matrix directly.

`env_dist` Distributional form of the per-predictor noise. The `env_noise` SDs set the *magnitude* of the perturbation; `env_dist` sets its *shape*. For every distribution other than `"gaussian"`, the noise is calibrated so that (approximately) $E[\tilde{x}] = x$ and $\mathrm{Var}[\tilde{x}] = \sigma^2$, using a Gaussian copula to honour `env_cov`. One of:

- `NULL` (default): `"gaussian"` for every predictor — additive Gaussian noise, legacy behaviour.
- A single string (`"gaussian"`, `"lognormal"`, `"gamma"`, `"beta"`): applied to all predictors.
- A named list / character vector with one entry per predictor to override the default, e.g.\ `list(PPT = "gamma", tmax = "gaussian")`.

Distributions:

`"gaussian"` Additive normal noise ($\tilde{x} = x + \varepsilon$, $\varepsilon \sim N(0, \sigma^2)$). Appropriate for symmetric measurement error on a continuous, potentially negative scale (temperature, anomalies).

`"lognormal"` Multiplicative noise: $\log \tilde{x} \sim N(\log x - s^2/2,\ s^2)$ with $s^2 = \log(1 + (\sigma/x)^2)$. Preserves positivity; right-tail skewed. Natural for strictly positive continuous variables whose error scales with magnitude (e.g.\ enzyme activity, biomass). Rows with $x \leq 0$ are left unperturbed.

`"gamma"` $\tilde{x} \sim \mathrm{Gamma}(\mathrm{shape} = (x/\sigma)^2,\ \mathrm{rate} = x/\sigma^2)$. Positive support, right-skewed, analytic mean/variance match. Natural for precipitation, rates, and other non-negative continuous variables. Rows with $x \leq 0$ are left unperturbed.

`"beta"` $\tilde{x} \sim \mathrm{Beta}(\alpha, \beta)$ with $\alpha + \beta = x(1-x)/\sigma^2 - 1$. Support in $(0, 1)$; appropriate for proportions and probabilities (allele frequencies, presence rates). Rows with $x \notin (0, 1)$ or $\sigma^2 \geq x(1-x)$ are left unperturbed.

Correlation (`env_cov`) is applied to the latent standard-normal draws before the marginal quantile transform, so rank correlations are preserved across distributions.

`env_ensemble` Optional pathwise driver ensemble for forecasting under uncertain future covariates. A **named list**, one entry per uncertain driver predictor, where each entry is an $M \times H$ matrix of M scenario trajectories over the $H = \mathrm{nrow}(\mathrm{newdata})$ forecast steps (rows are scenarios, columns are horizon steps). Unlike `env_noise` — which draws *independent* per-observation jitter that averages out and leaves the driver variance flat with lead time — each posterior draw here is paired with a whole *trajectory*, so the driver uncertainty is temporally coherent and **accumulates with lead time** as a real driver ensemble (e.g.\ CMIP members, or resampled climatology) fans out. Predictors absent from `env_ensemble` are held at their `newdata` values. When supplied, `env_ensemble` supersedes `env_noise` for the perturbation and is folded into the credible interval by default. This is the recommended way to build a genuine *reforecast* in which only information available at the issue date is used.

`n_draws` Integer or `NULL`. Number of posterior draws to use. The default `NULL` uses *every* draw the fit holds, which is almost always what you want: `total_var` is the

measured variance of the predictive draws, so its Monte Carlo error is what the iid `closure_gap` reports, and subsampling widens that gap, and loosens every interval, PIT and shelf-life quantile, for nothing, since the draws are already computed. Supply an integer only to bound memory on very wide `newdata`; it is capped at the draws available in the fit.

`ci_levels` Numeric vector. Credible interval levels to compute (default `c(0.5, 0.8, 0.9, 0.95)`).

`n_perturb` Integer. Number of posterior draws used for the environmental perturbation step (default `n_draws`, i.e.\ every draw). Reducing it speeds up the perturbation at the cost of a smaller sample for *the whole env-inclusive budget*: the perturbed mean of draw s must be paired with the residual of that same draw s, so when `n_perturb < n_draws` and environmental uncertainty is present, the predictive draws and every decomposition component are computed on the first `n_perturb` draws rather than recycling the perturbation across all of them. Recycling would destroy $\mathrm{Cov}(\mu^{(s)}, y^{pp,(s)} - \mu^{(s)})$, which is substantially negative for an `ar()` fit and inflates the predictive variance (measured at up to 196x `env_var` on a near-unit-root series). Leave at the default unless the perturbation is the bottleneck.

`n_env_draws` Integer. Number of independent environmental perturbations averaged *per posterior draw* when estimating `env_var` (default `1`). Increasing this reduces Monte Carlo noise on the environmental-variance estimate at the cost of proportional computation. The decomposition always reports a Monte Carlo SE (`v_env_mcse`) alongside `env_var`; it decreases roughly like $1/\sqrt{n_env_draws \cdot n_perturb}$.

`interval_type` Character. Which draws to use when computing credible intervals:

- `"predictive"` (default): draws from `posterior_predict`, which include sigma (residual noise). Use this when forecasting **individual observations** — e.g. a single population's allele frequency, one site's ozone reading on a specific day.
- `"linpred"`: draws from `posterior_linpred`, which capture only parameter uncertainty (no sigma). Use this when forecasting the **mean response** — e.g. the expected ozone across many similar days, or mean delta f across replicate populations. These intervals are always narrower; they will undercover individual observations unless sigma is negligible.

The decomposition components and `posterior_predict` / `posterior_linpred` matrices are always computed regardless of this setting.

`include_env_in_ci`

Logical or `NULL`. Controls whether environmental (predictor) uncertainty is folded into the credible interval when `interval_type = "predictive"`. When `TRUE`, intervals are built from **environmentally inflated** draws in which the draws are generated at the env-perturbed mean. For a Gaussian identity link that is the location shift $\tilde{y} = \tilde{\mu} + (y^{pp} - \mu)$, which is exactly a draw from $N(\tilde{\mu}, \sigma^2)$ carrying that draw's own residual. For any other family the draw is taken from the response distribution *at* $\tilde{\mu}$, since the shift would keep the dispersion at μ while moving only the location (for a count model it also produced non-integer and negative draws). Models with a residual autocorrelation term keep the shift whatever the family, because $y^{pp} - \mu$ is what carries the `brms` forward iteration; such a fit reports a first-order approximation and says so. The interval variance

is then param + env + residual, coherent with `total_var`. The default `NULL` means **auto**: env is folded in whenever the caller supplied non-zero `env_noise`, and omitted otherwise. Pass `FALSE` to force a parameter + residual interval even when `env_noise` is given — note that this makes the reported interval deliberately narrower than `total_var` implies, since `total_var` is always the variance of the env-inclusive draws.

`var_trim` Numeric in $[0, 0.5)$, default `0`. Winsorization applied when computing *every* variance component of the decomposition: each column of draws is clipped to its $[$`var_trim`, $1 -$ `var_trim`$]$ quantiles before `var()`. The default `0` is the plain sample variance, so the reported budget describes exactly the distribution the quantile credible interval is drawn from. A non-zero value trades that coherence for robustness against a heavy-tailed predictive distribution, and is applied uniformly across `param_var`, `env_var`, the posterior-predictive variance and hence `temporal_var` — never to one component only, which would bias their differences.

Winsorizing is **not** the right remedy for a near-unit-root autocorrelation posterior: it masks a diverging forecast variance rather than fixing it, and leaves the budget describing a different distribution from the interval. Prefer a stationarity-respecting prior at fit time (`et_fit(ar_prior = "stationary")`).

`seed` Integer or `NULL` (default). Seed for the random draws this function makes: the posterior-predictive draw and the driver perturbation of `env_noise` / `env_ensemble`. `NULL` takes the seed the model was fitted with (`model$config$seed`), so a prediction is reproducible from the model alone and two scripts that reach the same fit by different routes agree. The caller's random stream is saved and restored, so seeding here never disturbs anything downstream. Pass `NA` to keep the ambient stream and leave the draws free. For an `et_model_list` the seed is offset by group position, so the groups neither share a perturbation stream nor stop being reproducible.

`...` Passed to methods.

Value

An `et_prediction` object (list) containing:

`posterior_predict` Matrix `[n_draws x n_obs]`: unperturbed posterior predictive draws (parameter + residual uncertainty).

`posterior_linpred` Matrix `[n_draws x n_obs]`: linear predictor draws on the **link scale** (parameter uncertainty only).

`lp_perturbed` Matrix `[n_perturb x n_obs]`: linear predictor on the link scale computed on environmentally perturbed inputs.

`predictive_draws` Matrix `[n_draws x n_obs]`: the posterior predictive draws from which `credible_intervals`, `et_pit`, and `et_skill_score` are computed (includes environmental uncertainty when `include_env_in_ci` is `TRUE`).

`sigma_draws` Numeric vector: posterior draws of sigma (`NA` for families without a sigma parameter, e.g.\ Binomial).

`credible_intervals` data.frame with columns `row_id`, `ci_level`, `lower`, `median`, `upper`, `width`.

`decomposition` data.frame with columns `obs_id`, `total_var`, `param_var`, `env_var`, `v_env_mcse`, `residual_var`, plus `group_var` when predicting for new random-effect levels, and `temporal_var` for autocorrelation models or `closure_gap` for iid ones. All components are on the **response scale**. `total_var` is the **measured** variance of the env-inclusive predictive draws, not the sum of the components; see `decompose_uncertainty`. `v_env_mcse` is the Monte Carlo SE of `env_var`. `residual_var` is per-observation for non-Gaussian families (e.g.\ Binomial: $E_s[n\mu^{(s)}(1-\mu^{(s)})]$) and constant for Gaussian.

`newdata` The input `newdata`.

`model` Reference to the `et_model` used.

`env_noise` The `env_noise` specification supplied.

`env_cov` The $p \times p$ correlation matrix actually used for perturbation (identity for `env_cov = NULL`).

`env_dist` Named character vector mapping each predictor to the distribution actually used for its perturbation.

`env_ensemble` Summary list (`n_scenarios`, `drivers`) when `env_ensemble` was supplied, otherwise `NULL`.

`n_draws`, `n_perturb`, `interval_type`, `include_env_in_ci` Effective draw counts and interval settings.

See Also

`decompose_uncertainty`, `shelf_life`, `et_calibrate`

`et_priors_split` *Extract priors from data held out from the likelihood*

Description

The standard workflow fits a regularized model and the Bayesian model on the *same* rows. Even with `shrinkage = "zero"`, which never reuses a point estimate as a prior mean, two things still cross over: the prior *scale* is set from those rows, and — more consequentially — when the first-stage model performs variable *selection*, the surviving predictor set is chosen using the same data that then forms the likelihood. Reported coverage is therefore conditional on that selection being correct, which is easy to satisfy in a simulation with orthogonal nuisance predictors and much less so in the correlated designs typical of real covariates.

Usage

```
et_priors_split(data, prior_fun, prop = 0.5, seed = NULL, strata = NULL, ...)
```

Arguments

`data`	A `data.frame` containing both the first-stage predictors and the response.
`prior_fun`	A function taking a `data.frame` and returning a fitted model that `extract_priors` accepts (e.g.\ an `lm`/`glm`/`cv.glmnet` fit).

`prop`	Proportion of rows used for the **prior** stage (default `0.5`). The remainder is returned for the likelihood.
`seed`	Optional integer seed for the split, for reproducibility.
`strata`	Optional column name in `data`. When supplied the split is stratified within its levels, so each level is represented in both halves — important for grouped or seasonal designs where a naive split can leave a level entirely absent from one side.
`...`	Passed to `extract_priors` (e.g.\ `multiplier`, `min_sd`, `shrinkage`).

Details

`et_priors_split()` removes both by construction: the first-stage model is fitted on a random subset, and the rows returned for the Bayesian fit are its complement. Selection and likelihood then share no observations, so the posterior needs no post-selection caveat.

Value

A list with:

priors The `et_prior_spec` object from the prior-stage rows.

fit_data Rows to pass to `et_fit` — disjoint from the rows used to build the priors.

prior_data Rows used for the first stage, returned so the split is auditable rather than hidden.

prop, n_prior, n_fit The realised split.

The trade-off, stated plainly

Splitting costs sample size. With `prop = 0.5` the likelihood sees half the data, so the posterior is genuinely wider — that width is honest rather than pessimistic, but at small n the loss can dominate whatever the prior contributes. Splitting is worth it when selection stability is in doubt (many correlated candidate predictors) and not worth it when the predictor set is fixed a priori, where there is no selection to protect against and the full sample should go to the likelihood.

See Also

`extract_priors` for the single-sample workflow.

Examples

```
set.seed(1)
d <- data.frame(x1 = rnorm(80), x2 = rnorm(80))
d$y <- 1 + 2 * d$x1 + rnorm(80)
sp  <- et_priors_split(d, function(df) lm(y ~ x1 + x2, data = df), seed = 1)
fit <- et_fit(y ~ x1 + x2, data = sp$fit_data, priors = sp$priors,
              chains = 1, iter = 500, refresh = 0)
```

`et_sensitivity_profile` *Sensitivity profile of the environmental uncertainty component*

Description

Sweeps a grid of noise magnitudes, re-runs `et_predict` for each, and summarises how the environmental variance component and the forecast shelf life respond. This turns the subjective choice of `env_noise` into an auditable *curve*: instead of reporting a single shelf life at one (often hand-picked) measurement-error level, the user sees how the horizon degrades as assumed noise grows.

Usage

```
et_sensitivity_profile(
  model,
  newdata,
  response_scale,
  fraction_grid = NULL,
  absolute_grid = NULL,
  env_cov = NULL,
  env_dist = NULL,
  include_env_in_ci = TRUE,
  ci_level = 0.9,
  ci_levels = c(0.5, 0.8, 0.9, 0.95),
  threshold = 1,
  time_col = NULL,
  n_draws = 2000L,
  n_perturb = NULL,
  max_extrapolation_factor = 10,
  verbose = TRUE,
  plausible_range = NULL
)
```

Arguments

`model`	An `et_model` from `et_fit`.
`newdata`	`data.frame` passed to `et_predict`.
`response_scale`	Two-element numeric vector `c(min, max)`, as in `shelf_life`. The effective range is `diff(response_scale)`.
`fraction_grid`	Optional numeric vector of scalar noise fractions.
`absolute_grid`	Optional `list` of `env_noise` arguments (each a named list / vector). If supplied together with `fraction_grid`, `fraction_grid` is ignored.
`env_cov, env_dist`	Passed through to `et_predict`.

include_env_in_ci
: Logical. If TRUE (default), credible intervals — and hence the shelf-life horizon — are computed from environmentally inflated draws (et_predict(..., include_env_in_ci = TRUE)). Set FALSE to see how env_var evolves while holding the CI fixed at parameter + residual.

ci_level
: Numeric. Used for shelf life and CI width tracking (default 0.90). Must be in ci_levels.

ci_levels
: Numeric vector of CI levels computed per iteration (default c(0.5, 0.8, 0.9, 0.95)).

threshold
: Numeric. Shelf-life threshold (default 1.0).

time_col
: Character. Optional time column for shelf life.

n_draws, n_perturb
: Passed to et_predict.

max_extrapolation_factor
: Passed to shelf_life.

verbose
: Logical. If TRUE (default), logs each iteration.

plausible_range
: Deprecated. Use response_scale instead.

Details

Three argument styles are supported for the grid:

- fraction_grid: scalar fractions of each predictor's SD in newdata. These are passed straight to the scalar form of et_predict's env_noise. Use this for an apples- to-apples sweep that scales all predictors together.
- absolute_grid: a list of named numeric lists / vectors; each list element becomes a single env_noise argument (so you can sweep absolute SDs for one predictor while holding others fixed).
- Neither supplied (NULL): a default log-spaced fraction grid c(0, 0.01, 0.025, 0.05, 0.1, 0.2, 0.4, 0.8) is used.

Each iteration calls et_predict(..., env_noise = g) then shelf_life and records:

- Mean parameter / environmental / residual / total variance across forecast observations.
- The horizon description ("observed", "projected", or "lower_bound") and numeric horizon if any.
- Mean / max CI width / plausible-range ratio.

Value

An et_sensitivity object: a data.frame with one row per grid point and columns

grid_id 1-indexed step.

label Short descriptor of the env_noise used (e.g.\ "fraction = 0.05").

fraction Scalar fraction when applicable; NA for absolute-grid rows.

`param_var`, `env_var`, `residual_var`, `total_var` Mean across forecast observations.

`env_share` `env_var` / `total_var` — the fraction of total predictive variance attributable to predictor noise. `total_var` is the measured variance of the env-inclusive posterior predictive draws, so `env_var` is a genuine sub-share of it and this sits in $[0, 1]$ up to Monte Carlo error.

`ci_width_mean`, `ci_width_max` At `ci_level`.

`ratio_mean`, `ratio_max` CI width / plausible range.

`horizon_type` One of `"observed"`, `"projected"`, `"lower_bound"`.

`horizon` Numeric horizon (observed or projected) or `NA` for lower-bound rows.

`horizon_description` The long description returned by `shelf_life`.

The returned object carries the original call and `response_scale` as attributes for use by `et_plot_sensitivity`.

See Also

`et_predict`, `shelf_life`, `et_plot_sensitivity`

`et_shelf_life_pool` *Pool forecast shelf lives across multiple forecast origins*

Description

A shelf life read off a *single* forecast origin is a property of that training window as much as of the system: it inherits whatever was idiosyncratic about the final training years. Established practice in ecological forecast evaluation is to issue forecasts repeatedly from rolling origins and summarise skill indexed by **both** origin and lead time (Dietze 2017; Thomas et al. 2020; Petchey et al. 2015). This function does the pooling half of that: given the horizons obtained at several origins, it returns a horizon with an interval rather than a point.

Usage

```
et_shelf_life_pool(horizons, conf_level = 0.95)
```

Arguments

`horizons`	Either a list of `et_shelf_life` objects (one per forecast origin, in any order), or a `data.frame` with columns `lead` (numeric horizon in lead time) and `censored` (logical, `TRUE` when the forecast was still informative at the last available lead). A `group` column, when present, is summarised separately.
`conf_level`	Confidence level for the Kaplan–Meier interval on the median horizon (default `0.95`).

Value

A `data.frame`, one row per group (or a single row when ungrouped), with columns:

group Group label, when supplied.

n_origins Number of forecast origins contributing.

n_observed Origins at which the horizon was reached in-window.

n_censored Origins right-censored (still informative at the end).

median_lead Pooled horizon in lead time. `NA` when every origin is censored — which is itself a result: the forecast never became uninformative from any origin.

lower, upper Confidence bounds on the median.

min_lead, max_lead Range of the observed horizons.

method `"kaplan-meier"` or `"median (uncensored only)"`.

Why censoring matters

Later origins have fewer lead times available, so a long horizon may not be observed before the data run out — the forecast is still informative at the last available lead. That is **right-censoring**, not a missing value. Dropping those origins would bias the pooled horizon downward (only the short horizons survive), and treating the last lead as the horizon would bias it downward too. Both are avoided by treating the pooled horizon as a time-to-event problem and estimating it with Kaplan–Meier, which uses the censored origins as the partial information they are.

When **survival** is available the median horizon and its confidence interval come from `survival::survfit()`. Otherwise the function falls back to the median of the observed horizons and says so in the `method` field — a fallback that is biased low whenever anything is censored, which is why the interval is reported as `NA` there.

References

Dietze, M. C. (2017) Prediction in ecology: a first-principles framework. *Ecological Applications* 27:2048–2060.

Petchey, O. L. *et al.* (2015) The ecological forecast horizon, and examples of its uses and determinants. *Ecology Letters* 18:597–611.

See Also

`shelf_life` for the single-origin horizon.

Examples

```
# Horizons from five origins; the last was censored.
h <- data.frame(lead     = c(2, 3, 2, 3, 5),
                censored = c(FALSE, FALSE, FALSE, FALSE, TRUE))
et_shelf_life_pool(h)
```

`et_sim` *Simulated allele-frequency-change dataset for ErrorTracer tutorials*

Description

A named list containing training data, forecast predictors, validation responses, and ground-truth parameters for two synthetic SNP clusters (A and B) at a hypothetical mountain plant site. The dataset is designed to exercise every step of the ErrorTracer pipeline and to support parameter-recovery validation (true coefficients are known).

Usage

```
et_sim
```

Format

A named `list` with seven elements:

`train` `data.frame` with 200 rows and 16 columns (2 clusters $\times$ 100 training years, 1920–2019):

year Integer. Calendar year.

cluster_id Character. SNP cluster identifier: `"A"` or `"B"`.

Tmean Numeric. Standardised mean growing-season temperature (original unit: °C; standardised using training-period mean and SD).

PPT Numeric. Standardised total growing-season precipitation (original unit: mm).

SWE Numeric. Standardised peak snow water equivalent (original unit: mm).

z_diff Numeric. Simulated allele-frequency change on the arcsin-sqrt scale ($\arcsin(\sqrt{f})$ transformation). This transformation is unbounded and has no fixed $[-1, 1]$ constraint; the response scale should be derived from the training data or from the theoretical bounds ($[0, \pi/2]$\ on the arcsin scale).

d1, . . . , d10 Numeric. Ten independent standardised nuisance predictors with zero true effect on `z_diff`.

`forecast` `data.frame` with 30 rows and 15 columns (2 clusters $\times$ 15 forecast years, 2020–2034). Same columns as `train` except `z_diff` is absent — these are the prediction targets. Predictors are standardised using the training-period statistics stored in `standardization`.

`validation` `data.frame` with 30 rows and 3 columns (`year`, `cluster_id`, `z_diff`). True response values for the forecast period; used with `et_calibrate` to assess posterior predictive coverage.

`true_params` Named `list` with one element per cluster. Each element is a named numeric vector of the true data-generating parameters: `intercept`, `Tmean`, `PPT`, `SWE`, and `sigma` (residual SD).

Cluster A `intercept` = `0.00`, `Tmean` = `0.50`, `PPT` = `-0.30`, `SWE` = `0.20`, `sigma` = `0.30`

Cluster B `intercept` = `0.10`, `Tmean` = `0.30`, `PPT` = `-0.20`, `SWE` = `-0.25`, `sigma` = `0.35`

`env_noise` Named `list` of length 13. Suggested per-predictor environmental noise SDs (on the standardised scale) for use with the `env_noise` argument of `et_predict`: `Tmean` = `0.30`, `PPT` = `0.20`, `SWE` = `0.15`, and `0` for each of `d1`, . . . , `d10`.

`standardization` Named `list` with one element per predictor. Each element is a named numeric vector `c(mean = ..., sd = ...)` giving the training-period statistics used to standardise the data. Needed if you wish to back-transform predictions to the original (unstandardised) scale with `unstandardize`.

`description` Character string. Human-readable description of the dataset and how it was generated.

Details

The climate time series are simulated as AR(1) processes with a warming trend in `Tmean` (+0.015 °C yr^{-1}, cumulating to ~0.30 SD above the training mean over the 15-year forecast window). `SWE` is generated with a weak dependence on `Tmean` (negative coupling) and `PPT` (positive coupling) plus a dominant independent noise component, so that the three predictors have only mild pairwise correlation ($|R| < 0.2$ on the training subset). This makes all regression coefficients reliably identifiable in a single replicate. All predictors are standardised using training-period statistics only.

In addition to the three real climate predictors, the dataset includes ten independent standardised nuisance predictors `d1`, ..., `d10` with zero true effect on the response. They give the regularized-prior extraction step a real selection job: cv.glmnet (alpha = 0.5) is expected to identify the three real predictors and shrink the ten dummies toward zero. Without them, regularization on three well-identified predictors merely biases the true coefficients without selecting anything.

Responses are generated from a linear model with Gaussian noise:

$$z_diff_t = \alpha + \beta_1 Tmean_t + \beta_2 PPT_t + \beta_3 SWE_t + \varepsilon_t, \quad \varepsilon_t \sim \mathcal{N}(0, \sigma^2)$$

The true parameters are stored in `et_sim$true_params` for parameter-recovery validation.

The dataset was generated with `set.seed(111)`. The full generation script is at `data-raw/generate_et_sim.R`.

Source

Generated by `data-raw/generate_et_sim.R` with `set.seed(111)`.

Examples

```
data(et_sim)

# Inspect structure
str(et_sim, max.level = 2)

# Training data
head(et_sim$train)

# True parameters for cluster A
et_sim$true_params$A

# Suggested noise SDs for et_predict()
et_sim$env_noise
```

`et_skill_score` *Null-model-relative forecast skill (CRPS)*

Description

Scores a forecast against a null model with the continuous ranked probability score (CRPS) and returns the per-lead-time skill, $1 - \mathrm{CRPS}_{\mathrm{model}}/\mathrm{CRPS}_{\mathrm{null}}$ (positive when the model beats the null). This is the accuracy-relative counterpart to `shelf_life`'s precision criterion; report both. The **forecast limit** — the first lead time beginning a sustained run of non-skillful periods — is attached as an attribute.

Usage

```
et_skill_score(
  predictions,
  observed,
  response_col = NULL,
  time_col = NULL,
  null = c("climatology", "random_walk"),
  climatology = NULL,
  rw_sd = NULL,
  rw_start = NULL,
  min_run = 2L,
  ...
)
```

Arguments

`predictions`	An `et_prediction` or `et_prediction_list`.
`observed`	A `data.frame` of true responses positionally matched to `predictions$newdata` (with the grouping column for grouped input).
`response_col`	Character. Response column name; inferred from the model formula when `NULL`.
`time_col`	Character. Optional time column in `newdata` used for the `time` axis (lead time otherwise defaults to the row index).
`null`	Character. The null model: `"climatology"` (default; the unconditional response distribution) or `"random_walk"` (persistence: the last observed value carried forward with variance growing linearly with lead time).
`climatology`	Optional numeric vector giving the climatological reference distribution. Defaults to the training response values.
`rw_sd`, `rw_start`	Optional random-walk per-step innovation SD and start value. Default to `sd(diff(train_response))` and the last training response, respectively.
`min_run`	Integer. Number of *consecutive* non-skillful periods required before the forecast limit is declared (default 2). Skill near zero crosses by chance, and a bare first-crossing rule (`min_run = 1`, the previous behaviour) promotes a lone dip to a horizon — the same failure mode `shelf_life` guards against. Isolated dips are still reported via `n_below` / `first_below`.

...	Unused.

Value

A data.frame with columns obs_id, time, crps_model, crps_null, skill, and skillful (skill > 0); a leading group column for grouped input. The attribute "forecast_limit" holds a list with the null-relative horizon, its type ("observed" or "lower_bound"), and the diagnostics n_below, first_below and min_run; or is per-group for grouped input.

See Also

shelf_life, et_calibrate

---

et_sobol *Global (Sobol) variance-based sensitivity of the predictive mean*

Description

An optional, order-independent alternative to the additive budget from decompose_uncertainty. Decomposes the variance of the response-scale predictive mean $\mu = g^{-1}(\eta)$ into first-order **parameter** and **environmental** (driver) Sobol indices plus their **interaction**, by independently resampling the parameter draws and the predictor perturbations (Saltelli 2010 first-order; Jansen total-order). Unlike the sequential additive split, this is insensitive to the order in which factors are added and makes any parameter×driver interaction explicit — the general case a non-linear link or correlated drivers can produce.

Usage

```
et_sobol(predictions, n_sobol = 1024L, seed = NULL, ...)
```

Arguments

predictions	An et_prediction that was produced with non-zero env_noise (the environmental factor needs a perturbation scale).
n_sobol	Integer. Base sample size for the Sobol estimator (default 1024). Total model evaluations per observation are 4 * n_sobol.
seed	Optional integer for reproducible sampling.
...	Unused.

Value

A data.frame with one row per forecast observation:

obs_id Observation index.

S_param, S_env First-order Sobol indices (fraction of the predictive-mean variance from parameters / drivers alone).

ST_param, ST_env Total-order indices (including interactions).

interaction `1 - S_param - S_env`: the share of predictive-mean variance attributable to the parameter×driver interaction.

var_mu Variance of the predictive mean (the quantity being decomposed).

residual_var Mean within-draw family variance (the irreducible part; `var_mu + residual_var` approximates the total predictive variance).

See Also

`decompose_uncertainty` (the default additive budget).

`et_theme` *Minimal ggplot2 theme for ErrorTracer plots*

Description

Minimal ggplot2 theme for ErrorTracer plots

Usage

```
et_theme(base_size = 12)
```

Arguments

`base_size`	Base font size (default 12).

Value

A `ggplot2` theme object.

`extract_priors` *Extract brms prior specification from a regularized or standard regression model*

Description

Converts a fitted model object into a `brms` prior specification suitable for `et_fit`. The regularized or standard fit sets the *scale* of each coefficient's prior (its SD); the `shrinkage` argument controls the prior *mean*. With the default `shrinkage = "zero"` the priors are centred at zero — a regularizing (ridge-style) prior whose width is informed by the fit but whose location carries no reused point estimate. With `shrinkage = "estimate"` the coefficient estimates are used as informative prior means, so the Bayesian model starts close to the regularized solution.

Usage

```
extract_priors(
  model,
  multiplier = 2,
  min_sd = 0.1,
  shrinkage = c("zero", "estimate"),
  intercept_prior_sd = NULL,
  sigma_prior_scale = 1,
  ...
)

## S3 method for class 'lm'
extract_priors(
  model,
  multiplier = 2,
  min_sd = 0.1,
  shrinkage = c("zero", "estimate"),
  intercept_prior_sd = NULL,
  sigma_prior_scale = 1,
  ...
)

## S3 method for class 'glm'
extract_priors(
  model,
  multiplier = 2,
  min_sd = 0.1,
  shrinkage = c("zero", "estimate"),
  intercept_prior_sd = NULL,
  sigma_prior_scale = 1,
  ...
)

## S3 method for class 'cv.glmnet'
extract_priors(
  model,
  multiplier = 2,
  min_sd = 0.1,
  shrinkage = c("zero", "estimate"),
  intercept_prior_sd = NULL,
  sigma_prior_scale = 1,
  lambda = "lambda.min",
  ...
)

## S3 method for class 'glmnet'
extract_priors(
  model,
```

```
  multiplier = 2,
  min_sd = 0.1,
  shrinkage = c("zero", "estimate"),
  intercept_prior_sd = NULL,
  sigma_prior_scale = 1,
  s = 1L,
  ...
)

## S3 method for class 'ranger'
extract_priors(
  model,
  multiplier = 2,
  min_sd = 0.1,
  shrinkage = c("zero", "estimate"),
  intercept_prior_sd = NULL,
  sigma_prior_scale = 1,
  ...
)
```

Arguments

`model`	A fitted model. Supported classes: • `cv.glmnet` / `glmnet` — elastic net / lasso • `lm` — ordinary least squares • `glm` — generalized linear model • `ranger` — random forest (importance-scaled flat priors)
`multiplier`	Numeric scalar. Prior SD is set to `multiplier * |coef|` under the default `shrinkage = "zero"` (or for `glmnet`), `multiplier * SE` for `lm`/`glm` when `shrinkage = "estimate"`, and `multiplier * importance_normalised` for `ranger`. Default 2.0.
`min_sd`	Numeric scalar. Minimum prior SD to avoid degenerate (spike) priors on near-zero coefficients. Default 0.1.
`shrinkage`	Character. Sets the prior *mean*: `"zero"` (default) centres every coefficient prior at 0 (a regularizing prior with a data-informed scale `multiplier * |coef|` but no reused location); `"estimate"` uses the fitted coefficient as the prior mean (informative, but reuses the data — see the double-use note above). For `ranger` the mean is always 0 (no signed coefficients), so `shrinkage` has no effect.
`intercept_prior_sd`	Optional prior SD for the intercept term. The default `NULL` emits *no* explicit intercept prior and lets `brms` pick its data-aware default (`student_t(3, median(y), mad(y))`). If you supply a numeric value, the prior becomes `normal(0, intercept_prior_sd)` — this is only appropriate when the response has been centred (or nearly so) before fitting, since `brms`'s `class = "Intercept"` refers to the intercept at the centre of the predictors, whose posterior mean equals `E[y]` there. Supplying a small `intercept_prior_sd` for an uncentred response will pull the intercept toward zero and cripple the fit.

`sigma_prior_scale`
: Scale parameter for the half-Cauchy prior on the residual SD sigma. Default 1.0.

`...`
: Additional arguments passed to methods.

`lambda`
: Which lambda to extract coefficients from when the model is a `cv.glmnet` object. Either `"lambda.min"` (default) or `"lambda.1se"`.

`s`
: Index (integer) or value of lambda to extract coefficients at when the model is a plain `glmnet` object. Defaults to the first lambda (smallest regularisation).

Details

The `ranger` path is experimental. Random-forest permutation importance has no sign and no natural scale in the units of a GLM coefficient, so the mapping used here — priors centred at zero with SD set to `multiplier * importance_normalised` (importance normalised to `[min_sd, 1]`; only variables with positive importance retained) — is a heuristic, not a calibrated correspondence. It is offered for exploratory feature screening only; for a principled prior prefer `glmnet`/ `lm`/`glm`, whose coefficients are on the model's scale. A signed importance (e.g. from SHAP values) would be needed to inform the prior mean.

Value

An `et_prior_spec` list containing:

`prior` A `brmsprior` object for use in `brms::brm()`.

`pred_names` Character vector of included predictor names.

`coefs` Named numeric vector of first-stage coefficients (`NULL` for `ranger`, which uses importance instead).

`method` Character: the dispatch method used.

`multiplier`, `min_sd`, `shrinkage`, `intercept_prior_sd`, `sigma_prior_scale` Settings echo.

Prior/likelihood double use

Centring the priors on the coefficient *estimates* (`shrinkage = "estimate"`) and then refitting the Bayesian model on the *same* data uses those data twice — once to locate the prior mean and once through the likelihood — which can make posteriors overconfident, especially at small n. The default `shrinkage = "zero"` avoids this by not reusing the estimated location: only the prior scale is data-informed, which is a standard weakly-informative device. If you use `shrinkage = "estimate"`, check calibration with `et_calibrate`, or build the priors on data held out from the likelihood fit.

Examples

```
fit_lm <- lm(mpg ~ wt + hp + cyl, data = mtcars)
ps <- extract_priors(fit_lm, multiplier = 2, min_sd = 0.1)
print(ps)
```

`shelf_life` *Compute the forecast shelf life*

Description

Quantifies *when* a forecast becomes uninformative by comparing the width of credible intervals to a response scale. A forecast is uninformative when its CI width exceeds `threshold * response_scale`.

Usage

```
shelf_life(
  predictions,
  response_scale = NULL,
  ci_level = 0.9,
  threshold = 1,
  time_col = NULL,
  skill = NULL,
  min_slope_for_projection = 1e-04,
  max_extrapolation_factor = 10,
  min_run = 2L,
  projection_alpha = 0.05,
  ...,
  plausible_range = NULL
)
```

Arguments

`predictions`	An `et_prediction` or `et_prediction_list`.
`response_scale`	Numeric vector of length 2 (`c(min, max)`) giving the response scale used as the denominator in the CI-width / range ratio. Supply a biologically motivated interval when one exists. When `NULL` (default), the observed range of the **training response** is used as a documented, reproducible default (with an informational message) instead of an arbitrary number. The effective range is `diff(response_scale)`.
`ci_level`	Numeric. The credible interval level to use (default 0.90). Must be present in the `et_prediction` object.
`threshold`	Numeric. CI width / response scale above which the forecast is uninformative (default 1.0).
`time_col`	Character. Optional column in `predictions$newdata` to use as the time axis. If `NULL`, observation index is used.
`skill`	Optional skill gate. A `data.frame` returned by `et_skill_score` (positionally matched to the forecast rows; its `skillful` column is used) or a bare logical vector. When supplied, a forecast period is `informative` only if it is both precise *and* skillful, so a precise-but-biased forecast does not pass. When `NULL` (default) the precision criterion is used alone.

`min_slope_for_projection`
: Numeric. Minimum linear slope (of ratio vs.\ time) required to attempt extrapolation when all periods are informative. Below this value the shelf life is reported as a lower bound only. Default `1e-4`.

`max_extrapolation_factor`
: Numeric. Cap on how far the linear projection may reach beyond the observed window. If the projected crossing time exceeds `max(time) + max_extrapolation_factor * (max(time) - min(time))`, the result is reported as a lower bound instead of a projection. Set to `Inf` to disable the cap. Default `10`.

`min_run`
: Integer. Number of *consecutive* uninformative periods required before the threshold counts as crossed (default `2`). Guards against a single noisy period manufacturing a horizon when the ratio hovers near `threshold`. Set `min_run = 1` to recover the pre-1.3.1 first-exceedance behaviour; raise it for noisier series.

`projection_alpha`
: Numeric. Significance level for the one-sided test that the fitted ratio-vs-time slope is positive (default `0.05`). A slope can clear `min_slope_for_projection` while being statistically indistinguishable from flat; extrapolating it yields a confident-looking crossing time whose interval may span centuries and include the past. When the slope fails this test the result is reported as a lower bound instead of a projection. Set to `1` to disable the test and recover the pre-1.3.1 behaviour.

`...`
: Unused.

`plausible_range`
: Deprecated. Use `response_scale` instead.

Details

Shelf life is a **precision** criterion on the response scale — a deliberate *complement* to accuracy-relative forecast limits (Petchey et al. 2015; Wesselkamp et al. 2025), not a replacement. It answers "when do the error bars get too wide to act on?", whereas a forecast limit answers "when does the model stop beating a null?". Because a forecast can be precise yet biased, pass a `skill` table from `et_skill_score` to **gate** the shelf life on skill: a period then counts as informative only if it is both precise *and* beats the null model. This couples the two views and prevents a precise-but-biased forecast from silently passing.

The function operates in three modes depending on the available data and whether the uninformative threshold is crossed within the forecast window:

Observed The threshold is crossed within the forecast/validation window *and the crossing persists*. The shelf life is the first time point beginning a run of `min_run` consecutive periods with `ratio >= threshold`. Requiring persistence matters: when the ratio hovers near `threshold` without trending, a single noisy period can exceed it by chance, and the first-exceedance rule used before ErrorTracer 1.3.1 would report that excursion as a horizon. Isolated exceedances are now reported in the horizon diagnostics (`n_exceedances`, `first_exceedance`) instead of being promoted to a crossing.

Projected No sustained crossing occurs in-window but the CI/range ratio is trending upward *detectably* — the fitted slope must exceed `min_slope_for_projection` **and** be significantly positive at `projection_alpha`. A linear trend is extrapolated to estimate when the threshold

would be reached. The projected crossing time $t^* = (\tau - a)/b$ (where τ is the threshold, a the fitted intercept, b the fitted slope) is reported together with a standard error `se_t_star` derived via the delta method.

Lower bound No sustained crossing and no trend distinguishable from flat (or a projection beyond the extrapolation cap). The shelf life is reported as a lower bound: `> last observed time`. This is the honest outcome for a forecast whose precision simply does not degrade in-window.

The intended workflow is:

1. Fit the model (`et_fit`).
2. Predict on held-out data or a future time window (`et_predict`).
3. Call `shelf_life()` on those predictions.
4. If the threshold is not crossed in the held-out window, the *projected* mode extrapolates the horizon automatically.

Value

An `et_shelf_life` object (a `data.frame`) with columns:

obs_id Observation index.

time Time axis value.

ci_width Width of the credible interval at `ci_level`.

plausible_range Effective response scale (scalar diff).

ratio CI width / response scale.

informative Logical; `TRUE` when ratio < threshold.

For grouped predictions a `group` column is prepended. The object carries three attributes that drive `print()`:

`horizon` Named list with elements `value`, `type` (`"observed"`, `"projected"`, or `"lower_bound"`), `last_informative`, `description`, (for projected) `se_t_star`, and the exceedance diagnostics `n_exceedances`, `frac_exceedance`, `first_exceedance` and `min_run`. Comparing `first_exceedance` with `value` shows whether the reported horizon rests on a persistent crossing or whether isolated excursions preceded it.

`horizon_by_group` For grouped objects: named list of per-group horizon lists.

`threshold` The threshold value used.

Examples

```
set.seed(1)
df  <- data.frame(y = rnorm(20), year = 2001:2020, x1 = rnorm(20))
fit <- et_fit(y ~ x1, data = df,
              chains = 1, iter = 500, warmup = 250,
              cores = 1, refresh = 0)
new_df <- data.frame(x1 = rnorm(10), year = 2021:2030)
pred   <- et_predict(fit, newdata = new_df,
                     n_draws = 200)
sl <- shelf_life(pred,
```

```
                  response_scale            = range(df$y),
                  ci_level                  = 0.90,
                  threshold                 = 1.0,
                  time_col                  = "year",
                  max_extrapolation_factor  = 10)
print(sl)
```

`standardize` *Standardize a numeric vector (mean-centre, unit-variance)*

Description

Standardize a numeric vector (mean-centre, unit-variance)

Usage

```
standardize(x)
```

Arguments

`x`	Numeric vector.

Value

Standardized numeric vector. Returns zeros if variance is zero.

`unstandardize` *Reverse standardization*

Description

Reverse standardization

Usage

```
unstandardize(z, mu, s)
```

Arguments

`z`	Standardized values.
`mu`	Original mean.
`s`	Original standard deviation.

Value

Values on the original scale.

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