

Package ‘SppTrend’

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Title Analyzing Linear Trends in Species Occurrence Data

Version 0.5

Description Provides a comparative framework to detect species-specific spatial and thermal responses to climate change using opportunistic occurrence data. Species temporal trends in geographic position (via Earth-Centred Earth-Fixed vector analysis) and environmental variables (temperature and elevation) are contrasted against the overall trend of the complete dataset, allowing classification of species into ecologically interpretable response categories. Approach described in Lobo et al. (2023) <[doi:10.1002/ece3.10674](https://doi.org/10.1002/ece3.10674)>.

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get_elevation	<i>Extract elevation from DEM</i>
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Description

This function retrieves elevation values from a Digital Elevation Model (DEM) based on their geographic coordinates (lon/lat).

Usage

```
get_elevation(data, dem_file)
```

Arguments

data	A data frame containing species records. Must include lon, lat, year, and month columns.
dem_file	Full character path to the downloaded DEM raster file.

Value

The input data frame data with a new column (ele) containing the extracted elevation values.

get_era5_tme	<i>Extract temperature data from ERA5 NetCDF file</i>
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Description

This function retrieves mean monthly air temperature values associated with species occurrence records based on their geographic coordinates (lon/lat) and sampling date (year/month).

Usage

```
get_era5_tme(data, nc_file)
```

Arguments

data	A data frame containing species records. Must include lon, lat, year, and month columns.
nc_file	Full character path to the downloaded ERA5-Land raster (.nc) file.

Value

The input data frame data with a new column named (tme), containing the temperature values.

get_fast_info

Quick visual diagnostic of the input data

Description

This function provides a quick visual diagnostic of the input data. It generates a map showing the spatial distribution of occurrence records together with a time-series plot derived from a NetCDF environmental dataset, including a linear trend analysis. Using the geographic coordinates of the occurrence records, the function extracts the complete climate time-series (from the earliest to the latest year represented in the data) for the corresponding occupied cells. All temperature values from occupied cells are then added annually to estimate and visualise the overall temperature trend (including slope and associated p-value). This diagnostic step allows users to quickly assess the climate trajectory of the regions where the species have been recorded and to evaluate whether sufficient temporal and environmental variation is present for subsequent analyses.

Usage

```
get_fast_info(data, nc_file)
```

Arguments

data	A data frame containing species records. Must include lon, lat, year, and month columns.
nc_file	Full character path to the downloaded ERA5-Land raster (.nc) file.

Value

Invisibly returns a composite plot. Displays a composite plot showing the geographic distribution and the thermal trend with its corresponding global slope and p-value.

spp_trend_environmental

Analyse Long-Term Environmental Niche Trends Across Species

Description

spp_trend_environmental() models temporal trends in environmental variables - Temperature and/or Elevation - for each species in a community dataset and evaluates whether species-specific shifts differ from the pooled community trend.

For every requested response variable the function fits:

1. A **global ordinary least-squares (OLS) regression** pooled across all valid species, capturing the average community-level temporal trend.
2. An **independent OLS regression per species**, yielding species-specific temporal slopes together with their standard errors, t-statistics, and 95 \

Species-specific slopes are then compared against the global slope using **Welch-Satterthwaite t-tests**. Raw p-values from both the individual species regressions and the slope-difference tests are corrected for multiple testing with the **Benjamini-Hochberg False Discovery Rate (FDR)** procedure, applied separately for each response variable. An optional sample-size correction penalises the significance threshold for well-sampled species ($N > 100$).

Usage

```
spp_trend_environmental(
  data,
  spp = NULL,
  responses = c("Temperature", "Elevation"),
  min_records = 20,
  min_years = 5,
  alpha_ref = 0.05,
  use_Ncorrected_alpha = TRUE,
  individual_lm_min_thresholds = c(Temperature = 0.01, Elevation = 50),
  individual_lm_threshold_type = "speciesslope",
  verbose = TRUE
)
```

Arguments

data	A data frame or <code>data.table</code> containing the raw observational records. Must include the following columns (exact names required): Species Character or factor. Taxonomic name or identifier for each observation. Year Integer or numeric. Calendar year of the observation. Month Integer or numeric. Calendar month (1-12) of the observation. Temperature Numeric. Environmental temperature associated with the observation (e.g. mean monthly temperature in deg C at the sampling location). Required when "Temperature" is included in responses. Elevation Numeric. Elevation (m a.s.l.) associated with the observation. Required when "Elevation" is included in responses. Rows with NA in Species, Year, or Month, and rows where Month is outside 1-12, are silently removed before analysis.
spp	Character vector or NULL (default NULL). Names of the species to include in the analysis. If NULL, all unique species present in data are used. Species named in spp that are absent from data trigger a warning; if none of the requested species are found the function stops with an error.
responses	Character vector specifying which environmental variables to model. Allowed values are "Temperature", "Elevation", or both (default <code>c("Temperature", "Elevation")</code>). The vector is matched against the allowed set in the order <code>c("Temperature", "Elevation")</code> , so any duplicate or out-of-order entries are normalised automatically.
min_records	Positive integer (default 20). Minimum number of non-missing records a species must have for a given response variable to be retained in the analysis. Species below this threshold are excluded and reported in <code>species_filter</code> .

min_years	Positive integer (default 5). Minimum number of distinct calendar years a species must have data in (for a given response variable) to be retained. Acts alongside min_records; a species must satisfy both criteria.
alpha_ref	Numeric scalar in (0, 1) (default 0.05). Baseline significance level used for all hypothesis tests and confidence-interval calculations. This value is also the starting point for the sample-size correction applied when use_Ncorrected_alpha = TRUE.
use_Ncorrected_alpha	Logical (default TRUE). When TRUE, the effective significance threshold for any individual species with more than 100 records is reduced according to

$$\alpha_{\text{eff}} = \alpha_{\text{ref}} \times \sqrt{100/N}$$

where N is the number of records for that species and response variable. This penalises the inflated statistical power that comes with large sample sizes, requiring a larger observed effect before a species is classified as significant. When FALSE, alpha_ref is applied uniformly to all species.

individual_lm_min_thresholds	Named numeric vector or NULL (default c(Temperature = 0.01, Elevation = 50)). Minimum ecological effect size that must be exceeded before a species can be assigned a non-conformance class (TT, TA, SA, or SD). Names must be a subset of c("Temperature", "Elevation") and all values must be positive. The quantity being thresholded depends on individual_lm_threshold_type: <ul style="list-style-type: none"> "speciesslope" (default) The absolute value of the species-specific temporal slope must exceed the threshold (e.g. slope > 0.01 deg C yr⁻¹ for Temperature). Evaluates how much the species is shifting in absolute terms. "slopediff" The absolute value of the difference between the species slope and the global slope must exceed the threshold. Evaluates how much the species is shifting relative to the average community trend. If NULL, no ecological threshold is applied and classification relies entirely on statistical significance. Must be NULL jointly with individual_lm_threshold_type, or non-NULL jointly; mixed states produce an error.
individual_lm_threshold_type	Character scalar (default "speciesslope"). Determines which quantity is compared against individual_lm_min_thresholds. Must be one of: <ul style="list-style-type: none"> "speciesslope" Threshold is applied to the absolute species-specific slope. "slopediff" Threshold is applied to the absolute difference between the species slope and the global slope.
verbose	Logical (default TRUE). When TRUE, the function prints progress messages to the console via message(), including the number of species retained or excluded at the filtering step for each response variable. Set to FALSE to suppress all messages (useful inside loops or parallel computations).

Value

A named list with the following elements:

params Named list storing the values of all function arguments (except data and spp) as supplied by the caller. Useful for reproducibility and logging.

species_filter Data frame with one row per species x response combination, summarising the filtering step. Columns:

- Species** Character. Species name.
- response** Character. Response variable ("Temperature" or "Elevation").
- n_records** Integer. Total number of non-missing records for this species and response.
- n_years** Integer. Number of distinct calendar years with at least one non-missing record.
- retained** Logical. TRUE if the species meets both `min_records` and `min_years` thresholds and was therefore included in the modelling step.

environmental_global_lm Data frame with one row per response variable containing statistics from the pooled (community-level) OLS regression. Columns:

- response** Character. Response variable.
- model** Character. Always "global_lm".
- global_lm_slope** Numeric. Estimated temporal slope of the global model (units per year: deg C yr⁻¹ or m yr⁻¹).
- global_lm_se** Numeric. Standard error of the global slope.
- global_lm_t** Numeric. t-statistic for the global slope (H0: slope = 0).
- global_lm_p_value** Numeric. Two-tailed p-value for the global slope test.
- global_lm_conf_low** Numeric. Lower bound of the 95 \ confidence interval for the global slope.
- global_lm_conf_high** Numeric. Upper bound of the 95 \ confidence interval for the global slope.
- n_records** Integer. Total number of records used to fit the global model (all valid records across retained species).
- n_years** Integer. Number of distinct calendar years represented in the global model dataset.

environmental_individual_lm Data frame with one row per species x response combination for all species that passed the filtering step. Contains species-level OLS statistics plus comparisons against the global model. Columns:

- Species** Character. Species name.
- response** Character. Response variable.
- n_records** Integer. Number of records used to fit this species model.
- n_years** Integer. Number of distinct years in the species data for this response.
- individual_slope** Numeric. Estimated temporal slope for this species (deg C yr⁻¹ or m yr⁻¹).
- individual_slope_se** Numeric. Standard error of the species-specific slope.
- individual_t** Numeric. t-statistic for the species slope (H0: slope = 0).
- individual_p_value** Numeric. Two-tailed p-value for the species slope test (raw, before FDR correction).
- individual_conf_low** Numeric. Lower bound of the 95 \ confidence interval for the species slope.
- individual_conf_high** Numeric. Upper bound of the 95 \ confidence interval for the species slope.

global_lm_slope Numeric.Global slope for this response variable (copied from environmental_global_lm for convenience).
 slope_diff_signed Numeric.Signed difference between the species slope and the global slope (individual_slope - global_lm_slope).Positive values indicate the species trend is steeper than the community average.
 slope_diff_direction Character.Direction of slope_diff_signed: "positive", "negative", or "zero".
 slope_diff Numeric.Absolute value of slope_diff_signed.
 slope_diff_t Numeric.Welch-Satterthwaite t-statistic for the test of equality between the species slope and the global slope.
 slope_diff_df Numeric.Welch-Satterthwaite degrees of freedom for slope_diff_t.
 slope_diff_p_value Numeric.Two-tailed p-value for the slope-difference test (raw, before FDR correction).
 individual_direction Character.Direction of the species slope itself: "positive", "negative", or "zero".
 individual_p_adj_fdr Numeric.FDR-adjusted (BH method) p-value for the species slope test, computed within each response variable separately.
 slope_diff_p_adj_fdr Numeric.FDR-adjusted (BH method) p-value for the slope-difference test.
 alpha Numeric.Effective significance threshold applied to this species.Equals alpha_ref for species with ≤ 100 records, or the sample-size-corrected value when use_Ncorrected_alpha = TRUE and $N > 100$.
 individual_significant Logical.TRUE if individual_p_adj_fdr $<$ alpha for this species.
 slope_diff_significant Logical.TRUE if slope_diff_p_adj_fdr $<$ alpha for this species.
 environmental_comparison Data frame extending environmental_individual_lm with the classification columns added by classify_lm_individual_slope().Contains all the columns described for environmental_individual_lm plus:
 individual_slope_above_threshold Logical.TRUE if the relevant quantity (species slope or slope difference, depending on individual_lm_threshold_type) exceeds the minimum ecological threshold defined in individual_lm_min_thresholds. Always TRUE when no threshold is specified.Retained for downstream quality audits.
 individual_response_class Character.Final environmental response classification for this species and response variable. Possible values: "TT" (Thermal Tolerance), "TA" (Thermal Adjustment), "TC" (Thermal Conformance) for Temperature; "SA" (Spatial Adaptation), "SD" (Spatial Discordance), "SC" (Spatial Conformance) for Elevation.A non-conformance class (TT, TA, SA, SD) is assigned only when both individual_significant and slope_diff_significant are TRUE and individual_slope_above_threshold is TRUE. Otherwise the species defaults to the conformance class (TC or SC).

Classification system

Each species is assigned an **environmental response class** reflecting the direction and significance of its temporal trend (or its deviation from the global trend, depending on individual_lm_threshold_type):

"TT" - **Thermal Tolerance** Temperature response.The species is moving toward warmer environments over time: its individual slope (or its deviation from the global slope, under "slopediff") is positive, statistically significant, and exceeds the minimum ecological threshold.

"TA" - **Thermal Adjustment** Temperature response. The species is shifting toward cooler environments: slope (or deviation) is negative, significant, and exceeds the threshold.

"TC" - **Thermal Conformance** Temperature response. Default class assigned when the individual trend is non-significant or not distinguishable from the global trend.

"SA" - **Spatial Adaptation** Elevation response. The species is tracking higher elevations over time: slope (or deviation) is positive, significant, and exceeds the threshold.

"SD" - **Spatial Discordance** Elevation response. The species is shifting to lower elevations: slope (or deviation) is negative, significant, and exceeds the threshold.

"SC" - **Spatial Conformance** Elevation response. Default class when the elevation trend is non-significant or indistinguishable from the global trend.

Time variable

Internally the function constructs a continuous, mean-centred time predictor (`time_cont_c`) from Year and Month as $\text{Year} + (\text{Month} - 1) / 12 - \text{mean}(\dots)$. Slopes are therefore expressed in **environmental units per year** (deg C yr^{-1} for Temperature, m yr^{-1} for Elevation).

Examples

```
# Minimal example with simulated data
set.seed(42)
n <- 600
sim_data <- data.frame(
  Species = sample(paste0("Sp", 1:5), n, replace = TRUE),
  Year = sample(2000:2020, n, replace = TRUE),
  Month = sample(1:12, n, replace = TRUE),
  Temperature = rnorm(n, mean = 15, sd = 3),
  Elevation = rnorm(n, mean = 500, sd = 100))

results <- spp_trend_environmental(
  data = sim_data,
  responses = c("Temperature", "Elevation"),
  min_records = 20,
  min_years = 5,
  alpha_ref = 0.05,
  use_Ncorrected_alpha = FALSE,
  individual_lm_min_thresholds = c(Temperature = 0.01, Elevation = 50),
  individual_lm_threshold_type = "speciesslope",
  verbose = FALSE
)

# Inspect the classification table
head(results$environmental_comparison)

# Species retained per response
results$species_filter[results$species_filter$retained, ]

# Global community trends
results$environmental_global_lm
```

spp_trend_spatial	<i>Analyse Temporal Changes in Species Geographical Position Using ECEF Vector Analysis</i>
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Description

Estimates temporal trends in the spatial distribution of species by modelling the annual displacement of each species' geographical centroid in three-dimensional Earth-Centred Earth-Fixed (ECEF) Cartesian coordinates derived from the WGS84 reference ellipsoid.

For each species (and for a pooled global reference), the function computes monthly ECEF centroids from occurrence records, fits a multivariate linear regression of centroid position against a continuous time variable ($\text{time_cont} = \text{Year} + (\text{Month} - 1)/12$), and projects the resulting three-dimensional slope vector onto the local tangent plane at the species centroid to obtain ecologically interpretable quantities: surface displacement speed (km yr^{-1}) and absolute geographical bearing.

Each species is compared against a single global reference vector estimated from all retained records pooled together. Uncertainty is propagated via covariance-based multivariate simulation, and each species is assigned a spatial class:

SA (Spatial Adaptation) The species moves faster than the global pool, or moves in a significantly different direction that is poleward, consistent with a climate-driven distributional shift.

SD (Spatial Discordance) The species moves slower than the global pool, or moves in a significantly different direction that is non-poleward, inconsistent with strict climatic control of distribution.

SC (Spatial Conformance) Neither speed nor direction differs significantly from the global spatial pattern.

The ECEF coordinate system used here places the X-axis towards the intersection of the Equator and the Greenwich meridian, the Y-axis towards 90 deg E longitude, and the Z-axis towards the North Pole.

Usage

```
spp_trend_spatial(
  data,
  spp = NULL,
  min_records = 20,
  min_years = 5,
  spatial_simulation_n = 1000,
  spatial_probability_threshold = 0.9,
  direction_angle_threshold_deg = 68,
  random_seed = NULL,
  verbose = TRUE
)
```

Arguments

<code>data</code>	<p>A <code>data.frame</code> containing occurrence records. Must include the columns <code>Species</code>, <code>Year</code>, <code>Month</code>, <code>Latitude</code>, and <code>Longitude</code> (additional columns are permitted and ignored).</p> <p><code>Species</code> Character or factor. Taxon name identifying each occurrence record.</p> <p><code>Year</code> Numeric. Four-digit calendar year of the record. Values that cannot be coerced to a finite number are dropped.</p> <p><code>Month</code> Numeric. Calendar month (1-12) of the record. Values outside this range or non-numeric entries are dropped.</p> <p><code>Latitude</code> Numeric. Decimal degrees latitude (-90 to +90). Records outside this range are dropped.</p> <p><code>Longitude</code> Numeric. Decimal degrees longitude (-180 to +180). Records outside this range are dropped.</p>
<code>spp</code>	Character vector of species names to analyse. When NULL (default) all species present in data are considered. Species listed here that are absent from data are silently ignored after a warning.
<code>min_records</code>	Integer (default 20). Minimum total number of valid occurrence records a species must have across the entire dataset to be retained for analysis. Species with fewer records are excluded and flagged in <code>\$species_filter</code> .
<code>min_years</code>	Integer (default 5). Minimum number of distinct calendar years in which a species must have been recorded to be retained for analysis. Species spanning fewer years are excluded and flagged in <code>\$species_filter</code> . The same threshold is applied to the global pool's temporal centroids.
<code>spatial_simulation_n</code>	Integer (default 1000). Number of multivariate normal random vectors drawn from the slope covariance matrix to estimate the probability distributions of speed and directional differences relative to the global reference. Larger values reduce Monte Carlo noise at the cost of computation time.
<code>spatial_probability_threshold</code>	Numeric in (0, 1) (default 0.90). Proportion of simulations that must support a speed or directional difference for that difference to be considered statistically significant when assigning the spatial class. A conservative default of 0.90 is used to reduce overinterpretation of uncertain trends.
<code>direction_angle_threshold_deg</code>	Numeric (default 68). Minimum three-dimensional angle (degrees) between a species ECEF slope vector and the global ECEF slope vector for their directions to be considered different. Angles below this threshold indicate roughly parallel movement; angles at or above it indicate orthogonal or opposite movement.
<code>random_seed</code>	Integer or NULL (default NULL). If a non-null integer is supplied it is passed to <code>set.seed</code> before the Monte Carlo simulations, ensuring reproducible results.
<code>verbose</code>	Logical (default TRUE). If TRUE, a progress message summarising the number of species retained after filtering is printed to the console via <code>message</code> .

Details

Coordinate transformation: Latitude and longitude (decimal degrees, WGS84) are converted to ECEF Cartesian coordinates (kilometres) using the standard geodetic transformation with WGS84 parameters: semi-major axis $a = 6378.137$ km and flattening $f = 1/298.257223563$. The prime vertical radius of curvature $N(\phi) = a/\sqrt{1 - e^2 \sin^2 \phi}$ accounts for the ellipsoidal shape of the Earth.

Temporal centroids: Records are grouped by species and year-month combination. Within each group the arithmetic mean of the ECEF coordinates is computed to produce a temporal centroid. Groups with fewer records than $\lfloor \min_records / \max(1, \min_years) \rfloor$ are discarded. Global-pool centroids use all retained species combined.

ECEF slope model: A multivariate ordinary least-squares regression is fitted:

$$\mathbf{C}(t) = \alpha + \beta t + \varepsilon$$

where $\mathbf{C}(t)$ is the 3×1 vector of ECEF coordinates at time t , and β is the slope vector (km yr^{-1}) of interest. The residual covariance matrix $\hat{\Sigma}$ is used together with $(X^T X)^{-1}$ to construct the 3×3 covariance matrix of $\hat{\beta}$, which propagates uncertainty into the Monte Carlo simulations.

Tangent-plane projection: The ECEF slope vector is projected onto the local east-north-up frame at the species centroid. The east and north components are used to compute surface speed and bearing; the up component is reported as `radial_km_year`.

Spatial classification hierarchy:

1. **Direction test.** If `prob_direction_different_from_global` \geq `spatial_probability_threshold` and `angle_to_global_3d_deg` \geq `direction_angle_threshold_deg`, the direction is considered significantly different. Under this condition, poleward movement -> **SA**; non-poleward movement -> **SD**.
2. **Speed test (direction not significant).** If `prob_speed_greater_than_global` \geq `spatial_probability_threshold` poleward movement -> **SA**; non-poleward -> **SD**. If `prob_speed_lower_than_global` \geq `spatial_probability_threshold` -> **SD**.
3. **Default.** Neither speed nor direction differs significantly -> **SC**.

Poleward movement is defined as a positive northward component in the Northern Hemisphere or a negative northward component in the Southern Hemisphere.

Value

A named list with three elements:

`spatial` A data.frame with one row per entity analysed. The first row always corresponds to the global pooled reference (`Species == "__GLOBAL_POOL__"`); subsequent rows correspond to individual species. Columns:

`Species` Character. Species name, or `"__GLOBAL_POOL__"` for the global reference row.

`analysis` Character. Identifies the type of analysis: `"spatial_ecef_centroid_vector_global_pool"` for the global row or `"spatial_ecef_centroid_vector_species"` for individual species.

`n_records` Integer. Total number of valid occurrence records used. For the global pool this is the sum across all temporal centroids.

`n_time_steps` Integer. Number of year-month combinations (temporal centroids) used to fit the ECEF slope model.

`centroid_Longitude` Numeric. Decimal degrees longitude of the mean ECEF centroid, converted back to geodetic coordinates.

`centroid_Latitude` Numeric. Decimal degrees latitude of the mean ECEF centroid, converted back to geodetic coordinates.

`hemisphere` Character. "Northern" if `centroid_Latitude` ≥ 0 , otherwise "Southern".

`poleward_status` Character. "poleward" when the northward component of the displacement vector is positive in the Northern Hemisphere or negative in the Southern Hemisphere; "non_poleward" otherwise. NA for the global pool row.

`slope_ecef_x_km_year` Numeric. Annual rate of change (km yr^{-1}) of the ECEF X-coordinate centroid, estimated from the multivariate linear regression.

`slope_ecef_y_km_year` Numeric. Annual rate of change (km yr^{-1}) of the ECEF Y-coordinate centroid.

`slope_ecef_z_km_year` Numeric. Annual rate of change (km yr^{-1}) of the ECEF Z-coordinate centroid.

`speed_chord_km_year` Numeric. Magnitude of the 3-D ECEF slope vector (km yr^{-1}), representing the straight-line chord displacement speed through the Earth's interior. Equal to $\sqrt{\dot{X}^2 + \dot{Y}^2 + \dot{Z}^2}$.

`speed_surface_km_year` Numeric. Horizontal surface displacement speed (km yr^{-1}) obtained by projecting the ECEF slope vector onto the local tangent plane at the centroid and taking the magnitude of the east and north components. This is the ecologically preferred speed metric.

`direction_bearing_deg` Numeric. Absolute geographical bearing (0-360 deg, clockwise from North) of the displacement vector on the local tangent plane. NA when the surface speed is zero or not finite.

`direction_cardinal` Character. Eight-point compass direction corresponding to `direction_bearing_deg`: one of "N", "NE", "E", "SE", "S", "SW", "W", or "NW".

`east_km_year` Numeric. Eastward component (km yr^{-1}) of the tangent-plane displacement vector. Positive values indicate eastward movement.

`north_km_year` Numeric. Northward component (km yr^{-1}) of the tangent-plane displacement vector. Positive values indicate northward movement in geographic coordinates.

`radial_km_year` Numeric. Radial (vertical) component (km yr^{-1}) of the ECEF slope vector projected onto the local up direction. Non-zero values indicate apparent elevation change and should be close to zero for purely horizontal distributional shifts.

`global_speed_surface_km_year_full` Numeric. Surface displacement speed (km yr^{-1}) of the global reference vector (estimated from all retained records). Provided as a fixed reference for comparison. NA for the global pool row itself.

`speed_diff_surface_km_year` Numeric. Difference between the species surface speed and the global surface speed (km yr^{-1}). Positive values indicate the species is moving faster than the global pattern. NA for the global pool row.

`speed_ratio_to_global` Numeric. Ratio of the species surface speed to the global surface speed. A value greater than 1 indicates faster movement than the global reference. NA when the global speed is zero or for the global pool row.

`angle_to_global_3d_deg` Numeric. Three-dimensional angle (degrees, 0-180) between the species ECEF slope vector and the global ECEF slope vector. Values near 0 deg indicate

- nearly parallel movement; values near 90 deg indicate orthogonal movement; values near 180 deg indicate opposite movement. NA for the global pool row.
- prob_speed_greater_than_global Numeric (0-1). Estimated probability, derived from `spatial_simulation_n` Monte Carlo draws, that the species surface speed exceeds the global surface speed. NA for the global pool row.
- prob_speed_lower_than_global Numeric (0-1). Estimated probability that the species surface speed is lower than the global surface speed. NA for the global pool row.
- prob_direction_different_from_global Numeric (0-1). Estimated probability that the three-dimensional angle between the species slope vector and the global slope vector is at least `direction_angle_threshold_deg` degrees, indicating directional divergence from the global pattern. NA for the global pool row.
- direction_angle_threshold_deg Numeric. The value of the `direction_angle_threshold_deg` argument used in the analysis, stored here for traceability.
- spatial_class_LatitudeLon Character. Joint spatial classification assigned to each species: "SA" (Spatial Adaptation), "SD" (Spatial Discordance), or "SC" (Spatial Conformance). See Details for the full decision hierarchy. NA for the global pool row.
- species_filter A data.frame with one row per species found in data (after optional spp sub-setting). Records whether each species passed the data-sufficiency filters. Columns:
- Species Character. Species name.
 - n_records Integer. Total number of valid records for this species after cleaning.
 - n_years Integer. Number of distinct calendar years in which the species was recorded.
 - retained Logical. TRUE if the species met both `min_records` and `min_years` thresholds and was included in the spatial analysis; FALSE otherwise.
- metadata A named list documenting analysis settings and methodological details. Elements:
- analysis Character. Fixed label "spatial_ecef_wgs84_vector_only".
 - time_variable Character. Description of the continuous time variable: "time_cont = Year + (Month - 1) / 12".
 - coordinate_system Character. Coordinate system and units: "WGS84 ECEF, kilometres".
 - model Character. Formula of the multivariate regression: "cbind(ecef_x_km, ecef_y_km, ecef_z_km) ~ time_cont".
 - joint_spatial_classification Character. Human-readable description of the hierarchical decision rule used to assign SA, SD, or SC, including the threshold values applied.
 - spatial_simulation_n Integer. Value of the `spatial_simulation_n` argument used.
 - spatial_probability_threshold Numeric. Value of the `spatial_probability_threshold` argument used.
 - direction_angle_threshold_deg Numeric. Value of the `direction_angle_threshold_deg` argument used.
 - min_records Integer. Value of the `min_records` argument used.
 - min_years Integer. Value of the `min_years` argument used.

See Also

[lm](#) for the underlying regression engine.

Examples

```
# Minimal example with simulated data
set.seed(42)
n <- 600
sim_data <- data.frame(Species = sample(c("Sp_A", "Sp_B", "Sp_C"), n, replace = TRUE),
  Year = sample(2000:2020, n, replace = TRUE),
  Month = sample(1:12, n, replace = TRUE),
  Latitude = runif(n, 30, 65),
  Longitude = runif(n, -10, 30)
)

result <- spp_trend_spatial(
  data= sim_data,
  min_records = 20,
  min_years = 5,
  spatial_simulation_n = 100,
  spatial_probability_threshold = 0.90,
  direction_angle_threshold_deg = 68,
  random_seed = 1,
  verbose = FALSE
)

# Main results table
head(result$spatial)

# Species filtering summary
result$species_filter

# Analysis metadata
result$metadata

# Extract classified species only (excluding global pool row)
classified <- result$spatial[result$spatial$Species != "__GLOBAL_POOL__", ]
table(classified$spatial_class_Latitudelon)
```

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