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Description Energy landscape analysis (ELA) is a systematic method for analyzing an energy landscape represented as a weighted network. This R package is especially designed to analyze ecological dynamics, i.e., transitions in community compositions. For details of the analysis framework, please visit Suzuki K et al. (2021) <[doi:10.1002/ecm.1469](https://doi.org/10.1002/ecm.1469)>.

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Contents

ELAplus-package	3
baseabtable	5
basemetadata	5
Bi	6
bin2id	7
bootstrap_ELA	7
bootstrap_SA	8
deltaE_histogram	9
DisconnectivityGraph	10
ELA	11
ELPruning	12
Energy	13
Findbp	13
Formatting	15
GELAObj	16
GradELA	16
GradientDescent	17
gStability	18
hb.paramgen	19
HeatBath	20
id2bin	21
MinTippingPath	21
OnestepHBS	22
PCplot	22
plotSAtest	23
runSA	23
sa2params	25
saEndpoint	25
showDG	26
showGELA3D	27
showIntrGraph	27
showSSD	28
showSSD_ggplot	28
SSentropy	29
sstable	29
Stability	30
SteepestDescent	31
tptable	31

Index

33

Description

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Details

This package provides tools for energy landscape analysis (ELA), a framework for analyzing dynamical systems represented as weighted networks. The main functions support construction of energy landscapes, by fitting the community composition data to a pairwise maximum entropy model (or its extension) and subsequent identification of stable states, and analysis of transitions between community compositions.

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References

Suzuki, K., Nakaoka, S., Fukuda, S., & Masuya, H. (2021). "Energy landscape analysis elucidates the multistability of ecological communities across environmental gradients." *Ecological Monographs*. doi:10.1002/ecm.1469 <https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/ecm.1469>

See Also

GitHub: <https://github.com/kecosz/rELA>, Portal: <https://elaportal.org>

Examples

```
# load sample dataset
data("baseabtable")
data("basemetadata")
# Formatting dataset
formatted <- Formatting(baseabtable, basemetadata, 0, c(0.05, 0.05, 0.95))
ocvecs <- formatted[[1]]
envecs <- formatted[[3]]
# Example (without environmental parameters)
# Fitting the data to the extended maximum pairwise entropy model
# without explicit environmental parameters
sa <- runSA(
```

```

ocvecs,
enmat = NULL,
rep = 1,
getall = FALSE,
lambda = 0.01,
we = 0.001,
maxlr = 0.005,
totalit = 1000
)

# Using the fitted model, normal ELA is run.
ela <- ELA(sa, env=NULL,
           threads=1,SS.itr=2000,
           FindingTip.itr=1000,
           reporting=TRUE)
# Pruning stable states
elap <- ELPruning(ela, th=0.1)
# show disconnectivity graph
showDG(elap[[1]], ocvecs, "test")
# show species interaction graph
showIntrGraph(elap[[1]], sa, th=0.01,
              annot_adj=c(0.75, 2.00))

# Example (with environmental parameters)
# Find best parameter sets for the machine learning (with envecs)

bpresult <- Findbp(ocvecs,enmat=envecs,rep=1,threads=1,nrepeat=1,cvmode="5fold")
bp <- bpresult[[1]]
bpm <- as.numeric(unlist(strsplit(names(bp)[1], split = "_")))
# Fitting the data to the extended maximum pairwise entropy model
# with explicit environmental parameters
sa <- runSA(
  ocvecs,
  enmat = envecs,
  rep = 16,
  getall = FALSE,
  lambda = bpm[[1]],
  we = bpm[[2]],
  maxlr = bpm[[3]],
  totalit = bpm[[4]]
)
# Using the fitted model, gradient ELA is run.
gela <- GradELA(
  sa = sa,
  eid = "factor.1",
  enmat = envecs,
  env = NULL,
  range = c(0, 1),
  steps = 32,
  th = 0.05,
  threads = 2
)
showSSD(gela)

```

baseabtable	<i>Abundance table for 16 taxa across 256 samples</i>
-------------	---

Description

'baseabtable' is a data frame containing abundance for 16 taxa across 256 samples.

Usage

```
baseabtable
```

Format

A data frame with 256 rows and 16 variables:

Details

Each row corresponds to a sample, and each column represents the abundance of a specific taxon.

The values represent abundance measurements for each taxon in each sample. The exact definition of "abundance" (e.g., counts, relative abundance, or normalized values) depends on the data preprocessing pipeline used.

Source

Generated for example purposes (replace with actual source if applicable)

Examples

```
data(baseabtable)
head(baseabtable)
formatted <- Formatting(baseabtable = baseabtable)
```

basemetadata	<i>Environmental metadata for 256 samples</i>
--------------	---

Description

'basemetadata' is a data frame containing environmental parameters associated with the same 256 samples as in baseabtable.

Usage

```
basemetadata
```

Format

A data frame with 256 rows and 2 variables:

Details

Each row corresponds to a sample, and each column represents an environmental variable.

The rows in this data frame correspond to the same samples and ordering as in `baseabtable`. These variables can be used for ELA with environmental parameters such as `gradELA`

Source

Generated for example purposes (replace with actual source if applicable)

Examples

```
data(baseabtable)
data(basemetadata)
head(basemetadata)
formatted <- Formatting(baseabtable = baseabtable, basemetadata = basemetadata)
```

Bi

Bi

Description

Identify basin (stable state) and its energy for a given state.

Applies [SteepestDescent](#) to the input state and returns the basin (stable state) reached, together with its energy. The stable state is encoded as an integer ID using [bin2id](#).

Usage

```
Bi(xi, h, j)
```

Arguments

<code>xi</code>	Binary vector representing the initial state.
<code>h</code>	vector of implicit/explicit environmental effects on species.
<code>j</code>	Matrix of species interactions.

Value

A list with two elements: (1) integer stable state ID (basin assignment), (2) energy of the corresponding stable state.

bin2id	<i>bin2id: map a binary vector to a 64base characters</i>
--------	---

Description

Encode a binary vector into a base-64 id string index.

Usage

```
bin2id(bin)
```

Arguments

bin A binary vector (0/1, community composition) to encode.

Value

A character scalar representing the encoded id.

bootstrap_ELA	<i>Energy landscape analysis with bootstrap resampled SA results</i>
---------------	--

Description

Running energy landscape analysis with bootstrap sampling of estimated saresults

Performs [ELA](#) and [ELPruning](#) using SA fitting results based on the bootstrap resampled occurrence and environmental data using [bootstrap_SA](#).

Basically, representative ELA results with original occurrence and environmental data should be given by `e1a=e1a`, alternatively the function can select a representative parameter where commonly appearing stable states are most frequent.

The function computes bootstrap energy distributions for all stable states and tipping points appearing in the specified pruned landscape. Energies that are not present in a given trial are stored as NaN in the summary table.

Usage

```
bootstrap_ELA(
  bs_params,
  ocmat,
  ela = NULL,
  env = NULL,
  enmat = NULL,
  threads = 1,
  reporting = FALSE
)
```

Arguments

bs_params	output of bootstrap_SA . list of estimated parameters using bootstrap resampled data set.
ocmat	community composition matrix.
ela	representative ELA result (output of ELA). If NULL, the function returns the most representative one.
env	target environmental factor.
enmat	array of the vectors of environmental factors for each sample. Normalization required.
threads	number of cores (threads) used for calculation.
reporting	enable/disable the reporting function.

Value

A list with two elements: (1) representative pruned ELA result (stable states, energies, tipping points, tipping energies), (2) a data frame of bootstrap energies (rows = state IDs, columns = trials) with NaN for missing states.

bootstrap_SA

Parameter fitting with bootstrap sampling of datasets

Description

Perform [runSA](#) algorithm and estimate parameters using bootstrap resampled data set (ocmat and enmat). The basic configuration is same as [runSA](#).

Usage

```
bootstrap_SA(
  ocmat,
  enmat = NULL,
  bootstrap.it = 2000,
  rep = 128,
  threads = 1,
  we = 0.001,
  totalit = 1000,
  lambda = 0.01,
  runadamW = TRUE,
  maxlr = 0.005,
  sparse = TRUE,
  reporting = TRUE
)
```

Arguments

ocmat	Numeric matrix (0/1). Rows are samples and columns are species.
enmat	Optional numeric matrix. Environmental variables for each sample. Should be normalized/standardized beforehand.
bootstrap.it	number of bootstrap trials (default: 1000).
rep	Integer. Number of parallel runs (replicates) for optimization.
threads	Integer. Number of cores used when running in parallel.
we	Numeric. Weight decay parameter for AdamW.
totalit	Integer. Total number of optimization iterations.
lambda	Numeric. Sparsity penalty parameter (used when sparse = TRUE).
runadamw	Logical. If TRUE, use AdamW-style optimization.
maxlr	Numeric. Maximum learning rate.
sparse	Logical. If TRUE, apply sparsity constraint.
reporting	Logical. If TRUE, print progress messages.

Value

a list of SA parameters estimated with bootstrap resampling (length `bootstrap.it`).

`deltaE_histogram` *Plot histograms of bootstrap deltaE values*

Description

For each stable state, this function computes the difference between the energy values of the corresponding tipping point and the stable state across bootstrap samples, then draws a histogram of the resulting deltaE values.

Usage

```
deltaE_histogram(bootstrap_ene, grobj_to_plot, getData = TRUE)
```

Arguments

bootstrap_ene	A data frame containing energies in stable states and tipping points, output of bootstrap_ELA .
grobj_to_plot	A data frame containing stable state - tipping point relationship, output of showDG
getData	Logical. If 'TRUE', return the computed deltaE values as a list. If 'FALSE', return 'NULL'.

Value

If 'getData = TRUE', a list of numeric vectors, one per deltaE for each stable state. If 'getData = FALSE', 'NULL'.

 DisconnectivityGraph *DisconnectivityGraph: Generate a disconnectivity graph*

Description

Draws a disconnectivity graph from the data frame returned by GraphObj. Nodes are plotted at their assigned x-positions and energy levels, and are connected to their parent components by paths.

If show_pvalue = TRUE, approximate p-values for the energy gaps of stable states are displayed. The p-values are shown on a log10 scale using the values specified in scale_labels.

Usage

```
DisconnectivityGraph(
  grobj,
  s,
  DG_sample = "DG_sample",
  annot_adj = c(0.75, 2),
  min_pval = 0.05,
  scale_labels = c(0.05, 0.1, 0.2, 0.5),
  show_pvalue = FALSE,
  getGraphObj = FALSE,
  plot = TRUE
)
```

Arguments

grobj	A data frame returned by GraphObj.
s	Integer; number of species/features (used for labeling by id2bin).
DG_sample	Character; title of the plot.
annot_adj	Numeric vector of length 2; horizontal and vertical adjustment for labels.
min_pval	Numeric (must be > 0); minimum p-value shown in the visualization. This is usually set to the minimum detection level in bootstrap sampling (e.g., if the number of bootstrap iterations is 1000, the minimum level is 1/1000 = 0.001).
scale_labels	Numeric vector of values between 0 and 1; labels for the p-value scale. These values are converted to log-scaled values for plotting.
show_pvalue	Logical; if TRUE, plots approximate p-values based on the energy gaps between each stable state and its corresponding tipping point estimated by bootstrap re-sampling.
getGraphObj	Logical; if TRUE, returns the data frame used for plotting the disconnectivity graph, so that users can manually modify the graphical settings.
plot	Logical; if TRUE, show disconnectivity graph

Value

If getGraphObj = TRUE, returns a data frame containing energy values, x-positions, and p-values for the energy gaps of the identified stable states and tipping points. Otherwise, returns NULL.

Description

Identifying stable states and tipping points.

This function estimates stable states by repeated steepest-descent searches `SSestimate` and then checks tipping points between all pairs of stable states using `FindingTippingpoint_cpp`. The result is summarized and converted by `elaconvert` into a list of stable state IDs, their energies, tipping point IDs, and tipping energies.

Usage

```
ELA(  
  sa = sa,  
  env = NULL,  
  SS.itr = 20000,  
  FindingTip.itr = 10000,  
  threads = 1,  
  reporting = TRUE,  
  fork = TRUE  
)
```

Arguments

<code>sa</code>	output of <code>runSA</code> function.
<code>env</code>	vector of environmental factors for specifying a single environmental condition (optional).
<code>SS.itr</code>	number of iterations of the process to identify the stable states.
<code>FindingTip.itr</code>	number of iterations of the process to identify the tipping points.
<code>threads</code>	number of cores (threads) used for calculation.
<code>reporting</code>	enable/disable the reporting function.
<code>fork</code>	logical; if <code>TRUE</code> and <code>threads > 1</code> , a cluster is created internally for parallel execution.

Value

A list returned by `elaconvert`: (1) stable state IDs, (2) stable state energies, (3) tipping point ID matrix/list, and (4) tipping energies matrix/list.

 ELPruning

ELPruning

Description

Pruning shallow stable states of energy landscape.

Iteratively prunes stable states (merges basins). If `type="relative"`, stable state whose energy depth is smaller than `th` times the deepest basin depth are pruned and merged to the deeper basins. If `type="bootstrap"`, stable state whose bootstrap confidence interval (default: 95 cross zero is pruned. The function updates stable states and corresponding tipping structures, and returns both the pruned ELA object and a mapping table from stable states before pruning to those after pruning.

Usage

```
ELPruning(
  ela,
  type = "relative",
  th = 0.05,
  lower_qr = 0.05,
  bootstrap_ene = NULL,
  threads = 1,
  reporting = TRUE,
  fork = TRUE
)
```

Arguments

<code>ela</code>	output of ELA function.
<code>type</code>	the type of pruning "relative"(use with <code>th</code>) or "bootstrap" (use with <code>lower_qr</code> and <code>bootstrap_ene</code>)
<code>th</code>	ratio of the depth of the basin to be pruned with respect to the deepest basin.
<code>lower_qr</code>	Numeric value. Quantile used for constructing confidence intervals from bootstrap samples to check whether the estimated energy gaps include zero. Default is <code>lower_qr = 0.05</code> .
<code>bootstrap_ene</code>	a data frame of bootstrap energies generated by bootstrap_ELA . Necessary when <code>type="quantile"</code> .
<code>threads</code>	number of cores (threads) used for calculation.
<code>reporting</code>	enable/disable the reporting function.
<code>fork</code>	logical; if TRUE and <code>threads > 1</code> , a cluster is created internally for parallel execution.

Value

A list of two elements: (1) pruned ELA tuple (same format as [ELA](#) output), and (2) a data frame with columns `ss.before.pruning` and `ss.after.pruning`.

Energy	<i>Energy</i>
--------	---------------

Description

Calculate energy of a given state.

Computing energy in state using given parameters, alpha and beta based on the (extended) maximum pairwise entropy model.

Usage

Energy(state, alpha, beta)

Arguments

state	Binary vector representing a state (community composition).
alpha	vector of implicit/explicit environmental effects on species.
beta	Matrix of species interactions.

Value

A numeric scalar giving the energy of the state.

Findbp	<i>Search best hyperparameters for SA fitting (lambda and weight decay) by cross-validation</i>
--------	---

Description

Repeating cross-validation over a grid of hyperparameters for simulated annealing-based fitting, evaluates prediction/fitting errors on held-out samples, and returns candidate best parameter/timepoint combinations.

Usage

```
Findbp(
  ocmat,
  enmat = NULL,
  cvmode = c("10fold", "5fold", "loo"),
  nrepeat = 5,
  we = c(0.001),
  maxlrs = c(0.005),
  totalit = 4000,
  lmd = c(5e-04, 0.001, 0.0025, 0.005, 0.0075),
  rep = 8,
```

```

    intv = 100,
    threads = 1,
    tol = 0.03,
    runadamW = TRUE,
    sparse = TRUE,
    fastfitting = TRUE,
    reporting = TRUE
  )

```

Arguments

<code>ocmat</code>	Numeric matrix (0/1). occurrence matrix of the communities.
<code>enmat</code>	Optional environmental parameter matrix.
<code>cvmode</code>	Cross-validation mode. One of "10fold", "5fold", or "loo". "loo" performs leave-one-out cross-validation. Default is "10fold".
<code>nrepeat</code>	Number of repeated cross-validation runs for k-fold CV. Ignored when 'cvmode = "loo"'. Default is '10'.
<code>we</code>	Numeric vector. Candidate weight decay values.
<code>maxlrs</code>	Numeric vector. Maximum learning rate.
<code>totalit</code>	Integer. Total iterations for SA.
<code>lmd</code>	Numeric vector. Candidate lambda values.
<code>rep</code>	Integer. Number of replicates for runSA .
<code>intv</code>	Integer. Recording interval.
<code>threads</code>	Integer. Number of cores.
<code>tol</code>	Numeric. Error tolerance for finding the best hyperparameters (default: 0.03)
<code>runadamW</code>	Logical. Use AdamW.
<code>sparse</code>	Logical. Use sparsity penalty.
<code>fastfitting</code>	Logical. If TRUE, returns early iterations within the range specified by the parameter <code>tol</code> (default: 0.03) of best error.
<code>reporting</code>	Logical. Print progress.

Value

A list with:

best_candidates A named list of best hyperparameter settings and scores.

allresults All validation results for each grid point.

 Formatting

Formatting

Description

Generate occurrence(binary)/abundance/factor matrices and labels from input abundance/metadata tables.

Usage

```
Formatting(
  baseabtable,
  basemetadata = NULL,
  normalize = 1,
  parameters = c(0.05, 0.05, 0.95),
  grouping = 0,
  grouping_th = 0,
  reporting = TRUE
)
```

Arguments

baseabtable	Abundance table (samples x species) as data.frame/matrix.
basemetadata	Optional environmental metadata table (samples x factors); NULL/empty for none.
normalize	Integer 0 or 1. If 1, normalize within each sample to sum to 1.
parameters	Numeric vector/list of thresholds (following 3 parameters). 1. "0/1 threshold" 2. "min occurrence threshold" 3. "max occurrence threshold" (e.g., c(0.05, 0.05, 0.95) : species abundance > 0.05 is regarded as present, and species occurring in more than 0.05 and less than 0.95 in the all samples are kept.)
grouping	Integer 0 or 1. If 1, group similar occurrence patterns.
grouping_th	Numeric threshold for grouping (relative Hamming distance).
reporting	Logical. If TRUE, print processing summary.

Value

A list: (ocmatrix, abmatrix, fctmatrix, samplelabel, specieslabel, factorlabel).

GELAObj	<i>GELAObj</i>
---------	----------------

Description

Construct smoothed energy landscape surface objects from GELA output and parameters.

Usage

```
GELAObj(gela, sa, threads = 1)
```

Arguments

<code>gela</code>	GELA object/list
<code>sa</code>	Parameter list generated by runSA
<code>threads</code>	Number of parallel workers.

Value

A list containing surface grid data and state-specific surface points.

GradELA	<i>GradELA</i>
---------	----------------

Description

Estimate energy landscape across environmental gradients.

Runs [ELA](#) and [ELPruning](#) comprehensively across specified environmental parameters. One environmental parameter can be changed by specifying `eid` over steps within range. If `env` is not given, the mean vector of `enmat` is used as the reference environmental condition.

Usage

```
GradELA(
  sa = sa,
  pruning_type = "relative",
  eid = NULL,
  enmat = enmat,
  env = NULL,
  range = NULL,
  steps = 16,
  th = 0.05,
  threads = 1,
  SS.itr = 20000,
  FindingTip.itr = 10000,
```

```

    lower_qr = 0.05,
    bs_params = NULL,
    ocmat = NULL
)

```

Arguments

sa	output of runSA function.
pruning_type	the type of pruning "relative"(use with th) or "bootstrap" (use with lower_qr,ocmat and bs_params)
eid	target environmental factor: the specified environmental factor to be changed.
enmat	array/matrix of environmental factors for each sample (normalization required).
env	array of environmental factor values. For the environmental parameters that are not specified for eid, these values are used as references. If not specified, then the mean of values in enmat are used as references.
range	range over which the environmental factor specified by eid is changed.
steps	number of steps in the range.
th	ratio of the depth of the basin to be pruned with respect to the deepest basin.
threads	number of cores (threads) used for calculation.
SS.itr	number of iterations to identify stable states.
FindingTip.itr	number of iterations to identify tipping points.
lower_qr	Numeric value. Quantile used for constructing confidence intervals from bootstrap samples to check whether the estimated energy gaps include zero. Default is lower_qr = 0.05,necessary when type="bootstrap".
bs_params	output of bootstrap_SA . list of estimated parameters using bootstrap resampled data set. necessary when type="bootstrap".
ocmat	community composition matrix.

Value

A list of three elements: (1) ELA results for each step (pruned), (2) the sequence of environmental values, and (3) the reference env vector.

GradientDescent

Gradient descent estimation of model parameters

Description

Estimates parameters h and J by iterative gradient updates to match first and second moments of the observed binary data under an maximum pairwise entropy model.

Usage

```
GradientDescent(data, maxit)
```

Arguments

data	Numeric matrix (typically 0/1). Rows are samples and columns are species or taxa.
maxit	Integer. Maximum number of gradient descent iterations.

Details

This function calls `Energy()` to compute energies for candidate states. Ensure that `Energy` is available in the package namespace.

Value

A list with elements:

h.est Numeric vector of estimated implicit environmental parameters.

j.est Numeric matrix of estimated interaction matrix.

gStability

gstability

Description

Calculate energy gap, energy barrier and stable state entropy.

This function evaluates stability indices for both (i) the pruned and (ii) the non-pruned energy landscape. For each sample, it assigns the basin by **Bi** and computes: - energy gap (sample energy minus basin energy), - energy barrier (minimum tipping energy connected to the basin minus basin energy), - stable state entropy (SSentropy).

For basin connectivity: when only one stable state exists, tipping energy is treated as Inf and therefore energy barrier is returned as Inf.

Usage

```
gStability(
  sa,
  ocmat,
  enmat = NULL,
  seitr = 1000,
  seconvTime = 10000,
  pruning_type = "relative",
  th = 0.1,
  lower_qr = 0.05,
  threads = 1,
  reporting = TRUE,
  bs_params = NULL
)
```

Arguments

sa	: output of runSA function.
ocmat	: matrix of presence/absence status for each sample.
enmat	: matrix of environmental factors for each sample. Normalization required.
seitr	: Number of stochastic search iterations.
seconvTime	: Maximum number of iterations for each search.
pruning_type	the type of pruning "relative"(use with th) or "bootstrap" (use with lower_qr and bootstrap_ene)
th	: Numerical (0~1). Ratio of the depth of the basin to be pruned with respect to the deepest basin in each pair.
lower_qr	Numeric value. Quantile used for constructing confidence intervals from bootstrap samples to check whether the estimated energy gaps include zero. Default is lower_qr = 0.05,necessary when type="bootstrap".
threads	number of cores (threads) used for calculation.#' @param threads : number of cores (threads) used for calculation.
reporting	: enable/disable the reporting function.
bs_params	output of bootstrap_SA . list of estimated parameters using bootstrap resampled data set, necessary when type="bootstrap".

Value

A list of four elements: (1) pruned stability data frame, (2) non-pruned stability data frame, (3) auxiliary object for pruned landscape (parameters + stable states table), and (4) auxiliary object for sample-wise evaluation (inputs and ELA objects).

hb.paramgen

Randomly generate model parameters for heat-bath sampling

Description

Generates random implicit environmental parameters h and a interaction matrix J. Optionally generates explicit environmental coefficients g. The j_connectivity parameter controls the fraction of non-zero off-diagonal interactions.

Usage

```
hb.paramgen(nn, ne = 0, j_connectivity = 1)
```

Arguments

nn	Integer. Number of units (species, taxa, or members).
ne	Integer. Number of environmental factors. If ne > 0, g is generated.
j_connectivity	Numeric in [0, 1]. Fraction of possible pairwise interactions set to non-zero.

Value

A list containing at least:

h Named numeric vector of length nn . Implicit environmental parameters

J Named numeric matrix ($nn \times nn$), symmetric. Interaction matrix

If $ne > 0$, also includes:

g Named numeric matrix ($nn \times ne$). Explicit environmental parameters

 HeatBath

Heat-bath sampling of binary states

Description

Generates samples of binary state vectors using heat-bath updates under an extended maximum pairwise entropy model parameterized by implicit environmental parameters h and interaction matrix J . Optionally includes environmental effects g , in which case an environmental matrix is generated internally.

Usage

```
HeatBath(steps, nproc, h, J, g = NULL)
```

Arguments

<code>steps</code>	Integer. Number of heat-bath iterations to run.
<code>nproc</code>	Integer. Number of parallel samples (rows) to maintain.
<code>h</code>	Numeric vector of length nn , implicit environmental parameters.
<code>J</code>	Numeric matrix of size $nn \times nn$, interaction matrix.
<code>g</code>	Optional numeric matrix of size $nn \times ne$, environmental coefficients.

Value

A list with components:

y Numeric matrix ($nproc \times nn$) of sampled states (0/1).

enmat Numeric matrix ($nproc \times ne$) of environmental values, or NULL if g is NULL.

Examples

```
set.seed(1)
nn <- 5
pars <- hb.paramgen(nn)
res <- HeatBath(steps = 10, nproc = 8, h = pars[[1]], J = pars[[2]])
str(res)
```

id2bin	<i>id2bin: map a 64base characters to a binary vector</i>
--------	---

Description

Decode a base-64 id string index to a binary vector of length s.

Usage

```
id2bin(id, s)
```

Arguments

id	A character scalar encoded by bin2id .
s	Integer number of bits to return.

Value

An integer vector of 0/1 bits of length s.

MinTippingPath	<i>MinTippingPath</i>
----------------	-----------------------

Description

Compute a minimum “tipping” energy path between two states.

Usage

```
MinTippingPath(s1, s2, hg, j, tmax)
```

Arguments

s1	Another integer state ID
s2	Another integer state ID
hg	explicit/implicit environmental factors
j	species interaction matrix
tmax	Iteration limit.

Value

Numeric vector of energies along the selected path (or scalar if s1==s2).

OnestepHBS	<i>Perform one heat-bath update step</i>
------------	--

Description

Updates each row (sample) of a binary state matrix by choosing one random position per row and resampling it according to precomputed heat-bath probabilities.

Usage

```
OnestepHBS(y, logmo)
```

Arguments

<code>y</code>	Numeric matrix of size <code>nproc</code> x <code>nn</code> (typically 0/1), current states.
<code>logmo</code>	Numeric matrix of probabilities compatible with <code>y</code> . Each row corresponds to a row in <code>y</code> ; entries are used to sample 0/1 updates.

Value

A numeric matrix with the same dimensions as `y`, updated states.

PCplot	<i>PCplot: Scatter plot of community compositions colored by basin label</i>
--------	--

Description

Performs PCA on the community composition matrix (`ocmat`) and plots the first two PCs. Points are colored by the stable state (basin) label estimated from [Bi](#). If `pruned = TRUE`, colors correspond to the pruned/merged basin labels in `ssrep` (`stablestates2`), otherwise to the original labels (`stablestates`). When `export = TRUE`, the plotting data frame (stable-state labels + PCs + merged labels) is returned.

Usage

```
PCplot(ocmat, sa = sa, env = NULL, ssrep = NULL, pruned = TRUE, export = FALSE)
```

Arguments

<code>ocmat</code>	Data frame (or matrix) of community compositions (rows = samples, columns = species/features).
<code>sa</code>	Parameter set passed to sa2params .
<code>env</code>	Optional environment object passed to sa2params .
<code>ssrep</code>	Data frame-like object providing stable state label mapping with two columns: <code>stablestates</code> and <code>stablestates2</code> .
<code>pruned</code>	Logical; if <code>TRUE</code> , use <code>stablestates2</code> for coloring.
<code>export</code>	Logical; if <code>TRUE</code> , return the data used for plotting.

Value

NULL invisibly (or a data frame when `export = TRUE`).

plotSAtest	<i>plotSAtest: plot the results of SA fitting (Findbp output)</i>
------------	---

Description

Plot mean validation scores over time for the results returned by [Findbp](#), including 95% confidence intervals.

Usage

```
plotSAtest(sa_results, ylim = c("auto", "auto"))
```

Arguments

sa_results	Output list from Findbp .
ylim	Numeric length-2 vector (ymin, ymax). Default: <code>c("auto", "auto")</code> .

Details

This function uses **ggplot2** and tidyverse-style data manipulation. Ensure required packages are installed.

Value

A **ggplot2** object.

runSA	<i>Stochastic approximation for parameter fitting</i>
-------	---

Description

Estimate species interaction parameters and (optionally) environmental preference parameters by stochastic approximation (SA). The function runs multiple SA optimizations in parallel (when `threads > 1`) using **foreach**.

Usage

```
runSA(
  ocmat,
  enmat = NULL,
  rep = 128,
  threads = 1,
  we = 0.001,
  totalit = 1000,
  lambda = 0.01,
  intv = 100,
  runadamW = TRUE,
  maxlr = 0.005,
  sparse = TRUE,
  getall = FALSE,
  reporting = TRUE
)
```

Arguments

ocmat	Numeric matrix (0/1). Rows are samples and columns are species.
enmat	Optional numeric matrix. Environmental variables for each sample. Should be normalized/standardized beforehand.
rep	Integer. Number of parallel runs (replicates) for optimization.
threads	Integer. Number of cores used when running in parallel.
we	Numeric. Weight decay parameter for AdamW.
totalit	Integer. Total number of optimization iterations.
lambda	Numeric. Sparsity penalty parameter (used when sparse = TRUE).
intv	Integer. Interval of iterations at which intermediate results are recorded.
runadamW	Logical. If TRUE, use AdamW-style optimization.
maxlr	Numeric. Maximum learning rate.
sparse	Logical. If TRUE, apply sparsity constraint.
getall	Logical. If TRUE, return all replicate trajectories.
reporting	Logical. If TRUE, print progress messages.

Value

If `getall = TRUE`, a list of SA trajectories (length `rep`). Otherwise, a list with two elements, `c(params, enmat)` is returned. `params` is the concatenated matrix of the estimated parameter set:

h Implicit environmental effects on species occurrence

J Species-species interaction matrix

g (If `enmat` is not `NULL`) Explicit effects of the environmental factors.

sa2params	<i>Convert SA output to model parameter objects</i>
-----------	---

Description

Convert the output of [runSA](#) / [saEndpoint](#) into parameter objects in (extended) maximum pairwise entropy model: h, J, and optionally g when environmental parameter matrix is specified.

Usage

```
sa2params(sa, env = NULL)
```

Arguments

sa	A list in the form <code>list(param_matrix, enmat)</code> where <code>param_matrix</code> contains estimated parameters.
env	Optional numeric vector of environmental values (column names correspond to environmental factors). Default is NULL.

Value

A list with elements `he` (h), `je` (J), `ge` (g or NULL), and `hge` (combined field).

saEndpoint	<i>Extract endpoint parameters from runSA output</i>
------------	--

Description

Summarize the final parameter estimates across SA replicates by averaging the last recorded block of parameters.

Usage

```
saEndpoint(fittingMat, ocmat, enmat = NULL)
```

Arguments

fittingMat	A list of SA trajectories returned by <code>runSA(getall = TRUE)</code> .
ocmat	Numeric matrix (0/1). Rows are samples and columns are species.
enmat	Optional environmental parameter matrix used in fitting.

Value

A numeric matrix of median endpoint parameters across serials. Rownames correspond to samples and Colnames correspond to species list

 showDG

showDG: draw DisconnectivityGraph

Description

Computing graph objects from `ela` (and optionally bootstrap energies) and draw the disconnectivity graph for a given community composition matrix `oc`. More than two stable state are required.

Usage

```
showDG(
  ela,
  oc,
  label = "",
  bootstrap_ene = NULL,
  min_pval = 0.05,
  plot = TRUE,
  scale_labels = c(0.05, 0.1, 0.2, 0.5),
  getGraphObj = FALSE
)
```

Arguments

<code>ela</code>	ELA output tuple/list used by <code>GraphObj</code> .
<code>oc</code>	Community composition matrix/data frame (used to infer $s = \text{ncol}(oc)$).
<code>label</code>	Character; plot title.
<code>bootstrap_ene</code>	Optional bootstrap energy matrix/data frame for computing statistical significance levels of energy gaps.
<code>min_pval</code>	Numeric; minimum p-value shown in the visualization. This is usually set to the minimum detection level in bootstrap sampling (e.g., if the number of bootstrap iterations is 1000, the minimum level is $1/1000 = 0.001$).
<code>plot</code>	Logical; if TRUE, show disconnectivity graph
<code>scale_labels</code>	Numeric vector of values between 0 and 1; labels for the p-value scale. These values are converted to log-scaled values for plotting.
<code>getGraphObj</code>	Logical; if TRUE, returns <code>data.frame</code> object used for plotting Disconnectivity-Graph Users can manually change the graphical configurations.

Value

A data frame containing energy values, xpositions, pvalues for energy gaps in identified stable states and tipping points.

showGELA3D	<i>GELA3D: draw 3D plot of energy landscape</i>
------------	---

Description

Draws a 3D surface of the energy landscape and overlays line trajectories using **plot3D** function.

Usage

```
showGELA3D(gelsobj, theta = 25, phi = 50)
```

Arguments

gelsobj	List with two elements: surface data frame and line data frame.
theta	numeric value. <code>plot3D</code> option: Azimuth angle (in degrees) controlling rotation around the z-axis.
phi	numeric value. <code>plot3D</code> option: Elevation angle (in degrees) controlling the vertical viewing position.

Value

NULL (produces a 3D plot as side effect).

showIntrGraph	<i>showIntrGraph: draw interaction matrix on a PCoA plot</i>
---------------	--

Description

Computes a 2D PCoA embedding from the interaction matrix (`jest`) and overlays interaction links above a threshold `th`. Positive and negative links are drawn separately, and species names are annotated at their coordinates.

Usage

```
showIntrGraph(ela, sa, env = NULL, th = 0, annot_adj = c(0.75, 2))
```

Arguments

ela	ELA output tuple/list (used to obtain stable states etc.; currently mainly used for context).
sa	Parameter set passed to sa2params .
env	target environmental factor.
th	Numeric threshold for drawing links (absolute value).
annot_adj	Numeric length-2; horizontal/vertical adjustment for labels.

Value

NULL.

showSSD	<i>showSSD: draw stable state diagram</i>
---------	---

Description

Plots energy values of stable states across a factor (e.g., environmental or control parameter) using the output from `gela`. Each unique stable state is drawn as a separate line with points, and a legend is added.

Usage

```
showSSD(gela)
```

Arguments

<code>gela</code>	The output of GradELA . Object containing stable state lists, energies, the factor, and environment labels as used in the code.
-------------------	---

Value

NULL (produces a plot as side effect).

showSSD_ggplot	<i>showSSD_ggplot: draw stable state diagram using ggplot</i>
----------------	---

Description

Plots energy values of stable states across a factor (e.g., environmental or control parameter) using the output from `gela`. Each unique stable state is drawn as a separate line with points, and a legend is added.

Usage

```
showSSD_ggplot(gela, plot = TRUE, getSSDobj = TRUE)
```

Arguments

<code>gela</code>	The output of GradELA . Object containing stable state lists, energies, the factor, and environment labels as used in the code.
<code>plot</code>	Logical; if TRUE, show SSD plot
<code>getSSDobj</code>	Logical; if TRUE, returns <code>data.frame</code> object used for plotting SSD diagram Users can manually change the graphical configurations.

Value

A data frame used for plotting SSD diagram.

SSentropy	<i>SSentropy</i>
-----------	------------------

Description

Estimate stable state entropy for a given state.

Evaluating the entropy of transitions among stable states starting from a given community state.

The returned value includes the estimated entropy, the convergence time, and the number of successful convergences within the given iteration limits.

Usage

```
SSentropy(state, ss, alpha, beta, seitr = 1000, convTime = 10000)
```

Arguments

state	Binary vector (or matrix with one row) representing the current state.
ss	Matrix of stable states.
alpha	Vector of implicit or explicit environmental effects.
beta	Matrix of species interactions.
seitr	Number of stochastic search iterations.
convTime	Maximum number of iterations for each search.

Value

A numeric matrix with three columns: (1) stable state entropy, (2) convergence time, (3) number of converged searches.

sstable	<i>sstable</i>
---------	----------------

Description

Summary of stable states.

Builds a table of stable states and their energies from an ELA output. The returned data frame contains stable state IDs and the corresponding binary presence/absence vector (per species). This function is typically used for inspecting stable states after pruning (if `ela` is pruned) or before pruning.

Usage

```
sstable(ela, ocmat)
```

Arguments

`ela` output of ELA or the first return value of ELPruning.
`ocmat` community composition matrix.

Value

A data frame with columns ID, Energy.

Stability	<i>stability</i>
-----------	------------------

Description

Calculate energy gap and stable state entropy as stability indices and returns a dataframe.

For each sample state, this function identifies the basin (stable state) by [Bi](#), then computes (i) the energy gap and (ii) stable state entropy estimated by [SSentropy](#). If `enmat` is provided and `sa` was estimated with environmental factors, the basin assignment is computed for each sample-specific env.

Note: the returned stable state id corresponds to the basin (stable state) the sample is assigned to.

Usage

```
Stability(
  sa,
  ocmat,
  enmat = NULL,
  seitr = 1000,
  seconvTime = 10000,
  threads = 1,
  reporting = TRUE
)
```

Arguments

`sa` : output of runSA function.
`ocmat` : array of the vectors of presence/absence status for each sample.
`enmat` : array of the vectors of environmental factors for each sample. Normalization required.
`seitr` : Number of stochastic search iterations.
`seconvTime` : Maximum number of iterations for each search.
`threads` : number of cores (threads) used for calculation.
`reporting` : enable/disable the reporting function.

Value

A data frame with stability indices. Columns include at least `energy.gap`, `ss.entropy`, `e.realize`, `e.stable`, `state.id`, and `stable.state.id` (and may include `conv.time` and convergence depending on the branch).

SteepestDescent	<i>SteepestDescent</i>
-----------------	------------------------

Description

Perform steepest descent on the energy landscape.

Starting from an initial binary state, the steepest descent algorithm will find a local minimum of the energy landscape. The computation is delegated to the C++ implementation `SteepestDescent_cpp`.

Usage

```
SteepestDescent(state, alpha, beta)
```

Arguments

<code>state</code>	Binary vector representing the initial state.
<code>alpha</code>	vector of implicit/explicit environmental effects.
<code>beta</code>	Matrix of species interactions.

Value

A numeric vector of the reached binary stable state and its energy.

tptable	<i>tptable</i>
---------	----------------

Description

Summary of tipping points.

Builds a table of tipping points (transition states) and their energies from an ELA output. This function lists only finite tipping points (i.e., entries not equal to `Inf`), and returns the corresponding binary state vectors.

Two stable states are required at least.

Usage

```
tptable(ela, ocmat)
```

Arguments

`ela` output of [ELA](#) or the first return value of [ELPruning](#).
`ocmat` community composition matrix.

Value

A data frame with columns TP, SS1, SS2, Energy, and one column per species (binary state vector).
If no tipping points exist, returns NULL (invisibly) after printing a message.

Index

- * **datasets**
 - baseabtable, [5](#)
 - basemetadata, [5](#)
- * **models**
 - ELAplus-package, [3](#)
- * **multivariate**
 - ELAplus-package, [3](#)

- baseabtable, [5](#)
- basemetadata, [5](#)
- Bi, [6](#), [18](#), [22](#), [30](#)
- bin2id, [6](#), [7](#), [21](#)
- bootstrap_ELA, [7](#), [9](#), [12](#)
- bootstrap_SA, [7](#), [8](#), [8](#), [17](#), [19](#)

- deltaE_histogram, [9](#)
- DisconnectivityGraph, [10](#)

- ELA, [7](#), [8](#), [11](#), [12](#), [16](#), [27](#), [32](#)
- ELAplus (ELAplus-package), [3](#)
- ELAplus-package, [3](#)
- ELPruning, [7](#), [12](#), [16](#), [32](#)
- Energy, [13](#)

- Findbp, [13](#), [23](#)
- Formatting, [15](#)

- GELAObj, [16](#)
- GradELA, [16](#), [28](#)
- GradientDescent, [17](#)
- gStability, [18](#)

- hb.paramgen, [19](#)
- HeatBath, [20](#)

- id2bin, [10](#), [21](#)

- MinTippingPath, [21](#)

- OnestepHBS, [22](#)

- PCplot, [22](#)

- plotSAtest, [23](#)

- runSA, [8](#), [14](#), [16](#), [23](#), [25](#)

- sa2params, [22](#), [25](#), [27](#)
- saEndpoint, [25](#), [25](#)
- showDG, [9](#), [26](#)
- showGELA3D, [27](#)
- showIntrGraph, [27](#)
- showSSD, [28](#)
- showSSD_ggplot, [28](#)
- SSentropy, [29](#), [30](#)
- sstable, [29](#)
- Stability, [30](#)
- SteepestDescent, [6](#), [31](#)

- tptable, [31](#)