

Package ‘EcoEnsemble’

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Title A General Framework for Combining Ecosystem Models

Version 1.0.1

Description Fit and sample from the ensemble model described in Spence et al (2018): “A general framework for combining ecosystem models” <<https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12310>>.

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'EnsembleFit-class.R' 'EnsembleSample-class.R'
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EcoEnsemble-package *A general framework for combining ecosystem models*

Description

The EcoEnsemble package implements the framework for combining ecosystem models laid out in Spence et al (2018).

Details

The ensemble model can be implemented in three main stages:

1. Eliciting priors on discrepancy terms: This is done by using the EnsemblePrior constructor.
2. Fitting the ensemble model: Using `fit_ensemble_model` with simulator outputs, observations and prior information. The ensemble model can be fit, obtaining either the point estimate, which maximises the posterior density, or running Markov chain Monte Carlo to generate a sample from the posterior density of the ensemble model.
3. Sampling the latent variables from the fitted model: Using `generate_sample` with the fitted ensemble object, the discrepancy terms and the ensemble's best guess of the truth can be generated. Similarly to `fit_ensemble_model`, this can either be a point estimate or a full sample.

References

Stan Development Team (2020). RStan: the R interface to Stan. R package version 2.21.2. <https://mc-stan.org>

Spence, M. A., J. L. Blanchard, A. G. Rossberg, M. R. Heath, J. J. Heymans, S. Mackinson, N. Serpetti, D. C. Speirs, R. B. Thorpe, and P. G. Blackwell. 2018. "A General Framework for Combining Ecosystem Models." *Fish and Fisheries* 19: 1013-42. <https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12310>

EnsembleData *Constructor for the EnsembleData class*

Description

A constructor for the EnsembleData class. This is used to convert input data into the required form for `fit_ensemble_model`.

Usage

```
EnsembleData(observations, simulators, priors)
```

Arguments

- observations** A list of length 2 containing observations and a covariance matrix. The first element is a `data.frame` or `matrix` with each column giving observations of each output of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is a $d \times d$ matrix where d is the number of columns of the observations data frame / matrix. This matrix is the covariance matrix of the observations.
- simulators** A list with length equal to the number of simulators. For each simulator, there is a list of 2 objects containing the simulator output and covariance matrix. The first element is a `data.frame` or `matrix` with each column giving a simulator outputs of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is a $n_k \times n_k$ matrix where n_k is the number of columns of the simulators output data frame / matrix. This matrix is the covariance matrix of the simulator outputs.
- priors** An `EnsemblePrior` object specifying the prior distributions for the ensemble.

Value

An object of class `EnsembleData`

See Also

[EnsembleData](#), [EnsemblePrior](#), [fit_ensemble_model](#)

Examples

```
ensemble_data <- EnsembleData(observations = list(SSB_obs, Sigma_obs),
                             simulators = list(list(SSB_ewe, Sigma_ewe, "EwE"),
                                                list(SSB_fs, Sigma_fs, "FishSUMS"),
                                                list(SSB_lm, Sigma_lm, "LeMans"),
                                                list(SSB_miz, Sigma_miz, "mizer")),
                             priors = EnsemblePrior(4))
```

`EnsembleData-class` *A class to hold the Ensemble data*

Description

A class that holds the observation data, simulator outputs, and prior information to convert into the required form for `fit_ensemble_model`.

Slots

- stan_input** A list of parameters in the correct form to fit the ensemble model in Stan.
- observations** A list of length 2 containing observations and a covariance matrix. The first element is a `data.frame` or `matrix` with each column giving observations of each output of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is the covariance matrix of the observations.

`simulators` A list with length equal to the number of simulators. For each simulator, there is a list of 2 objects containing the simulator output and covariance matrix. The first element is a `data.frame` or `matrix` with each column giving a simulator outputs of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is the covariance matrix of the simulator outputs.

`priors` An `EnsemblePrior` object specifying the prior distributions for the ensemble.

See Also

[EnsembleData](#), [EnsemblePrior](#), [fit_ensemble_model](#)

EnsembleFit

The constructor for the EnsembleFit object

Description

The constructor for an `EnsembleFit` object. This function need not be called as an `EnsembleFit` object is constructed automatically by the `fit_ensemble_model` function. The `samples` slot contains the samples from the MCMC if a full sampling was completed, otherwise the `point_estimate` slot contains information about a point estimate.

Usage

```
EnsembleFit(ensemble_data, samples = NULL, point_estimate = NULL)
```

Arguments

`ensemble_data` An `EnsembleData` object encapsulating the data used to fit the ensemble model.

`samples` A `stanfit` object containing the samples drawn from the fitted model. The default value is `NULL`.

`point_estimate` A list output of the optimised model. The default value is `NULL`.

Value

An object of class `EnsembleFit`

References

Stan Development Team (2020). RStan: the R interface to Stan. R package version 2.21.2. <https://mc-stan.org>

See Also

[EnsembleFit](#), [fit_ensemble_model](#),

EnsembleFit-class *A class to hold the samples or point estimates from the ensemble model.*

Description

An EnsembleFit object is returned by the `fit_ensemble_model` function. The object contains a slot for the EnsembleData object originally used to fit the ensemble model. The `samples` slot contains the samples from the MCMC if a full sampling was completed, otherwise the `point_estimate` slot contains information about a point estimate.

Slots

`ensemble_data` An EnsembleData object encapsulating the data used to fit the ensemble model.

`samples` A stanfit object containing the samples drawn from the fitted model. The default value is NULL.

`point_estimate` A list output of the optimised model. The default value is NULL.

References

Stan Development Team (2020). RStan: the R interface to Stan. R package version 2.21.2. <https://mc-stan.org>

See Also

[EnsembleFit](#), [fit_ensemble_model](#), [generate_sample](#)

EnsemblePrior-class *A class to hold the priors for the ensemble model.*

Description

An EnsemblePrior object encapsulates the prior information for the ensemble model.

Slots

`d` A numeric specifying the number of variables of interest in the ensemble.

`ind_st_params` A list containing a prior specification for the individual short-term discrepancies $z_k^{(t)}$. See details of the EnsemblePrior() constructor.

`ind_lt_params` A list containing a prior specification for the individual long-term discrepancies γ_k . See details of the EnsemblePrior() constructor.

`sha_st_params` A list containing a prior specification for the shared short-term discrepancies $\eta^{(t)}$. See details of the EnsemblePrior() constructor.

- `sha_lt_params` A numeric containing the standard deviations for the normal prior used on the shared short-term discrepancy μ . If a single value is supplied, this is repeated for each variable
- `truth_params` A list containing a prior specification for the processes on the truth $y^{(t)}$. See details of the `EnsemblePrior()` constructor. The default value is `TruthPrior(d)`.
- `priors_stan_input` A list containing the prior data in the correct form to fit the model in Stan. This information is automatically generated by the constructor.

References

- Stan Development Team (2020). RStan: the R interface to Stan. R package version 2.21.2. <https://mc-stan.org>
- Lewandowski, Daniel, Dorota Kurowicka, and Harry Joe. 2009. "Generating Random Correlation Matrices Based on Vines and Extended Onion Method." *Journal of Multivariate Analysis* 100: 1989–2001.

EnsembleSample *A constructor for the EnsembleSample object*

Description

A constructor for the `EnsembleSample` class. These objects are generated automatically using the `generate_sample` function.

Usage

```
EnsembleSample(ensemble_fit, mle, samples)
```

Arguments

- `ensemble_fit` An `EnsembleFit` object containing the fitted ensemble model.
- `mle` An array of dimension $T \times (M + 2) \times N_{sample}$ containing MLE point estimates from the `ensemble_fit` object, where T is the total time, M is the number of simulators and N_{sample} is the number of samples. For each time step, the t th element of the array is a matrix where each column is a sample and the rows are the variables:

$$\left(y^{(t)}, \eta^{(t)}, z_1^{(t)}, z_2^{(t)}, \dots, z_M^{(t)} \right)'$$

where $y^{(t)}$ is the ensemble model's prediction of the latent truth value at time t , $\eta^{(t)}$ is the shared short-term discrepancy at time t , $z_i^{(t)}$ is the individual short-term discrepancy of simulator i at time t .

- `samples` An array of dimension $T \times (M + 2) \times N_{sample}$ containing samples from the `ensemble_fit` object, where T is the total time, M is the number of simulators and N_{sample} is the number of samples. For each time step, the t th element of the array is a matrix where each column is a sample and the rows are the variables:

$$\left(y^{(t)}, \eta^{(t)}, z_1^{(t)}, z_2^{(t)}, \dots, z_M^{(t)} \right)'$$

where $y^{(t)}$ is the ensemble model's prediction of the latent truth value at time t , $\eta^{(t)}$ is the shared short-term discrepancy at time t , $z_i^{(t)}$ is the individual short-term discrepancy of simulator i at time t .

Value

An object of class EnsembleSample

See Also

[EnsembleSample](#), [generate_sample](#)

EnsembleSample-class *A class to hold samples of the ensemble model*

Description

EnsembleSample objects are generated using the generate_sample function.

Slots

`ensemble_fit` An EnsembleFit object containing the fitted ensemble model.

`mle` An array of dimension $T \times (M + 2) \times N_{sample}$ containing MLE point estimates from the `ensemble_fit` object, where T is the total time, M is the number of simulators and N_{sample} is the number of samples. For each time step, the t th element of the array is a matrix where each column is a sample and the rows are the variables:

$$\left(y^{(t)}, \eta^{(t)}, z_1^{(t)}, z_2^{(t)}, \dots, z_M^{(t)} \right)'$$

where $y^{(t)}$ is the ensemble model's prediction of the latent truth value at time t , $\eta^{(t)}$ is the shared short-term discrepancy at time t , $z_i^{(t)}$ is the individual short-term discrepancy of simulator i at time t .

`samples` An array of dimension $T \times (M + 2) \times N_{sample}$ containing samples from the `ensemble_fit` object, where T is the total time, M is the number of simulators and N_{sample} is the number of samples. For each time step, the t th element of the array is a matrix where each column is a sample and the rows are the variables:

$$\left(y^{(t)}, \eta^{(t)}, z_1^{(t)}, z_2^{(t)}, \dots, z_M^{(t)} \right)'$$

where $y^{(t)}$ is the ensemble model's prediction of the latent truth value at time t , $\eta^{(t)}$ is the shared short-term discrepancy at time t , $z_i^{(t)}$ is the individual short-term discrepancy of simulator i at time t .

See Also

[EnsembleSample](#), [generate_sample](#)

fit_ensemble_model	<i>Fits the ensemble model</i>
--------------------	--------------------------------

Description

fit_ensemble_model runs an MCMC of the ensemble model. This process can take a long time depending on the size of the datasets.

Usage

```
fit_ensemble_model(
  observations,
  simulators,
  priors,
  full_sample = TRUE,
  control = list(adapt_delta = 0.95),
  ...
)
```

Arguments

observations	A list of length 2 containing observations and a covariance matrix. The first element is a <code>data.frame</code> or <code>matrix</code> with each column giving observations of each output of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is a $d \times d$ matrix where d is the number of columns of the observations data frame / matrix. This matrix is the covariance matrix of the observations.
simulators	A list with length equal to the number of simulators. For each simulator, there is a list of 2 objects containing the simulator output and covariance matrix. The first element is a <code>data.frame</code> or <code>matrix</code> with each column giving a simulator outputs of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is a $n_k \times n_k$ matrix where n_k is the number of columns of the simulators output data frame / matrix. This matrix is the covariance matrix of the simulator outputs.
priors	An <code>EnsemblePrior</code> object specifying the prior distributions for the ensemble.
full_sample	A logical that runs a full sampling of the posterior density of the ensemble model if TRUE. If FALSE, returns the point estimate which maximises the posterior density of the ensemble model.
control	If creating a full sample, this is a named list of parameters to control Stan's sampling behaviour. See the documentation of the <code>stan()</code> function in the <code>rstan</code> package for details. The default value is <code>list(adapt_delta = 0.95)</code> . If optimizing, this value is ignored.
...	Additional arguments passed to the function <code>rstan::sampling</code> or <code>rstan::optimizing</code> .

Value

An `EnsembleFit` object.

References

Stan Development Team (2020). RStan: the R interface to Stan. R package version 2.21.2.
<https://mc-stan.org>

See Also

[EnsembleFit](#), [EnsembleSample](#)

Examples

```
fit <- fit_ensemble_model(observations = list(SSB_obs, Sigma_obs),
  simulators = list(list(SSB_ewe, Sigma_ewe, "EwE"),
    list(SSB_fs, Sigma_fs, "FishSUMS"),
    list(SSB_lm, Sigma_lm, "LeMans"),
    list(SSB_miz, Sigma_miz, "Mizer")),
  priors = EnsemblePrior(4),
  full_sample = FALSE) #Only optimise in this case
#Run a full sample
fit1 <- fit_ensemble_model(observations = list(SSB_obs, Sigma_obs),
  simulators = list(list(SSB_ewe, Sigma_ewe, "EwE"),
    list(SSB_fs, Sigma_fs, "FishSUMS"),
    list(SSB_lm, Sigma_lm, "LeMans"),
    list(SSB_miz, Sigma_miz, "Mizer")),
  priors = EnsemblePrior(4),
  control = list(adapt_delta = 0.99)) # Additional Stan parameters.
```

generate_sample

Generate samples from a fitted ensemble model.

Description

Methods to generates samples of the latent variables from a fitted ensemble model.

Usage

```
generate_sample(fit, num_samples = 1)

get_transformed_data(fit)

get_parameters(ex.fit, x = 1)

get_mle(x = 1, ex.fit, transformed_data, time)

gen_sample(x = 1, ex.fit, transformed_data, time)
```

Arguments

<code>fit</code>	An EnsembleFit object.
<code>num_samples</code>	A numeric specifying the number of samples to be generated. The default is 1.
<code>ex.fit</code>	A list containing the samples / point estimate from the EnsembleFit object.
<code>x</code>	A numeric specifying which sample from the posterior to use. The default is 1.
<code>transformed_data</code>	A list of transformed input data.
<code>time</code>	A numeric specifying the time for which the ensemble model was run.

Details

The samples are created using the methods described in Strickland et. al. (2009) and Durbin and Koopman (2002).

Value

`generate_sample` gives a list of length 2, the first element being the MLE of latent variables and the second element being a set of samples of the latent variables.

- If `fit` is a sampling of the ensemble model parameters, then:
 - `mle` is a $\text{time} \times (3M + 2) \times \text{num_samples}$ array, where M is the number of simulators and `num_samples` is the number of samples from the ensemble model, giving the MLE of the latent variables for each available sample from the ensemble model.
 - `sample` is a $\text{time} \times (3M + 2) \times \text{num_samples}$ array, giving a sample of the latent variables for each available sample of the ensemble model.
- If `fit` is a point estimate of the ensemble model parameters, then:
 - `mle` is a $\text{time} \times (3M + 2) \times 1$ array giving the MLE of the latent variables for the point estimate of the ensemble model.
 - `sample` is a $\text{time} \times (3M + 2) \times \text{num_samples}$ array, giving `num_samples` samples of the latent variables for the single point estimate of the ensemble model.

`get_transformed_data` gives a list of transformed input data.

`get_parameters` gives a list of ensemble parameters from the requested sample.

`get_mle` If `fit` is a sampling of the ensemble model parameters, then this is a $\text{time} \times (3M + 2) \times \text{num_samples}$ array. If `fit` is a point estimate of the ensemble model parameters, then this is a $\text{time} \times (3M + 2) \times 1$ array giving the MLE of the latent variables for the point estimate of the ensemble model.

`gen_sample` If `fit` is a sampling of the ensemble model parameters, then this is a $\text{time} \times (3M + 2) \times \text{num_samples}$ array, giving a sample of the latent variables for each available sample of the ensemble model. If `fit` is a point estimate of the ensemble model parameters, then this is a $\text{time} \times (3M + 2) \times \text{num_samples}$ array.

References

J. Durbin, S. J. Koopman (2002) A simple and efficient simulation smoother for state space time series analysis *Biometrika*, Volume 89, Issue 3, August 2002, Pages 603–616,

Chris M.Strickland, Ian. W.Turner, RobertDenhamb, Kerrie L.Mengersena. Efficient Bayesian estimation of multivariate state space models *Computational Statistics & Data Analysis* Volume 53, Issue 12, 1 October 2009, Pages 4116-4125

Examples

```
fit <- fit_ensemble_model(observations = list(SSB_obs, Sigma_obs),
                        simulators = list(list(SSB_ewe, Sigma_ewe, "EwE"),
                                         list(SSB_fs, Sigma_fs, "FishSUMS"),
                                         list(SSB_lm, Sigma_lm, "LeMans"),
                                         list(SSB_miz, Sigma_miz, "Mizer")),
                        priors = EnsemblePrior(4))
samples <- generate_sample(fit, num_samples = 2000)

# A quicker way to get the MLE for the first sample from the ensemble
transf_data <- get_transformed_data(fit)
ex.fit <- rstan::extract(fit@samples)
mle_sample <- get_mle(1, ex.fit = ex.fit, transformed_data = transformed_data,
                    time = fit@ensemble_data@stan_input$time, simplify = F)
```

```
get_mcmc_ensemble_model
```

Return the compiled ensemble model Stan object.

Description

Gets the unfit, compiled stanmodel object encoding the ensemble model. This allows for manual fitting of the ensemble model directly using.

Usage

```
get_mcmc_ensemble_model()
```

Value

The stanmodel object encoding the ensemble model.

Examples

```
mod <- get_mcmc_ensemble_model()

priors <- EnsemblePrior(4)
ensemble_data <- EnsembleData(observations = list(SSB_obs, Sigma_obs),
```

```

simulators = list(list(SSB_ewe, Sigma_ewe, "EwE"),
                  list(SSB_fs, Sigma_fs, "FishSUMS"),
                  list(SSB_lm, Sigma_lm, "LeMans"),
                  list(SSB_miz, Sigma_miz, "mizer")),
priors = priors)

out <- rstan::sampling(mod, ensemble_data@stan_input, chains = 1)

```

IndLTPrior

Constructor for the EnsemblePrior class

Description

Constructors for the EnsemblePrior class and related classes. These functions are used to encode prior information for the ensemble model. The IndSTPrior, IndLTPrior, ShaSTPrior, and TruthPrior constructors encapsulate prior information.

Usage

```

IndLTPrior(
  parametrisation_form = "lkj",
  var_params = list(1, 1),
  cor_params = 1
)

IndSTPrior(
  parametrisation_form = "hierarchical",
  var_params = list(-3, 1, 8, 4),
  cor_params = list(0.1, 0.1, 0.1, 0.1),
  AR_params = c(2, 2)
)

ShaSTPrior(
  parametrisation_form = "lkj",
  var_params = list(1, 10),
  cor_params = 1,
  AR_params = c(2, 2)
)

TruthPrior(
  d,
  initial_mean = 0,
  initial_var = 100,
  rw_covariance = list(2 * d, diag(d))
)

EnsemblePrior(

```

```

d,
ind_st_params = IndSTPrior(),
ind_lt_params = IndLTPrior(),
sha_st_params = ShaSTPrior(),
sha_lt_params = 5,
truth_params = TruthPrior(d)
)

```

Arguments

parametrisation_form	The parametrisation by which the covariance matrix of the noise of the AR process (in the case of IndSTPrior and ShaSTPrior objects or the covariance of the distribution of long-term discrepancies for IndLTPrior objects) is decomposed. The default is hierarchical for IndSTPrior objects, and lkj otherwise. See details.
var_params	The parameters characterising the variance of the AR process (in the case of IndSTPrior and ShaSTPrior objects or the variance of the distribution of long-term discrepancies for IndLTPrior objects) on the discrepancy. The default value is <code>list(-3, 1, 8, 4)</code> for IndSTPrior objects, <code>list(1, 1)</code> for IndLTPrior objects, and <code>list(1, 10)</code> for ShaSTPrior objects. See details.
cor_params	The parameters characterising the correlations of the AR process (or the distribution of long-term discrepancies) on the short-term discrepancies. The default value is <code>list(0.1, 0.1, 0.1, 0.1)</code> for IndSTPrior objects, and 1 for IndLTPrior and ShaSTPrior objects. See details.
AR_params	The parameters giving the beta parameters for the prior distribution on the autoregressive parameter of the AR(1) process. The default is <code>c(2, 2)</code> . See details.
d	A numeric specifying the number of variables of interest in the ensemble.
initial_mean	A numeric giving the mean of the normal distribution giving the prior on the initial value of the random walk. This is the same value for each variable Default value is 0.
initial_var	A numeric giving the variance of the normal distribution giving the prior on the initial value of the random walk. This is the same value for each variable Default value is 100.
rw_covariance	A list of length 2 containing the inverse-Wishart parameters for the covariance of the random walk of the truth. The default value is <code>list(2*d, diag(d))</code> .
ind_st_params	An IndSTPrior object specifying priors for the individual short-term discrepancies $z_k^{(t)}$. The default value is <code>IndSTPrior("hierarchical", list(-3, 1, 8, 4), list(0.1, 0.1, 0.1, 0.1), c(2, 2))</code> .
ind_lt_params	An IndLTPrior object specifying priors for the individual long-term discrepancies γ_k . The default value is <code>IndLTPrior("lkj", list(1, 1), 1)</code> .
sha_st_params	A ShaSTPrior object specifying priors for the shared short-term discrepancies $\eta^{(t)}$. The default value is <code>ShaSTPrior("lkj", list(1, 10), 1, c(2, 2))</code> .
sha_lt_params	A numeric of length d or 1 containing the standard deviations for the normal prior used on the shared short-term discrepancy μ . If a single value is supplied, this is repeated for each variable of interest. The default value is 5.

`truth_params` A TruthPrior object specifying priors for the processes on the truth $y^{(t)}$. The default value is TruthPrior(d).

Details

IndSTPrior and ShaSTPrior discrepancy prior parameter objects contain 4 slots corresponding to:

1. `parametrisation_form` - A character specifying how the priors are parametrised. Currently supported priors are 'LKJ', 'inv_wishart', 'beta', or 'hierarchical' ('hierarchical' is only supported for IndSTPrior objects).
2. `var_params` - The prior parameters for the discrepancy variances, either a list of length 2 or a numeric of length 4. See below.
3. `cor_params` - The correlation matrix parameters, either a list of length 2 or a numeric of length 4. See below.
4. `AR_params` - Parameters for the autoregressive parameter as a numeric of length 2.

IndLTPrior discrepancy prior parameter objects contain the slots `parametrisation_form`, `var_params`, and `cor_params`.

There are currently four supported prior distributions on covariance matrices. As in Spence et. al. (2018), the individual and shared short-term discrepancy covariances, Λ_k and Λ_η , as well as the individual long-term discrepancy covariance, Λ_γ , are decomposed into a vector of variances and a correlation matrix

$$\Lambda = \sqrt{\text{diag}(\pi)}P\sqrt{\text{diag}(\pi)},$$

where π is the vector of variances for each variable of interest (VoI), and P is the correlation matrix.

Selecting 'lkj', 'inv_wishart', 'beta', or 'hierarchical' refers to setting LKJ, inverse Wishart, beta, or hierarchical prior distributions on the covariance matrix respectively. The variance parameters should be passed through as the `var_params` slot of the object and the correlation parameters should be passed through as the `cor_params`. For 'lkj', 'inv_wishart', and 'beta' selections, variances are parameterised by gamma distributions, so the `var_params` slot should be a list of length two, where each element gives the shape and rate parameters for each VoI (either as a single value which is the same for each VoI or a numeric with the same length as the number of VoI). For example, setting `var_params = list(c(5, 6, 7, 8), c(4, 3, 2, 1))` would correspond to a Gamma(5, 4) prior on the variance of the first VoI, a Gamma(6, 3) prior on the variance of the second VoI, etc... The correlations should be in the following form:

- If 'lkj' is selected, then `cor_params` should be a numeric η giving the LKJ shape parameter, such that the probability density is given by (Lewandowski et. al. 2009)

$$f(\Sigma|\eta) \propto \det(\Sigma)^{\eta-1}.$$

Variances are parameterised by gamma distributions.

- If 'inv_wishart' is selected, then `cor_params` should be a list containing a scalar value ν (giving the degrees of freedom) and a symmetric, positive definite matrix Σ (giving the scale matrix). The dimensions of Σ should be the same as the correlation matrix it produces (i.e. $d \times d$ where d is the number of VoI). The density of an inverse Wishart is given by

$$f(W|\eta, S) = \frac{1}{2^{\eta d/2} \Gamma_N\left(\frac{\eta}{2}\right)} |S|^{\eta/2} |W|^{-(\eta+d+1)/2} \exp\left(-\frac{1}{2} \text{tr}(SW^{-1})\right),$$

where Γ_N is the multivariate gamma function and $\text{tr}(X)$ is the trace of X . Note that inverse Wishart distributions act over the space of all covariance matrices. When used for a correlation matrix, only the subset of valid covariance matrices that are also valid correlation matrices are considered. Variances are parameterised by gamma distributions.

- If 'beta' is selected, then `cor_params` should be a list containing two symmetric $d \times d$ matrices A and B giving the prior success parameters and prior failure parameters respectively. The correlation between the i th and j th VoI is $\rho_{i,j}$ with

$$\frac{1}{\pi} \tan^{-1} \frac{\rho_{i,j}}{\sqrt{1 - \rho_{i,j}^2}} + \frac{1}{2} \sim \text{beta}(A_{i,j}, B_{i,j}).$$

Variances are parameterised by gamma distributions.

- If 'hierarchical' is selected, then variances are parameterised by log-normal distributions:

$$\log \pi_{k,i} \sim N(\mu_i, \sigma_i^2)$$

with priors

$$\mu_i \sim N(\alpha_\pi, \beta_\pi),$$

$$\sigma_i^2 \sim \text{InvGamma}(\gamma_\pi, \delta_\pi).$$

The `var_params` slot should then be a numeric of length 4, giving the $\alpha_\pi, \beta_\pi, \gamma_\pi, \delta_\pi$ hyperparameters respectively. Correlations ($\rho_{k,i,j}$ where $\rho_{k,i,j}$ is the correlation between VoI i and j for the k th simulator) are parameterised by hierarchical beta distributions.

$$\frac{\rho_{k,i,j} + 1}{2} \sim \text{beta}(c_{k,i,j}, d_{k,i,j})$$

with priors

$$c_{k,i,j} \sim \text{gamma}(\alpha_\rho, \beta_\rho),$$

$$d_{k,i,j} \sim \text{gamma}(\gamma_\rho, \delta_\rho).$$

The `cor_params` slot should be a numeric of length 4 giving the $\alpha_\rho, \beta_\rho, \gamma_\rho, \delta_\rho$ hyperparameters. respectively. NOTE: This options is only supported for the individual short-term discrepancy terms.

Priors may also be specified for the autoregressive parameters for discrepancies modelled using autoregressive processes (i.e. for `IndSTPrior` and `ShaSTPrior` objects). These are parametrised via beta distributions such that the autoregressive parameter $R \in (-1, 1)$ satisfies

$$\frac{R + 1}{2} \sim \text{Beta}(\alpha, \beta)$$

.

In addition to priors on the discrepancy terms, it is also possible to add prior information on the truth. We require priors on the truth at $t = 0$. By default, a $N(0, 10)$ prior is used on the initial values., however this can be configured by the `truth_params` argument. The covariance matrix of the random walk of the truth Λ_y can be configured using an inverse-Wishart prior. The `truth_params` argument should be a `TruthPrior` object.

Value

EnsemblePrior returns an object of class EnsemblePrior. IndSTPrior returns an object of class IndSTPrior. IndLTPrior returns an object of class IndLTPrior. ShaSTPrior returns an object of class ShaSTPrior. TruthPrior returns an object of class TruthPrior.

References

Spence et. al. (2018). A general framework for combining ecosystem models. *Fish and Fisheries*, 19(6):1031-1042.

Examples

```
##### Different forms of the individual long term discrepancy priors
#LKJ(10) priors on correlation matrices and gamma(5, 3) priors on the variances
ist_lkj <- IndSTPrior("lkj", list(5, 3), 10)#

#Same as above but with an additional beta(2, 4) prior on
#the autoregressive parameter of the AR process.
ist_lkj <- IndSTPrior("lkj", list(5, 3), 10, AR_params = c(2, 4))

#Same as above but with different variance priors for 5 different variables of interest.
#This encodes that there is a gamma(1, 1) prior on the variance of the first variable,
#a gamma(23, 1) on the second variable etc...
ist_lkj <- IndSTPrior("lkj", list(c(1,23,24,6,87), c(1,1,1,1,5)), 10, AR_params = c(2, 4))

#Hierarchical priors with gamma(1,2) and gamma(10, 1) on the variance hyperparameters and
#gamma(3,4), gamma(5,6) on the correlation hyperparameters
ist_hie <- IndSTPrior("hierarchical", list(1,2,10,1), list(3,4,5,6))

#Beta priors via the method of concordance. We have gamma(5,3) priors on the variance
# and beta(40,40) on each of the correlations in the correlation matrix.
ist_bet <- IndSTPrior("beta", list(5, 3), list(matrix(40, 5, 5), matrix(40, 5, 5)))

#Inverse Wishart correlation priors. Gamma(2, 1/3) priors are on the variances and
#inv-Wishart(5, diag(5)) on the correlation matrices.
ist_inW <- IndSTPrior("inv_wishart", list(2, 1/3),list(5, diag(5)))

##### TruthPrior
#Simple default truth prior with 7 variables of interest
truth_def <- TruthPrior(7)
# A more fine-tuned truth prior for an ensemble with 7 species.
truth_cus <- TruthPrior(7, initial_mean = 2, initial_var = 10, rw_covariance = list(10, diag(7)))

#The default priors for an ensemble with 8 variables of interest
priors <- EnsemblePrior(8)

#With 4 variables of interest.
priors <- EnsemblePrior(4)

#Defining custom priors for a model with 4 species.
num_species <- 5
priors <- EnsemblePrior(
```

```

d = num_species,
ind_st_params = IndSTPrior("lkj", list(3, 2), 3, AR_params = c(2,4)),
ind_lt_params = IndLTPrior(
  "beta",
  list(c(10,4,8, 7,6),c(2,3,1, 4,4)),
  list(matrix(5, num_species, num_species),
        matrix(0.5, num_species, num_species))
),
sha_st_params = ShaSTPrior("inv_wishart",list(2, 1/3),list(5, diag(num_species))),
sha_lt_params = 5,
truth_params = TruthPrior(d = num_species, initial_mean = 5, initial_var = 10,
                           rw_covariance = list(10, diag(10)))
)

```

IndLTPrior-class

A class to hold the priors for the ensemble model.

Description

An IndLTPrior object encapsulates the prior information for the long-term discrepancies of the individual simulators within the ensemble model.

Details

Individual long-term discrepancies γ_k are drawn from a distribution

$$\gamma_k \sim N(0, C_\gamma).$$

Accepted parametrisation forms for this discrepancy are lkj, beta, or inv_wishart. See details of the EnsemblePrior() constructor for more details.

Slots

`parametrisation_form` The parametrisation by which the covariance matrix of the noise of the AR process is decomposed.

`var_params` The parameters characterising the variance of the distribution of the individual long-term discrepancy.

`cor_params` The parameters characterising the correlations of the distribution of the individual long-term discrepancy.

See Also

[IndSTPrior](#), [ShaSTPrior](#), [TruthPrior](#),

IndSTPrior-class *A class to hold the priors for the ensemble model.*

Description

An IndSTPrior object encapsulates the prior information for the short-term discrepancies of the individual simulators within the ensemble model.

Details

Individual short-term discrepancies $z_k^{(t)}$ are modelled as an AR(1) process so that

$$z_k^{(t+1)} \sim N(R_k z_k^{(t)}, \Lambda_k).$$

Accepted parametrisation forms for this discrepancy are `lkj`, `beta`, `inv_wishart`, or `hierarchical`. See details of the `EnsemblePrior()` constructor for more details.

Slots

`AR_param` The parameters giving the beta parameters for the autoregressive parameter of the AR(1) process.

`parametrisation_form` The parametrisation by which the covariance matrix of the noise of the AR process is decomposed.

`var_params` The parameters characterising the variance of the AR process on the individual short-term discrepancy.

`cor_params` The parameters characterising the correlations of the AR process on the individual short-term discrepancy. .

See Also

[IndLTPrior](#), [ShaSTPrior](#), [TruthPrior](#),

`plot.EnsembleSample` *Plot the ensemble output*

Description

Plots the latent variables predicted by the ensemble model, along with simulator outputs and observations.

Usage

```
## S3 method for class 'EnsembleSample'
plot(x, variable = NULL, quantiles = c(0.05, 0.95), ...)
```

Arguments

x	An EnsembleSample object.
variable	The name of the variable to plot. This can either be a character string in the same form as the observation variable, or an index for the column in the observations data frame.
quantiles	A numeric vector of length 2 giving the quantiles for which to plot ribbons if doing a full sampling of the ensemble model. The default is $c(0.05, 0.95)$.
...	Other arguments passed on to methods. Not currently used.

Value

The ggplot object.

Examples

```
fit <- fit_ensemble_model(observations = list(SSB_obs, Sigma_obs),
                        simulators = list(list(SSB_ewe, Sigma_ewe, "EwE"),
                                         list(SSB_fs, Sigma_fs, "FishSUMS"),
                                         list(SSB_lm, Sigma_lm, "LeMans"),
                                         list(SSB_miz, Sigma_miz, "Mizer")),
                        priors = EnsemblePrior(4))
samples <- generate_sample(fit)
plot(samples)
plot(samples, variable = "Cod", quantiles=c(0.2, 0.8))

fit_point <- fit_ensemble_model(observations = list(SSB_obs, Sigma_obs),
                              simulators = list(list(SSB_ewe, Sigma_ewe, "EwE"),
                                                  list(SSB_fs, Sigma_fs, "FishSUMS"),
                                                  list(SSB_lm, Sigma_lm, "LeMans"),
                                                  list(SSB_miz, Sigma_miz, "Mizer")),
                              priors = EnsemblePrior(4),
                              full_sample = FALSE)
samples1 <- generate_sample(fit_point)
plot(samples1, variable="Herring")
```

prior_ensemble_model *Generate samples of parameters from prior distribution*

Description

Methods to generates samples of the parameters from the prior distribution of the ensemble model.

Usage

```
prior_ensemble_model(  
  priors,  
  M = 1,  
  full_sample = TRUE,  
  control = list(adapt_delta = 0.95),  
  ...  
)
```

Arguments

priors	An EnsemblePrior object specifying the prior distributions for the ensemble.
M	A numeric that represents the number of simulators. The default is 1.
full_sample	A logical that runs a full sampling of the prior density of the ensemble model if TRUE. If FALSE, returns the point estimate which maximises the prior density of the ensemble model.
control	If creating a full sample, this is a named list of parameters to control Stan's sampling behaviour. See the documentation of the stan() function in the rstan package for details. The default value is list(adapt_delta = 0.95). If optimizing, this value is ignored.
...	Additional arguments passed to the function rstan::sampling or rstan::optimizing.

Value

A list containing two items named `samples` and `point_estimate`. If `full_sample==TRUE`, `samples` is a `stanfit` and `point_estimate` is a `NULL` object, else `samples` is a `NULL` and `point_estimate` is a list object.

References

Stan Development Team (2020). RStan: the R interface to Stan. R package version 2.21.2. <https://mc-stan.org>

See Also

[EnsembleFit](#)

Examples

```
priors <- EnsemblePrior(4)  
prior_density <- prior_ensemble_model(priors, M = 4)
```

sample_prior	<i>Generate samples of latent variables from prior predictive distribution</i>
--------------	--

Description

Methods to generates samples of the latent variables from the prior predictive distribution of the ensemble model.

Usage

```
sample_prior(
  observations,
  simulators,
  priors,
  sam_priors,
  num_samples = 1,
  full_sample = TRUE,
  ...
)
```

Arguments

observations	A list of length 2 containing observations and a covariance matrix. The first element is a <code>data.frame</code> or <code>matrix</code> with each column giving observations of each output of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is a $d \times d$ matrix where d is the number of columns of the observations data frame / matrix. This matrix is the covariance matrix of the observations.
simulators	A list with length equal to the number of simulators. For each simulator, there is a list of 2 objects containing the simulator output and covariance matrix. The first element is a <code>data.frame</code> or <code>matrix</code> with each column giving a simulator outputs of interest and each row a time. Rows should be named with the times and columns should be named the variables. The second element is a $n_k \times n_k$ matrix where n_k is the number of columns of the simulators output data frame / matrix. This matrix is the covariance matrix of the simulator outputs.
priors	An <code>EnsemblePrior</code> object specifying the prior distributions for the ensemble.
sam_priors	A list containing two items named <code>samples</code> and <code>point_estimate</code> . <code>samples</code> is either a <code>NULL</code> or a <code>stanfit</code> object containing the samples drawn from the prior distribution of the ensemble model and <code>point_estimate</code> is either a <code>NULL</code> or a list object containing the optimised prior distribution of the ensemble model. If this object is missing then <code>sample_prior</code> generates it.
num_samples	A numeric specifying the number of samples to be generated. The default is 1.
full_sample	A logical that runs a full sampling of the prior density of the ensemble model if <code>TRUE</code> . If <code>FALSE</code> , returns the point estimate which maximises the prior density of the ensemble model.
...	Additional arguments passed to the function <code>rstan::sampling</code> or <code>rstan::optimizing</code> .

Details

The samples are created using the methods described in Strickland et. al. (2009) and Durbin and Koopman (2002).

Value

An EnsembleSample object.

References

J. Durbin, S. J. Koopman (2002) A simple and efficient simulation smoother for state space time series analysis *Biometrika*, Volume 89, Issue 3, August 2002, Pages 603-616,

Chris M.Strickland, Ian. W.Turner, RobertDenhamb, Kerrie L.Mengersena. Efficient Bayesian estimation of multivariate state space models *Computational Statistics & Data Analysis* Volume 53, Issue 12, 1 October 2009, Pages 4116-4125

See Also

[EnsembleFit](#), [EnsembleSample](#), [generate_sample](#), [prior_ensemble_model](#)

Examples

```
priors <- EnsemblePrior(4)
prior_density <- prior_ensemble_model(priors, M = 4)
samples <- sample_prior(observations = list(SSB_obs, Sigma_obs),
  simulators = list(list(SSB_miz, Sigma_miz),
    list(SSB_ewe, Sigma_ewe),
    list(SSB_fs, Sigma_fs),
    list(SSB_lm, Sigma_lm)),
  priors = priors,
  sam_priors = prior_density)
plot(samples) #Plot the prior predictive density.
```

ShaSTPrior-class

A class to hold the priors for the ensemble model.

Description

An ShaSTPrior object encapsulates the prior information for the short-term discrepancies of the shared discrepancy of the ensemble model.

Details

Shared short-term discrepancies $\eta^{(t)}$ are modelled as an AR(1) process so that

$$\eta^{(t+1)} \sim N(R_\eta \eta, \Lambda_\eta).$$

Accepted parametrisation forms for this discrepancy are lkj, beta, or inv_wishart. See details of the EnsemblePrior() constructor for more details.

Slots

- AR_param The parameters giving the beta parameters for the main parameter of the AR(1) process.
- parametrisation_form The parametrisation by which the covariance matrix of the noise of the AR process is decomposed.
- var_params The parameters characterising the variance of the AR process on the shared short-term discrepancy.
- cor_params The parameters characterising the correlations of the AR process on the shared short-term discrepancy.

Sigma_ewe	<i>Ecopath with EcoSim Sigma</i>
-----------	----------------------------------

Description

A 4x4 covariance matrix quantifying the parameter uncertainty of Ecopath with EcoSim

Usage

Sigma_ewe

Format

A 4x4 matrix.

References

Mackinson, S., Platts, M., Garcia, C., and Lynam, C. (2018). Evaluating the fishery and ecological consequences of the proposed North Sea multi-annual plan. PLOS ONE, 13(1), 1–23.

Sigma_fs	<i>FishSUMS Sigma</i>
----------	-----------------------

Description

A 3x3 covariance matrix quantifying the parameter uncertainty of FishSUMS

Usage

Sigma_fs

Format

A 3x3 matrix.

References

Spence, M. A., Blanchard, J. L., Rossberg, A. G., Heath, M. R., Heymans, J. J., Mackinson, S., Serpetti, N., Speirs, D. C., Thorpe, R. B., and Blackwell, P. G. (2018). A general framework for combining ecosystem models. *Fish and Fisheries*, 19(6), 1031–1042.

 Sigma_lm

LeMans Sigma

Description

LeMans Sigma

Usage

Sigma_lm

Format

A 4x4 matrix. A 4x4 covariance matrix quantifying the parameter uncertainty of LeMans

References

Thorpe, R. B., Le Quesne, W. J. F., Luxford, F., Collie, J. S., and Jennings, S. (2015). Evaluation and management implications of uncertainty in a multispecies size-structured model of population and community responses to fishing. *Methods in Ecology and Evolution*, 6(1), 49–58.

 Sigma_miz

mizer Sigma

Description

mizer Sigma

Usage

Sigma_miz

Format

A 4x4 matrix. A 4x4 covariance matrix quantifying the parameter uncertainty of mizer

References

Spence, M. A., Blackwell, P. G., and Blanchard, J. L. (2016). Parameter uncertainty of a dynamic multispecies size spectrum model. *Canadian Journal of Fisheries and Aquatic Sciences*, 73(4), 589–59

 Sigma_obs

Stock assessment Sigma

Description

A 4x4 covariance matrix quantifying the covariances of the stock assessment estimates of biomass.

Usage

Sigma_obs

Format

A 4x4 matrix.

References

Herring Assessment Working Group for the Area South of 62 N (HAWG). Technical report, ICES Scientific Reports. ACOM:07. 960 pp, ICES, Copenhagen.

Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak. Technical report, ICES Scientific Reports. ACOM:22.pp, ICES, Copenhagen.

 SSB_ewe

Ecopath with EcoSim SSB

Description

A dataset containing the predictions for spawning stock biomass of Norway Pout, Herring, Cod, and Sole in the North Sea between 1991-2050 under an MSY fishing scenario from EcoPath with EcoSim.

Usage

SSB_ewe

Format

A data.frame with 60 rows and 4 variables:

N.pout Spawning stock biomass of Norway Pout, in log tonnes.

Herring Spawning stock biomass of Herring, in log tonnes.

Cod Spawning stock biomass of Cod, in log tonnes.

Sole Spawning stock biomass of Sole, in log tonnes.

References

ICES (2016). Working Group on Multispecies Assessment Methods (WGSAM). Technical report, International Council for Exploration of the Seas.

 SSB_fs

FishSUMS SSB

Description

A data frame containing the predictions for spawning stock biomass of Norway Pout, Herring, and Cod in the North Sea between 1984-2050 under an MSY fishing scenario from FishSUMS. Note that FishSUMS does not produce outputs for Sole.

Usage

SSB_fs

Format

A data.frame with 67 rows and 3 variables:

N.pout Spawning stock biomass of Norway Pout, in log tonnes.

Herring Spawning stock biomass of Herring, in log tonnes.

Cod Spawning stock biomass of Cod, in log tonnes.

References

Speirs, D., Greenstreet, S., and Heath, M. (2016). Modelling the effects of fishing on the North Sea fish community size composition. *Ecological Modelling*, 321, 35–45

 SSB_lm

LeMans SSB

Description

A data.frame containing the predictions for spawning stock biomass of Norway Pout, Herring, Cod, and Sole in the North Sea between 1986-2050 under an MSY fishing scenario from the LeMaRns package.

Usage

SSB_lm

Format

A data.frame with 65 rows and 4 variables:

N.pout Spawning stock biomass of Norway Pout, in log tonnes.

Herring Spawning stock biomass of Herring, in log tonnes.

Cod Spawning stock biomass of Cod, in log tonnes.

Sole Spawning stock biomass of Sole, in log tonnes.

References

Thorpe, R. B., Le Quesne, W. J. F., Luxford, F., Collie, J. S., and Jennings, S. (2015). Evaluation and management implications of uncertainty in a multispecies size-structured model of population and community responses to fishing. *Methods in Ecology and Evolution*, 6(1), 49–58.

SSB_miz

mizer SSB

Description

A data.frame containing the predictions for spawning stock biomass of Norway Pout, Herring, Cod, and Sole in the North Sea between 1984-2050 under an MSY fishing scenario from mizer.

Usage

SSB_miz

Format

A data frame with 67 rows and 4 variables:

N.pout Spawning stock biomass of Norway Pout, in log tonnes.

Herring Spawning stock biomass of Herring, in log tonnes.

Cod Spawning stock biomass of Cod, in log tonnes.

Sole Spawning stock biomass of Sole, in log tonnes.

References

Blanchard, J. L., Andersen, K. H., Scott, F., Hintzen, N. T., Piet, G., and Jennings, S. (2014). Evaluating targets and trade-offs among fisheries and conservation objectives using a multispecies size spectrum model. *Journal of Applied Ecology*, 51(3), 612–622

SSB_obs	<i>Stock assessment SSB</i>
---------	-----------------------------

Description

A data frame containing the single species stock assessment estimates of spawning stock biomass of Norway Pout, Herring, Cod, and Sole in the North Sea between 1984-2017.

Usage

SSB_obs

Format

A data frame with 34 rows and 4 variables:

N.pout Spawning stock biomass of Norway Pout, in log tonnes.

Herring Spawning stock biomass of Herring, in log tonnes.

Cod Spawning stock biomass of Cod, in log tonnes.

Sole Spawning stock biomass of Sole, in log tonnes.

References

Herring Assessment Working Group for the Area South of 62 N (HAWG)(2020). Technical report, ICES Scientific Reports. ACOM:07. 960 pp, ICES, Copenhagen.

Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (2020). Technical report, ICES Scientific Reports. ACOM:22.pp, ICES, Copenhagen.

TruthPrior-class	<i>A class to hold the priors for the truth model in the ensemble framework</i>
------------------	---

Description

An TruthPrior object encapsulates the prior information for the short-term discrepancies of the shared discrepancy of the ensemble model.

Details

The truth $\mathbf{y}^{(t)}$ is modelled as a random walk such that

$$\mathbf{y}^{(t+1)} \sim N(\mathbf{y}^{(t)}, \Lambda_y).$$

The covariance matrix Λ_y is parameterised by an inverse Wishart distribution (contained in the rw_covariance slot) and the initial value is modelled as drawn from a normal distribution.

Slots

- d A numeric giving the number of variables of interest in the ensemble model.
- initial_mean A numeric giving the standard deviation of the normal prior on the initial mean value of the random walk. This is the same standard deviation for each variable of interest.
- initial_var A list of length 2 containing the shape and scale parameters (respectively) for the gamma priors on the variance of the initial value of the truth.
- rw_covariance A list of length 2 containing the inverse-Wishart parameters for the covariance of the random walk of the truth.

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