

Package ‘mppR’

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Title Multi-Parent Population QTL Analysis

Description Analysis of experimental multi-parent populations to detect regions of the genome (called quantitative trait loci, QTLs) influencing phenotypic traits measured in unique and multiple environments. The population must be composed of crosses between a set of at least three parents (e.g. factorial design, 'diallel', or nested association mapping). The functions cover data processing, QTL detection, and results visualization. The implemented methodology is described in Garin, Wimmer, Mezouk, Malosetti and van Eeuwijk (2017) <[doi:10.1007/s00122-017-2923-3](https://doi.org/10.1007/s00122-017-2923-3)>, in Garin, Malosetti and van Eeuwijk (2020) <[doi:10.1007/s00122-020-03621-0](https://doi.org/10.1007/s00122-020-03621-0)>, and in Garin, Diallo, Tekete, Thera, ..., and Rami (2024) <[doi:10.1093/genetics/iyae003](https://doi.org/10.1093/genetics/iyae003)>.

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Imports dplyr, ggplot2, graphics, grDevices, igraph, Matrix, methods, nlme, parallel, qtl, stats, utils

Depends R(>= 3.1.0)

Suggests knitr, rmarkdown, testthat

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URL <https://github.com/vincentgarin/mppR>

BugReports <https://github.com/vincentgarin/mppR/issues>

VignetteBuilder knitr

NeedsCompilation no

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| | |
|-----------------------------|---|
| <code>create.mppData</code> | <i>Create a multi-parent population data object</i> |
|-----------------------------|---|

Description

This function combines all raw data sources in a single data object of class `mppData`.

Usage

```
create.mppData(  
  geno.off = NULL,  
  geno.par = NULL,  
  map = NULL,  
  pheno = NULL,  
  cross.ind = NULL,  
  par.per.cross = NULL  
)
```

Arguments

| | |
|-----------------------|--|
| <code>geno.off</code> | Character marker score matrix of the offspring with genotypes as row and markers as column. Rows names must be the offspring genotypes identifiers similar to the one used in <code>pheno</code>. The columns names must be the marker names similar to the one used in <code>map</code>. Marker scores must be coded using one letter per allele. For example, AA, CC, GG, etc. Missing values must be coded NA. |
| <code>geno.par</code> | Character marker score matrix of the parents with genotypes as row and markers as column. Rows names must be the parents genotypes identifiers similar to the one used in <code>par.per.cross</code>. The columns names must be the marker names similar to the one used in <code>map</code>. Marker scores must be coded using one letter per allele. For example, AA, CC, GG, etc. Missing values must be coded NA. |
| <code>map</code> | Three columns data.frame with: 1) character marker identifiers; 2) numeric chromosome; 3) numeric positions in centi-Morgan. The marker identifiers must be identical to the column names of the maker matrices (<code>geno.off</code> and <code>geno.par</code>). The chromosome identifiers must start by 1 and increase by 1 unit, e.g. 1, 2, 3, ... |

| | |
|--------------|-----------------------------------|
| CV_partition | <i>Cross validation partition</i> |
|--------------|-----------------------------------|

Description

Partition the genotype indices into training and validation sets for cross-validation (CV).

Usage

```
CV_partition(cross.ind, k = 5)
```

Arguments

| | |
|-----------|--|
| cross.ind | Character vector with the same length as the number of genotypes which specifies to which cross each genotype belongs. |
| k | Numeric value representing the number of subsets (fold) into which data are spread within cross. Default = 5. |

Details

The genotype indices are randomly assigned within cross to k subsets (folds). Then each subset is used once as validation set, the remaining data go in the training set.

Value

Return:

| | |
|------|---|
| fold | List of k lists (one for each fold). Each fold list contains two vectors with genotypes indices of the training (<code>\$train.set</code>) and the validation set (<code>\$val.set</code>). |
|------|---|

Author(s)

Vincent Garin

See Also

[mpp_CV](#)

Examples

```
data(mppData)

part.cv <- CV_partition(cross.ind = mppData$cross.ind, k = 5)

part.cv[[1]]$train.set
part.cv[[1]]$val.set
```

design_connectivity *Connected parts of a MPP design*

Description

Determine the connected parts of a MPP design using the method of Weeks and Williams (1964) and the package igraph.

Usage

```
design_connectivity(par_per_cross, plot_des = TRUE, output_loc = NULL)
```

Arguments

| | |
|---------------|---|
| par_per_cross | Three columns character matrix specifying : 1) the cross indicators ; 2) the parents 1 identifiers of the crosses; 3) the parents 2 identifiers of the crosses. |
| plot_des | Logical value indicating if connected part of the design should be plotted. Default = TRUE. |
| output_loc | Path where the plot of the design will be saved if the argument is given. Default = NULL. |

Value

Return a list with each element representing one connected part of the design and the list of parents contained in this part.

If plot_des = TRUE and output_loc has been specified. A plot of the graph (con_plot.pdf) will be saved at the specified location.

Author(s)

Vincent Garin

References

Weeks, D. L., & Williams, D. R. (1964). A note on the determination of connectedness in an N-way cross classification. *Technometrics*, 6(3), 319-324.

Examples

```
data(mppData)

par_per_cross <- mppData$par.per.cross

con.part <- design_connectivity(par_per_cross)
```

EC_effect

*Determine EC effects***Description**

Determine the effect of environmental covariates (EC) on the mean of a trait across environments and the time range where this effect is the strongest. The procedure was originally proposed by Li et al. (2018).

Usage

```
EC_effect(
  trait_env_mean,
  crop_duration,
  EC_list,
  type,
  min_win = 20,
  sel_criteria = "global",
  plot = TRUE,
  plot_dir = NULL,
  p_title = "EC_plot",
  env_nm = NULL
)
```

Arguments

| | |
|-----------------------------|---|
| <code>trait_env_mean</code> | vector of trait mean over environment. |
| <code>crop_duration</code> | numerical value indicating the crop duration. |
| <code>EC_list</code> | list EC parameter matrix. one per environment. The order of the environment must be the same as the one of the trait mean. |
| <code>type</code> | character string vector indicating the type of statistic that correspond to the EC. Either the cumulated sum ('sum') or the average ('mean'). |
| <code>min_win</code> | Numerical value indicating the minimum size of the range between start and end day when the EC values are measured. Default = 20 |
| <code>sel_criteria</code> | Character specifying the selection criteria. Default = 'global' |
| <code>plot</code> | Logical value indicating if a plot of the EC effects over time should be returned. Default = FALSE, |
| <code>plot_dir</code> | Directory where the plot should be returned. Default = NULL |
| <code>p_title</code> | Title of the plot. Default = 'EC_plot' |
| <code>env_nm</code> | Optional vector of environment name. Default = NULL. |

Value

Return:

data.frame that contains the following elements for each EC (line). The first line is the value of the EC in the different environments:

1. Start and end date of the optimal window
2. R2 of correlation between trait and EC
3. Direction of the correlation
4. Average R2 value over all tested windows
5. EC value in the different environments for the optimal time window

Author(s)

Vincent Garin

References

Li, X., Guo, T., Mu, Q., Li, X., & Yu, J. (2018). Genomic and environmental determinants and their interplay underlying phenotypic plasticity. *Proceedings of the National Academy of Sciences*, 115(26), 6679-6684.

IBD.mppData

IBD coding for mppData objects

Description

The function first converts genotype data into ABH format. Then it calculates within cross identical by descent (IBD) probabilities.

Usage

```
IBD.mppData(
  mppData,
  het.miss.par = TRUE,
  subcross.ind = NULL,
  par.per.subcross = NULL,
  type,
  F.gen = NULL,
  BC.gen = NULL,
  type.mating = NULL,
  error.prob = 1e-04,
  map.function = "haldane"
)
```


Arguments

| | |
|-------------------------------|--|
| <code>mppData</code> | An object of class <code>mppData</code> . the <code>mppData</code> must have been processed using: create.mppData , QC.mppData , and IBS.mppData . |
| <code>het.miss.par</code> | Logical value. if <code>het.miss.par = TRUE</code> , the function will use the offspring segregation to try to infer the allele that was transmitted by the heterozygous or missing parent at a particular locus to make the ABH conversion. Default = <code>TRUE</code> . |
| <code>subcross.ind</code> | Optional character vector specifying to which sub-cross each genotype belong. Default = <code>NULL</code> . |
| <code>par.per.subcross</code> | Optional three columns Character matrix specifying : 1) the sub-cross indicators; 2) the parents 1 identifiers of the sub-crosses; 3) the parents 2 identifiers of the sub-crosses. Default = <code>NULL</code> . |
| <code>type</code> | Character indicator for the type of population analyzed: <code>type = "F"</code> for <code>Fn</code> (F cross n generations); <code>type = "BC"</code> for <code>BCn</code> (backcross n generations); <code>type = "BCsFt"</code> for backcross followed by selfing; <code>type = "DH"</code> for double haploids; and <code>type = "RIL"</code> for recombinant inbred lines. For RIL type specify if the population was obtain using selfing or sibling mating using <code>type.mating</code> . If <code>type = "RIL"</code> or <code>"DH"</code> , the function does not assume heterozygous marker scores for these populations and convert them into missing (NA). |
| <code>F.gen</code> | Numeric integer representing the number of F generations. For example <code>F.gen = 2</code> for <code>F2</code> . Default = <code>NULL</code> . |
| <code>BC.gen</code> | Numeric integer representing the number of backcross generations. For example <code>BC.gen = 1</code> for single backcross. Default = <code>NULL</code> . |
| <code>type.mating</code> | Character specifying for a RIL population if it was obtained by selfing ("selfing") or by sibling mating ("sib.mat"). Default = <code>NULL</code> . |
| <code>error.prob</code> | Numeric value for assumed genotyping error rate used in the calculation of the penetrance $Pr(\text{observed genotype} \text{true genotype})$. Default = 0.0001. |
| <code>map.function</code> | Character expression specifying the type of map function used to infer the IBD probabilities. possibility to choose between "haldane", "kosambi", "c-f", "morgan". Default = "haldane". |

Details

The function first transforms genotype data into within cross ABH format. The function takes the parents of the different cross as reference and assigns the following scores: "A" if the offspring score is equivalent to parent 1; "B" if it is equivalent to parent 2; "H" if it is heterozygous. The function attributes NA for missing when: 1) the offspring score is missing; 2) the two parents have the same score; or 3) when at least one parental score is missing.

If a parent score is heterozygous or missing (`het.miss.par = TRUE`), the assignment rules are the following. If the two parents are heterozygous or one parent is heterozygous and the other missing, the offspring get NA since the parental origin can not be inferred with certainty. If one parent is heterozygous or missing and the second parent is homozygous, the function looks at offspring segregating pattern to infer which allele was transmitted by the heterozygous parent. If this is possible we consider the heterozygous parent as homozygous for the transmitted allele and use this allele score for ABH assignment.

The ABH assignment can be performed using sub-cross structure providing information about sub-cross in arguments `subcross.ind` and `par.per.subcross`.

Then the function calculates the IBD probabilities using `read.cross()` and `calc.genoprob()` functions from the R/qtl package (Broman et al. 2009).

The type of population must be specified in argument `type`. Different population types are possible: F-type ('F'), back-cross ('BC'), backcross followed by selfing ('BCsFt'), double haploid ('DH'), and recombinant inbred lines ('RIL'). The number of F and BC generations can be specified using `F.gen` and `BC.gen`. The argument `type.mating` specifies if F and RIL populations were obtained by selfing or by sibling mating.

DH and RIL populations are read as back-cross by R/qtl. For these two population types, heterozygous scores will be treated as missing values.

Value

an increased `mppData` object containing the the same elements as the `mppData` object provided as argument and the following new elements:

| | |
|-----------------------|---|
| <code>geno.IBD</code> | A R/qtl <code>cross.object</code> containing the IBD probabilities. |
| <code>n.zigo</code> | Numeric value Indicating the number of different genotypes: 2 (AA/BB) or 3 (AA/AB/BB) |
| <code>type</code> | Character expression indicating the type of population. |

Author(s)

Vincent Garin

References

Broman KW, Wu H, Sen S, Churchill GA (2003) R/qtl: QTL mapping in experimental crosses. *Bioinformatics* 19:889-890.

Broman, K. W., & Sen, S. (2009). *A Guide to QTL Mapping with R/qtl* (Vol. 46). New York: Springer.

See Also

[create.mppData](#), [QC.mppData](#), [IBS.mppData](#)

Examples

```
data(mppData_init)

mppData <- QC.mppData(mppData_init)
mppData <- IBS.mppData(mppData = mppData)

mppData <- IBD.mppData(mppData = mppData, het.miss.par = TRUE, type = 'RIL',
                      type.mating = 'selfing')
```

IBS.mppData*IBS coding for mppData objects*

Description

Transform the genotype marker matrix of a mppData object into Identical by state (IBS) 0, 1, 2 format. The IBS score represent the number of copies of the minor allele.

Usage

```
IBS.mppData(mppData)
```

Arguments

mppData An object of class mppData. The mppData must have been processed using: [create.mppData](#) and [QC.mppData](#).

Value

an increased mppData object containing the the same elements as the mppData object provided as argument and the following new elements:

| | |
|------------|--|
| geno.IBS | Marker matrix with marker scores coded as 0, 1, 2 corresponding to the number of copies of the least frequent SNP allele. |
| allele.ref | matrix with reference allele scores. The first row represents the minor allele (lowest frequency), the second the one represent the major allele (largest frequency) and the two others the heterozygous scores. |

Author(s)

Vincent Garin

See Also

[create.mppData](#), [QC.mppData](#)

Examples

```
data(mppData_init)

mppData <- QC.mppData(mppData_init)

mppData <- IBS.mppData(mppData = mppData)
```

| | |
|-------------|-----------------------------|
| inc_mat_QTL | <i>QTL incidence matrix</i> |
|-------------|-----------------------------|

Description

Build a single position QTL incidences matrix.

Usage

```
inc_mat_QTL(x, mppData, Q.eff, order.MAF = FALSE, ref_par = NULL)
```

Arguments

| | |
|-----------|---|
| x | Integer value indicating the genetic position on the map (mppData\$map) of the QTL incidence matrix. |
| mppData | An object of class mppData. |
| Q.eff | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |
| order.MAF | Logical value specifying if the QTL incidence matrix should be ordered by allele frequency for a parental and ancestral QTL incidence matrix. The column will be ordered from the least to the most frequent allele. Default = FALSE. |
| ref_par | Optional Character expression defining the parental allele that will be used as reference for the parental model. Default = NULL |

Value

Return:

| | |
|---------|---|
| QTL.mat | QTL incidence matrix. For the cross-specific model, it represents the difference between the number of allele from parent 2 or B and parent 1 or A divided by two. For parental (ancestral) model it represents the expected number of parental (ancestral) allele copies. For the bi-allelic model, it represents the number of copies of the least frequent allele. |
|---------|---|

Author(s)

Vincent Garin

Examples

```
data(mppData)

QTLmatCr <- inc_mat_QTL(x = 2, mppData = mppData, Q.eff = "cr")

QTLmatPar <- inc_mat_QTL(x = 2, mppData = mppData, Q.eff = "par")
```

```
QTLmatAnc <- inc_mat_QTL(x = 2, mppData = mppData, Q.eff = "anc")
QTLmatBi <- inc_mat_QTL(x = 2, mppData = mppData, Q.eff = "biall")
```

mppData

Complete mppData object

Description

Complete mppData object made from a sample data of the maize US nested association mapping (NAM) population. This mppData object went through all the steps of the data processing: [create.mppData](#), [QC.mppData](#), [IBS.mppData](#), [IBD.mppData](#), [parent_cluster.mppData](#). The mppData contain all the data necessary for the QTL analysis procedures.

Usage

```
data(mppData)
```

Format

```
mppData
```

Details

The complete mppData object is a list containing the following elements:

1. geno.IBS: IBS genotype marker matrix.
2. geno.IBD: R/qt1 cross.object containing the genotype within cross IBD probabilities.
3. geno.id: List of genotypes.
4. allele.ref: Matrix containing for each marker the most and least frequent marker scores and the two heterozygous scores.
5. geno.par: Parents marker matrix.
6. geno.par.clu: Parent marker data used to cluster the parents.
7. par.clu: Parent clustering results.
8. mono.anc: Positions for which the ancestral clustering was monomorphic.
9. pheno: Phenotypic trait matrix.
10. map: Genetic map corresponding to the geno (IBS, IBD, par) arguments.
11. haplo.map: Genetic map corresponding to geno.par.clu.
12. cross.ind: Vector indicating to which cross each genotype belongs.
13. par.per.cross: Matrix with for each cross the parent 1 and 2.
14. parents: Vector of parents.
15. type: Type of population.

- 16. n.cr: Number of crosses.
- 17. n.par: Number of parents.
- 18. n.anc: Average number of ancestral group along the genome.
- 19. n.zigo: Number of possible allelic computations 2 (AA/BB) or 3 (AA/AB/BB).
- 20. rem.mk: Removed markers in the data processing.
- 21. rem.gen: Removed genotypes in the data processing.
- 22. status: Indicates the level of progression in the data processing.

See Also

[create.mppData](#), [QC.mppData](#), [IBS.mppData](#), [IBD.mppData](#), [parent_cluster.mppData](#)

Examples

```
data(mppData)
```

| | |
|--------------------------------|--|
| <code>mppData_add_pheno</code> | <i>Add new phenotypic values to a mppData object</i> |
|--------------------------------|--|

Description

Add the new phenotypic values contained in 'pheno' to a mppData object.

Usage

```
mppData_add_pheno(mppData, pheno)
```

Arguments

| | |
|----------------------|---|
| <code>mppData</code> | An object of class mppData. |
| <code>pheno</code> | data.frame with : 1) character genotypes identifiers; 2) numeric trait values. The genotypes identifiers must be identical to mppData\$geno.id. |

Value

Return:

| | |
|----------------------|--|
| <code>mppData</code> | New mppData object with new phenotypic values added. |
|----------------------|--|

Author(s)

Vincent Garin

See Also

[mppData_mdf_pheno](#), [subset.mppData](#),

Examples

```
data(mppData)
pheno_new <- data.frame(geno.id = mppData$geno.id, ph1 = rnorm(498))

mppData <- mppData_add_pheno(mppData = mppData, pheno = pheno_new)
```

mppData_GE

*Example mppData object***Description**

Example mppData object representing a subset from the maize EU-NAM Flint population (Bauer et al. 2013, Lehermeier et al. 2014, Giraud et al. 2014).

Usage

```
data(mppData_GE)
```

Format

```
mppData
```

Details

Sample data from the maize EU-NAM Flint population. The genotype data were obtained from <http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE50558>. The genotypes come from the five following crosses: (UH007 x D152), (UH007 x F03802), (UH007 x F2), (UH007 x F283), and (UH007 x DK105). We selected 100 markers randomly spread on chromosomes five and six. The genetic map was downloaded here http://maizegdb.org/data_center/reference?id=9024747.

The phenotypic data represent the within environment adjusted means for dry matter yield (DMY) calculated at La Coruna (CIAM), at Roggenstein (TUM), at Einbeck (KWS), and at Ploudaniel (INRA_P). The raw plot data were obtained here: <http://www.genetics.org/content/198/1/3/suppl/DC1>.

References

- Bauer, E., Falque, M., Walter, H., Bauland, C., Camisan, C., Campo, L., ... & Altmann, T. (2013). Intraspecific variation of recombination rate in maize. *Genome biology*, 14(9), R103.
- Giraud, H., Lehermeier, C., Bauer, E., Falque, M., Segura, V., Bauland, C., ... & Schipprack, W. (2014). Linkage disequilibrium with linkage analysis of multiline crosses reveals different multiallelic QTL for hybrid performance in the flint and dent heterotic groups of maize. *Genetics*, 198(4), 1717-1734.
- Lehermeier, C., Krämer, N., Bauer, E., Bauland, C., Camisan, C., Campo, L., ... & Moreau, L. (2014). Usefulness of multiparental populations of maize (*Zea mays* L.) for genome-based prediction. *Genetics*, 198(1), 3-16.

Examples

```
data(mppData_GE)
```

| | |
|--------------|-------------------------------------|
| mppData_init | mppData <i>object with raw data</i> |
|--------------|-------------------------------------|

Description

mppData object with raw genotypic and phenotypic data of a sample of the maize US nested association mapping (NAM) population. Different operations of quality control and data processing still need to be performed before the QTL detection analysis.

Usage

```
data(mppData_init)
```

Format

```
mppData
```

Details

see examples of the [create.mppData](#).

See Also

```
create.mppData
```

Examples

```
data(mppData_init)
```

| | |
|-------------------|---|
| mppData_mdf_pheno | <i>Modify the phenotypic values of a mppData object</i> |
|-------------------|---|

Description

Modify the phenotypic values of a mppData object.

Usage

```
mppData_mdf_pheno(mppData, pheno)
```


Arguments

| | |
|---------|--|
| mppData | An object of class mppData. |
| pheno | Two columns data.frame with : 1) character genotypes identifiers; 2) numeric trait values. The genotypes identifiers must be identical to mppData\$geno.id. The trait value identifiers must correspond to a trait already in the mppData object. |

Value

| | |
|---------|---|
| Return: | |
| mppData | New mppData object with modified phenotypic values added. |

Author(s)

Vincent Garin

See Also

[mppData_add_pheno](#), [subset.mppData](#),

Examples

```
data(mppData)
pheno_new <- data.frame(geno.id = mppData$geno.id, ULA = rnorm(498))

mppData <- mppData_mdf_pheno(mppData = mppData, pheno = pheno_new)
```

mppGE_CIM

MPP GxE Composite Interval Mapping

Description

Computes multi-QTL models with cofactors along the genome using an approximate mixed model computation. An initial variance covariance (VCOV) structure is calculated using function from the nlme package. Then, this information is used to estimate the QTL global and within parental effect significance using a Wald test.

Usage

```
mppGE_CIM(
  mppData,
  trait,
  VCOV = "UN",
  VCOV_data = "unique",
  cofactors = NULL,
  cof_red = FALSE,
```

```

    cof_pval_sign = 0.1,
    window = 20,
    ref_par = NULL,
    n.cores = 1,
    maxIter = 100,
    msMaxIter = 100
)

```

Arguments

| | |
|----------------------------|--|
| <code>mppData</code> | An object of class <code>mppData</code> . |
| <code>trait</code> | Character vector specifying which traits (environments) should be used. |
| <code>VCOV</code> | VCOV Character expression defining the type of variance covariance structure used. 'CS' for compound symmetry assuming a unique genetic covariance between environments. 'CSE' for cross-specific within environment error term. 'CS_CSE' for both compound symmetry plus cross-specific within environment error term. 'UN' for unstructured environmental variance covariance structure allowing a specific genotypic covariance for each pair of environments. Default = 'UN' |
| <code>VCOV_data</code> | Character specifying if the reference VCOV should be formed taking all cofactors into consideration ("unique") or if different VCOVs should be formed by removing the cofactor information that is too close of a tested QTL position ("minus_cof"). Default = "unique" |
| <code>cofactors</code> | Object of class <code>QTLlist</code> representing a list of selected marker positions obtained with the function <code>QTL_select()</code> or a vector of character marker positions names. Default = <code>NULL</code> . |
| <code>cof_red</code> | Logical value specifying if the cofactor matrix should be reduced by only keeping the significant allele by environment interaction. Default = <code>FALSE</code> |
| <code>cof_pval_sign</code> | Numeric value specifying the p-value significance of an allele by environment term to be kept in the model. Default = 0.1 |
| <code>window</code> | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 20. |
| <code>ref_par</code> | Optional Character expression defining the parental allele that will be used as reference for the parental model. Default = <code>NULL</code> |
| <code>n.cores</code> | Numeric. Specify here the number of cores you like to use. Default = 1. |
| <code>maxIter</code> | maximum number of iterations for the lme optimization algorithm. Default = 100. |
| <code>msMaxIter</code> | maximum number of iterations for the optimization step inside the lme optimization. Default = 100. |

Details

The estimated model is the following:

$$\underline{y}_{icj} = E_j + C_{cj} + \sum_{qc=1}^{n_{cof}} x_{iqcp} + \beta_{pj} + x_{iqp} * \beta_{pj} + \underline{GE}_{icj} + e_{icj}$$

For further details see the vignette.

It is possible to calculate one initial VCOV using a null model with all the cofactors (VCOV_data = "unique") or one VCOV per combination of cofactors (VCOV_data = "minus_cof"). In the later case, the cofactor that fall within a distance of window on the left and right of a QTL position is removed for the calculation of the initial VCOV. Therefore, N_cof + 1 VCOV are calculated.

Value

Return:

| | |
|-----|---|
| CIM | Data.frame of class QTLprof. with five columns : 1) QTL marker or in between position names; 2) chromosomes; 3) integer position indicators on the chromosome; 4) positions in centi-Morgan; and 5) -log10(p-val) of the global QTL effect across environments 6) p-values of the within environment QTL effects (one column per environment); and p-values of the within environment parental QTL allelic effects (one column per parent environment combination). |
|-----|---|

Author(s)

Vincent Garin

References

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2021). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-152, <URL: <https://CRAN.R-project.org/package=nlme>>.

[mppGE_SIM](#), [mppGE_proc](#)

Examples

```
data(mppData_GE)

cofactors <- mppData_GE$map$mk.names[c(35, 61)]

CIM <- mppGE_CIM(mppData = mppData_GE, trait = c('DMY_CIAM', 'DMY_TUM'),
               cofactors = cofactors, window = 20)

Qpos <- QTL_select(CIM)

plot(CIM)

plot_allele_eff_GE(mppData = mppData_GE, nEnv = 2, EnvNames = c('CIAM', 'TUM'),
                  Qprof = CIM, Q.eff = 'par', QTL = Qpos, text.size = 14)
```

mppGE_proc

MPP GxE QTL analysis

Description

QTL detection in MPP characterized in multiple environments.

Usage

```
mppGE_proc(
  pop.name = "MPP",
  trait.name = "trait1",
  mppData,
  trait,
  EnvNames = NULL,
  VCOV = "UN",
  ref_par = NULL,
  VCOV_data = "unique",
  SIM_only = FALSE,
  thre.cof = 4,
  win.cof = 50,
  cof_red = FALSE,
  cof_pval_sign = 0.1,
  window = 20,
  thre.QTL = 4,
  win.QTL = 20,
  text.size = 18,
  n.cores = 1,
  maxIter = 100,
  msMaxIter = 100,
  verbose = TRUE,
  output.loc = NULL
)
```

Arguments

| | |
|------------|--|
| pop.name | Character name of the studied population. Default = "MPP". |
| trait.name | Character name of the studied trait. Default = "trait1". |
| mppData | An object of class mppData. |
| trait | Character vector specifying which traits (environments) should be used. |
| EnvNames | character expression indicating the environment or trait labels. By default: Env_1, 2, 3, etc. |
| VCOV | VCOV Character expression defining the type of variance covariance structure used. 'CS' for compound symmetry assuming a unique genetic covariance between environments. 'CSE' for cross-specific within environment error term. |

| | |
|---------------|---|
| | 'CS_CSE' for both compound symmetry plus cross-specific within environment error term. 'UN' for unstructured environmental variance covariance structure allowing a specific genotypic covariance for each pair of environments. Default = 'UN' |
| ref_par | Optional Character expression defining the parental allele that will be used as reference for the parental model. Default = NULL |
| VCOV_data | Character specifying if the reference VCOV of the CIM profile computation should be formed taking all cofactors into consideration ("unique") or if different VCOVs should be formed by removing the cofactor information that is too close of a tested cofactor position ("minus_cof"). Default = "unique" |
| SIM_only | Logical value specifying if the procedure should only calculate a SIM profile (no CIM). This option can be used with large dataset to save time. Default = FALSE |
| thre.cof | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be selected as cofactor. Default = 4. |
| win.cof | Numeric value in centi-Morgan representing the minimum distance between two selected cofactors. Default = 50. |
| cof_red | Logical value specifying if the cofactor matrix should be reduced by only keeping the significant allele by environment interaction. Default = FALSE |
| cof_pval_sign | Numeric value specifying the p-value significance of an allele by environment term to be kept in the model. Default = 0.1 |
| window | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 20. |
| thre.QTL | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be selected as QTL. Default = 4. |
| win.QTL | Numeric value in centi-Morgan representing the minimum distance between two selected QTLs. Default = 20. |
| text.size | Numeric value specifying the size of graph axis text elements. Default = 18. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |
| maxIter | maximum number of iterations for the lme optimization algorithm. Default = 100. |
| msMaxIter | maximum number of iterations for the optimization step inside the lme optimization. Default = 100. |
| verbose | Logical value indicating if the steps of mpp_proc should be printed. Default = TRUE. |
| output.loc | Path where a folder will be created to save the results. Default = NULL. |

Details

The procedure is the following:

1. Simple interval mapping (SIM) to select cofactors ([mppGE_SIM](#)).
2. Composite interval mapping (CIM) with selected cofactors ([mppGE_CIM](#)).
3. Estimation of QTLs additive allelic effect ([QTL_effect_GE](#)).
4. Estimation of the global QTLs effect R squared and individual QTL effect R squared ([QTL_R2_GE](#)).

Value

Return:

List containing the following items:

| | |
|-----------|---|
| n.QTL | Number of detected QTLs. |
| cofactors | Data.frame with cofactors positions. |
| QTL | Data.frame with QTL positions. |
| Q_eff | list containing the estimated QTL allelic effects. |
| R2 | List containing R squared statistics of the QTL effects |

Some output files are also saved at the specified location (output.loc):

1. The SIM and CIM results in a RData file (SIM.RData, CIM.RData).
2. The list of cofactors (cofactors.RData).
3. The list of QTL (QTLs.RData).
4. The list of QTL allelic effects (QTL_effects.RData).
5. The QTL R squared statistics (QTL_R2.RData)
6. The number of detected QTLs and adjusted R2 (Glb_res.RData)
7. The plot of the CIM profile (QTL_profile.pdf) with dotted vertical lines representing the cofactors positions and the plot of the genetic effects per cross or parents obtained with [plot_allele_eff_GE](#) (gen_eff.pdf) with dashed lines representing the QTL positions.

Author(s)

Vincent Garin

See Also

[mppGE_CIM](#), [mppGE_SIM](#), [QTL_effect_GE](#), [QTL_R2_GE](#)

Examples

```
## Not run:

data(mppData_GE)

MPP_GE_QTL <- mppGE_proc(pop.name = 'EUNAM', trait.name = 'DMY',
  mppData = mppData_GE, trait = c('DMY_CIAM', 'DMY_TUM'),
  n.cores = 1, output.loc = tempdir())

## End(Not run)
```

mppGE_SIM

*MPP GxE Simple Interval Mapping***Description**

Computes single QTL models along the genome using an approximate mixed model computation. An initial variance covariance (VCOV) structure is calculated using function from the nlme package. Then, this information is used to estimate the QTL global and within parental effect significance using a Wald test.

Usage

```
mppGE_SIM(
  mppData,
  trait,
  VCOV = "UN",
  ref_par = NULL,
  n.cores = 1,
  maxIter = 100,
  msMaxIter = 100
)
```

Arguments

| | |
|-----------|--|
| mppData | An object of class mppData. |
| trait | Character vector specifying which traits (environments) should be used. |
| VCOV | VCOV Character expression defining the type of variance covariance structure used. 'CS' for compound symmetry assuming a unique genetic covariance between environments. 'CSE' for cross-specific within environment error term. 'CS_CSE' for both compound symmetry plus cross-specific within environment error term. 'UN' for unstructured environmental variance covariance structure allowing a specific genotypic covariance for each pair of environments. Default = 'UN' |
| ref_par | Optional Character expression defining the parental allele that will be used as reference for the parental model. Default = NULL |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |
| maxIter | maximum number of iterations for the lme optimization algorithm. Default = 100. |
| msMaxIter | maximum number of iterations for the optimization step inside the lme optimization. Default = 100. |

Details

The estimated model is the following:

$$y_{icj} = E_j + C_{cj} + x_{i_{qp}} * \beta_{pj} + \underline{GE}_{icj} + \underline{e}_{icj}$$

For further details see the vignette.

Value

Return:

SIM Data.frame of class QTLprof. with five columns : 1) QTL marker or in between position names; 2) chromosomes; 3) integer position indicators on the chromosome; 4) positions in centi-Morgan; and 5) -log10(p-val) of the global QTL effect across environments 6) p-values of the within environment QTL effects (one column per environment); and p-values of the within environment parental QTL allelic effects (one column per parent environment combination).

Author(s)

Vincent Garin

References

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2021). nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-152, <URL: <https://CRAN.R-project.org/package=nlme>>.

See Also

[mppGE_CIM](#), [mppGE_proc](#)

Examples

```
data(mppData_GE)

SIM <- mppGE_SIM(mppData = mppData_GE, trait = c('DMY_CIAM', 'DMY_TUM'))

Qpos <- QTL_select(Qprof = SIM, threshold = 3, window = 50)

plot(x = SIM, QTL = Qpos)

plot_allele_eff_GE(mppData = mppData_GE, nEnv = 2, EnvNames = c('CIAM', 'TUM'),
                   Qprof = SIM, Q.eff = 'par', QTL = Qpos, text.size = 14)
```

mpp_back_elim

Backward elimination on QTL candidates

Description

Performs a backward elimination using a list of given QTLs positions. The positions with a p-value above the significance level alpha, are successively removed.

Usage

```
mpp_back_elim(mppData, trait = 1, QTL = NULL, Q.eff = "cr", alpha = 0.05)
```


Arguments

| | |
|---------|---|
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| QTL | Object of class QTLlist representing a list of selected position obtained with the function QTL_select or vector of character marker positions names. Default = NULL. |
| Q.eff | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |
| alpha | Numeric value indicating the level of significance for the backward elimination. Default = 0.05. |

Details

The function starts with all QTL positions in the model and test the inclusion of each position as the last in the model. If all position p-values are below alpha the procedure stop. If not the position with the highest p-value is remove and the procedure continue until there is no more insignificant position.

Value

Return:

| | |
|-----|--|
| QTL | Data.frame of class QTLlist with five columns : 1) QTL marker names; 2) chromosomes; 3) interger position indicators on the chromosome; 4) positions in centi-Morgan; and 5) -log10(p-values). |
|-----|--|

Author(s)

Vincent Garin

See Also

[mpp_SIM](#)

Examples

```
data(mppData)

SIM <- mpp_SIM(mppData)

QTL <- QTL_select(SIM)

QTL.sel <- mpp_back_elim(mppData = mppData, QTL = QTL)
```

mpp_CIM

*MPP Composite Interval Mapping***Description**

Compute QTL models along the genome using cofactors representing other genetic positions for control.

Usage

```
mpp_CIM(
  mppData,
  trait = 1,
  Q.eff = "cr",
  cofactors = NULL,
  window = 20,
  plot.gen.eff = FALSE,
  n.cores = 1
)
```

Arguments

| | |
|--------------|---|
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| Q.eff | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |
| cofactors | Object of class QTLlist representing a list of selected position obtained with the function QTL_select or vector of character marker positions names. Default = NULL. |
| window | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 20. |
| plot.gen.eff | Logical value. If plot.gen.eff = TRUE, the function will save the decomposed genetic effects per cross/parent. These results can be plotted with the function plot.QTLprof to visualize a genome-wide decomposition of the genetic effects. This functionality is only available for the cross-specific, parental and ancestral models. Default value = FALSE. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |

Details

For more details about the different models, see documentation of the function [mpp_SIM](#). The function returns a $-\log_{10}(\text{p-value})$ QTL profile.

Value

Return:

CIM Data.frame of class QTLprof. with five columns : 1) QTL marker names; 2) chromosomes; 3) interger position indicators on the chromosome; 4) positions in centi-Morgan; and 5) $-\log_{10}(\text{p-val})$. And if `plot.gen.eff = TRUE`, p-values of the cross or parental QTL effects.

Author(s)

Vincent Garin

See Also[mpp_SIM](#), [QTL_select](#)**Examples**

```
# Cross-specific effect model
#####

data(mppData)

SIM <- mpp_SIM(mppData = mppData, Q.eff = "cr")

cofactors <- QTL_select(Qprof = SIM, threshold = 3, window = 20)

CIM <- mpp_CIM(mppData = mppData, Q.eff = "cr", cofactors = cofactors,
               window = 20, plot.gen.eff = TRUE)

plot(x = CIM)
plot(x = CIM, gen.eff = TRUE, mppData = mppData, Q.eff = "cr")

# Bi-allelic model
#####

cofactors <- mppData$map[c(15, 63), 1]

CIM <- mpp_CIM(mppData = mppData, Q.eff = "biall", cofactors = cofactors,
               window = 20)

plot(x = CIM, type = "h")
```

mpp_CV*MPP cross-validation*

Description

Evaluation of MPP QTL detection procedure by cross-validation (CV).

Usage

```

mpp_CV(
  pop.name = "MPP_CV",
  trait.name = "trait1",
  mppData,
  trait = 1,
  her = 1,
  Rep = 10,
  k = 5,
  Q.eff = "cr",
  thre.cof = 3,
  win.cof = 50,
  N.cim = 1,
  window = 20,
  thre.QTL = 3,
  win.QTL = 20,
  backward = TRUE,
  alpha.bk = 0.05,
  n.cores = 1,
  verbose = TRUE,
  output.loc
)

```

Arguments

| | |
|------------|---|
| pop.name | Character name of the studied population. Default = "MPP_CV". |
| trait.name | Character name of the studied trait. Default = "trait1". |
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| her | Numeric value between 0 and 1 representing the heritability of the trait. her can be a single value or a vector specifying each within cross heritability. Default = 1. |
| Rep | Numeric value representing the number of repetition of the k-fold procedure. Default = 10. |
| k | Numeric value representing the number of folds for the within cross partition of the population. Default = 5. |
| Q.eff | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |
| thre.cof | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be peaked as a cofactor. Default = 3. |
| win.cof | Numeric value in centi-Morgan representing the minimum distance between two selected cofactors. Default = 50. |
| N.cim | Numeric value specifying the number of time the CIM analysis is repeated. Default = 1. |

| | |
|------------|---|
| window | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 20. |
| thre.QTL | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be selected as QTL. Default = 3. |
| win.QTL | Numeric value in centi-Morgan representing the minimum distance between two selected QTLs. Default = 20. |
| backward | Logical value. If backward = TRUE, the function performs a backward elimination on the list of selected QTLs. Default = TRUE. |
| alpha.bk | Numeric value indicating the significance level for the backward elimination. Terms with p-values above this value will iteratively be removed. Default = 0.05. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |
| verbose | Logical value indicating if the progresses of the CV should be printed. Default = TRUE. |
| output.loc | Path where a folder will be created to save the results. |

Details

For details on the MPP QTL detection models see [mpp_SIM](#) documentation. The CV scheme is adapted from Utz et al. (2000) to the MPP context. A single CV run works like that:

1. Generation of a k-fold partition of the data. The partition is done within crosses. Each cross is divided into k subsets. Then for the kth repetition, the kth subset is used as validation set, the rest goes into the training set.
2. For the kth repetition, utilization of the training set for cofactor selection and multi-QTL model determination ([mpp_SIM](#) and [mpp_CIM](#)). If backward = TRUE, the final list of QTLs is tested simultaneously using a backward elimination ([mpp_back_elim](#)).
3. Use the list of detected QTLs in the training set to calculate the proportion of genetic variance explained by all detected QTLs in the training set ($p.ts = R2.ts/h2$). Where $R2.ts$ is the adjusted R squared and $h2$ is the average within cross heritability (her). By default, her = 1, which mean that

For each single QTL effect, difference partial R squared are also calculated. Difference R squared are computed by doing the difference between a model with all QTLs and a model without the ith position. For details about R squared computation and adjustment look at [QTL_R2](#).

4. Use the estimates of the QTL effects in the training set (B.ts) to predict the phenotypic values of the validation set. $y.pred.vs = X.vs * B.ts$. Computes the predicted R squared in the validation set using the squared Pearson correlation coefficient between the real values (y.vs) and the predicted values (y.pred.vs). $R2.vs = \text{cor}(y.ts, y.pred.ts)^2$. Then the predicted genetic variance in the validation set (p.vs) is equal to $p.vs = R2.vs/h2$. For heritability correction, the user can provide a single value for the average within cross heritability or a vector specifying each within cross heritability. By default, her = 1, which means that the results represent the proportion of phenotypic variance explained (predicted) in the training (validation) sets.

The predicted R squared is computed per cross and then averaged at the population level (p.ts). Both results are returned. Partial QTL predicted R squared are also calculated using the difference between the predicted R squared using all QTL and the predicted R squared without QTL i. The bias between p.ts and p.vs is calculated as $\text{bias} = 1 - (p.vs/p.ts)$.

Value

List containing the following results items:

| | |
|--------------|---|
| CV_res | Data.frame containing for each CV run: 1) the number of detected QTL; 2) the proportion of explained genetic variance in the TS (p.ts); 3) the proportion of predicted genetic variance in the VS (p.vs) at the population level (average of within cross prediction); the bias between p.ts and p.vs (bias = 1-(p.vs/p.ts)). |
| p.vs.cr | Matrix containing the within cross p.vs for each CV run. |
| QTL | Data.frame containing: 1) the list of QTL position detected at least one time during the entire CV process; 2) the number of times the position has been detected; 3) the average partial p.ts of the QTL position; 4) the average partial p.vs of the QTL position; 5) the average partial bias of the QTL position. |
| QTL.profiles | Data.frame -log10(p-value) QTL profiles of the different CV runs. |

The results elements return as R object are also saved as text files at the specified output location (output.loc). A transparency plot of the CV results (plot.pdf) is also saved.

Author(s)

Vincent Garin

References

Utz, H. F., Melchinger, A. E., & Schon, C. C. (2000). Bias and sampling error of the estimated proportion of genotypic variance explained by quantitative trait loci determined from experimental data in maize using cross validation and validation with independent samples. *Genetics*, 154(4), 1839-1849.

See Also

[mpp_back_elim](#), [mpp_CIM](#), [mpp_perm](#), [mpp_SIM](#), [QTL_R2](#)

Examples

```
## Not run:

data(mppData)

# Specify a location where your results will be saved
my.loc <- tempdir()

CV <- mpp_CV(pop.name = "USNAM", trait.name = "ULA", mppData = mppData,
her = .4, Rep = 1, k = 3, verbose = FALSE, output.loc = my.loc)

## End(Not run)
```

mpp_forward

*MPP QTL analysis using forward regression***Description**

Multi-parent population QTL analysis model using a forward regression.

Usage

```
mpp_forward(
  pop.name = "MPP",
  trait.name = "trait1",
  mppData,
  trait = 1,
  Q.eff = "cr",
  ref.par = NULL,
  sum_zero = FALSE,
  threshold = 4,
  window = 30,
  backward = TRUE,
  alpha.bk = 0.05,
  plot.Qprof = FALSE,
  plot.gen.eff = FALSE,
  CI = FALSE,
  drop = 1.5,
  text.size = 18,
  n.cores = 1,
  verbose = TRUE,
  output.loc
)
```

Arguments

| | |
|------------|---|
| pop.name | Character name of the studied population. Default = "MPP". |
| trait.name | Character name of the studied trait. Default = "trait1". |
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| Q.eff | Character expression indicating the assumption concerning the QTL effect: 1) "cr" for cross-specific effects; 2) "par" parental effects; 3) "anc" for an ancestral effects; 4) "biall" for a bi-allelic effects. For more details see mpp_SIM . Default = "cr". |
| ref.par | Optional Character expression defining the parental allele that will be used as reference to calculate the allelic effects of the parental model. For the ancestral model, the ancestral class containing the reference parent will be set as |

| | |
|--------------|---|
| | reference. This option can only be used if the MPP design is composed of a unique connected part. Default = NULL. |
| sum_zero | Optional Logical value specifying if the QTL effect of a parental or an ancestral model should be calculated using the sum to zero constraint. Default = FALSE. |
| threshold | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be considered as significant. Default = 4. |
| window | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 30. |
| backward | Logical value. If backward = TRUE, the function performs a backward elimination on the list of selected QTLs. Default = TRUE. |
| alpha.bk | Numeric value indicating the significance level for the backward elimination. Default = 0.05. |
| plot.Qprof | Logical value. If plot = TRUE, the function will plot the QTL profile last run of the forward regression. Default = FALSE. |
| plot.gen.eff | Logical value. If plot.gen.eff = TRUE, the function will save the decomposed genetic effects per cross/parent. These results can be plotted with the function plot.QTLprof to visualize a genome-wide decomposition of the genetic effects. This plot will be realized on the last run of the forward regression. This functionality is only available for the cross-specific, parental and ancestral models. Default value = FALSE. |
| CI | Logical value. If CI = TRUE, the function will compute a $-\log_{10}(\text{pval})$ drop confidence interval for each QTL using the QTL profile of the last iteration. Default = FALSE. |
| drop | Numeric $-\log_{10}(\text{p-value})$ drop value at the limits of the interval. Default = 1.5. |
| text.size | Numeric value specifying the size of graph axis text elements. Default = 18. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |
| verbose | Logical value indicating if the steps of the procedure should be printed. Default = TRUE. |
| output.loc | Path where a folder will be created to save the results. By default the function uses the current working directory. |

Details

The function runs a full MPP QTL detection using models with different possible assumptions concerning the number of alleles at the QTL position. For more details about the different models, see documentation of the function [mpp_SIM](#). The procedure is the following:

1. Forward regression to determine the a multi-QTL model. The function selects successively QTL positions with $-\log_{10}(\text{pval})$ above the threshold. Those positions are added as cofactors for following detection run. The procedure stop when no more position has a $-\log_{10}(\text{pval})$ above the threshold ([QTL_forward](#)).
2. If backward = TRUE, backward elimination on the final list of detected QTLs.
3. Estimation of the QTL genetic effects and R squared statistics ([QTL_gen_effects](#) and [QTL_R2](#)).

4. If `CI = TRUE`, confidence interval calculation based on a CIM- (composite interval mapping removing all cofactors on the scanned chromosome) of the last run of the forward regression.
5. If `plot.Qprof = TRUE`, plot of the last run of the forward regression using [plot.QTLprof](#).
6. If `plot.gen.eff = TRUE`, plot of the genetic effect distribution along the genome of the last run of the forward regression using [plot.QTLprof](#).

Value

Return:

List containing the following items:

| | |
|--------------------------|---|
| <code>n.QTL</code> | Number of detected QTLs. |
| <code>QTL</code> | <code>Data.frame</code> with QTL positions. |
| <code>R2</code> | List containing R squared statistics of the QTL effects. For details see QTL_R2 output section. |
| <code>QTL.effects</code> | List of QTLs genetic effects. For details see QTL_gen_effects output section. |
| <code>QTL.CI</code> | If <code>CI = TRUE</code> , confidence interval information of the QTLs. |

Some output files are also saved at the specified location (`output.loc`):

1. A QTL report (`QTL_REPORT.txt`) with: 1) the number of detected QTLs; 2) the global R squared statistics; 3) for each QTL, position information (plus confidence interval if `CI = TRUE`) and estimated QTL genetic effects per cross or parents (for details see [QTL_gen_effects](#)).
2. The list of QTL (`QTL.txt`).
3. The QTL R squared statistics (`QTL_R2.txt`) (for details see [QTL_R2](#)).
4. If `CI = TRUE`, the QTL confidence intervals (`QTL_CI.txt`).
5. General results of the QTL detection process: number of QTLs and global adjusted and non-adjusted R squared statistics (`QTL_genResults.txt`).
6. If `plot.Qprof = TRUE`, the plot of the last regression run (`QTL_profile.pdf`). If `plot.gen.eff = TRUE`, plot of the genetic effects per cross or parents (`gen_eff.pdf`) with dashed lines representing the QTL positions. For more details see [plot.QTLprof](#)

Author(s)

Vincent Garin

See Also

[mpp_SIM](#), [plot.QTLprof](#), [QTL_gen_effects](#), [QTL_forward](#), [QTL_R2](#)

Examples

```
## Not run:

data(mppData)

# Specify a location where your results will be saved
my.loc <- "C:/.../..."

# Cross-specific model

USNAM_cr <- mpp_forward(pop.name = "USNAM", trait.name = "ULA",
                        mppData = mppData, plot.gen.eff = TRUE,
                        plot.Qprof = TRUE, CI = TRUE, output.loc = my.loc)

## End(Not run)
```

mpp_perm

QTL significance threshold by permutation

Description

Determination of an empirical null distribution of the QTL significance threshold for a MPP QTL analysis using permutation test (Churchill and Doerge, 1994).

Usage

```
mpp_perm(
  mppData,
  trait = 1,
  Q.eff = "cr",
  N = 1000,
  q.val = 0.95,
  verbose = TRUE,
  n.cores = 1
)
```

Arguments

| | |
|---------|---|
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| Q.eff | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |

| | |
|---------|--|
| N | Number of permutations. Default = 1000. |
| q.val | Single numeric value or vector of desired quantiles from the null distribution. Default = 0.95. |
| verbose | Logical value indicating if progression of the function should be printed. It will not affect the printing of the other functions called by mpp_perm(), especially the printing of asreml(). Default = TRUE. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |

Details

Performs N permutations of the trait data and computes each time a genome-wide QTL profile. For every run, it stores the highest $-\log_{10}(p\text{-val})$. These values can be used to build a null distribution for the QTL significance threshold. Quantile values can be determined from the previous distribution. For more details about the different possible models and their assumptions see [mpp_SIM](#) documentation.

Value

Return:

List with the following object:

| | |
|----------|--|
| max.pval | Vector of the highest genome-wide $-\log_{10}(p\text{-values})$. |
| q.val | Quantile values from the QTL significance threshold null distribution. |
| seed | Numeric vector of random generated seed values for each permutation. |

Author(s)

Vincent Garin

References

Churchill, G. A., & Doerge, R. W. (1994). Empirical threshold values for quantitative trait mapping. *Genetics*, 138(3), 963-971.

See Also

[mpp_SIM](#)

Examples

```
data(mppData)
```

```
Perm <- mpp_perm(mppData = mppData, Q.eff = "cr", N = 5)
```

mpp_proc

MPP QTL analysis

Description

Multi-parent population QTL analysis.

Usage

```
mpp_proc(
  pop.name = "MPP",
  trait.name = "trait1",
  mppData,
  trait = 1,
  Q.eff = "cr",
  plot.gen.eff = FALSE,
  thre.cof = 3,
  win.cof = 50,
  N.cim = 1,
  window = 20,
  thre.QTL = 3,
  win.QTL = 20,
  backward = TRUE,
  alpha.bk = 0.05,
  ref.par = NULL,
  sum_zero = FALSE,
  CI = FALSE,
  drop = 1.5,
  text.size = 18,
  n.cores = 1,
  verbose = TRUE,
  output.loc
)
```

Arguments

| | |
|------------|---|
| pop.name | Character name of the studied population. Default = "MPP". |
| trait.name | Character name of the studied trait. Default = "trait1". |
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| Q.eff | Character expression indicating the assumption concerning the QTL effect: 1) "cr" for cross-specific effects; 2) "par" parental effects; 3) "anc" for an ancestral effects; 4) "biall" for a bi-allelic effects. For more details see mpp_SIM . Default = "cr". |

| | |
|--------------|---|
| plot.gen.eff | Logical value. If plot.gen.eff = TRUE, the function will save the decomposed genetic effects per cross/parent. These results can be plotted with the function plot.QTLprof to visualize a genome-wide decomposition of the genetic effects. This functionality is only available for the cross-specific, parental and ancestral models. Default value = FALSE. |
| thre.cof | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be peaked as a cofactor. Default = 3. |
| win.cof | Numeric value in centi-Morgan representing the minimum distance between two selected cofactors. Default = 50. |
| N.cim | Numeric value specifying the number of time the CIM analysis is repeated. Default = 1. |
| window | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 20. |
| thre.QTL | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be selected as QTL. Default = 3. |
| win.QTL | Numeric value in centi-Morgan representing the minimum distance between two selected QTLs. Default = 20. |
| backward | Logical value. If backward = TRUE, the function performs a backward elimination on the list of selected QTLs. Default = TRUE. |
| alpha.bk | Numeric value indicating the significance level for the backward elimination. Terms with p-values above this value will iteratively be removed. Default = 0.05. |
| ref.par | Optional Character expression defining the parental allele that will be used as reference to compute QTL effects for the parental model. For the ancestral model, the ancestral class containing the reference parent will be set as reference. This option can only be used if the MPP design is composed of a unique connected part. Default = NULL. |
| sum_zero | Optional Logical value specifying if the QTL effect of a parental or an ancestral model should be calculated using the sum to zero constraint. Default = FALSE. |
| CI | Logical value. If CI = TRUE, the function will compute a $-\log_{10}(\text{pval})$ drop confidence interval for each QTL after calculating a CIM- profile (without cofactors on the scanned chromosome). Default = FALSE. |
| drop | Numeric $-\log_{10}(\text{p-value})$ drop value at the limits of the interval. Default = 1.5. |
| text.size | Numeric value specifying the size of graph axis text elements. Default = 18. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |
| verbose | Logical value indicating if the steps of mpp_proc should be printed. Default = TRUE. |
| output.loc | Path where a folder will be created to save the results. |

Details

The function run a full MPP QTL detection using models with different possible assumptions concerning the number of alleles at the QTL position. For more details about the different models, see documentation of the function [mpp_SIM](#). The procedure is the following:

1. Simple interval mapping (SIM) to select cofactor ([mpp_SIM](#)).
2. Composite interval mapping (CIM) with selected cofactors ([mpp_CIM](#)).
3. Optional backward elimination on the list of QTL candidates (backward = TRUE) ([mpp_back_elim](#)).
4. Computation of the QTL genetic effects ([QTL_gen_effects](#)) and proportion of the phenotypic variation explained by the QTLs (R squared) ([QTL_R2](#)).
5. Optional QTL confidence interval computation from a CIM- profile (excluding cofactors on the scanned chromosome) (argument CI=TRUE).

Value

Return:

List containing the following items:

| | |
|-------------|---|
| n.QTL | Number of detected QTLs. |
| cofactors | Data.frame with cofactors positions. |
| QTL | Data.frame with QTL positions. |
| R2 | List containing R squared statistics of the QTL effects. For details see QTL_R2 output section. |
| QTL.effects | List of QTLs genetic effects. For details see QTL_gen_effects output section. |
| QTL.CI | If CI = TRUE, confidence interval information of the QTLs. |

Some output files are also saved at the specified location (`output.loc`):

1. A QTL report (QTL_REPORT.txt) with: 1) the number of detected QTLs; 2) the global R squared statistics; 3) for each QTL, position information (plus confidence interval if CI = TRUE) and estimated QTL genetic effects per cross or parents (for details see [QTL_gen_effects](#)).
2. The SIM and CIM results in a text file (SIM.txt, CIM.txt).
3. The list of cofactors (cofactors.txt).
4. The list of QTL (QTL.txt).
5. The QTL R squared statistics (QTL_R2.txt) (for details see [QTL_R2](#)).
6. If CI = TRUE, the QTL confidence intervals (QTL_CI.txt).
7. General results of the QTL detection process: number of QTLs and global adjusted and non-adjusted R squared statistics (QTL_genResults.txt).
8. The plot of the CIM profile (QTL_profile.pdf) with dotted vertical lines representing the cofactors positions. If `plot.gen.eff = TRUE`, plot of the genetic effects per cross or parents (gen_eff.pdf) with dashed lines representing the QTL positions. For more details see [plot.QTLprof](#)

Author(s)

Vincent Garin

See Also

[mpp_back_elim](#), [mpp_CIM](#), [mpp_perm](#), [mpp_SIM](#), [plot.QTLprof](#), [QTL_gen_effects](#), [QTL_R2](#)

Examples

```
data(mppData)

# Specify a location where your results will be saved
my.loc <- tempdir()

# Cross-specific model
USNAM_cr <- mpp_proc(pop.name = "USNAM", trait.name = "ULA",
                     mppData = mppData, plot.gen.eff = TRUE, CI = TRUE,
                     verbose = FALSE, output.loc = my.loc)
```

mpp_SIM

MPP Simple Interval Mapping

Description

Computes single QTL models along the genome using different models.

Usage

```
mpp_SIM(mppData, trait = 1, Q.eff = "cr", plot.gen.eff = FALSE, n.cores = 1)
```

Arguments

| | |
|--------------|---|
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| Q.eff | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |
| plot.gen.eff | Logical value. If plot.gen.eff = TRUE, the function will save the decomposed genetic effects per cross/parent. These results can be plotted with the function plot.QTLprof to visualize a genome-wide decomposition of the genetic effects. This functionality is only available for the cross-specific, parental and ancestral models. Default value = FALSE. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |

Details

The implemented models vary according to the number of alleles assumed at the QTL position and their origin. Four assumptions for the QTL effect are possible.

Concerning the type of QTL effect, the first option is a cross-specific QTL effects model (`Q.eff = "cr"`). In this model, the QTL effects are assumed to be nested within cross which leads to the estimation of one parameter per cross. The cross-specific model corresponds to the disconnected model described in Blanc et al. 2006.

A second possibility is the parental model (`Q.eff = "par"`). The parental model assumes one QTL effect (allele) per parent that are independent from the genetic background. This means that QTL coming from parent *i* has the same effect in all crosses where this parent is used. This model is supposed to produce better estimates of the QTL due to larger sample size when parents are shared between crosses.

In a connected MPP (`design_connectivity`), if $n_p - 1 < n_c$, where n_p is the number of parents and n_c the number of crosses, the parental model should be more powerful than the cross-specific model because it estimate a reduced number of QTL parameters. This gain in power will be only true if the assumption of constant parental effect through crosses holds. Calculated with HRT assumption, the parental model corresponds to the connected model presented in Blanc et al. (2006).

The third type of model is the ancestral model (`Q.eff = "anc"`). This model tries to use genetic relatedness that could exist between parents. Indeed, the parental model assumes that parent are independent which is not the case. Using genetic relatedness between the parents, it is possible group these parents into a reduced number of ancestral cluster. Parents belonging to the same ancestral group are assumed to transmit the same allele (Jansen et al. 2003; Leroux et al. 2014). The ancestral model estimate therefore one QTL effect per ancestral class. Once again, the theoretical expectation is a gain of QTL detection power by the reduction of the number of parameters to estimate. The HRT ancestral model correspond to the linkage disequilibrium linkage analysis (LDLA) models used by Bardol et al. (2013) or Giraud et al. (2014).

The final possibility is the bi-allelic model (`Q.eff = "biall"`). Bi-allelic genetic predictor are a single vector with value 0, 1 or 2 corresponding to the number of allele copy of the least frequent SNP allele. Relatedness between lines is therefore defined via identical by state (IBS) measurement. This model corresponds to models used for association mapping. For example, it is similar to model B in Wurschum et al. (2012) or association mapping model in Liu et al. (2012).

Value

Return:

| | |
|-----|---|
| SIM | Data.frame of class QTLprof. with five columns : 1) QTL marker names; 2) chromosomes; 3) interger position indicators on the chromosome; 4) positions in centi-Morgan; and 5) $-\log_{10}(p\text{-val})$. And if <code>plot.gen.eff = TRUE</code> , p-values of the cross or parental QTL effects. |
|-----|---|

Author(s)

Vincent Garin

References

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- Meuwissen T and Luo, Z. (1992). Computing inbreeding coefficients in large populations. *Genetics Selection Evolution*, 24(4), 305-313.
- Wurschum, T., Liu, W., Gowda, M., Maurer, H. P., Fischer, S., Schechert, A., & Reif, J. C. (2012). Comparison of biometrical models for joint linkage association mapping. *Heredity*, 108(3), 332-340.

See Also

[plot.QTLprof](#)

Examples

```
# Cross-specific model
#####

data(mppData)

SIM <- mpp_SIM(mppData = mppData, Q.eff = "cr", plot.gen.eff = TRUE)

plot(x = SIM)
plot(x = SIM, gen.eff = TRUE, mppData = mppData, Q.eff = "cr")

# Bi-allelic model
#####
```

```
SIM <- mpp_SIM(mppData = mppData, Q.eff = "biall")

plot(x = SIM, type = "h")
```

MQE_gen_effects

QTL genetic effects multi-QTL effect model

Description

Compute a multi-QTL model with a list of QTL candidates (QTL) and return the decomposed QTL genetic effects per cross or per parents. The list of QTL can be of different types (cross-specific, parental, ancestral or bi-allelic). The type of QTL effects are specified in the vector `Q.eff`.

Usage

```
MQE_gen_effects(mppData = NULL, trait = 1, QTL = NULL, Q.eff, ref.par = NULL)
```

Arguments

| | |
|----------------------|--|
| <code>mppData</code> | An object of class <code>mppData</code> |
| <code>trait</code> | Numerical or character indicator to specify which trait of the <code>mppData</code> object should be used. Default = 1. |
| <code>QTL</code> | Vector of character markers positions names. Default = <code>NULL</code> . |
| <code>Q.eff</code> | Character vector indicating for each QTL position the type of QTL effect among: "cr", "par", "anc" and "biall". For details look at mpp_SIM . |
| <code>ref.par</code> | Optional Character expression defining the parental allele that will be used as reference for the parental model. For the ancestral model, the ancestral class containing the reference parent will be set as reference. This option can only be used if the MPP design is composed of a unique connected part. Default = <code>NULL</code> . |

Details

This function computes for each QTL position the genetic effects of the cross, parental, ancestral or SNP allele components. For the cross-specific model (`Q.eff = "cr"`), the genetics effects represent the substitution effect of an single allele from the parent 2 (or B) with respect to an allele coming from the parent 1 or A. All effects are given in absolute value with the parent that carry the positive allele.

For the parental and the ancestral model (`Q.eff = "par"` or `"anc"`), the reference allele is defined per interconneted part. The most frequent parental (ancestral) allele is set as reference. Effects of the other alleles are estimated as deviation with respect to the reference. For more details about reference definition see [QTL_gen_effects](#) and [design_connectivity](#).

For the bi-allelic model (`Q.eff = "biall"`), the genetic effects represent the effects of a single allele copy of the least frequent allele.

Value

Return:

`results` List of `data.frame` (one per QTL) containing the following information:

1. QTL genetic effects per cross or parent.
2. Standard error of the QTL effects.
3. Test statistics of the effects (t-test or Wald statistic).
4. P-value of the test statistics.
5. Significance of the QTL effects.
6. For cross-specific model, parent with the positive additive effects.
7. For parental and ancestral model, indicator of connected part of the design and reference.
8. Allele scores of the parents if `geno.par` is non NULL in the `mppData` object.

Author(s)

Vincent Garin

See Also

[MQE_proc](#), [mpp_SIM](#), [QTL_gen_effects](#), [design_connectivity](#)

Examples

```
data(mppData)

SIM <- mpp_SIM(mppData = mppData)
QTL <- QTL_select(SIM)

QTL.eff <- MQE_gen_effects(mppData = mppData, QTL = QTL[, 1],
                           Q.eff = c("anc", "par", "biall"))
```

Description

Build multi-QTL effects (MQE) models in which different QTL effects (cross-specific, parental, ancestral or bi-allelic) can be assumed at different loci.

Usage

```
MQE_proc(
  pop.name = "MPP_MQE",
  trait.name = "trait1",
  mppData = NULL,
  trait = 1,
  Q.eff,
  ref.par = NULL,
  threshold = 4,
  window = 30,
  backward = TRUE,
  alpha.bk = 0.05,
  plot.MQE = FALSE,
  CI = FALSE,
  drop = 1.5,
  n.cores = 1,
  verbose = TRUE,
  output.loc
)
```

Arguments

| | |
|------------|--|
| pop.name | Character name of the studied population. Default = "MPP_MQE". |
| trait.name | Character name of the studied trait. Default = "trait1". |
| mppData | An object of class mppData. |
| trait | Numerical or character indicator to specify which trait of the mppData object should be used. Default = 1. |
| Q.eff | Character vector of possible QTL effects the user want to test. Elements of Q.eff can be "cr", "par", "anc" or "biall". For details look at mpp_SIM . |
| ref.par | Optional Character expression defining the parental allele that will be used as reference to calculate the allelic effects of the parental model. For the ancestral model, the ancestral class containing the reference parent will be set as reference. This option can only be used if the MPP design is composed of a unique connected part. Default = NULL. |
| threshold | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be considered as significant. Default = 4. |
| window | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 30. |
| backward | Logical value. If backward = TRUE, the function performs a backward elimination on the list of selected QTLs. Default = TRUE. |
| alpha.bk | Numeric value indicating the significance level for the backward elimination. Default = 0.05. |
| plot.MQE | Logical value. If plot.MQE = TRUE, the function will plot the last run of the MQE model determination. Default = FALSE. |

| | |
|------------|--|
| CI | Logical value. If CI = TRUE, the function will compute a $-\log_{10}(\text{pval})$ drop confidence interval for each QTL using the QTL profile of the last iteration. Default = FALSE. |
| drop | Numeric $-\log_{10}(\text{p-value})$ drop value at the limits of the interval. Default = 1.5. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |
| verbose | Logical value indicating if the steps of MQE_proc should be printed. Default = TRUE. |
| output.loc | Path where a folder will be created to save the results. |

Details

The possible QTL effect that the user wants to allow must be specified in `Q.eff`. The procedure is the following:

1. Forward regression to determine a MQE model with different possible assumptions for the QTL effect at different loci. The function use.
2. Optional backward elimination (`backward = TRUE`) on the final list of detected QTLs.
3. Estimation of the QTL genetic effects and R squared statistics.
4. If `plot.MQE = TRUE`, plot of the last CIM run of the forward regression.
5. If CI = TRUE, confidence interval calculation based on a CIM- (CIM without cofactor on the selected chromosome) of the last run of the forward regression.

Value

Return:

List containing the following items:

| | |
|-------------|---|
| n.QTL | Number of detected QTLs. |
| QTL | Data.frame with QTL positions. |
| R2 | list containing R squared statistics of the QTL effects. for details see QTL_R2 . |
| QTL.effects | List of genetic effects per QTL. |
| QTL.CI | If CI = TRUE, confidence interval information of the QTLs. |

Some output files are also saved at the location specified (`output.loc`):

1. A QTL report (QTL_REPORT.txt) with: 1) the number of detected QTLs; 2) the global R squared statistics; 3) for each QTL, position information and estimated QTL genetic effect per cross or parents.
2. The list of QTLs (QTL.txt).
3. The QTL R squared statistics (QTL_R2.txt) (for details see [QTL_R2](#)).
4. General results of the QTL detection process: Number of QTL and global adjusted and non-adjusted R squared statistics. (QTL_genResults.txt).
5. if `plot.MQE = TRUE`, a plot of the last QTL detection run profile (plot_MQE.pdf).
6. If CI = TRUE, the QTL confidence intervals (QTL_CI.txt).

Author(s)

Vincent Garin

See Also[mpp_SIM](#), [MQE_gen_effects](#)**Examples**

```
## Not run:

data(mppData)

# Specify a location where your results will be saved
my.loc <- tempdir()

MQE <- MQE_proc(pop.name = "USNAM", trait.name = "ULA", mppData = mppData,
                Q.eff = c("par", "biall"), verbose = FALSE,
                output.loc = my.loc)

## End(Not run)
```

parent_cluster.mppData

Parent clustering for mppData objects

Description

Integrate the parent clustering information to the mppData object. The parent clustering is necessary to compute the ancestral model. If the parent clustering step is skipped, the ancestral model can not be used but the other models (cross-specific, parental, and bi-allelic) can still be computed.

Usage

```
parent_cluster.mppData(mppData, par.clu = NULL)
```

Arguments

| | |
|---------|---|
| mppData | An object of class mppData. the mppData must have been processed using: create.mppData , QC.mppData , IBS.mppData , and IBD.mppData . |
| par.clu | Interger matrix representing the results of a parents genotypes clustering. The columns represent the parental lines and the rows the markers. The columns names must be the same as the parents list of the mppData object. The rownames must be the same as the map marker list of the mppData object. At a particular position, parents with the same value are assumed to inherit from the same ancestor. for more details, see par_clu . Default = NULL. |

Details

At a single marker position, two parents can be grouped into a similar ancestral classes if we assume that they receive there allele from a common ancestor. The parent clustering information (`par.clu`) describe parental relatedness and which parent belong to which ancestral group. For example, at marker *i*, we could have five parents (pA, pB, pC, pD, pE) and the following clustering information (1, 2, 1, 2, 3). This means that pA and pC received their allele from the same ancestor (A1). pB and pD also have a shared ancestor (A2) who is different from (A1). And pE was not included in any group and can be seen as an independent ancestral group (A3).

The parent clustering information is provided via `par.clu`. It is an interger matrix with markers in row and parents in columns. At a particular marker position, parents with the same value are assumed to inherit from the same ancestor. for more details, see [par.clu](#).

The marker positions that are considered as monomorphic given the parent clustering information are set back to one allele per parent to still allow the computation of the QTL allelic effect at those positions later.

The parent clustering can be performed using the R package 'clusthaplo' that can be found there: <https://cran.r-project.org/src/contrib/Archive/clusthaplo/>. The 'clusthaplo' option is not integrated in this version of mppR. However, a version of mppR with function calling clusthaplo can be found on github <https://github.com/vincentgarin/mppR> (branch master).

Value

An increased mppData object containing the the same elements as the mppData object provided as argument and the following new elements:

| | |
|-----------------------|--|
| <code>par.clu</code> | Integer matrix with rows representing markers and columns corresponding to the parents. At a single marker position, parents with the same value were clustered in the same ancestral group. |
| <code>n.anc</code> | Average number of ancestral clusters along the genome. |
| <code>mono.anc</code> | Positions for which the ancestral clustering was monomorphic. |

Author(s)

Vincent Garin

See Also

[create.mppData](#), [QC.mppData](#), [IBS.mppData](#), [IBD.mppData](#), [par.clu](#)

Examples

```
data(mppData_init)
data(par.clu)

mppData <- QC.mppData(mppData_init)
mppData <- IBS.mppData(mppData = mppData)

mppData <- IBD.mppData(mppData = mppData, type = 'RIL',
                      type.mating = 'selfing')
```

```
mppData <- parent_cluster.mppData(mppData = mppData, par.clu = par_clu)
```

| | |
|---------|----------------------------|
| par_clu | <i>Parental clustering</i> |
|---------|----------------------------|

Description

Example of parental clustering object.

Usage

```
data(par_clu)
```

Details

The parent clustering matrix specifies at each genome position the results of a parent clustering into ancestral groups. The matrix rows represent the position and the columns correspond to each parent. For example, if we have at the *i*th row (1, 2, 3, 2, 1), this means that parents 1 and 5 are in the same group, that 2 and 4 are in another one and that the third parent was assigned to any group.

See Also

```
parent\_cluster.mppData
```

Examples

```
data(par_clu)
```

| | |
|--------------|-------------------------|
| plot.QTLprof | <i>plot QTL profile</i> |
|--------------|-------------------------|

Description

Plots the $-\log_{10}(\text{p-val})$ profile of a QTL analysis or a genome-wide genetic effect plot using package `ggplot2`.

Usage

```
## S3 method for class 'QTLprof'
plot(
  x,
  gen.eff = FALSE,
  mppData,
  Q.eff,
  QTL = NULL,
  type = "l",
  main = "QTL profile",
  threshold = 3,
  text.size = 18,
  ...
)
```

Arguments

| | |
|-----------|--|
| x | Object of class QTLprof returned by the function mpp_SIM or mpp_CIM . |
| gen.eff | Logical. Specify the type of plot. If gen.eff = FALSE, standard QTL profile. If gen.eff = TRUE, genome-wide genetic effect plot. In that case, the QTLprof object in x must have been calculated with argument plot.gen.eff = TRUE. Default = FALSE. |
| mppData | An object of class mppData. Only required if gen.eff = TRUE. |
| Q.eff | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental effects; 3) "anc" for ancestral effects. Only required if gen.eff = TRUE |
| QTL | Optional argument. List of QTL positions. Object of class QTLlist representing a list of selected position obtained with the function QTL_select or two columns numeric matrix with the chromosome and the position in cM. These positions will be drawn on the graph. Default = NULL. |
| type | Character expression indicating the type of plot should be drawn: "l" for lines , "h" for vertical bar. Default = "l". |
| main | Title of the graph. Default = "QTL profile". |
| threshold | Numeric QTL significance threshold value draw on the plot. Default = 3. |
| text.size | Numeric value specifying the size of graph axis text elements. Default = 18. |
| ... | Ignored. |

Details

The user can plot regular QTL profiles (gen.eff = FALSE) with $-\log_{10}(p\text{-val})$ plotted against genetic position or genome-wide genetic effects plots (gen.eff = TRUE). To plot the genome-wide genetic effects, the SIM and CIM QTL profile must have been computed with `plot.gen.eff = TRUE`.

The genome-wide genetic effects plots is a visualisation of the significance of the QTL effect per cross or per parents along the genome. For a cross-specific QTL profile (Q.eff = "cr"): Blue color means that the allele coming from parent A(1) increases the phenotypic value and parent B(2) decreases it and red that parent A(1) decreases the trait and parent B(2) increases it.

For a parental (Q.eff = "par") or an ancestral model (Q.eff = "anc"), the results are given per parents. The significance of the effect must be interpreted as a deviation with respect to the reference of each connected part. The reference allele is always defined as the most frequent one. Blue (Red) colour means a significative negative (positive) effect with respect to the reference of the connected part.

The reference parental allele can change at each position according to the segregation rate. The parent are plotted from the top to the bottom according to the number of time their allele is set as reference. Therefore interpretation of the genetic effect plot should be done with caution. In that case, the plot should be taken as a rough indication of the signal distribution.

The colour intensity increase with the significance of the effect (p-val). The p-val are transformed into a color code (z). If p-val \in [0.00001; 0.05]: $z = -\log_{10}(\text{p-val})$. If p-val < 0.00001: $z=6$. This scale allows to plot only the significant effects (p-val \leq 0.05) and prevent the color scale to be determine by highly significant values (p-val < 0.00001). The colours red (positive) and blue (negative) correspond to the sign of the QTL effect.

For both type of plot, the user can pass a list of cofactors or QTL position to the argument QTL. These positions will be drawn on the graph using dotted lines.

Author(s)

Vincent Garin

See Also

[mpp_SIM](#), [mpp_CIM](#), [QTL_select](#)

Examples

```
data(mppData)

SIM <- mpp_SIM(mppData = mppData)
QTL <- QTL_select(SIM)
plot(x = SIM, QTL = QTL)

SIM <- mpp_SIM(mppData = mppData, Q.eff = "cr", plot.gen.eff = TRUE)
QTL <- QTL_select(SIM)
plot(x = SIM, gen.eff = TRUE, mppData = mppData, Q.eff = "cr", QTL = QTL)
```

plot_allele_eff_GE *plot of genome wide QTL allelic effect significance*

Description

Plot of the genome wide significance of the QTL allelic effects in multiple environments.

Usage

```
plot_allele_eff_GE(
  mppData,
  nEnv,
  EnvNames,
  Qprof,
  Q.eff = "par",
  QTL = NULL,
  ref_par = NULL,
  main = "QTL genetic effects plot",
  text.size = 18
)
```

Arguments

| | |
|------------------------|--|
| <code>mppData</code> | An object of class <code>mppData</code> . |
| <code>nEnv</code> | Numeric number of environment or trait. |
| <code>EnvNames</code> | character expression indicating the environment or trait labels. |
| <code>Qprof</code> | object obtained with function mppGE_SIM , mppGE_CIM , |
| <code>Q.eff</code> | one of "cr", "par", "anc" or "biall". For the moment only "par" is available. |
| <code>QTL</code> | Optional argument. Object of class <code>QTLlist</code> representing a list of selected position obtained with the function QTL_select or a vector of character marker or in between marker positions names. These positions will be plotted on the graph. Default = <code>NULL</code> . |
| <code>ref_par</code> | Charater specifying the reference parent. Default = <code>NULL</code> . |
| <code>main</code> | Title of the graph. Default = "QTL genetic effects plot". |
| <code>text.size</code> | Numeric value specifying the size of graph axis text elements. Default = 18. |

Author(s)

Vincent Garin

See Also

[mppGE_CIM](#), [mppGE_SIM](#)

Examples

```
data(mppData_GE)

SIM <- mppGE_SIM(mppData = mppData_GE, trait = c('DMY_CIAM', 'DMY_TUM'))

Qpos <- QTL_select(Qprof = SIM, threshold = 3, window = 50)

plot_allele_eff_GE(mppData = mppData_GE, nEnv = 2, EnvNames = c('CIAM', 'TUM'),
  Qprof = SIM, Q.eff = 'par', QTL = Qpos, text.size = 14)
```

plot_QxEC

*plot QTLxEC effect***Description**

Plot allowing the visualization of the QTL parental allelic effect variation given an environmental covariate (EC). The function plot the sensitivity curve of the parent allelic effects.

Usage

```
plot_QxEC(
  Qeff,
  EC,
  env_id = NULL,
  QTL,
  sign_thre = 0.05,
  EC_id = "EC",
  trait_id = "trait",
  main = "QTLxEC",
  col_vec = NULL,
  text_size = 14
)
```

Arguments

| | |
|-----------|--|
| Qeff | output from the function QTL_effect_main_QxEC . |
| EC | Numeric matrix containing the EC values of a single covariate with environments as row and EC as column. |
| env_id | Character vector specifying the environment names. By default, E1, ... En |
| QTL | Numeric value indicating which QTL to plot |
| sign_thre | Numeric value indicating the significance threshold for a parent sensitivity slope to be plotted. Default = 0.05 |
| EC_id | Character string indicating the name of the environmental covariate. Default = 'EC'. |
| trait_id | Character string indicating the name of the trait. Default = 'trait'. |
| main | Character string title of the plot. Default = 'QTLxEC' |
| col_vec | Character vector specifying colors for the parent sensitivity lines. Default = NULL |
| text_size | Numerical value specifying the size of the text in the plot. Default = 14. |

Value

QTLxEC sensitivity plot

Author(s)

Vincent Garin

Examples

```
## Not run:

data(mppData_GE)

Qpos <- c("PZE.105068880", "PZE.106098900")

EC <- matrix(c(180, 310, 240, 280), 4, 1)
rownames(EC) <- c('CIAM', 'TUM', 'INRA', 'KWS')
colnames(EC) <- 'cum_rain'

Qeff <- QTL_effect_main_QxEC(mppData = mppData_GE,
                             trait = c('DMY_CIAM', 'DMY_TUM', 'DMY_INRA_P', 'DMY_KWS'),
                             env_id = c('CIAM', 'TUM', 'INRA', 'KWS'),
                             QTL = Qpos, EC = EC)

p1 <- plot_QxEC(Qeff, EC = EC, env_id = c('CIAM', 'TUM', 'INRA', 'KWS'),
                QTL = 2, EC_id = 'cum rain', trait_id = 'DMY')

## End(Not run)
```

print.summary.mppData *Print summary.mppData object*

Description

Print summary.mppData object

Usage

```
## S3 method for class 'summary.mppData'
print(x, ...)
```

Arguments

| | |
|-----|---------------------------------|
| x | object of class summary.mppData |
| ... | Ignored. |

Examples

```
data(mppData)
sum.mppData <- summary(mppData)
print(sum.mppData)
```

```
print.summary.QeffRes  Print summary.QeffRes object
```

Description

Print summary.QeffRes object

Usage

```
## S3 method for class 'summary.QeffRes'  
print(x, ...)
```

Arguments

| | |
|-----|---------------------------------|
| x | object of class summary.QeffRes |
| ... | Ignored. |

Examples

```
data(mppData)  
SIM <- mpp_SIM(mppData)  
QTL <- QTL_select(SIM)  
QTL.effects <- QTL_gen_effects(mppData = mppData, QTL = QTL, Q.eff = "cr")  
sum.QeffRes <- summary(QTL.effects)  
print(sum.QeffRes)
```

```
print.summary.QR2Res  Print summary.QR2Res object
```

Description

Print summary.QR2Res object

Usage

```
## S3 method for class 'summary.QR2Res'  
print(x, ...)
```

Arguments

| | |
|-----|--------------------------------|
| x | object of class summary.QR2Res |
| ... | Ignored. |

Examples

```
data(mppData)
SIM <- mpp_SIM(mppData)
QTL <- QTL_select(SIM)
Q_R2 <- QTL_R2(mppData = mppData, QTL = QTL, Q.eff = "cr")
sum.QR2Res <- summary(Q_R2)
print(sum.QR2Res)
```

QC.mppData

Quality control for mppData objects

Description

Perform different operations of quality control (QC) on the marker data of an mppData object.

Usage

```
QC.mppData(
  mppData,
  mk.miss = 0.1,
  gen.miss = 0.25,
  n.lim = 15,
  MAF.pop.lim = 0.05,
  MAF.cr.lim = NULL,
  MAF.cr.miss = TRUE,
  MAF.cr.lim2 = NULL,
  verbose = TRUE,
  n.cores = 1
)
```

Arguments

| | |
|-------------|--|
| mppData | An object of class mppData formed with create.mppData . |
| mk.miss | Numeric maximum marker missing rate at the whole population level comprised between 0 and 1. Default = 0.1. |
| gen.miss | Numeric maximum genotype missing rate at the whole population level comprised between 0 and 1. Default = 0.25. |
| n.lim | Numeric value specifying the minimum cross size. Default = 15. |
| MAF.pop.lim | Numeric minimum marker minor allele frequency at the population level. Default = 0.05. |
| MAF.cr.lim | Numeric vector specifying the critical within cross MAF. Marker with a problematic segregation rate in at least one cross is either set as missing within the problematic cross (MAF.cr.miss = TRUE), or remove from the marker matrix (MAF.cr.miss = FALSE). For default value see details. |

| | |
|-------------|---|
| MAF.cr.miss | Logical value specifying if maker with a too low segregation rate within cross (MAF.cr.lim) should be put as missing (MAF.cr.miss = TRUE) or discarded (MAF.cr.miss = FALSE). Default = TRUE. |
| MAF.cr.lim2 | Numeric. Alternative option for marker MAF filtering. Only markers segregating with a MAF larger than MAF.cr.lim2 in at least one cross will be kept for the analysis. Default = NULL. |
| verbose | Logical value indicating if the steps of the QC should be printed. Default = TRUE. |
| n.cores | Numeric. Specify here the number of cores you like to use. Default = 1. |

Details

The different operations of the quality control are the following:

1. Remove markers with more than two alleles.
2. Remove markers that are monomorphic or fully missing in the parents.
3. Remove markers with a missing rate higher than mk.miss.
4. Remove genotypes with more missing markers than gen.miss.
5. Remove crosses with less than n.lim genotypes.
6. Keep only the most polymorphic marker when multiple markers map at the same position.
7. Check marker minor allele frequency (MAF). Different strategy can be used to control marker MAF:
 - A) A first possibility is to filter marker based on MAF at the whole population level using MAF.pop.lim, and/or on MAF within crosses using MAF.cr.lim. The user can give the its own vector of critical values for MAF within cross using MAF.cr.lim. By default, the within cross MAF values are defined by the following function of the cross-size n.ci: $MAF(n.ci) = 0.5$ if $n.ci \in [0, 10]$ and $MAF(n.ci) = (4.5/n.ci) + 0.05$ if $n.ci > 10$. This means that up to 10 genotypes, the critical within cross MAF is set to 50 decreases when the number of genotype increases until 5. If the within cross MAF is below the limit in at least one cross, then marker scores of the problematic cross are either put as missing (MAF.cr.miss = TRUE) or the whole marker is discarded (MAF.cr.miss = FALSE). By default, MAF.cr.miss = TRUE which allows to include a larger number of markers and to cover a wider genetic diversity.
 - B) An alternative is to select only markers that segregate in at least on cross at the MAF.cr.lim2 rate.

Value

a filtered mppData object containing the the same elements as [create.mppData](#) after filtering. It contains also the following new elements:

| | |
|---------|---|
| geno.id | Character vector of genotypes identifiers. |
| ped.mat | Four columns data.frame: 1) the type of genotype: "offspring" for the last generation and "founder" for the genotypes above the offspring in the pedigree; 2) the genotype indicator; 3-4) the parent 1 (2) of each line. |

| | |
|---------------------------|--|
| <code>geno.par.clu</code> | Parent marker matrix without monomorphic or completely missing markers. |
| <code>haplo.map</code> | Genetic map corresponding to the list of marker of the <code>geno.par.clu</code> object. |
| <code>parents</code> | List of parents. |
| <code>n.cr</code> | Number of crosses. |
| <code>n.par</code> | Number of parents. |
| <code>rem.mk</code> | Vector of markers that have been removed. |
| <code>rem.geno</code> | Vector of genotypes that have been removed. |

Author(s)

Vincent Garin

See Also

[create.mppData](#)

Examples

```
data(mppData_init)

mppData <- QC.mppData(mppData = mppData_init, n.lim = 15, MAF.pop.lim = 0.05,
                     MAF.cr.miss = TRUE, mk.miss = 0.1,
                     gen.miss = 0.25, verbose = TRUE)
```

QTL_effect_GE

MPP GxE QTL genetic effects

Description

Estimate the QTL parental allelic effects within environment. The estimation is performed using an exact mixed model with function from R package nlme. The significance of the allele effect is assessed using a Wald test.

Usage

```
QTL_effect_GE(
  mppData,
  trait,
  VCOV = "UN",
  ref_par = NULL,
  QTL = NULL,
  maxIter = 100,
  msMaxIter = 100
)
```

Arguments

| | |
|------------------------|--|
| <code>mppData</code> | An object of class <code>mppData</code> . |
| <code>trait</code> | Character vector specifying which traits (environments) should be used. |
| <code>VCOV</code> | VCOV Character expression defining the type of variance covariance structure used. 'CS' for compound symmetry assuming a unique genetic covariance between environments. 'CSE' for cross-specific within environment error term. 'CS_CSE' for both compound symmetry plus cross-specific within environment error term. 'UN' for unstructured environmental variance covariance structure allowing a specific genotypic covariance for each pair of environments. Default = 'UN' |
| <code>ref_par</code> | Optional Character expression defining the parental allele that will be used as reference for the parental model. Default = NULL |
| <code>QTL</code> | Object of class <code>QTLlist</code> representing a list of selected marker positions obtained with the function <code>QTL_select()</code> or a vector of character marker positions names. Default = NULL. |
| <code>maxIter</code> | maximum number of iterations for the lme optimization algorithm. Default = 100. |
| <code>msMaxIter</code> | maximum number of iterations for the optimization step inside the lme optimization. Default = 100. |

Details

The estimated model is the following:

$$\underline{y}_{icj} = E_j + C_{cj} + \sum_{q=1}^{n_{QTL}} x_{iqp} * \beta_{pj} + \underline{GE}_{icj} + \underline{e}_{icj}$$

For further details see the vignette.

Value

Return:

| | |
|-------------------|---|
| <code>Qeff</code> | List of data.frame (one per QTL) containing the following information: <ol style="list-style-type: none"> 1. QTL genetic effects 2. Standard error of the QTL effects. 3. Wald statistics of the effects. 4. P-value of the test statistics. 5. Significance of the QTL effects. |
|-------------------|---|

Author(s)

Vincent Garin

References

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2021). nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-152, <URL: <https://CRAN.R-project.org/package=nlme>>.

Examples

```
data(mppData_GE)

Qpos <- c("PZE.105068880", "PZE.106098900")

Qeff <- QTL_effect_GE(mppData = mppData_GE, trait = c('DMY_CIAM', 'DMY_TUM'),
                     QTL = Qpos)

Qeff
```

| | |
|---------------------|--|
| QTL_effect_main_QEI | <i>Main and QTL by environment interaction model</i> |
|---------------------|--|

Description

The function estimate a QTL model where each parental QTL allelic effect is decomposed into a main effect and a QTL by environment effect (QEI). It allows the user to determine which parental allelic effects have a significant interaction with the environment.

Usage

```
QTL_effect_main_QEI(
  mppData,
  trait,
  env_id = NULL,
  ref_env = NULL,
  ref_par = NULL,
  VCOV = "UN",
  QTL = NULL,
  maxIter = 100,
  msMaxIter = 100
)
```

Arguments

| | |
|----------------------|---|
| <code>mppData</code> | An object of class <code>mppData</code> . |
| <code>trait</code> | Character vector specifying which traits (environments) should be used. |
| <code>env_id</code> | Character vector specifying the environment names. By default, E1, ... En |
| <code>ref_env</code> | Optional Character expression defining the environment that will be used as reference for the parental model. By default, the last environment is set as reference. |
| <code>ref_par</code> | Optional Character expression defining the parental allele that will be used as reference for the parental model. Default = NULL |

| | |
|-----------|--|
| VCOV | VCOV Character expression defining the type of variance covariance structure used. 'CS' for compound symmetry assuming a unique genetic covariance between environments. 'CSE' for cross-specific within environment error term. 'CS_CSE' for both compound symmetry plus cross-specific within environment error term. 'UN' for unstructured environmental variance covariance structure allowing a specific genotypic covariance for each pair of environments. Default = 'UN' |
| QTL | Object of class QTLlist representing a list of selected marker positions obtained with the function QTL_select() or a vector of character marker positions names. Default = NULL. |
| maxIter | maximum number of iterations for the lme optimization algorithm. Default = 100. |
| msMaxIter | maximum number of iterations for the optimization step inside the lme optimization. Default = 100. |

Details

The function estimate the following model

$$y_{icj} = E_j + C_{c_j} + \sum_{q=1}^{n_{QTL}} x_{i_q p} * (\alpha_p + \beta_{pj}) + GE_{ijc} + e_{ijc}$$

where the QTL effect is decomposed into α_p that represent the main parental allelic effect across environments and β_{pj} which is the QEI effect. allelic effects must be interpreted as deviation with respect to the reference parent ('ref_par') in the reference environment ('ref_env'). By default the reference parent is the one with the highest allelic frequency (e.g. central parent in a NAM population).

The estimation is performed using an exact mixed model with function from R package nlme. The significance of the allele effect is assessed using a Wald test.

Value

Return:

List with one data.frame per QTL that contains the following elements:

1. To be filled
2. To be filled
3. Significance of the parent main effect expressed as the -log10(p-val)
4. Significance of the parent QTLxE effect expressed as the -log10(p-val)

Author(s)

Vincent Garin

References

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2021). nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-152, <URL: <https://CRAN.R-project.org/package=nlme>>.

Examples

```
## Not run:

data(mppData_GE)

Qpos <- c("PZE.105068880", "PZE.106098900")

Qeff <- QTL_effect_main_QEI(mppData = mppData_GE,
                           trait = c('DMY_CIAM', 'DMY_TUM', 'DMY_INRA_P', 'DMY_KWS'),
                           env_id = c('CIAM', 'TUM', 'INRA', 'KWS'),
                           QTL = Qpos)

Qeff

## End(Not run)
```

| | |
|----------------------|---|
| QTL_effect_main_QxEC | <i>Estimation of a model with main and QTL by environmental sensitivity terms</i> |
|----------------------|---|

Description

After estimating which parental allelic effects have a significant interaction with the environment (QEI), the function extends the model for the allelic effect with a significant QEI to characterize this interaction in terms of sensitivity to (a) specific environmental covariate(s).

Usage

```
QTL_effect_main_QxEC(
  mppData,
  trait,
  env_id = NULL,
  ref_env = NULL,
  ref_par = NULL,
  VCOV = "UN",
  QTL = NULL,
  thre_QTL = 2,
  EC,
  Qmain_QEI = NULL,
  maxIter = 100,
  msMaxIter = 100
)
```

Arguments

| | |
|-----------|--|
| mppData | An object of class mppData. |
| trait | Character vector specifying which traits (environments) should be used. |
| env_id | Character vector specifying the environment names. By default, E1, ... En |
| ref_env | Optional Character expression defining the environment that will be used as reference for the parental model. By default, the last environment is set as reference. |
| ref_par | Optional Character expression defining the parental allele that will be used as reference for the parental model. By default, the parent with the largest MAF is set as reference. |
| VCOV | VCOV Character expression defining the type of variance covariance structure used. 'CS' for compound symmetry assuming a unique genetic covariance between environments. 'CSE' for cross-specific within environment error term. 'CS_CSE' for both compound symmetry plus cross-specific within environment error term. 'UN' for unstructured environmental variance covariance structure allowing a specific genotypic covariance for each pair of environments. Default = 'UN' |
| QTL | Object of class QTLlist representing a list of selected marker positions obtained with the function QTL_select() or a vector of character marker positions names. Default = NULL. |
| thre_QTL | Numerical value specifying the -log10(p-val) threshold for a parental QTL allele to be considered as significant. By default, thre_QTL = 2, which correspond to a p-value of 0.01. |
| EC | Numeric matrix with environments as row and environmental covariates (EC) as column. The cell i, j of EC specify the value of the jth EC in environment i. |
| Qmain_QEI | results from QTL_effect_main_QEI |
| maxIter | maximum number of iterations for the lme optimization algorithm. Default = 100. |
| msMaxIter | maximum number of iterations for the optimization step inside the lme optimization. Default = 100. |

Details

The function first estimate the parental QTL allele main and QTLxE effect using the function [QTL_effect_main_QEI](#). Optionally the output of [QTL_effect_main_QEI](#) can be passed through the 'Qmain_QEI' argument. The function consider that a parental QTL allele significantly interacts with the environment if its QTLxE term is significant at the 'thre_QTL' level. Thre_QTL is expressed in terms of -log10(p-val). For example, for p-val = 0.01, thre_QTL = -log10(p-val) = 2. Given this information, the effect of the parental QTL allele with a significant QEI are extended like that $\beta_{pj} = EC_j * S_p + l_{pe}$ where EC_j represents the EC value in environment j associated with the sensitivity term S_p . The S_p determines the rate of change of the parental QTL allelic additive effect given an extra unit of EC. Finally, l_{pe} is a residual effect. The fitted model becomes:

$$\underline{y}_{icj} = E_j + C_{cj} + \sum_{q=1}^{n_{QTL}} x_{iqp}(\alpha_p + \beta_{pj}) + x_{iqp}(\alpha_p + EC_j * S_p + l_{pe}) + \underline{GE}_{icj} + \underline{e}_{icj}$$

The estimation is performed using an exact mixed model with function from R package nlme. The significance of S_p is assessed using a Wald test.

Value

Return:

List with one data.frame per QTL that contains the following elements:

1. QTL parent allele main effect expressed as deviation with respect to the reference parent
2. QTL parent allele effect in environment j expressed as deviation with respect to the reference parent
3. Significance of the parent main effect expressed as the $-\log_{10}(\text{p-val})$
4. Significance of the parent QTLxE effect expressed as the $-\log_{10}(\text{p-val})$

Author(s)

Vincent Garin

References

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2021). nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-152, <URL: <https://CRAN.R-project.org/package=nlme>>.

See Also

[QTL_effect_main_QEI](#)

Examples

```
## Not run:

data(mppData_GE)

Qpos <- c("PZE.105068880", "PZE.106098900")

EC <- matrix(c(180, 310, 240, 280), 4, 1)
rownames(EC) <- c('CIAM', 'TUM', 'INRA', 'KWS')
colnames(EC) <- 'cum_rain'

Qeff <- QTL_effect_main_QxEC(mppData = mppData_GE,
                           trait = c('DMY_CIAM', 'DMY_TUM', 'DMY_INRA_P', 'DMY_KWS'),
                           env_id = c('CIAM', 'TUM', 'INRA', 'KWS'),
                           QTL = Qpos, EC = EC)

Qeff

## End(Not run)
```

QTL_forward

*Forward regression QTL model***Description**

Determines a multi-QTL model using a forward regression.

Usage

```
QTL_forward(
  mppData = NULL,
  trait = 1,
  Q.eff,
  threshold = 4,
  window = 30,
  n.cores = 1,
  verbose = TRUE
)
```

Arguments

| | |
|------------------------|--|
| <code>mppData</code> | An object of class <code>mppData</code> |
| <code>trait</code> | Numerical or character indicator to specify which trait of the <code>mppData</code> object should be used. Default = 1. |
| <code>Q.eff</code> | Character vector of possible QTL effects the user want to test. Elements of <code>Q.eff</code> can be "cr", "par", "anc" or "biall". For details look at mpp_SIM . |
| <code>threshold</code> | Numeric value representing the $-\log_{10}(\text{p-value})$ threshold above which a position can be considered as significant. Default = 4. |
| <code>window</code> | Numeric distance (cM) on the left and the right of a cofactor position where it is not included in the model. Default = 30. |
| <code>n.cores</code> | Numeric. Specify here the number of cores you like to use. Default = 1. |
| <code>verbose</code> | Logical value indicating if the steps of the forward regression should be printed. Default = TRUE. |

Details

Forward regression to determine the a multi-QTL model. The function selects successively QTL positions with $-\log_{10}(\text{pval})$ above the threshold. Those positions are added as cofactors for following detection run. The procedure stop when no more position has a $-\log_{10}(\text{pval})$ above the threshold.

Value

Return:

| | |
|-----|---|
| QTL | Data.frame of class <code>QTLlist</code> with five columns : 1) QTL marker names; 2) chromosomes; 3) interger position indicators on the chromosome; 4) positions in centi-Morgan; and 5) $-\log_{10}(\text{p-values})$. |
|-----|---|

Author(s)

Vincent Garin

See Also

[mpp_SIM](#),

Examples

```
data(mppData)

QTL <- QTL_forward(mppData = mppData, Q.eff = "par")
```

QTL_gen_effects

QTL genetic effects

Description

Computes a multi-QTL model with a list of QTL candidates (QTL) and return the decomposed QTL effects per cross or per parents.

Usage

```
QTL_gen_effects(
  mppData,
  trait = 1,
  QTL = NULL,
  Q.eff = "cr",
  ref.par = NULL,
  sum_zero = FALSE
)
```

Arguments

| | |
|----------------------|---|
| <code>mppData</code> | An object of class <code>mppData</code> . |
| <code>trait</code> | Numerical or character indicator to specify which trait of the <code>mppData</code> object should be used. Default = 1. |
| <code>QTL</code> | Object of class <code>QTLlist</code> representing a list of selected position obtained with the function QTL_select or vector of character marker positions names. Default = <code>NULL</code> . |
| <code>Q.eff</code> | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |

| | |
|----------|--|
| ref.par | Optional Character expression defining the parental allele that will be used as reference for the parental model. For the ancestral model, the ancestral class containing the reference parent will be set as reference. This option can only be used if the MPP design is composed of a unique connected part. Default = NULL. |
| sum_zero | Optional Logical value specifying if the QTL effect of a parental or an ancestral model should be calculated using the sum to zero constraint. Default = FALSE. |

Details

This function computes for each QTL position the genetic effects of the cross, parental, ancestral or SNP allele components. For the cross-specific model (`Q.eff = "cr"`), the genetics effects represent the substitution effect of an single allele from the parent 2 (or B) with respect to an allele coming from the parent 1 or A. All effects are given in absolute value with the parent that carries the positive allele.

For the parental and the ancestral model (`Q.eff = "par"` or `"anc"`), it is possible to estimate maximum $n-1$ parental or ancestral alleles per interconnected part of the design. For these two models, one parental (ancestral) allele is set as reference per interconnected part of the design. Effects of the other alleles are estimated as deviation with respect to the reference. Connected parts of the design can be determined using Weeks and Williams (1964) method ([design_connectivity](#)). By default, the reference allele is the most frequent one. The user can also specify a parental allele that will be used as reference using the argument `ref.par`. This option is only available if the MPP design is composed of a unique connected part.

For the parental and ancestral model it is also possible to estimate the QTL effects using a sum to zero constraint `sum_zero = TRUE`. In that case, the effects of the different parental (ancestral) allele will represent the deviation with respect to the average trait value.

For the bi-allelic model (`Q.eff = "biall"`), the genetic effects represent the effects of a single allele copy of the least frequent allele.

Value

Return:

Object of class `QeffRes` containing the following elements:

| | |
|------|--|
| Qeff | List of <code>data.frame</code> (one per QTL) containing the following information: <ol style="list-style-type: none"> 1. QTL genetic effects per cross or parent. 2. Standard error of the QTL effects. 3. Test statistics of the effects (t-test or Wald statistic). 4. P-value of the test statistics. 5. Significance of the QTL effects. 6. For cross-specific model, parent with the positive additive effects. 7. For parental and ancestral model, indicator of connected part of the design and reference. 8. Allele scores of the parents if <code>geno.par</code> is non NULL in the <code>mppData</code> object. |
|------|--|

tab.Qeff data.frame with one column per QTL giving the QTL genetic effects per cross or per parent with its significance. The first two rows indicate the chromosome and the position in cM of each QTL.

Author(s)

Vincent Garin

References

Weeks, D. L., & Williams, D. R. (1964). A note on the determination of connectedness in an N-way cross classification. *Technometrics*, 6(3), 319-324.

See Also

[QTL_select](#), [summary.QeffRes](#)

Examples

```
data(mppData)

# QTL candidates

SIM <- mpp_SIM(mppData)
QTL <- QTL_select(SIM)

# Cross-specific model

QTL.effects <- QTL_gen_effects(mppData = mppData, QTL = QTL, Q.eff = "cr")
summary(QTL.effects)

# Parental model

QTL.effects <- QTL_gen_effects(mppData = mppData, QTL = QTL, Q.eff = "par")
summary(QTL.effects)

# Ancestral model

QTL.effects <- QTL_gen_effects(mppData = mppData, QTL = QTL, Q.eff = "anc")
summary(QTL.effects)

# Bi-allelic model

QTL.effects <- QTL_gen_effects(mppData = mppData, QTL = QTL, Q.eff = "biall")
summary(QTL.effects)
```

QTL_pred_R2

*Predicted QTL global and partial R squared***Description**

Compute predicted R squared in a validation set using QTLs detected in a training set. These values are corrected by the heritability her.

Usage

```
QTL_pred_R2(
  mppData.ts,
  mppData.vs,
  trait = 1,
  Q.eff = "cr",
  QTL = NULL,
  her = 1
)
```

Arguments

| | |
|-------------------------|---|
| <code>mppData.ts</code> | An object of class <code>mppData</code> for the training set. |
| <code>mppData.vs</code> | An object of class <code>mppData</code> for the validation set. |
| <code>trait</code> | Numerical or character indicator to specify which trait of the <code>mppData</code> object should be used. Default = 1. |
| <code>Q.eff</code> | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see mpp_SIM . Default = "cr". |
| <code>QTL</code> | Object of class <code>QTLlist</code> representing a list of selected position obtained with the function QTL_select or vector of character marker positions names. Default = NULL. |
| <code>her</code> | Numeric value between 0 and 1 representing the heritability of the trait. her can be a single value or a vector specifying each within cross heritability. Default = 1. |

Details

Compute QTLs predicted R squared in a validation set (`mppData.vs`). These QTLs have been previously detected in a training set (`mppData.ts`). The global R squared ($R^2 = \text{cor}(y.ts, y.\text{pred}.ts)^2$) is obtained using the Pearson squared correlation between the observed trait values in the validation set (`y.vs`) and predicted values using estimated QTL effects in the training set ($y.\text{pred}.vs = X.vs * B.ts$).

After that the values are corrected by the general or within cross heritability her. By default her = 1 which means that the R squared represent the proportion of explained phenotypic variance. The values are returned per cross (`R2.cr`) or averaged at the population level (`g1b.R2`).

Partial R squared statistics are also calculated for each individual position. The partial R squared are computed by making the difference between the global R squared and the R squared computed without the ith position.

Value

- Return:
- List containing the following objects:
- | | |
|--------------|---|
| glb.R2 | Global predicted R squared corrected for the heritability of all QTL terms. Doing the average of the within cross predicted R squared (R2.cr) |
| R2.cr | Within cross predicted R squared corrected for the heritability |
| part.R2.diff | Vector of predicted partial R squared corrected for the heritability doing the difference between the full model and a model minus the ith QTL. |

Author(s)

Vincent Garin

See Also

[QTL_R2](#), [QTL_select](#)

Examples

```
data(mppData)

folds <- CV_partition(cross.ind = mppData$cross.ind, k = 5)

mppData.ts <- subset(x = mppData, gen.list = folds[[1]]$train.set)

mppData.vs <- subset(x = mppData, gen.list = folds[[1]]$val.set)

SIM <- mpp_SIM(mppData = mppData)
QTL <- QTL_select(SIM)

QTL_pred_R2(mppData.ts = mppData.ts, mppData.vs = mppData.vs, QTL = QTL)
```

| | |
|--------|---|
| QTL_R2 | <i>QTL global and partial R squared</i> |
|--------|---|

Description

Computes the global and partial (adjusted) R squared of a list of QTLs using a linear model.

Usage

```
QTL_R2(mppData, trait = 1, QTL = NULL, Q.eff = "cr", glb.only = FALSE)
```

Arguments

| | |
|-----------------------|--|
| <code>mppData</code> | An object of class <code>mppData</code> . |
| <code>trait</code> | Numerical or character indicator to specify which trait of the <code>mppData</code> object should be used. Default = 1. |
| <code>QTL</code> | Object of class <code>QTLlist</code> representing a list of selected position obtained with the function <code>QTL_select</code> or vector of character marker positions names. Default = <code>NULL</code> . |
| <code>Q.eff</code> | Character expression indicating the assumption concerning the QTL effects: 1) "cr" for cross-specific; 2) "par" for parental; 3) "anc" for ancestral; 4) "biall" for a bi-allelic. For more details see <code>mpp_SIM</code> . Default = "cr". |
| <code>glb.only</code> | Logical value. If <code>glb.only = TRUE</code> , only the global and global adjusted R squared will be returned. Default = <code>FALSE</code> . |

Details

The function computes R squared statistics using a linear model. The extra variance explained by a full model containing the QTL terms with respect to a reduced model containing only the cross intercept terms and uses the ratio between the residual sum of square of these two models: $R^2 = 1 - (RSS(f))/(RSS(r))$.

Partial R squared for each individual QTL position can also be calculated. Two types of partial R squared are returned. The first one uses the difference between the R squared obtained with all QTL positions and the R squared obtain with all position minus the *ith* one (difference R squared). The second method used only the *ith* QTL position in the model (single R squared).

For both global and partial R squared, it is possible to obtained adjusted measurements taking the number of degrees of freedom into consideration using an adaptation of the formula given by Utz et al. (2000): $R_{adj} = R - (z/(N - z - n_{cr})) * (1 - R)$ where *z* is the total number of estimated components of the genetic effect. *N* is the total number of phenotypic information, and *n.cr* is the number of intercept (cross) terms.

Value

Return:

object of class `QR2Res` containing the following objects:

| | |
|-------------------------------|--|
| <code>glb.R2</code> | Global R squared of all QTL terms. |
| <code>glb.adj.R2</code> | Global adjusted R squared of all QTL terms. |
| <code>part.R2.diff</code> | Vector of partial R squared doing the difference between the full model and a model minus the <i>ith</i> QTL. |
| <code>part.adj.R2.diff</code> | Vector of partial adjusted R squared doing the difference between the full model and a model minus the <i>ith</i> QTL. |
| <code>part.R2.sg</code> | Vector of partial R squared using only the <i>ith</i> QTL. |
| <code>part.adj.R2.sg</code> | Vector of partial adjusted R squared using only the <i>ith</i> QTL. |

Author(s)

Vincent Garin

References

Utz, H. F., Melchinger, A. E., & Schon, C. C. (2000). Bias and sampling error of the estimated proportion of genotypic variance explained by quantitative trait loci determined from experimental data in maize using cross validation and validation with independent samples. *Genetics*, 154(4), 1839-1849.

See Also

[QTL_select](#), [summary.QR2Res](#)

Examples

```
data(mppData)

SIM <- mpp_SIM(mppData)
QTL <- QTL_select(Qprof = SIM, threshold = 3, window = 20)
Q_R2 <- QTL_R2(mppData = mppData, QTL = QTL, Q.eff = "cr")
summary(Q_R2)
```

| | |
|-----------|-----------------------|
| QTL_R2_GE | <i>MPP GxE QTL R2</i> |
|-----------|-----------------------|

Description

Compute global and partial R2 statistics for MPP GxE QTL using a linear model. The global R2 is the contribution of all QTL positions while the partial R2 is the specific contribution of an individual QTL position.

Usage

```
QTL_R2_GE(mppData, trait, QTL = NULL, glb.only = FALSE)
```

Arguments

| | |
|-----------------------|---|
| <code>mppData</code> | An object of class <code>mppData</code> . |
| <code>trait</code> | Character vector specifying which traits (environments) should be used. |
| <code>QTL</code> | Object of class <code>QTLlist</code> representing a list of selected marker positions obtained with the function <code>QTL_select()</code> or a vector of character marker positions names. Default = <code>NULL</code> . |
| <code>glb.only</code> | Logical value. If <code>glb.only = TRUE</code> , only the global and global adjusted R squared will be returned. Default = <code>FALSE</code> . |

Value

Return:

List containing the global unadjusted R2, the global adjusted R2, the partial unadjusted R2, and the partial adjusted R2.

Author(s)

Vincent Garin

Examples

```
data(mppData_GE)

Qpos <- c("PZE.105068880", "PZE.106098900")

R2 <- QTL_R2_GE(mppData = mppData_GE, trait = c('DMY_CIAM', 'DMY_TUM'),
               QTL = Qpos)
```

QTL_select

QTL candidates selection

Description

Selection of QTL candidate positions.

Usage

```
QTL_select(Qprof, threshold = 3, window = 50, verbose = TRUE)
```

Arguments

| | |
|-----------|--|
| Qprof | Object of class QTLprof returned by the function mpp_SIM or mpp_CIM . |
| threshold | Numeric value representing -log10(p-value) threshold above which a position can be considered as a QTL candidate. Default = 3. |
| window | Numeric value in centi-Morgan representing the minimum distance between two selected positions. Default = 50. |
| verbose | Logical value specifying if the detection of no QTL should be printed. Default = TRUE. |

Details

The function select QTL positions that are above the given threshold per chromosome. Once a position has been selected, and exclusion window is set around that position. Positions falling into that region will not be candidate anymore. The search continue until there is no more candidate position above the threshold.

Value

Return:

QTL Data.frame of class `QTLlist` with five columns : 1) QTL marker names; 2) chromosomes; 3) interger position indicators on the chromosome; 4) positions in centi-Morgan; and 5) $-\log_{10}(\text{p-values})$.

References

This function is a modification of the `QTL.reduce` function coming from the Biometris pipeline.

RAP (R Analytical Pipeline) (V0.9.1) May 2011

Authors: Paul Eilers (1), Gerrit Gort (1), Sabine Schnabel (1), Lucia Gutierrez(1, 2), Marcos Malosetti(1), Joost van Heerwaarden, and Fred van Eeuwijk(1)

(1) Wageningen University and Research Center, Netherlands (2) Facultad de Agronomia, UDELAR, Uruguay

See Also

[mpp_SIM](#), [mpp_CIM](#), [mpp_perm](#)

Examples

```
data(mppData)

SIM <- mpp_SIM(mppData)

QTL <- QTL_select(Qprof = SIM, threshold = 3)
```

| | |
|----------------|------------------------------|
| subset.mppData | <i>Subset mppData object</i> |
|----------------|------------------------------|

Description

Pull out a specified set of markers and/or genotypes from a `mppData` object.

Usage

```
## S3 method for class 'mppData'
subset(x, mk.list = NULL, gen.list = NULL, ...)
```

Arguments

| | |
|-----------------------|--|
| <code>x</code> | An object of class <code>mppData</code> . |
| <code>mk.list</code> | Optional character vector, numeric position vector or logical vector representing marker to keep. Default = <code>NULL</code> . |
| <code>gen.list</code> | Optional character vector, numeric position vector or logical vector representing genotypes to keep. Default = <code>NULL</code> . |
| <code>...</code> | Ignored. |

Value

Return:

The `mppData` object but with only the specified subset of data.

Author(s)

Vincent Garin

Examples

```
### Marker subset

data(mppData)

# Random selection of markers
mk.list <- sample(mppData$map[, 1], 50)
mppData_sub <- subset(x = mppData, mk.list = mk.list)

# Selection of chromosome 1 marker
mk.list <- (mppData$map[, 2] == 1)
mppData_sub <- subset(x = mppData, mk.list = mk.list)

### Genotype subset

# Random selection of genotypes
gen.list <- sample(mppData$geno.id, 200)
mppData_sub <- subset(x = mppData, gen.list = gen.list)

# Selection of genotype from cross 2 and 5
crosses <- unique(mppData$cross.ind)
gen.list <- mppData$geno.id[mppData$cross.ind %in% crosses[c(2, 5)]]
mppData_sub <- subset(x = mppData, gen.list = gen.list)

### Marker and genotype subset

mk.list <- sample(mppData$map[, 1], 50)
gen.list <- sample(mppData$geno.id, 200)
mppData_sub <- subset(x = mppData, mk.list = mk.list,
  gen.list = gen.list)
```

| | |
|-----------------|----------------------------------|
| summary.mppData | <i>Summary of mppData object</i> |
|-----------------|----------------------------------|

Description

summary for object of class mppData.

Usage

```
## S3 method for class 'mppData'  
summary(object, ...)
```

Arguments

| | |
|--------|-----------------------------|
| object | An object of class mppData. |
| ... | Ignored. |

Examples

```
data(mppData)  
summary(mppData)
```

| | |
|-----------------|----------------------------------|
| summary.QeffRes | <i>Summary of QeffRes object</i> |
|-----------------|----------------------------------|

Description

summary for object of class QeffRes.

Usage

```
## S3 method for class 'QeffRes'  
summary(object, QTL = NULL, ...)
```

Arguments

| | |
|--------|---|
| object | An object of class QeffRes obtained with function QTL_gen_effects . |
| QTL | Numeric vector indicating the QTL positions for which the QTL effect must be printed. Default = NULL. |
| ... | Ignored. |

See Also

[QTL_gen_effects](#)

Examples

```
data(mppData)
SIM <- mpp_SIM(mppData)
QTL <- QTL_select(SIM)
QTL.effects <- QTL_gen_effects(mppData = mppData, QTL = QTL, Q.eff = "cr")
summary(QTL.effects)
```

| | |
|----------------|---------------------------------|
| summary.QR2Res | <i>Summary of QR2Res object</i> |
|----------------|---------------------------------|

Description

summary for object of class QR2Res.

Usage

```
## S3 method for class 'QR2Res'
summary(object, ...)
```

Arguments

| | |
|--------|---|
| object | An object of class QR2Res obtained with function QTL_R2 . |
| ... | Ignored. |

See Also

[QTL_R2](#)

Examples

```
data(mppData)
SIM <- mpp_SIM(mppData)
QTL <- QTL_select(SIM)
Q_R2 <- QTL_R2(mppData = mppData, QTL = QTL, Q.eff = "cr")
summary(Q_R2)
```

USNAM_geno*Reduced genotype data maize US-NAM population*

Description

Selection of markers and genotypes from the maize US nested association mapping (NAM) population (McMullen et al., 2009).

Usage

```
data(USNAM_geno)
```

Format

```
data.frame
```

Details

Sample of the marker matrix of the US-NAM population. The selection correspond to 102 markers coming from the two first chromosomes present in [USNAM_map](#) and the 506 genotypes. These genotypes correspond to the selected phenotypic values in [USNAM_pheno](#). The selected genotypes come from the following crosses: (B73 x CML103), (B73 x CML322), (B73 x CML52), (B73 x Hp301), (B73 x M37W). The data of the 6 parental lines are also included. The data are available on www.panzea.org.

Source

<https://www.panzea.org/>

References

McMullen, M. D., Kresovich, S., Villeda, H. S., Bradbury, P., Li, H., Sun, Q., ... & Buckler, E. S. (2009). Genetic properties of the maize nested association mapping population. *Science*, 325(5941), 737-740.

See Also

[USNAM_pheno](#), [USNAM_map](#)

Examples

```
data(USNAM_geno)
```

USNAM_map

Reduced map maize US-NAM population

Description

Reduced map of the maize US nested association mapping (NAM) population (McMullen et al., 2009).

Usage

```
data(USNAM_map)
```

Format

```
data.frame
```

Details

Selection of 102 markers from the two first chromosomes of the Maize US-NAM population (McCullen et al., 2009). The data are available on www.panzea.org.

Source

<https://www.panzea.org>

References

McMullen, M. D., Kresovich, S., Villeda, H. S., Bradbury, P., Li, H., Sun, Q., ... & Buckler, E. S. (2009). Genetic properties of the maize nested association mapping population. *Science*, 325(5941), 737-740.

See Also

[USNAM_genotype](#), [USNAM_phenotype](#)

Examples

```
data(USNAM_map)
```

USNAM_pheno*Reduced phenotype data from Maize US-NAM population*

Description

Reduced phenotype data from the Maize US nested association mapping (NAM) population (McMullen et al., 2009).

Usage

```
data(USNAM_pheno)
```

Format

```
data.frame
```

Details

Upper leaf angle (ULA) trait values with genotypes identifiers as rownames. These genotypes correspond to the 500 offspring genotypes of the marker matrix [USNAM_geno](#). The data are available on www.panzea.org.

Source

<https://www.panzea.org>

References

McMullen, M. D., Kresovich, S., Villeda, H. S., Bradbury, P., Li, H., Sun, Q., ... & Buckler, E. S. (2009). Genetic properties of the maize nested association mapping population. *Science*, 325(5941), 737-740.

See Also

[USNAM_geno](#), [USNAM_map](#)

Examples

```
data(USNAM_pheno)
```

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