

# Genetic clustering and hybrid detection using *adeigenet*

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## **Abstract**

This tutorial presents an overview of likelihood-based genetic clustering in *adeigenet*, as implemented by the function `genclust.em`. After a brief presentation of the rationale of the method, we illustrate its use in two situations: for identifying genetic clusters, and then for detecting hybrids.

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# Contents

<b>1</b>	<b>The method, in a nutshell</b>	<b>3</b>
1.1	Model formulation . . . . .	3
1.1.1	Notations . . . . .	3
1.1.2	General likelihood . . . . .	3
1.1.3	Useful particular cases . . . . .	4
1.1.4	Group membership probabilities . . . . .	4
1.2	Estimation using the EM algorithm . . . . .	4
1.3	Identifying hybrids . . . . .	5
<b>2</b>	<b>Example using simulated data</b>	<b>5</b>
2.1	In the absence of hybrids: DAPC data revisited . . . . .	5
2.2	Identifying hybrids . . . . .	14
2.2.1	Simulating hybrids using <code>hybridize</code> . . . . .	14
2.2.2	Looking for hybrid using <code>genclust.em</code> . . . . .	15
2.2.3	Looking for first-generation hybrids (F1) . . . . .	15
2.2.4	Looking for F1 and back-crosses . . . . .	18

# 1 The method, in a nutshell

## 1.1 Model formulation

### 1.1.1 Notations

The following notations will be used to describe the model.

- $i = 1, \dots, I$ : index of individuals
- $j = 1, \dots, J$ : index of loci
- $k = 1, \dots, K$ : index of groups
- $x_{i,j}$ : vector of allele counts for individual  $i$  at locus  $j$
- $x_i$ : vector of allele counts of individual  $i$  for all loci, i.e. concatenation  $[x_{i,1} \dots x_{i,J}]$
- $x$ : matrix of allele counts, obtained by row-concatenation of the  $x_i$
- $g_i$ : group of individual  $i$  ( $g_i \in \{1, \dots, K\} \forall i \in \{1, \dots, I\}$ )
- $g$ : vector of group memberships ( $g = g_1, \dots, g_I$ )
- $f_{k,j}$ : vector of allele frequencies of group  $k$  at locus  $j$
- $f_k$ : vector of allele frequencies of group  $k$  for all loci, i.e. concatenation  $[f_{k,1} \dots f_{k,J}]$
- $f$ : matrix of all allele frequencies, obtained by row-concatenation of the  $f_k$
- $\pi$ : the ploidy of all individuals

### 1.1.2 General likelihood

Likelihood-based genetic clustering in *adegenet* is implemented by the function `genclust.em`. This approach uses Hardy-Weinberg's equilibrium to define the probabilities of observing given genotypes under known allele frequencies. For now, we assume the group to which  $i$  belongs is known (noted  $g_i$ ), and has known allele frequencies  $f_{g_i,j}$ . For any level of ploidy  $\pi$  and any codominant marker, the likelihood of  $x_{i,j}$  is defined as:

$$p(x_{i,j}|f_{g_i,j}, \pi) = \mathcal{M}(x_{i,j}, f_{g_i,j}, \pi) \quad (1)$$

where  $\mathcal{M}$  is the multinomial probability mass function.

Assuming independence between loci ( $j = 1, \dots, J$ ), the likelihood of individual  $i$  across all loci is:

$$p(x_i|f_{g_i}, \pi) = \prod_j p(x_{i,j}|f_{g_i,j}, \pi) \quad (2)$$

Assuming further independence between individuals, conditional on their group membership  $g$  and all allele frequencies  $f$ , the total likelihood is defined as:

$$p(x|f, g, \pi) = \prod_i p(x_i|f_{g_i}, \pi) \quad (3)$$

So that the general equation for the total log-likelihood of the model is computed as:

$$\mathcal{LL}(x, f, g, \pi) = \sum_i \sum_j \log(\mathcal{M}(x_{i,j}, f_{g_i,j}, \pi)) \quad (4)$$

Note that this model could easily accomodate varying ploidy through  $\pi_i$ ,  $\pi_j$  or  $\pi_{i,j}$  but we leave this out for now.

### 1.1.3 Useful particular cases

As particular case, the likelihood of all possible diploid genotypes with alleles  $A$  and  $B$  is defined, noting  $f_{g_i}$  the vector of allele frequencies in a given group  $g_i$  as:

$$p(AA|f_{g_i}, 2) = f_A^2 \quad (5)$$

$$p(BB|f_{g_i}, 2) = f_B^2 \quad (6)$$

$$p(AB|f_{g_i}, 2) = 2f_A f_B \quad (7)$$

Note that for haploid data, this is even simpler:

$$p(A|f_{g_i}, 1) = f_A \quad (8)$$

$$p(B|f_{g_i}, 1) = f_B \quad (9)$$

### 1.1.4 Group membership probabilities

Assuming any individual  $i$  comes from one of the sampled groups  $k = 1, \dots, K$ , the probability that  $i$  belongs to group  $k$  is defined as the standardized likelihood:

$$p(g_i = k) = \frac{p(x_i|g_i = k, f_k, \pi)}{\sum_q p(x_i|g_i = q, f_q, \pi)} \quad (10)$$

which ensures that:

$$\sum_k p(g_i = k) = 1 \quad (11)$$

## 1.2 Estimation using the EM algorithm

The model formulation above supposes that both the groups  $g$ , and the allele frequencies in these groups  $f$ , are known. In practice, though, these need to be estimated. This is achieved using the expectation-maximization algorithm, which we apply as follow:

1. define initial groups for invididuals,  $g$
2. (*expectation*) compute allele frequencies  $f$  and then  $p(g_i = k)$  for all  $i$  and  $k$
3. (*maximization*) assign individuals to their most likely group
4. return to 2) until convergence

Here, we consider that the algorithm has converged when the change in the global log-likelihood is less than 1e-14. The advantage of this algorithm is that it converges very fast, typically in less than 10 iterations. The first step can be achieved using random group allocation, in which case several runs of the EM algorithm can be useful to ensure that the best solution (with highest log-likelihood) is attained. Alternatively, clusters can be defined by another fast clustering method, such as the  $k$ -means implemented in `find.clusters`. This latter option is used by default in our implementation.

### 1.3 Identifying hybrids

The allele frequency  $f_{h_w}$  in a hybrid population  $h_w$  is modelled as weighted averages of the allele frequencies in the parental populations  $k$  and  $q$ :

$$f_{h_w} = wf_k + (1 - w)f_q \quad (12)$$

where  $w$  has value between 0 and 1. Typical values of  $w$  are 0.5 for F1 hybrids, 0.75 for backcrosses F1/1, 0.25 for backcrosses F1/2, etc.

The EM algorithm described above can be extended to account for various hybrids using:

1. define initial groups for individuals,  $g$
2. (expectation) define parental populations as the two groups most distant from each other; compute allele frequencies for parental populations  $f_k$  and  $f_q$  and subsequently for all hybrid populations  $h_w$ , and then  $p(g_i = k)$ ,  $p(g_i = q)$  and  $p(g_i = h_w)$  for all  $i$  and  $h_w$
3. (maximization) assign individuals to their most likely group
4. return to 2) until convergence

## 2 Example using simulated data

### 2.1 In the absence of hybrids: DAPC data revisited

The method described above is implemented in the function `genclust.em`. To illustrate it, we first re-analyse datasets originally simulated to illustrate the DAPC (Jombart *et al.* 2010, BCM Genetics). The data `dapcIllus` contains for datasets:

- \$a: island model with 6 demes
- \$b: hierarchical island model with 6 demes (3,2,1)
- \$c: one-dimensional stepping stone model with 12 demes
- \$d: one-dimensional stepping stone with a boundary in between sets of 12 demes

```
library(adegenet)
data(dapcIllus)
sapply(dapcIllus, nPop)

##  a  b  c  d
##  6  6 12 24
```

For each dataset, we identify clusters using `genclust.em`, indicating the right number of clusters, and compare the obtained clusters to the true clusters.

```
a.clust <- genclust.em(dapcIllus$a, k = 6)

## Error in genclust.em(dapcIllus$a, k = 6): object 'detailed' not found
class(a.clust)

## [1] "genclust.em" "list"

names(a.clust)

## [1] "group"      "ll"          "proba"       "converged"  "n.iter"
```

The output of `genclust.em` is a list containing the following information:

- **group**: a factor giving maximum-likelihood group assignment for each individual
- **ll**: the log-likelihood of the model
- **proba**: a matrix giving full group membership probabilities, with individuals in rows and clusters in column
- **converged**: a logical indicating if the algorithm converged before reaching the maximum number of iterations
- **n.iter**: the number of iterations after which the algorithm stopped

Let us examine these components:

```
head(a.clust$group, 12)

##  1  2  3  4  5  6  7  8  9 10 11 12
##  1  1  1  1  1  1  1  1  1  1  1  1
## Levels: 1 2 3 4 5 6

length(a.clust$group)

## [1] 600
```

```

a.clust$l1

## [1] -11933.4

dim(a.clust$proba)

## [1] 600 6

head(a.clust$proba)

##           1           2           3           4           5
## 1 0.9889863 1.967245e-05 2.750886e-06 1.099126e-02 1.864221e-09
## 2 1.0000000 2.744606e-12 2.685464e-12 3.936665e-10 4.165036e-10
## 3 1.0000000 3.925511e-10 1.029866e-09 1.018073e-08 1.846200e-13
## 4 0.9925573 2.253888e-05 7.419267e-03 8.688965e-07 9.585198e-10
## 5 1.0000000 1.007399e-11 4.500484e-08 1.473021e-10 1.049492e-09
## 6 0.9999987 3.898077e-11 1.266882e-06 2.842916e-11 2.134936e-09
##           6
## 1 3.080832e-10
## 2 1.644282e-15
## 3 1.872534e-11
## 4 1.500519e-09
## 5 9.216524e-11
## 6 3.928634e-11

head(round(a.clust$proba),3)

##    1 2 3 4 5 6
## 1 1 0 0 0 0 0
## 2 1 0 0 0 0 0
## 3 1 0 0 0 0 0

a.clust$converged

## [1] TRUE

a.clust$n.iter

## [1] 3

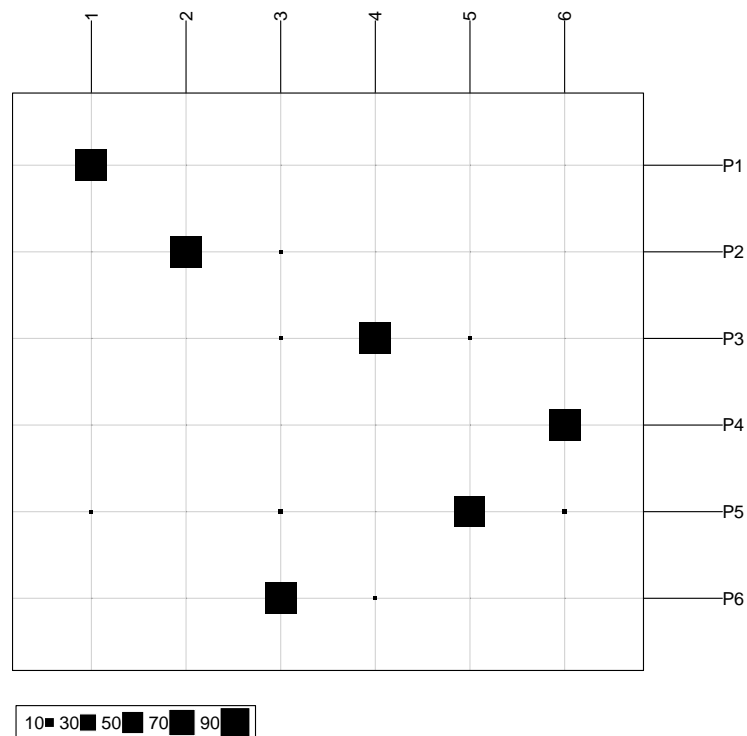
```

The inferred groups can be compared to the original ones using `table`, which builds a contingency table putting the original groups in rows, and the newly inferred groups in columns; results are visualised using `table.value`

```
a.tab <- table(pop(dapcIllus$a), a.clust$group)
a.tab
```

```
##
##      1  2  3  4  5  6
## P1 100  0  0  0  0  0
## P2  0 99  1  0  0  0
## P3  0  0  1 98  1  0
## P4  0  0  0  0  0 100
## P5  1  0  2  0 95  2
## P6  0  0 99  1  0  0
```

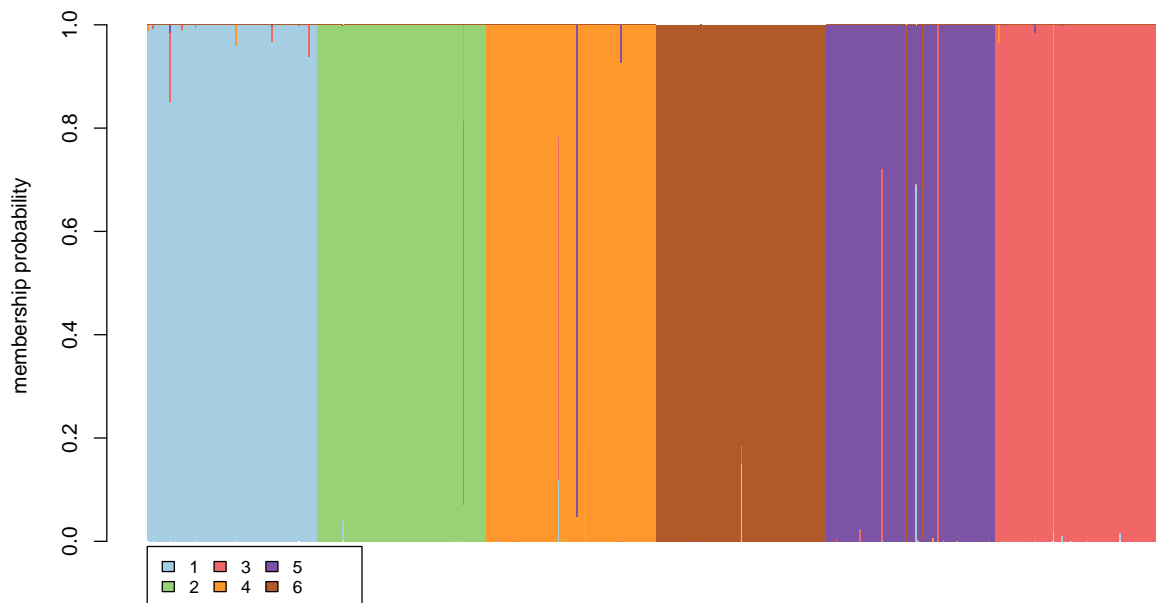
```
table.value(a.tab, col.labels = 1:6)
```



Here, original groups were nearly perfectly retrieved. Finally, we can visualise the group membership probabilities, which represent the probabilities that each genotype was generated under the various populations, using the `compoplot`:

```
compoplot(a.clust)
```



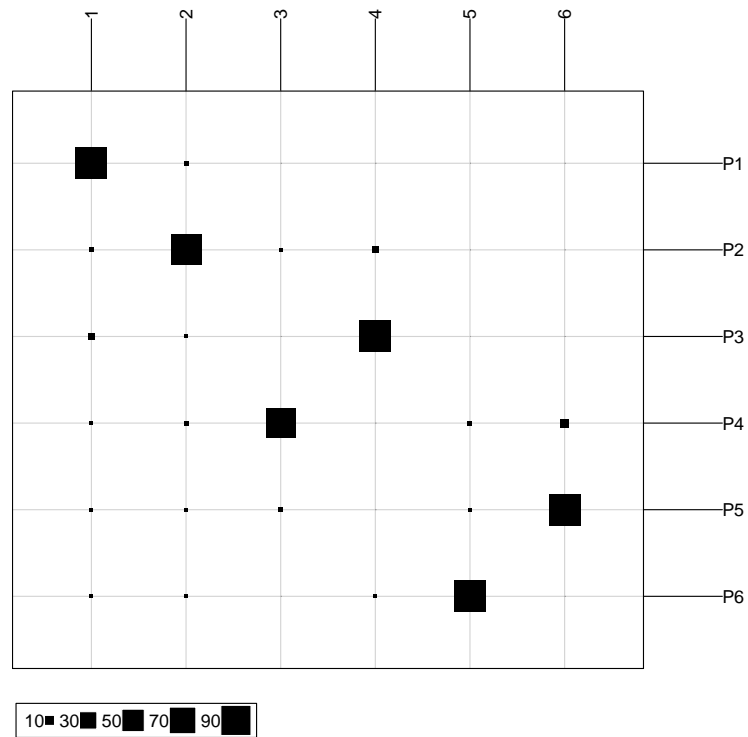


Here, assignment of individuals to their actual groups is essentially perfect; the few 'misclassified' individuals are effectively migrants. In fact, results remain very good in other models as well. Results are near perfect for the hierarchical island mode:

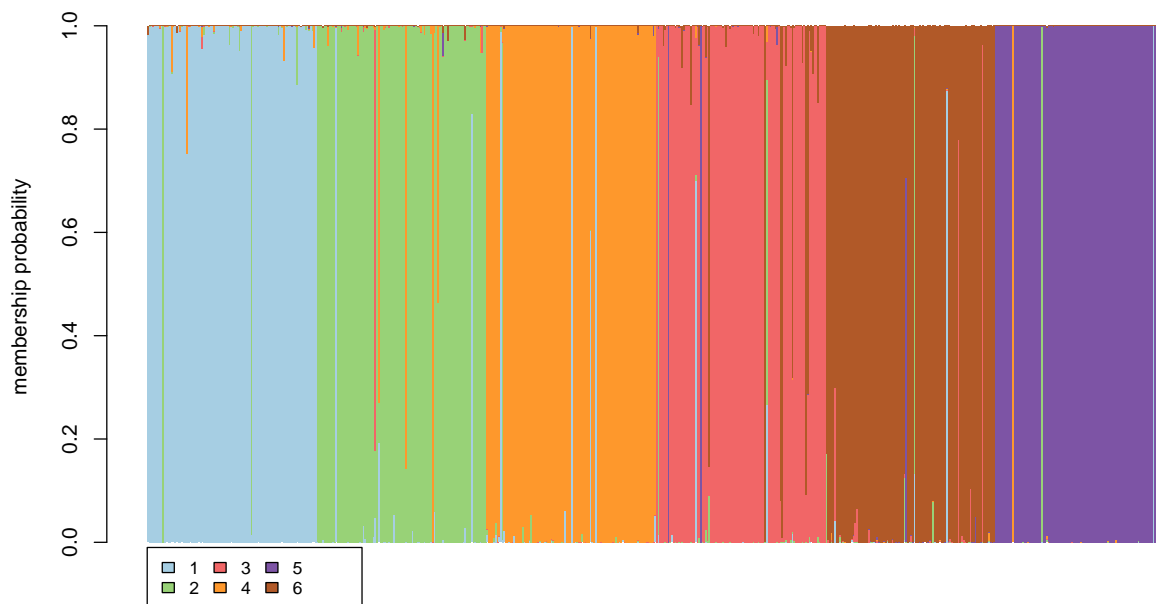
```
b.clust <- genclust.em(dapcIllus$b, k = 6)

## Error in genclust.em(dapcIllus$b, k = 6): object 'detailed' not found

b.tab <- table(pop(dapcIllus$b), b.clust$group)
table.value(b.tab, col.labels = 1:6)
```



```
compoplot(b.clust)
```

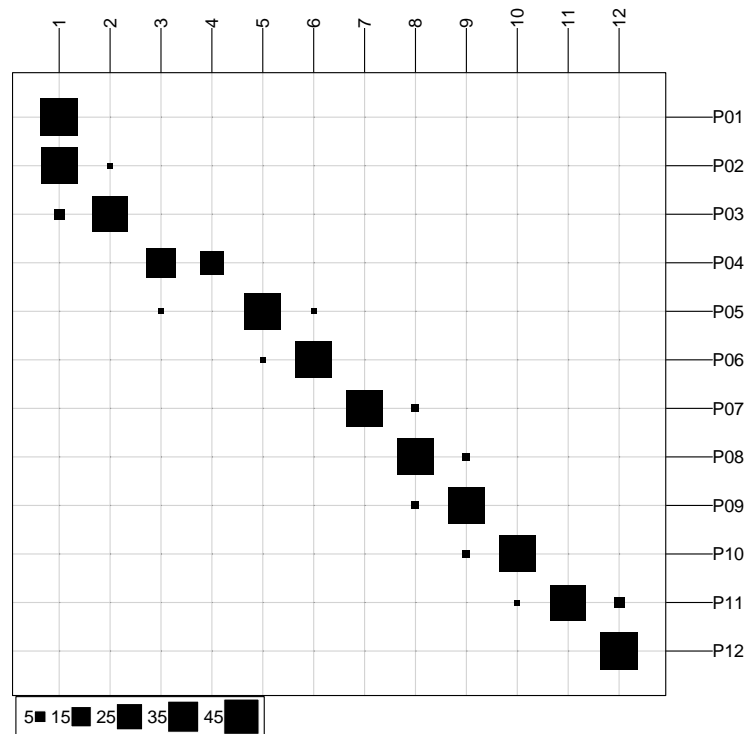


and for the stepping stone model:

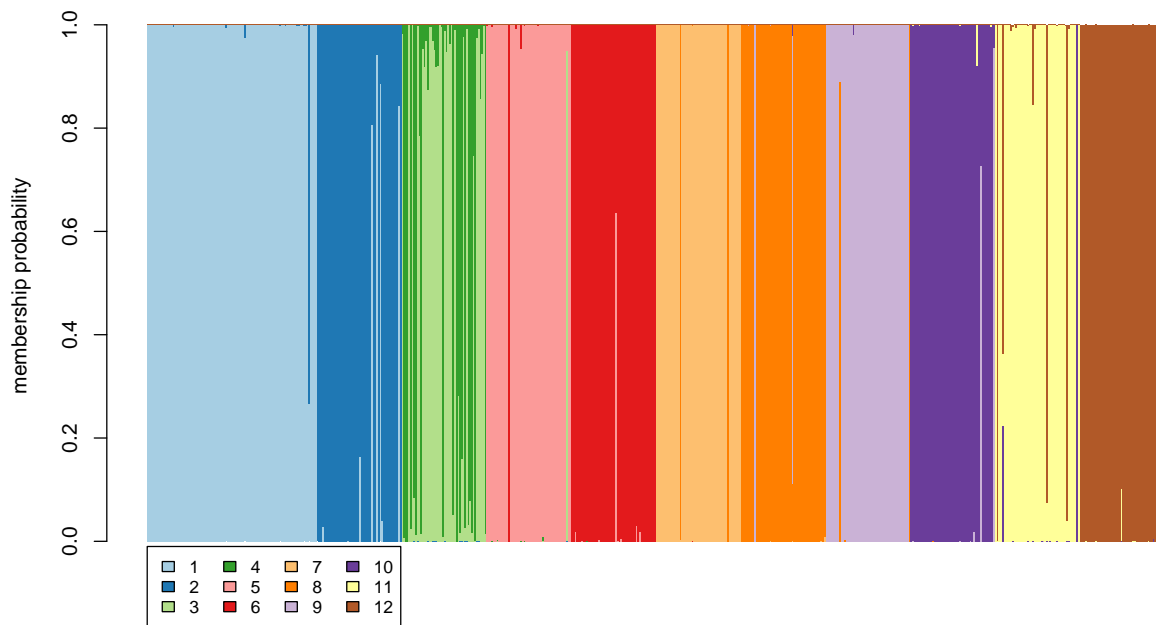
```
c.clust <- genclust.em(dapcIllus$c, k = 12)

## Error in genclust.em(dapcIllus$c, k = 12): object 'detailed' not found

c.tab <- table(pop(dapcIllus$c), c.clust$group)
table.value(c.tab, col.labels = 1:12)
```



```
compoplot(c.clust)
```

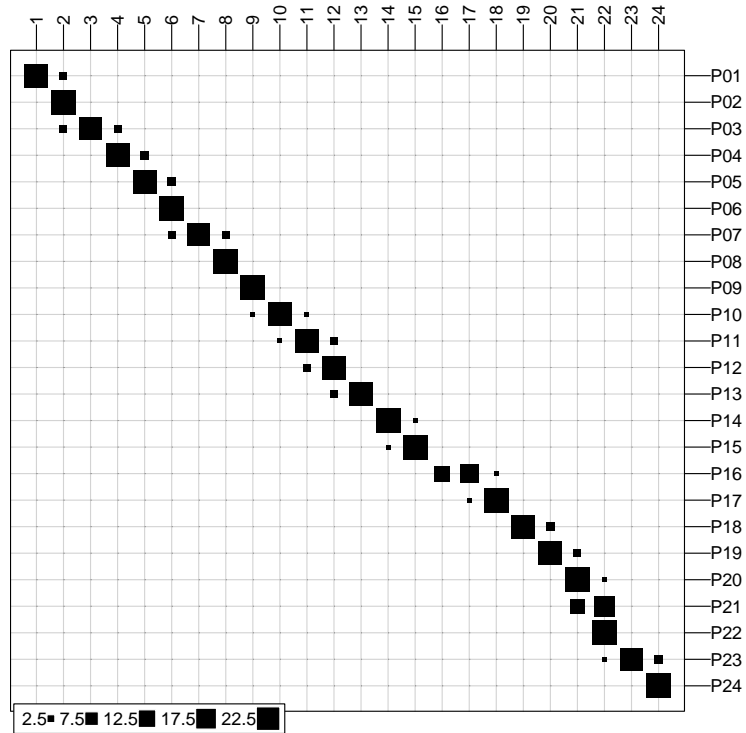


In the larger stepping stone model with a boundary, results remain very good but some neighbouring demes are harder to distinguish (especially 1-2, 3-4, 13-14 and 18-19).

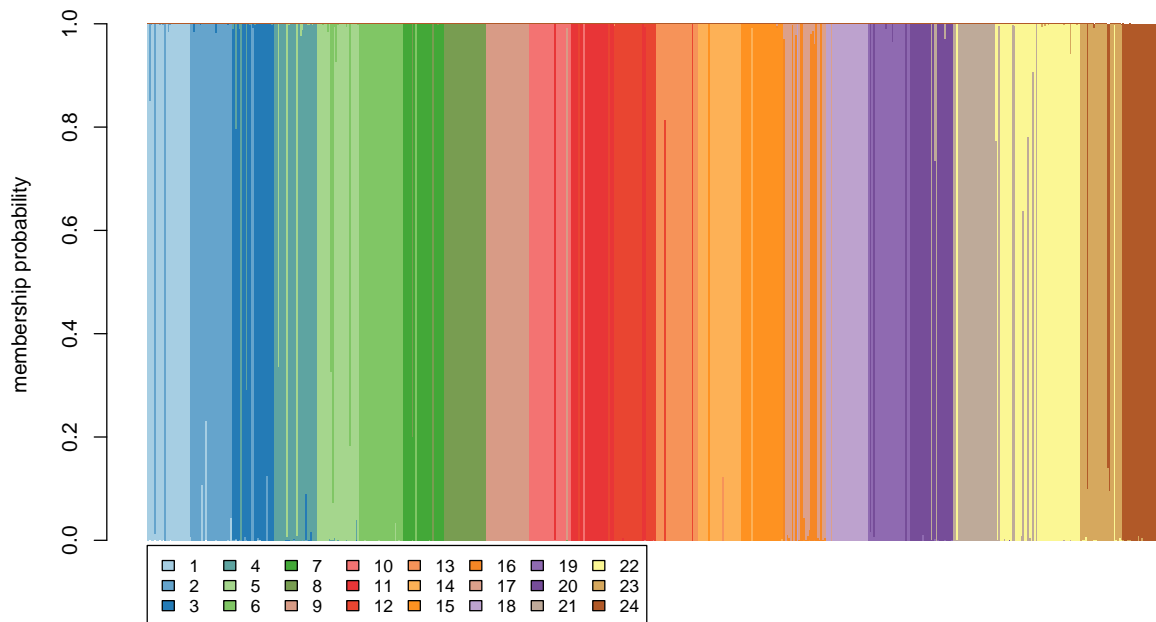
```
d.clust <- genclust.em(dapcIllus$d, k = 24)

## Error in genclust.em(dapcIllus$d, k = 24): object 'detailed' not found

d.tab <- table(pop(dapcIllus$d), d.clust$group)
table.value(d.tab, col.labels = 1:24, csize = .6)
```

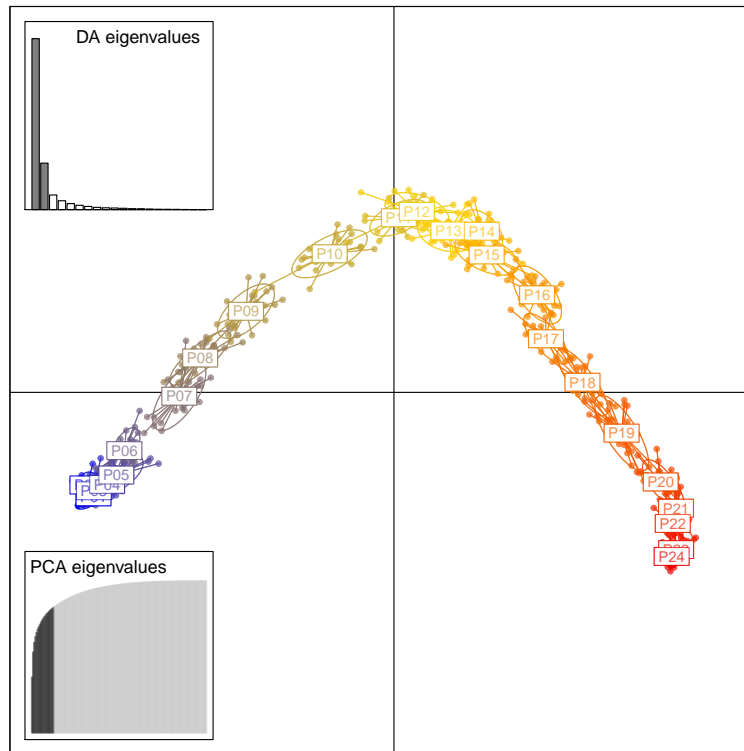


```
compoplot(d.clust, n.col=8)
```



However, note that this lack of distinction in some demes merely comes from a weak genetic differentiation:

```
d.dapc <- dapc(dapcIllus$d, n.pca = 20, n.da = 2)
scatter(d.dapc, clab = 0.85, col = deepseasun(24),
        posi.da="topleft", posi.pca = "bottomleft", scree.pca = TRUE)
```



## 2.2 Identifying hybrids

### 2.2.1 Simulating hybrids using hybridize

Simulate hybrids F1

```
set.seed(1)
data(microbov)

zebu <- microbov[pop="Zebu"]
salers <- microbov[pop="Salers"]
hyb <- hybridize(zebu, salers, n = 30)
x <- repool(zebu, salers, hyb)
```

Simulate hybrids backcross (F1 / parental)

```
f1.zebu <- hybridize(hyb, zebu, 20, pop = "f1.zebu")
f1.salers <- hybridize(hyb, salers, 25, pop = "f1.salers")
y <- repool(x, f1.zebu, f1.salers)
```

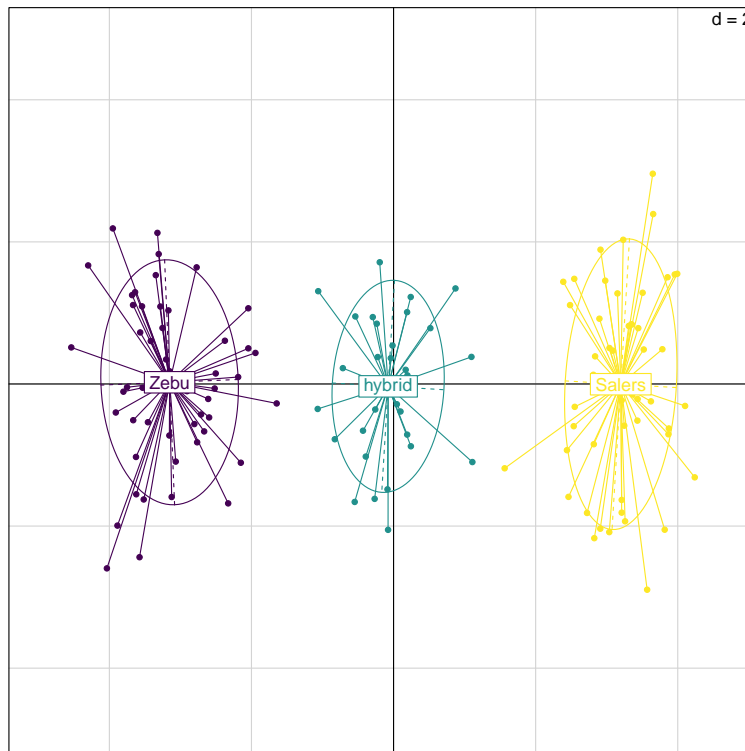
### 2.2.2 Looking for hybrid using genclust.em

`genclust.em` can also be used in the presence of hybridization. In this case, it will attempt to classify individuals into parental populations (later noted *A* and *B*), or various types of hybrids defined by the user. To activate the detection of hybrids, simply specify `hybrids = TRUE`, which will by default look for F1, i.e. 50% of genes coming from each parental population. Other types of hybrids can be specified through the argument `hybrid.coef`, which is a vector of *parental coefficients*. Each value in this vector defines a given type of hybrid, by the proportion of its gene pool contributed by the first parental population. Complementary coefficients will be added automatically for the second parental population. For instance, `hybrid.coef = c(0.25, 0.5)` will be converted into `hybrid.coef = c(0.75, 0.5, 0.25)`, respectively corresponding to backcross with *A*, F1, and backcross with *B*.

### 2.2.3 Looking for first-generation hybrids (F1)

We first use a Principal Component Analysis (PCA) to visualise the simulated hybrid data:

```
x.pca <- dudi.pca(tab(x, NA.method = "mean"), scannf = FALSE, scale = FALSE)
s.class(x.pca$li, pop(x), col = hybridpal()(3))
```

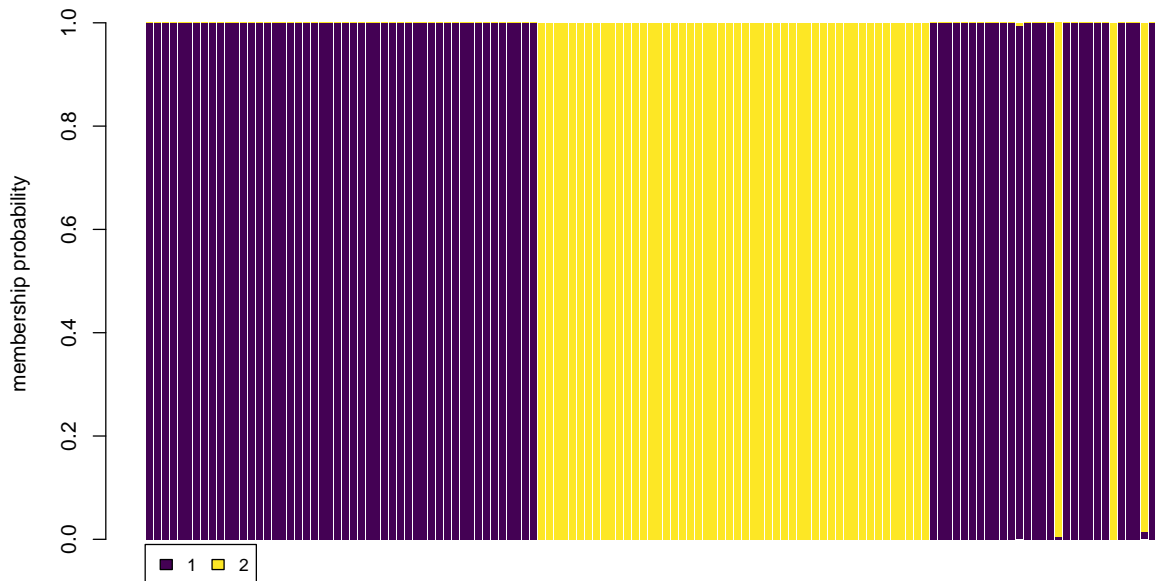


The method applied without hybrid detection correctly identifies the parental populations, but fails to classify hybrids:

```
res.no.hyb <- genclust.em(x, k = 2, hybrids = FALSE)

## Error in genclust.em(x, k = 2, hybrids = FALSE): object 'detailed' not
found

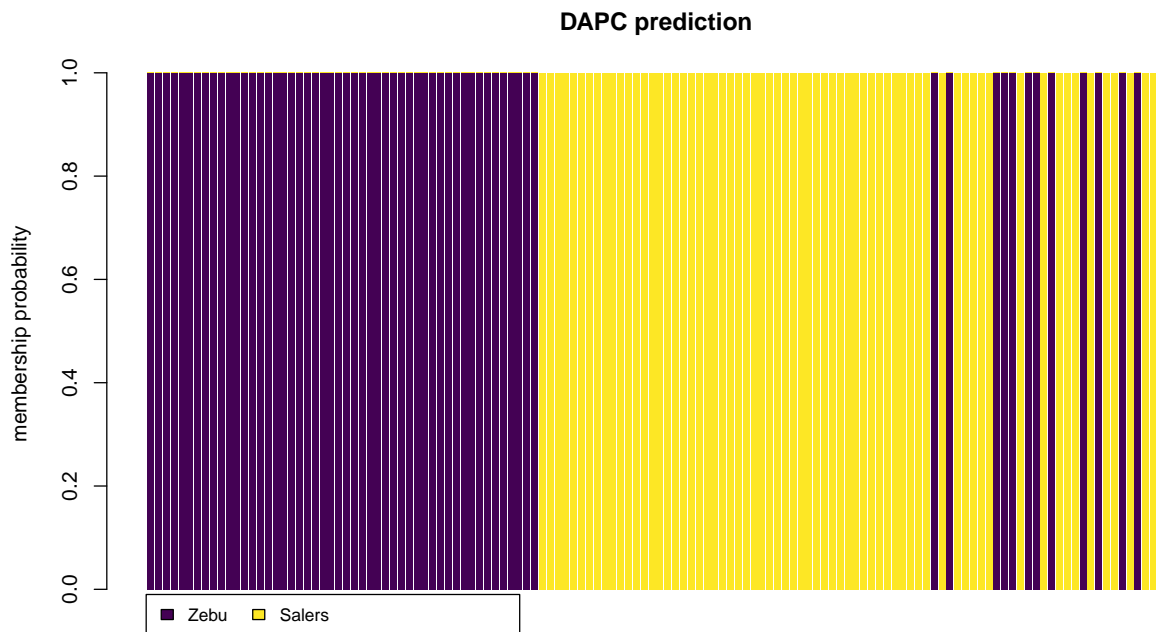
compoplot(res.no.hyb, n.col = 2, col.pal = hybridpal())
```



One may expect that hybrids would appear as individuals with group membership probabilities around 50% for each parental population. Interestingly, this is almost never the case, irrespective of the type of clustering method. The detail of likelihood contribution (results not shown) suggest that individuals slightly closer to either parental population are simply much more likely to belong to this population. The same can be observed in the Discriminant Analysis of Principal Components (DAPC), which does not use likelihood but a geometric criteria. This can be illustrated by analysing the parental population (first 100 individuals) and predicting the group membership of the hybrids as supplementary individuals:

```
x.dapc <- dapc(x[1:100], n.pca=80, n.da=2)
x.pred <- predict(x.dapc)$posterior
hyb.pred <- predict(x.dapc, newdata = x[-(1:100)])$posterior
compoplot(rbind(x.pred, hyb.pred), col.pal = virid, main = "DAPC prediction")
```



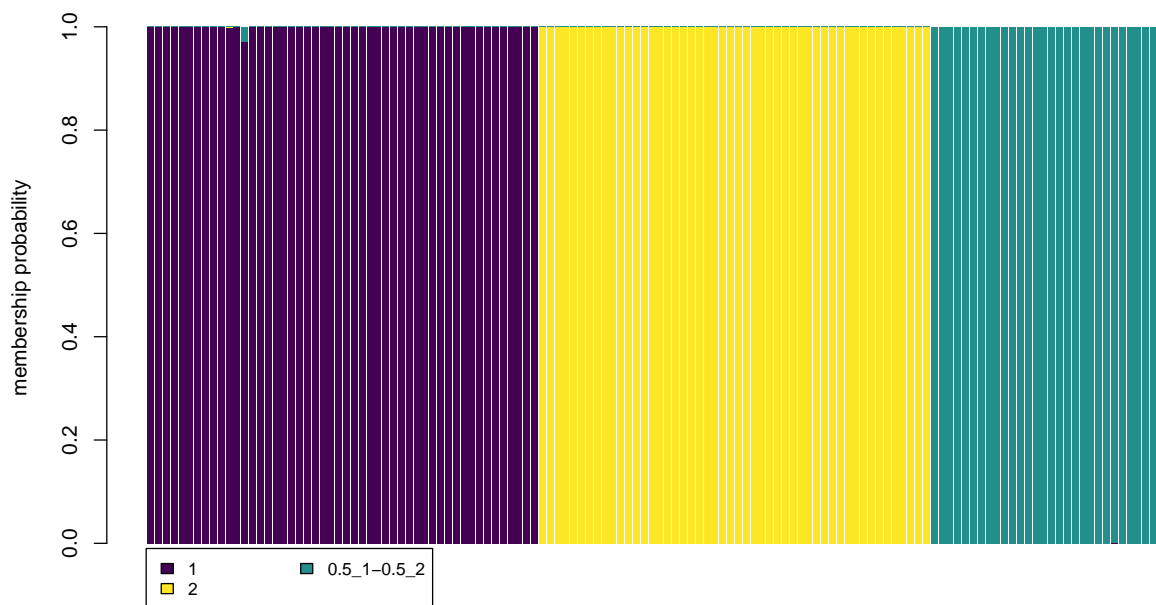


The problem of the above is that hybrids are seen as effectively outliers from the parental populations, so that their classification is inherently very unstable. To be formally identified, hybrids need to be modelled as a separate population, whose allele frequency distribution is somewhere between the parental populations. This is exactly the approach taken by `genclust.em`

```
res.hyb <- genclust.em(x, k = 2, hybrids = TRUE)

## Error in genclust.em(x, k = 2, hybrids = TRUE): object 'detailed' not
found

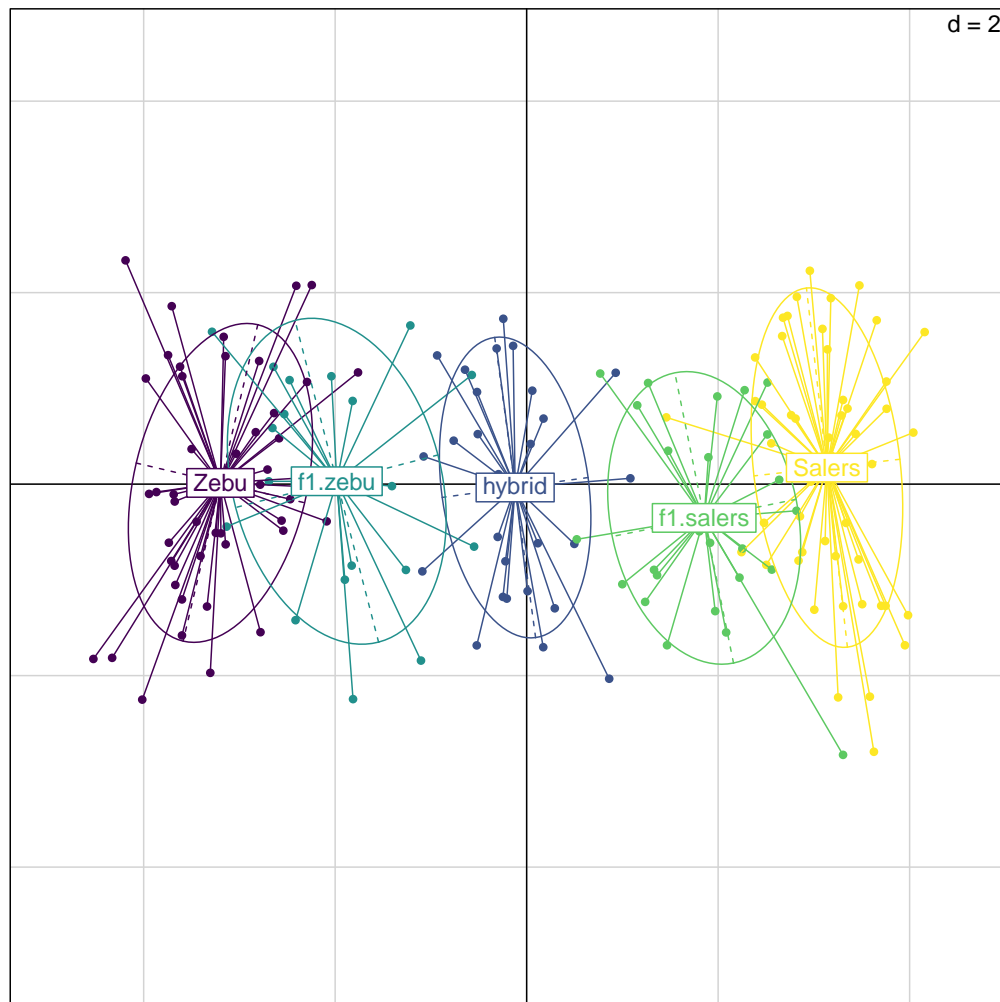
compoplot(res.hyb, n.col = 2, col.pal = hybridpal())
```



## 2.2.4 Looking for F1 and back-crosses

PCA:

```
y.pca <- dudi.pca(tab(y, NA.method = "mean"), scannf = FALSE, scale = FALSE)
s.class(y.pca$li, pop(y), col = hybridpal()(5))
```

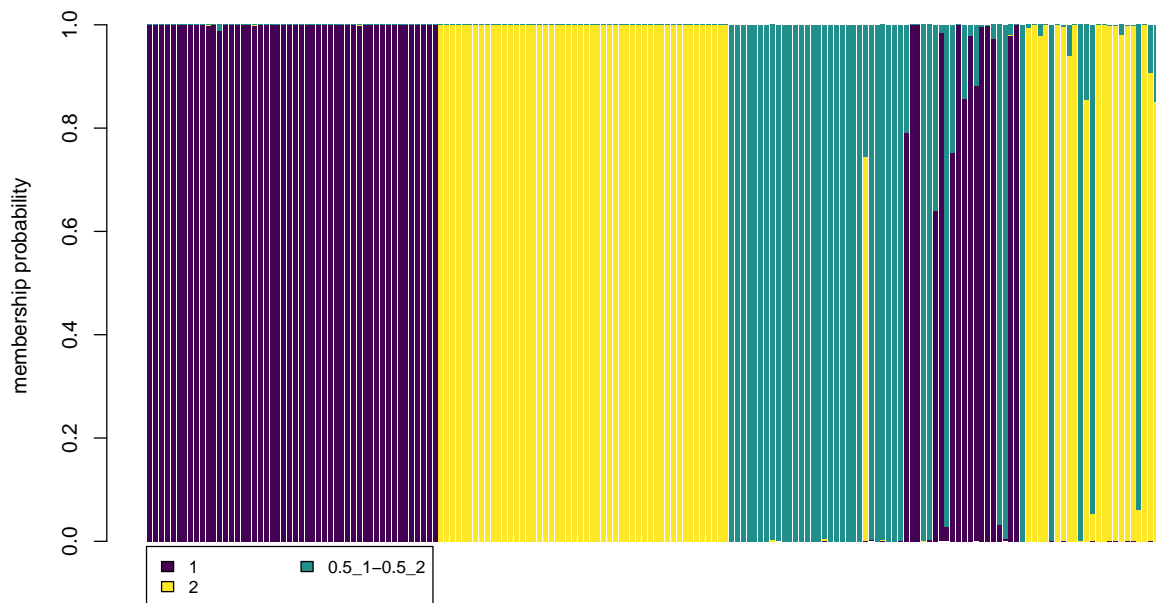


method with hybrids F1 only

```
res2.hyb <- genclust.em(y, k = 2, hybrids = TRUE)

## Error in genclust.em(y, k = 2, hybrids = TRUE): object 'detailed' not
found

compoplot(res2.hyb, n.col = 2, col.pal = hybridpal())
```



method with back-cross

```
res2.back <- genclust.em(y, k=2, hybrids = TRUE, hybrid.coef = c(.25,.5))

## Error in genclust.em(y, k = 2, hybrids = TRUE, hybrid.coef = c(0.25,
## 0.5)): object 'detailed' not found

complot(res2.back, col.pal = hybridpal())
```

