

Boosted Regression Trees for ecological modeling

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1 Introduction

This is a brief tutorial to accompany a set of functions that we have written to facilitate fitting BRT (boosted regression tree) models in R. This tutorial is a modified version of the tutorial accompanying Elith, Leathwick and Hastie's article in *Journal of Animal Ecology*. It has been adjusted to match the implementation of these functions in the 'dismo' package. The gbm* functions in the dismo package extend functions in the 'gbm' package by Greg Ridgeway. The goal of our functions is to make the functions in the 'gbm' package easier to apply to ecological data, and to enhance interpretation.

The tutorial is aimed at helping you to learn the mechanics of how to use the functions and to develop a BRT model in R. It does not explain what a BRT model is - for that, see the references at the end of the tutorial, and the documentation of the gbm package. For an example application with similar data as in this tutorial, see Elith et al., 2008.

The gbm functions in 'dismo' are as follows:

1. gbm.step - Fits a gbm model to one or more response variables, using cross-validation to estimate the optimal number of trees. This requires use of the utility functions roc, calibration and calc.deviance.
2. gbm.fixed, gbm.holdout - Alternative functions for fitting gbm models, implementing options provided in the gbm package.
3. gbm.simplify - Code to perform backwards elimination of variables, to drop those that give no evidence of improving predictive performance.
4. gbm.plot - Plots the partial dependence of the response on one or more predictors.
5. gbm.plot.fits - Plots the fitted values from a gbm object returned by any of the model fitting options. This can give a more reliable guide to the shape of the fitted surface than can be obtained from the individual functions, particularly when predictor variables are correlated and/or samples are unevenly distributed in environmental space.
6. gbm.interactions - Tests whether interactions have been detected and modelled, and reports the relative strength of these. Results can be visualised with gbm.perspec

2 Example data

Two sets of presence/absence data for *Anguilla australis* (Angaus) are available. One for model training (building) and one for model testing (evaluation). In the example below we load the training data. Presence (1) and absence (0) is recorded in column 2. The environmental variables are in columns 3 to 14. This is the same data as used in Elith, Leathwick and Hastie (2008).

```
> library(dismo)
> data(Anguilla_train)
> head(Anguilla_train)
```

	Site	Angaus	SegSumT	SegTSeas	SegLowFlow	DSDist	DSMaxSlope
1	1	0	16.0	-0.10	1.036	50.20	0.57
2	2	1	18.7	1.51	1.003	132.53	1.15
3	3	0	18.3	0.37	1.001	107.44	0.57
4	4	0	16.7	-3.80	1.000	166.82	1.72
5	5	1	17.2	0.33	1.005	3.95	1.15
6	6	0	15.1	1.83	1.015	11.17	1.72

	USAvgT	USRainDays	USSlope	USNative	DSDam	Method	LocSed
1	0.09	2.470	9.8	0.81	0	electric	4.8
2	0.20	1.153	8.3	0.34	0	electric	2.0
3	0.49	0.847	0.4	0.00	0	spo	1.0
4	0.90	0.210	0.4	0.22	1	electric	4.0
5	-1.20	1.980	21.9	0.96	0	electric	4.7
6	-0.20	3.300	25.7	1.00	0	electric	4.5

3 Fitting a model

To fit a gbm model, you need to decide what settings to use the article associated with this tutorial gives you information on what to use as rules of thumb. These data have 1000 sites, comprising 202 presence records for the short-finned eel (the command `sum(model.data$Angaus)` will give you the total number of presences). As a first guess you could decide: 1. There are enough data to model interactions of reasonable complexity 2. A lr of about 0.01 could be a reasonable starting point.

The below example shows how to use our function that steps forward and identifies the optimal number of trees (nt).

```
> angaus.tc5.lr01 <- gbm.step(data=Anguilla_train, gbm.x = 3:13, gbm.y = 2,
+                             family = "bernoulli", tree.complexity = 5,
+                             learning.rate = 0.01, bag.fraction = 0.5)
```

GBM STEP - version 2.9

Performing cross-validation optimisation of a boosted regression tree model

```
for Angaus with dataframe Anguilla_train and using a family of bernoulli
Using 1000 observations and 11 predictors
creating 10 initial models of 50 trees
```

```
  folds are stratified by prevalence
```

```
total mean deviance = 1.0063
```

```
tolerance is fixed at 0.001
```

```
ntrees resid. dev.
```

```
50    0.8457
```

```
now adding trees...
```

```
100   0.7719
```

```
150   0.7347
```

```
200   0.7137
```

```
250   0.7021
```

```
300   0.6932
```

```
350   0.6894
```

```
400   0.6847
```

```
450   0.6826
```

```
500   0.6813
```

```
550   0.681
```

```
600   0.6809
```

```
650   0.6821
```

```
700   0.6827
```

```
750   0.6837
```

```
800   0.6851
```

```
850   0.684
```

```
900   0.6836
```

```
950   0.6845
```

```
1000  0.6859
```

```
1050  0.6881
```

```
1100  0.6885
```

```
1150  0.6899
```

```
1200  0.6916
```

```
fitting final gbm model with a fixed number of 600 trees for Angaus
```

```
mean total deviance = 1.006
```

```
mean residual deviance = 0.463
```

```
estimated cv deviance = 0.681 ; se = 0.021
```

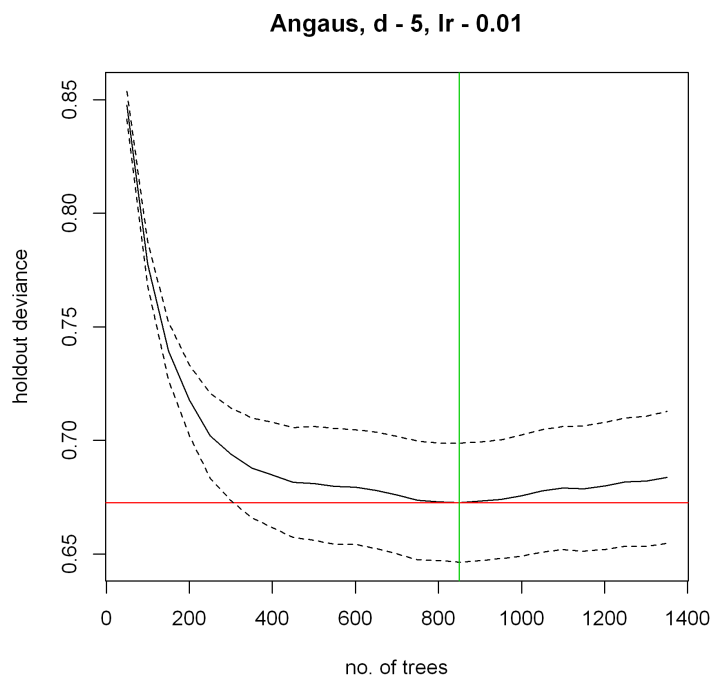
```
training data correlation = 0.777
```

```
cv correlation = 0.58 ; se = 0.022
```

```
training data ROC score = 0.959
```

```
cv ROC score = 0.874 ; se = 0.008
```

elapsed time - 0.51 minutes



Above we used the function `gbm.step`, this function is an alternative to the cross-validation provided in the `gbm` package. We have passed information to the function about data and settings. We have defined:

- the dataframe containing the data = `Anguilla_train`;

- the predictor variables - `gbm.x = c(3:13)` - which we do using a vector consisting of the indices for the data columns containing the predictors (i.e., here the predictors are columns 3 to 13 in `Anguilla_train`);

- the response variable - `gbm.y = 2` - indicating the column number for the species (response) data;

- the nature of the error structure - For example, `family = 'bernoulli'` (note the quotes);

- the tree complexity - we are trying a tree complexity of 5 for a start;

- the learning rate - we are trying with 0.01;

- the bag fraction - our default is 0.75; here we are using 0.5;

Everything else - i.e. all the other things that we could change if we wanted to (see the help file, and the documentation of the `gbm` package) - are set at their defaults if they are not named in the call. If you want to see what else you could change, you can type `gbm.step` and all the code will write itself to screen, or type `args(gbm.step)` and it will open in an editor window.

Running a model such as that described above writes progress reports to the screen, makes a graph, and returns an object containing a number of com-

ponents. Firstly, the things you can see: The R console will show something like this (not identical, because remember that these models are stochastic and therefore slightly different each time you run them, unless you set the seed or make them deterministic by using a bag fraction of 1)

This reports a brief model summary. All these values are also retained in the model object, so they will be permanently kept (as long as you save the R workspace before quitting).

This model was built with the default 10-fold cross-validation. The solid black curve is the mean, and the dotted curves about 1 standard error, for the changes in predictive deviance (ie as measured on the excluded folds of the cross-validation). The red line shows the minimum of the mean, and the green line the number of trees at which that occurs. The final model that is returned in the model object is built on the full data set, using the number of trees identified as optimal.

The returned object is a list (see R documentation if you don't know what that is), and the names of the components can be seen by typing:

To pull out one component of the list, use a number (`angaus.tc5.lr01[[29]]`) or name (`angaus.tc5.lr01$cv.statistics`) - but be careful, some are as big as the dataset, e.g. there will be 1000 fitted values. Find this by typing

```
length(angaus.tc5.lr01$fitted)
```

The way we organise our functions is to return exactly what Ridgeway's function in the gbm package returned, plus extra things that are relevant to our code. You will see by looking at the final parts of the gbm.step code that we have added components 25 onwards, that is, from gbm.call on. See the gbm documentation for what his parts comprise. Ours are:

- gbm.call - A list containing the details of the original call to gbm.step
- fitted - The fitted values from the final tree, on the response scale
- fitted.vars - The variance of the fitted values, on the response scale
- residuals - The residuals for the fitted values, on the response scale
- contributions - The relative importance of the variables, produced from the gbm summary function

- self.statistics - The relevant set of evaluation statistics, calculated on the fitted values - i.e. this is only interesting in so far as it demonstrates "evaluation" (i.e. fit) on the training data. It should NOT be reported as the model predictive performance.

- cv.statistics These are the most appropriate evaluation statistics. We calculate each statistic within each fold (at the identified optimal number of trees that is calculated on the mean change in predictive deviance over all folds), then present here the mean and standard error of those fold-based statistics.

- weights - the weights used in fitting the model (by default, "1" for each observation - i.e. equal weights).

- trees.fitted - A record of the number of trees fitted at each step in the stage-wise fitting; only relevant for later calculations

- training.loss.values - The stagewise changes in deviance on the training data

- cv.values - the mean of the CV estimates of predictive deviance, calculated at each step in the stagewise process - this and the next are used in the plot

shown above

cv.loss.ses - standard errors in CV estimates of predictive deviance at each step in the stagewise process

cv.loss.matrix - the matrix of values from which cv.values were calculated - as many rows as folds in the CV

cv.roc.matrix - as above, but the values in it are area under the curve estimated on the excluded data, instead of deviance in the cv.loss.matrix.

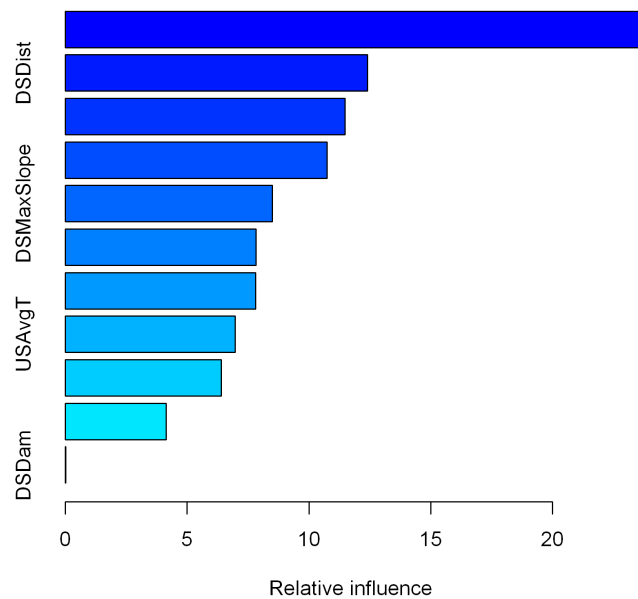
You can look at variable importance with the summary function

```
> names(angaus.tc5.lr01)
```

[1] "initF"	"fit"
[3] "train.error"	"valid.error"
[5] "oobag.improve"	"trees"
[7] "c.splits"	"bag.fraction"
[9] "distribution"	"interaction.depth"
[11] "n.minobsinnode"	"n.trees"
[13] "nTrain"	"response.name"
[15] "shrinkage"	"train.fraction"
[17] "var.levels"	"var.monotone"
[19] "var.names"	"var.type"
[21] "verbose"	"data"
[23] "Terms"	"cv.folds"
[25] "gbm.call"	"fitted"
[27] "fitted.vars"	"residuals"
[29] "contributions"	"self.statistics"
[31] "cv.statistics"	"weights"
[33] "trees.fitted"	"training.loss.values"
[35] "cv.values"	"cv.loss.ses"
[37] "cv.loss.matrix"	"cv.roc.matrix"

```
> summary(angaus.tc5.lr01)
```

	var	rel.inf
1	SegSumT	23.68567536
2	DSDist	12.40800003
3	USNative	11.48098929
4	Method	10.74245636
5	DSMaxSlope	8.49702227
6	USSlope	7.83477149
7	USRainDays	7.81812069
8	USAvgT	6.96694589
9	SegTSeas	6.39908327
10	SegLowFlow	4.13692361
11	DSDam	0.03001173



4 Choosing the settings

The above was a first guess at settings, using rules of thumb discussed in Elith et al. (2008). It made a model with only 650 trees, so our next step would be to reduce the lr. For example, try $lr = 0.005$, to aim for over 1000 trees:

```
> angaus.tc5.lr005 <- gbm.step(data=Anguilla_train, gbm.x = 3:13, gbm.y = 2,
+                               family = "bernoulli", tree.complexity = 5,
+                               learning.rate = 0.005, bag.fraction = 0.5)
```

GBM STEP - version 2.9

```
Performing cross-validation optimisation of a boosted regression tree model
for Angaus with dataframe Anguilla_train and using a family of bernoulli
Using 1000 observations and 11 predictors
creating 10 initial models of 50 trees
```

```

folds are stratified by prevalence
total mean deviance = 1.0063
tolerance is fixed at 0.001
ntrees resid. dev.
50    0.9104
```

now adding trees...

100	0.8476
150	0.8053
200	0.7751
250	0.7543
300	0.7395
350	0.7264
400	0.7179
450	0.712
500	0.7063
550	0.7028
600	0.6993
650	0.6954
700	0.6929
750	0.6911
800	0.689
850	0.6889
900	0.6881
950	0.6877
1000	0.6871
1050	0.6859
1100	0.6852
1150	0.6852
1200	0.685
1250	0.6845
1300	0.6849
1350	0.6846
1400	0.6845
1450	0.6845
1500	0.6847
1550	0.684
1600	0.6832
1650	0.684
1700	0.6851
1750	0.6852
1800	0.6854
1850	0.686
1900	0.686

fitting final gbm model with a fixed number of 1600 trees for Angaus

mean total deviance = 1.006

mean residual deviance = 0.416

estimated cv deviance = 0.683 ; se = 0.026

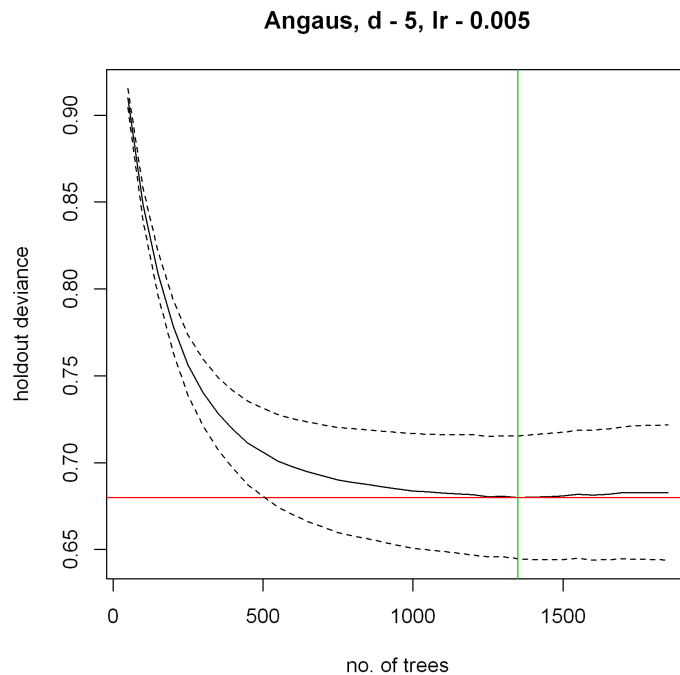
training data correlation = 0.811


```
cv correlation = 0.581 ; se = 0.022
```

```
training data ROC score = 0.97
```

```
cv ROC score = 0.873 ; se = 0.012
```

```
elapsed time - 0.91 minutes
```



To more broadly explore whether other settings perform better, and assuming that these are the only data available, you could either split the data into a training and testing set or use the cross-validation results. You could systematically alter `tc`, `lr` and the bag fraction and compare the results. See the later section on prediction to find out how to predict to independent data and calculate relevant statistics.

5 Alternative ways to fit models

The step function above is slower than just fitting one model and finding a minimum. If this is a problem, you could use our `gbm.holdout` code - this combines from the `gbm` package in ways we find useful. We tend to prefer `gbm.step`, especially when modelling many species, because it automatically finds the optimal number of trees. Alternatively, the `gbm.fixed` code allows you to fit a model of a set number of trees; this can be used, as in Elith et al. (2008),

to predict to new data (see later section).

6 Simplifying the model

For a discussion of simplification see Appendix 2 of the online supplement to Elith et al (2008). Simplification builds many models, so it can be slow. For example, the code below took a few minutes to run on a modern laptop. In it we assess the value in simplifying the model built with a *lr* of 0.005, but only test dropping up to 5 variables (the "n.drop" argument; the default is an automatic rule so it continues until the average change in predictive deviance exceeds its original standard error as calculated in *gbm.step*).

```
> angaus.simp <- gbm.simplify(angaus.tc5.lr005, n.drops = 5)
```

```
gbm.simplify - version 2.9
```

```
simplifying gbm.step model for Angaus with 11 predictors and 1000 observations  
original deviance = 0.6801(0.0353)
```

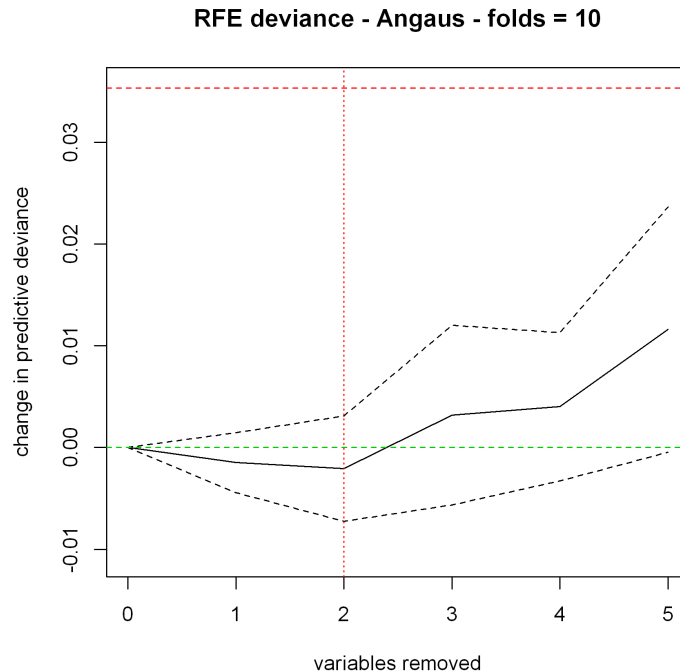
```
a fixed number of 5 drops will be tested
```

```
creating initial models...
```

```
dropping predictor:  1  2  3  4  5
```

```
now processing final dropping of variables with full data
```

```
1 - DSDam  
2 - SegLowFlow  
3 - SegTSeas  
4 - USAvgT  
5 - DSMaxSlope
```



For our run, this estimated that the optimal number of variables to drop was 1; yours could be slightly different:

You can use the number indicated by the red vertical line, or look at the results in the `angaus.simp` object. Now make a model with 1 predictor dropped, by indicating to the `gbm.step` call the relevant number of predictor(s) from the predictor list in the `angaus.simp` object - see highlights, below, in which we indicate we want to drop 1 variable by calling the second vector of predictor columns in the `pred` list, using a `[[1]]`:

```
> angaus.tc5.lr005.simp <- gbm.step(Anguilla_train,
+                                gbm.x=angaus.simp$pred.list[[1]], gbm.y=2,
+                                tree.complexity=5, learning.rate=0.005)
```

GBM STEP - version 2.9

Performing cross-validation optimisation of a boosted regression tree model for Angaus with dataframe `Anguilla_train` and using a family of bernoulli
Using 1000 observations and 10 predictors
creating 10 initial models of 50 trees

```
  folds are stratified by prevalence
total mean deviance =  1.0063
tolerance is fixed at  0.001
```

```

ntrees resid. dev.
50      0.9083
now adding trees...
100     0.8475
150     0.8063
200     0.777
250     0.7559
300     0.7391
350     0.7261
400     0.7163
450     0.7092
500     0.7028
550     0.6983
600     0.6949
650     0.692
700     0.6904
750     0.6891
800     0.6881
850     0.6869
900     0.6861
950     0.6851
1000    0.6844
1050    0.6838
1100    0.6837
1150    0.6834
1200    0.6833
1250    0.6837
1300    0.6838
1350    0.6838
1400    0.6838
1450    0.6837
1500    0.6841
1550    0.6849
1600    0.6852
1650    0.6856
1700    0.6859
fitting final gbm model with a fixed number of 1200 trees for Angaus

mean total deviance = 1.006
mean residual deviance = 0.457

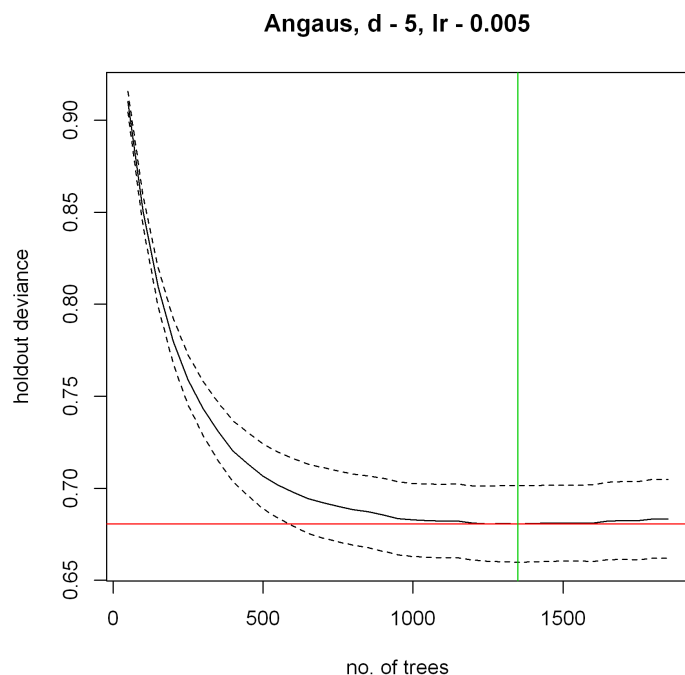
estimated cv deviance = 0.683 ; se = 0.041

training data correlation = 0.787
cv correlation = 0.58 ; se = 0.041

```

```
training data ROC score = 0.962
cv ROC score = 0.873 ; se = 0.016
```

```
elapsed time - 0.95 minutes
```

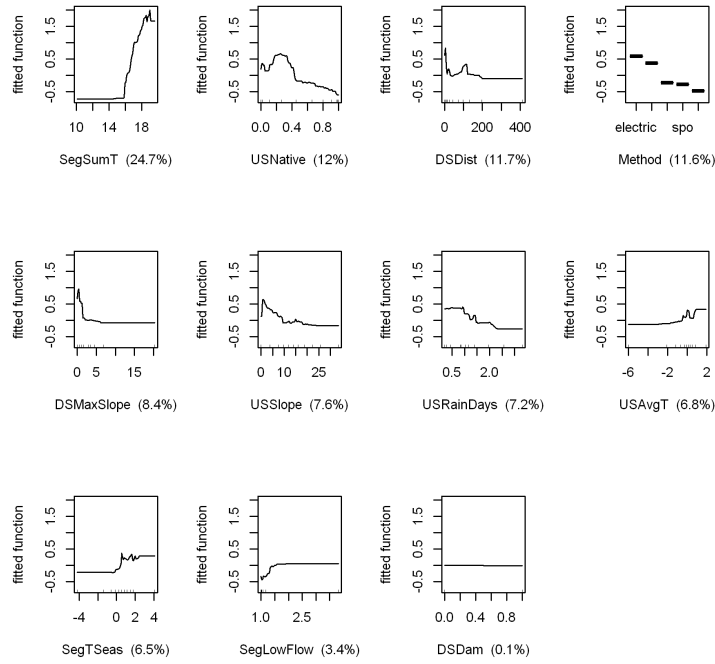


This has now made a new model (`angaus.tc5.lr005.simp`) with the same list components as described earlier. We could continue to use it, but given that we don't particularly want a more simple model (our view is that, in a dataset of this size, included variables that contribute little are acceptable), we won't use it further.

7 Plotting the functions and fitted values from the model

The fitted functions from a BRT model created from any of our functions can be plotted using `gbm.plot`. If you want to plot all variables on one sheet first set up a graphics device with the right set-up - here we will make one with 3 rows and 4 columns:

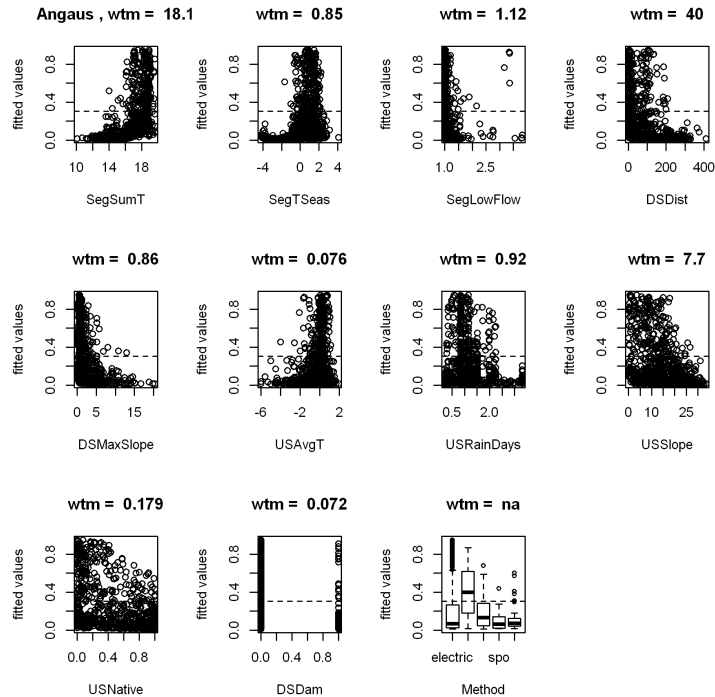
```
> gbm.plot(angaus.tc5.lr005, n.plots=11, write.title = FALSE)
```



Additional arguments to this function allow for making a smoothed representation of the plot, allowing different vertical scales for each variable, omitting (and formatting) the rugs, and plotting a single variable.

Depending on the distribution of observations within the environmental space, fitted functions can give a misleading indication about the distribution of the fitted values in relation to each predictor. The function `gbm.plot.fits` has been provided to plot the fitted values in relation to each of the predictors used in the model.

```
> gbm.plot.fits(angaus.tc5.lr005)
```



This has options that allow for the plotting of all fitted values or of fitted values only for positive observations, or the plotting of fitted values in factor type graphs that are much quicker to print. Values above each graph indicate the weighted mean of fitted values in relation to each non-factor predictor.

8 Interrogate and plot the interactions

This code assesses the extent to which pairwise interactions exist in the data. `find.int <- gbm.interactions(angaus.tc5.lr005)`. The returned object, here named `test.int`, is a list. The first 2 components summarise the results, first as a ranked list of the 5 most important pairwise interactions, and the second tabulating all pairwise interactions. The variable index numbers in `$rank.list` can be used for plotting.

```
> find.int <- gbm.interactions(angaus.tc5.lr005)
```

```
gbm.interactions - version 2.9
```

```
Cross tabulating interactions for gbm model with 11 predictors
```

```
1 2 3 4 5 6 7 8 9 10
```

```
> find.int$interactions
```

	SegSumT	SegTSeas	SegLowFlow	DSDist	DSMaxSlope	USAvgT
SegSumT	0	3.79	0.10	13.24	2.66	8.82

SegTSeas	0	0.00	0.67	5.47	1.02	0.60
SegLowFlow	0	0.00	0.00	0.63	0.36	0.42
DSDist	0	0.00	0.00	0.00	0.08	0.11
DSMaxSlope	0	0.00	0.00	0.00	0.00	0.36
USAvgT	0	0.00	0.00	0.00	0.00	0.00
USRainDays	0	0.00	0.00	0.00	0.00	0.00
USSlope	0	0.00	0.00	0.00	0.00	0.00
USNative	0	0.00	0.00	0.00	0.00	0.00
DSDam	0	0.00	0.00	0.00	0.00	0.00
Method	0	0.00	0.00	0.00	0.00	0.00

	USRainDays	USSlope	USNative	DSDam	Method
SegSumT	19.19	1.92	5.96	0.00	9.23
SegTSeas	1.86	0.24	0.20	0.00	1.84
SegLowFlow	0.28	1.13	0.27	0.00	0.45
DSDist	4.02	0.74	1.15	0.01	1.97
DSMaxSlope	0.43	1.03	1.84	0.00	1.06
USAvgT	0.07	0.09	1.90	0.00	0.54
USRainDays	0.00	0.12	2.36	0.00	2.27
USSlope	0.00	0.00	1.53	0.00	1.48
USNative	0.00	0.00	0.00	0.00	2.55
DSDam	0.00	0.00	0.00	0.00	0.00
Method	0.00	0.00	0.00	0.00	0.00

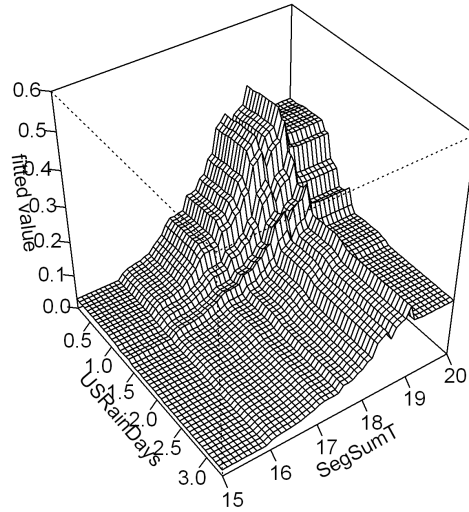
```
> find.int$rank.list
```

	var1.index	var1.names	var2.index	var2.names	int.size
1	7	USRainDays	1	SegSumT	19.19
2	4	DSDist	1	SegSumT	13.24
3	11	Method	1	SegSumT	9.23
4	6	USAvgT	1	SegSumT	8.82
5	9	USNative	1	SegSumT	5.96
6	4	DSDist	2	SegTSeas	5.47

You can plot pairwise interactions like this:

```
> gbm.perspec(angaus.tc5.lr005, 7, 1, y.range=c(15,20), z.range=c(0,0.6))
```

```
maximum value = 0.44
```

Additional options allow specifications of label names, rotations of the 3D graph and so on.

9 Predicting to new data

If you want to predict to a set of sites (rather than to a whole map), the general procedure is to set up a data.frame with rows for sites and columns for the variables that are in your model. R is case sensitive; the names need to exactly match those in the model. Other columns such as site IDs etc can also exist in the data.frame (and are ignored).

Our dataset for predicting to sites is in a file called `Anguilla_test`. The "Method" column needs to be converted to a factor, with levels matching those in the modelling data. To make predictions to sites from the BRT model use `predict` (or `predict.gbm`) from the `gbm` package. The predictions are in a vector called `preds`. These are evaluation sites, and have observations in column 1 (named `Angaus_obs`). They are independent of the model building set and were used for an evaluation with independent data. Note that the `calc.deviance` function has different formulae for different distributions of data; the default is binomial, so we didn't specify it in the call

```
> data(Anguilla_test)
> preds <- predict.gbm(angaus.tc5.lr005, Anguilla_test,
```

```

+           n.trees=angaus.tc5.lr005$gbm.call$best.trees, type="response")
> calc.deviance(obs=Anguilla_test$Angaus_obs, pred=preds, calc.mean=TRUE)

[1] 0.740576

> d <- cbind(Anguilla_test$Angaus_obs, preds)
> pres <- d[d[,1]==1, 2]
> abs <- d[d[,1]==0, 2]
> e <- evaluate(p=pres, a=abs)
> e

class           : ModelEvaluation
n presences     : 107
n absences      : 393
AUC             : 0.8617155
cor             : 0.5267795
max TPR+TNR at : 0.0969569

```

One useful feature of prediction in gbm is you can predict to a varying number of trees. See the highlighted code below to how to predict to a vector of trees. The full set of code here shows how to make one of the graphed lines from Fig. 2 in our paper, using a model of 5000 trees developed with gbm.fixed

```

> angaus.5000 <- gbm.fixed(data=Anguilla_train, gbm.x=3:13, gbm.y=2,
+           learning.rate=0.005, tree.complexity=5, n.trees=5000)

[1] fitting gbm model with a fixed number of 5000 trees for Angaus
[1] total deviance = 1006.33
[1] residual deviance = 205.37

> tree.list <- seq(100, 5000, by=100)
> pred <- predict.gbm(angaus.5000, Anguilla_test, n.trees=tree.list, "response")

```

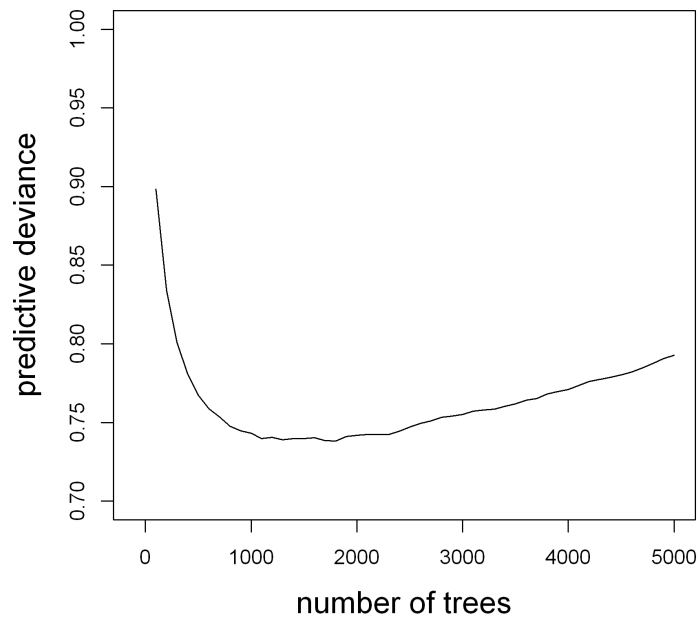
Note that the code above makes a matrix, with each column being the predictions from the model angaus.5000 to the number of trees specified by that element of tree.list - for example, the predictions in column 5 are for tree.list[5] = 500 trees. Now to calculate the deviance of all these results, and plot them:

```

> angaus.pred.deviance <- rep(0,50)
> for (i in 1:50) {
+   angaus.pred.deviance[i] <- calc.deviance(Anguilla_test$Angaus_obs,
+           pred[,i], calc.mean=TRUE)
+ }

> plot(tree.list, angaus.pred.deviance, ylim=c(0.7,1), xlim=c(-100,5000),
+   type='l', xlab="number of trees", ylab="predictive deviance",
+   cex.lab=1.5)

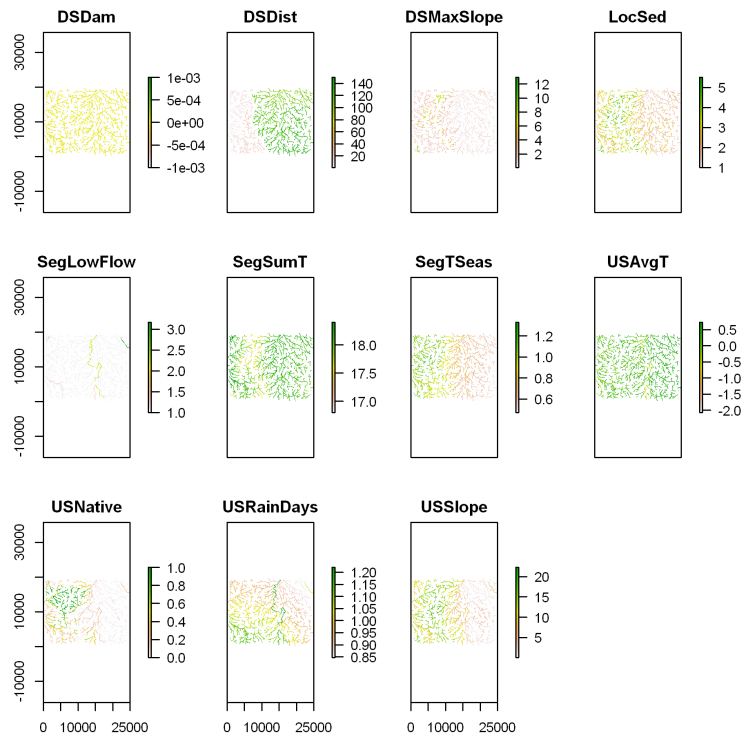
```



10 Spatial prediction

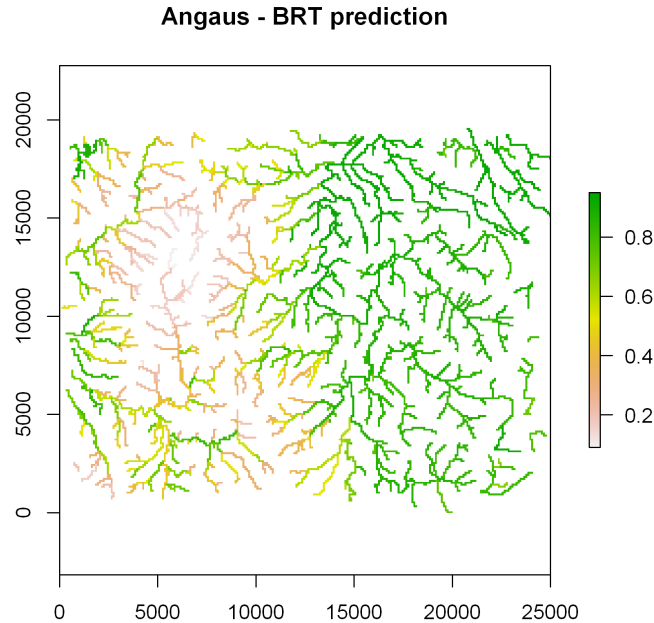
Here we show how to predict to a whole map (technically to a `RasterLayer` object) using the `predict` version in the package `'raster'`. The predictor variables are available as a `RasterBrick` (multi-layered raster) in `Anguilla_grids`.

```
> data(Anguilla_grids)
> plot(Anguilla_grids)
```



There is (obviously) no grid for fishing method. We create a data.frame with a constant value (of class 'factor') and pass that on to the predict function.

```
> Method=factor('electric', levels = levels(Anguilla_train$Method))
> add=data.frame(Method)
> p = predict(Anguilla_grids, angaus.tc5.lr005, const=add,
+             n.trees=angaus.tc5.lr005$gbm.call$best.trees, type="response")
> p = mask(p, raster(Anguilla_grids, 1))
> plot(p, main='Angaus - BRT prediction')
```



11 Further reading

The following includes a mix of both statistical papers and ecological applications:

- Elith, J., Leathwick, J.R., and Hastie, T. (2008). Boosted regression trees - a new technique for modelling ecological data. *Journal of Animal Ecology*
- Friedman, J.H. (2001) Greedy function approximation: a gradient boosting machine. *The Annals of Statistics*, 29, 1189-1232.
- Friedman, J.H. (2002) Stochastic gradient boosting. *Computational Statistics and Data Analysis*, 38, 367-378.
- Friedman, J.H., Hastie, T., and Tibshirani, R. (2000) Additive logistic regression: a statistical view of boosting. *The Annals of Statistics*, 28, 337-407.
- Friedman, J.H. and Meulman, J.J. (2003) Multiple additive regression trees with application in epidemiology. *Statistics in Medicine*, 22, 1365-1381.
- Hastie, T., R. Tibshirani, and J. H. Friedman. 2001. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*. Springer-Verlag, New York.
- Leathwick, J.R., Elith, J., Francis, M.P., Hastie, T., and Taylor, P. (2006a) Variation in demersal fish species richness in the oceans surrounding New Zealand: an analysis using boosted regression trees. *Marine Ecology Progress Series*, 321, 267-281.

- Moisen, G.G., Freeman, E.A., Blackard, J.A., Frescino, T.S., Zimmermann, N.E., and Edwards, T.C.. (2006) Predicting tree species presence and basal area in Utah: a comparison of stochastic gradient boosting, generalized additive models, and tree-based methods. *Ecological Modelling*, 199, 176-187.
- Ridgeway, G. (1999) The state of boosting. *Computing Science and Statistics*, 31, 172-181.
- Ridgeway, G. (2006) Generalized boosted regression models. Documentation on the R package "gbm", version 1.5-7. <http://www.i-pensieri.com/gregr/gbm.shtml>.
- Schapire, R. (2003). The boosting approach to machine learning - an overview. In *MSRI Workshop on Nonlinear Estimation and Classification, 2002*. (eds D.D. Denison, M.H. Hansen, C. Holmes, B. Mallick and B. Yu), Springer, NY.
- Wintle, B. A., J. Elith, and J. Potts. 2005. Fauna habitat modelling and mapping in an urbanising environment; A case study in the Lower Hunter Central Coast region of NSW. *Austral Ecology* 30:729-748.