Running Medium Term Forecasts with FLash

04 September, 2018

This tutorial describes how Medium-Term Forecasts (MTF) can be performed using **FLR**. It uses the **FLash** package for running projections as well as the **FLBRP** package for evaluating reference points.

MTFs use the same engine as Short-Term Forecasts (STFs). However, there are some key differences between them. MTFs typically project over 5 to 10 years instead of the usual 3 years for a STF. Because of this increase in projection length it is necessary to include a stock-recruitment relationship to simulate the dynamics of the biological stock (an STF uses a constant recruitment assumption). MTFs may also have a more complicated projection control object because they can try to simulate management objectives (e.g. decreases in F over time). Finally, MTFs may also include consideration of uncertainty by including stochasticity in the projections.

Special attention must be paid to the conditioning and future assumptions of the stock.

Required packages

To follow this tutorial you should have installed the following packages:

- FLR: FLCore, FLash, FLBRP, FLAssess

You can do so as follows,

```
install.packages(c("FLCore"), repos="http://flr-project.org/R")
install.packages(c("FLash"), repos="http://flr-project.org/R")
install.packages(c("FLBRP"), repos="http://flr-project.org/R")
install.packages(c("FLAssess"), repos="http://flr-project.org/R")
```

```
# This chunk loads all necessary packages, trims pkg messages
library(FLCore)
library(FLash)
library(FLBRP)
library(FLAssess)
```

Introduction to Medium Term Forecasts

Running a MTF is similar to running a STF in that we need several components:

1. An **FLStock** object set up for the future (assumptions);
2. A stock-recruiment relationship (SRR);
3. A projection control object;

However, there are some significant differences between an MTF and an STF:

1. An MTF is normally run for 5 to 10 years (an STF is normally 3 years);
2. An MTF can use different target types (e.g. setting catch targets, not just F targets);
3. A dynamic SRR should be used (the STF assumption of mean recruitment is not a good one for more a projection of more than 3 years);

4. We can include uncertainty in the recruitment and target values.

In this tutorial we will build a 10 year projection, introduce a range of target types (including minimum and maximum target values and relative target values), use a dynamic SRR and introduce uncertainty.

As ususal, we base the projections on plaice in the North Sea.

Conditioning the projection

The first step is to condition the projection by making assumptions about the stock in the future and by considering the SRR. This can be done in several different ways.

Making the future stock

As ever, load the ple4 data:

```
data(ple4)
```

We again use `stf()` to set up a future stock (see the STF tutorial. This makes a lot of assumptions about the future stock (see the LINK TO STF tutorial for more details). There are methods of setting up the future assumptions but these are not explored here. We may want to change some of these assumptions but for the moment we will use the defaults.

```
# Set up a 10 year MTF
ple4_mtf <- stf(ple4, nyears = 10)
```

Now the stock goes up to 2018:

```
summary(ple4_mtf)
```

```
An object of class "FLStock"

Name: PLE
Description: Plaice in IV. ICES WGNSSK 2018. FLAAP
Quant: age
Dims:  age  year    unit    season  area    iter
    10  71  1   1   1   1

Range:  min max pgroup  minyear maxyear minfbar maxfbar
    1   10  10  1957    2027    2   6

catch         : [ 1 71 1 1 1 1 ], units =  t
catch.n       : [ 10 71 1 1 1 1 ], units =  1000
catch.wt      : [ 10 71 1 1 1 1 ], units =  kg
discards      : [ 1 71 1 1 1 1 ], units =  t
discards.n    : [ 10 71 1 1 1 1 ], units =  1000
discards.wt   : [ 10 71 1 1 1 1 ], units =  kg
landings      : [ 1 71 1 1 1 1 ], units =  t
landings.n    : [ 10 71 1 1 1 1 ], units =  1000
landings.wt   : [ 10 71 1 1 1 1 ], units =  kg
```

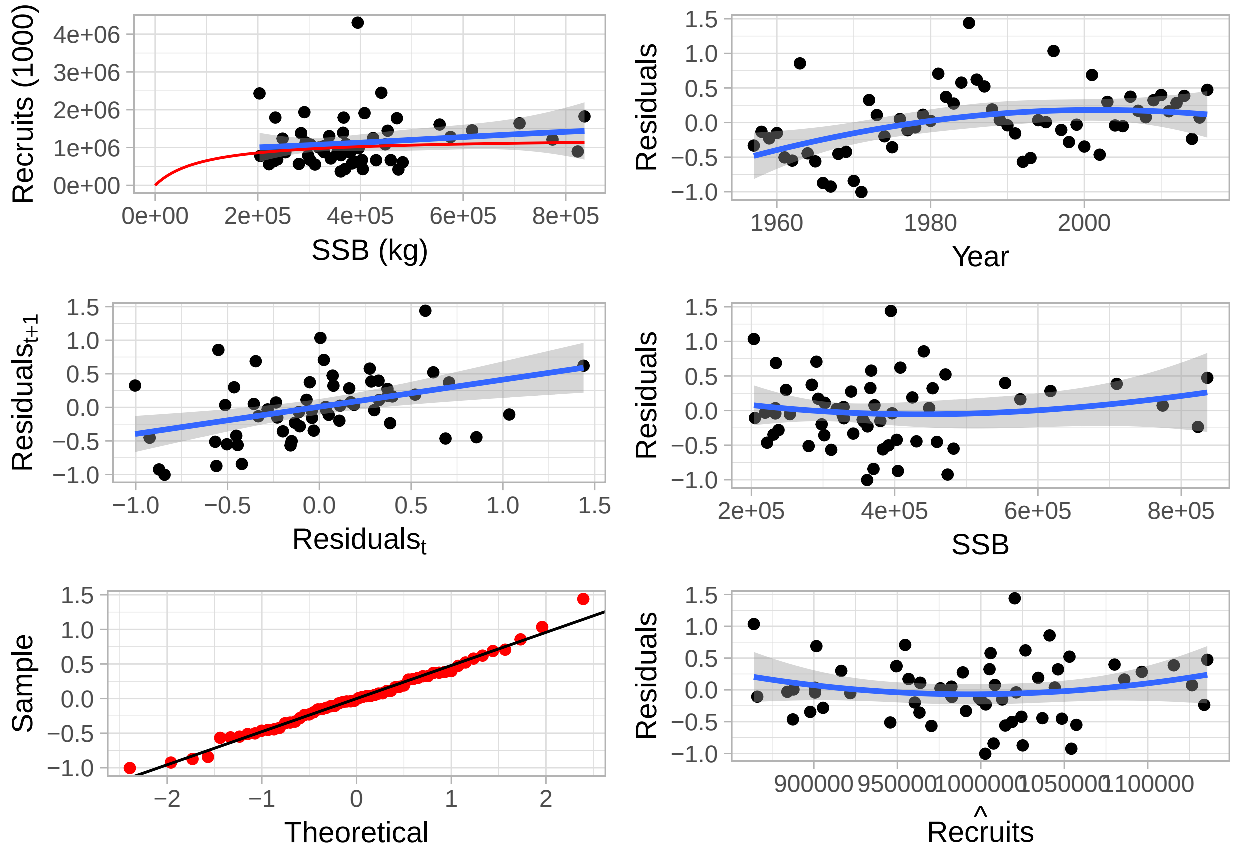


Figure 1: Fitted Beverton-Holt stock-recruitment relationship for the *ple4* stock object

```
stock          : [ 1 71 1 1 1 1 ], units =  t
stock.n        : [ 10 71 1 1 1 1 ], units =  1000
stock.wt       : [ 10 71 1 1 1 1 ], units =  kg
m              : [ 10 71 1 1 1 1 ], units =  m
mat            : [ 10 71 1 1 1 1 ], units =
harvest        : [ 10 71 1 1 1 1 ], units =  f
harvest.spwn   : [ 10 71 1 1 1 1 ], units =
m.spwn         : [ 10 71 1 1 1 1 ], units =
```

MORE ON ASSUMPTIONS AND CONDITIONING

The stock-recruitment relationship

In these examples we use a Beverton-Holt model (see the tutorial on fitting SRRs for more detail LINK TO SRR TUTORIAL).

```
ple4_sr <- fmle(as.FLSR(ple4, model="bevholt"), control=list(trace=0))
```

```
plot(ple4_sr)
```

The resulting SRR fit can be seen in Figure 1.

Example 1: F targets

We saw in the STF tutorial how to set an F target (LINK). Here is some quick revision.

We will set the future F at F status quo (again) and we assume that F status quo is the mean of the last 4 years

```
f_status_quo <- mean(fbar(ple4)[,as.character(2005:2008)])
f_status_quo
```

```
[1] 0.3177
```

Make the control *data.frame* including all the years of the projection:

```
ctrl_target <- data.frame(year = 2009:2018,
                quantity = "f",
                val = f_status_quo)
```

Make the *fwdControl* object from the control *data.frame*:

```
ctrl_f <- fwdControl(ctrl_target)
```

We can take a look at the control object. We have columns of `year`, `quantity` (target type), `min`, `val` and `max`. `min` and `max` can be ignored for now. There is also another table underneath (with `min`, `val` and `max`) - again, ignore this for now.

```
ctrl_f
```

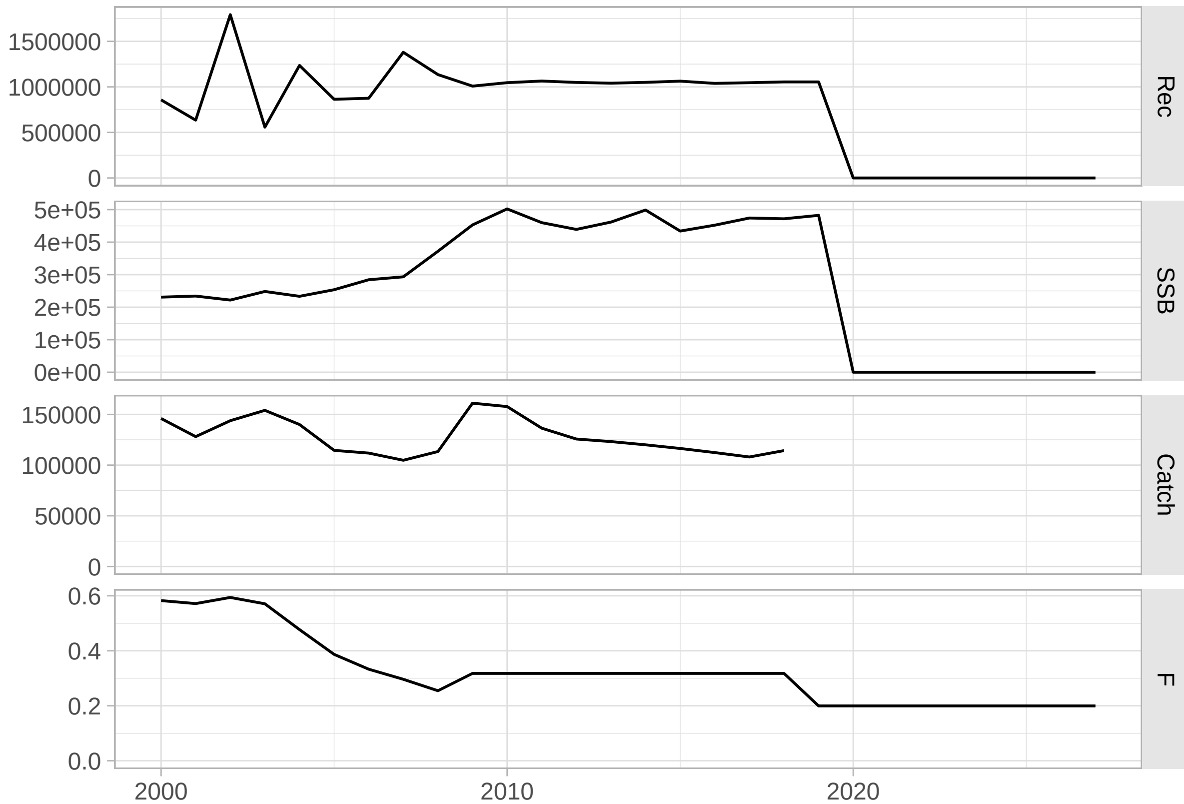
```
Target
   year quantity min    val max
1  2009        f  NA 0.3177  NA
2  2010        f  NA 0.3177  NA
3  2011        f  NA 0.3177  NA
4  2012        f  NA 0.3177  NA
5  2013        f  NA 0.3177  NA
6  2014        f  NA 0.3177  NA
7  2015        f  NA 0.3177  NA
8  2016        f  NA 0.3177  NA
9  2017        f  NA 0.3177  NA
10 2018        f  NA 0.3177  NA


     min     val     max
  1       NA 0.31768      NA
  2       NA 0.31768      NA
  3       NA 0.31768      NA
  4       NA 0.31768      NA
  5       NA 0.31768      NA
  6       NA 0.31768      NA
  7       NA 0.31768      NA
  8       NA 0.31768      NA
  9       NA 0.31768      NA
  10      NA 0.31768      NA
```

Run fwd() with our three ingredients

```
ple4_f_sq <- fwd(ple4_mtf, ctrl = ctrl_f, sr = ple4_sr)
```

What just happened? We plot the stock from the year 2000.

```
plot(window(ple4_f_sq, start=2000))
```



The future Fs are as we set in the control object (good):

```
fbar(ple4_f_sq)[,ac(2005:2018)]
```

```
, , unit = unique, season = all, area = unique

     year
age   2005    2006    2007    2008    2009
  all 0.38686 0.33299 0.29622 0.25465 0.31768

      [ ...  4 years]

     year
age   2014    2015    2016    2017    2018
  all 0.31768 0.31768 0.31768 0.31768 0.31768
```

What about recruitment? Remember we are now using a Beverton-Holt model.

```
rec(ple4_f_sq)[,ac(2005:2018)]
```

```
, , unit = unique, season = all, area = unique

   year
age 2005    2006    2007    2008    2009   
  1  863893  875191 1379750 1135050 1008401

      [ ...  4 years]

   year
age 2014    2015    2016    2017    2018   
  1 1049618 1062957 1038442 1045891 1054303
```

The recruitment is not constant but is not changing very much. That's because the fitted model looks flat REF BACK TO THE SRR FIGURE.

Example 2: A decreasing catch target #{ex2}

In this example we introduce two new things:

1. A new target type (catch);
2. A changing target value.

Setting a catch target allows to explore the consequences of different TAC strategies. In this example, the TAC (the total catch of the stock) is reduced 10% each year for 10 years.

We create a vector of future catches based on the catch in 2008:

```
future_catch <- c(catch(ple4)[,"2008"]) * 0.9^(1:10)
future_catch
```

```
 [1] 102057  91851  82666  74400  66960  60264  54237  48814  43932  39539
```

We create the *fwdControl* object, setting the quantity to `catch` and passing in the vector of future catches:

```
ctrl_catch <- fwdControl(
    data.frame(
        year=2009:2018,
        quantity = "catch",
        val=future_catch))
```

The control object has the desired catch target values.

```
ctrl_catch
```

```
Target
   year quantity min    val max
```

```
1  2009     catch  NA 102057  NA
2  2010     catch  NA  91851  NA
3  2011     catch  NA  82666  NA
4  2012     catch  NA  74400  NA
5  2013     catch  NA  66960  NA
6  2014     catch  NA  60264  NA
7  2015     catch  NA  54237  NA
8  2016     catch  NA  48814  NA
9  2017     catch  NA  43932  NA
10 2018     catch  NA  39539  NA
```

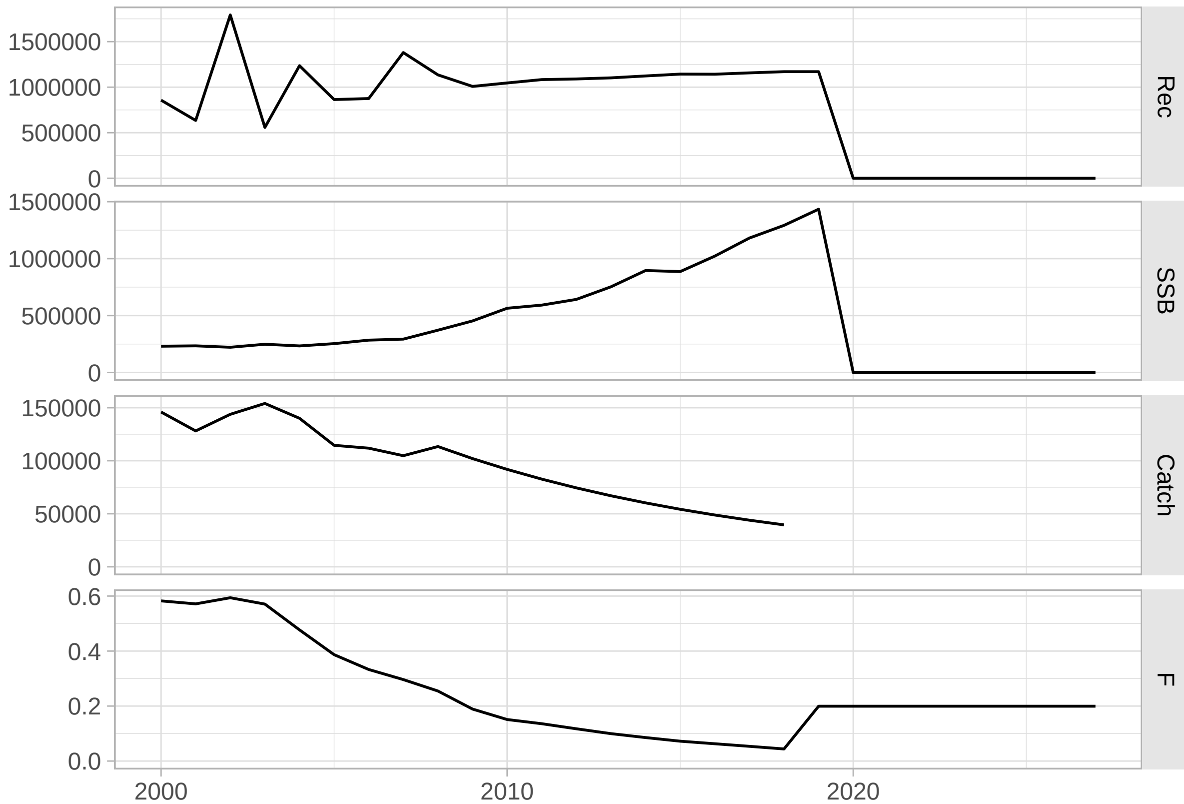
```
     min    val    max
  1      NA 102057     NA
  2      NA  91851     NA
  3      NA  82666     NA
  4      NA  74400     NA
  5      NA  66960     NA
  6      NA  60264     NA
  7      NA  54237     NA
  8      NA  48814     NA
  9      NA  43932     NA
  10     NA  39539     NA
```

We call `fwd()` with the stock, the control object and the SRR:

```
ple4_catch <- fwd(ple4_mtf, ctrl_catch, sr = ple4_sr)
```

And take a look at the results:

```
plot(window(ple4_catch, start=2000))
```



The decreasing catch targets have been hit. Note that F has to be similarly reduced to hit the catch targets, resulting in a surge in SSB.

Example 3: Setting an SSB target

In the previous examples we have set target types based on the activity of the fleet (F and catch). We can also set biological target types. This is useful when there are biological reference points, e.g. Bpa. Here we set SSB as the target.

Care with timing

When setting a biological abundance target we have to consider the timing of the target. In an **FLStock**, abundances are at the beginning of the year (or at the very end of the previous year). For example, if you look at the total stock abundances you get the stock at the beginning of each year, i.e. before any fishing has occurred.

Internally, **FLash** attempts to hit the desired target by finding the appropriate value of F. However, the stock abundance at the start of the year is the result of fishing in the previous year, i.e SSB in year Y depends on F in Y-1. This means that if you set an abundance based target, you are really finding the F in the previous year that will give you that target. Setting an SSB target in a year is the equivalent of setting an SSB target for the very `end` of that year (the same as setting a target for the very start of the next year). The result is that you have to be careful with the years in the control object when setting a target based on the stock abundance.

This is best illustrated with a simple example of a one year projection. If we want to hit an SSB target in 2009 (i.e. the SSB at the start of 2009 etc), we actually set it in the control object as being for 2008 as it is in

2008 that the F will be found that hits the SSB in 2009. In this example we want the future SSB to be high (we could have used **FLBRP** to come up with a suitable value, e.g. Bmsy but here we just pick a value).

```
future_ssb <- 150000
ctrl_ssb <- fwdControl(data.frame(year=2008, quantity = "ssb", val=future_ssb))
ctrl_ssb
```

```
Target
  year quantity min    val max
1 2008      ssb  NA 150000  NA


    min    val    max
  1     NA 150000     NA
```

```
ple4_ssb <- fwd(ple4_mtf, ctrl_ssb, sr = ple4_sr)
```

Remember, we have effectively set an SSB target for the very end of 2008 but we do not see this in the **FLStock** until the very beginning of 2009. The result is that we can see that the SSB target has been hit, but not until 2009.

```
ssb(ple4_ssb)[,ac(2005:2009)]
```

```
An object of class "FLQuant"
, , unit = unique, season = all, area = unique

     year
age   2005   2006   2007   2008   2009
  all 253737 284447 293330 371837 150000

units:  NA
```

A longer projection

Here we run a longer projection with a constant SSB target. The future stock object, `ple4_mtf`, only goes up to 2018. This means that in the control object we can only set an SSB target up to 2017. Setting an SSB target for 2018 would try to hit the SSB at the start of 2019 which is outside of our stock object, resulting in an error (try it, if you want).

```
future_ssb <- 300000
ctrl_ssb <- fwdControl(data.frame(year=2008:2017, quantity = "ssb", val=future_ssb))
ple4_ssb <- fwd(ple4_mtf, ctrl_ssb, sr = ple4_sr)
```

The SSB has been hit upto 2018.

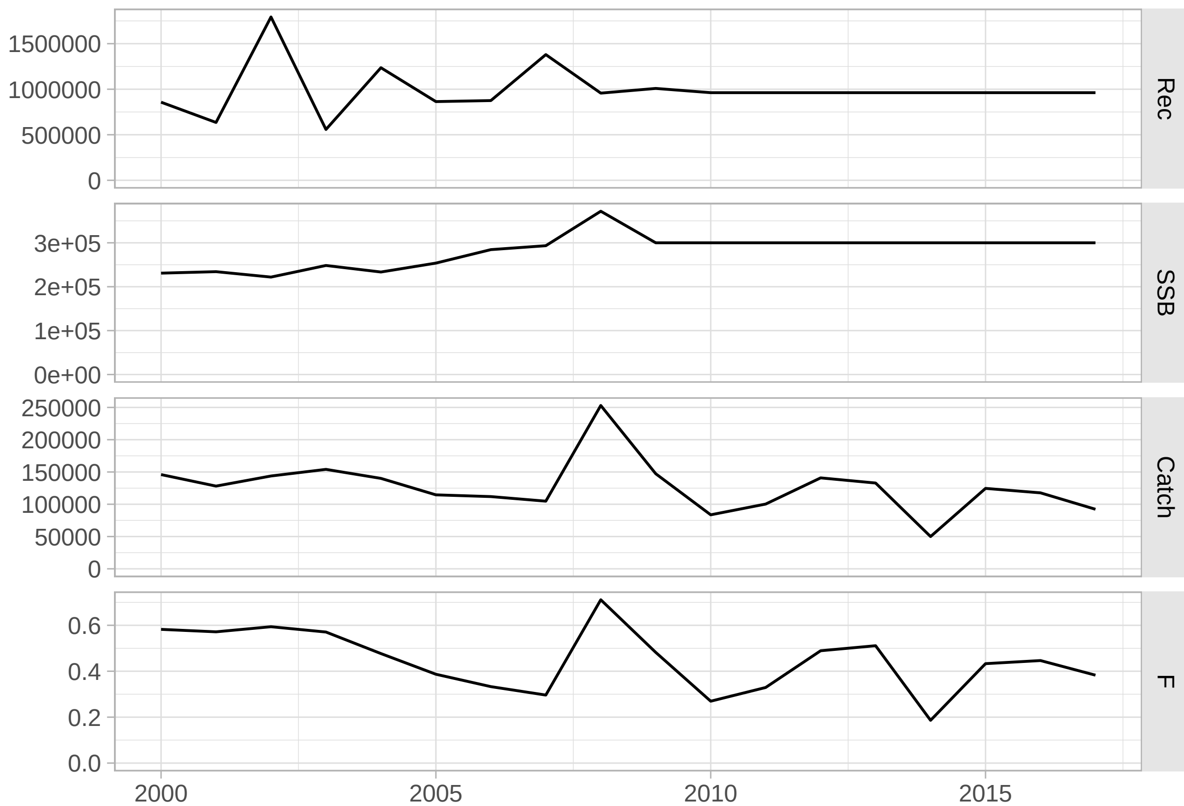
```
ssb(ple4_ssb)[,ac(2005:2018)]
```

```
, , unit = unique, season = all, area = unique
```

```
      year
age    2005   2006   2007   2008   2009
  all 253737 284447 293330 371837 300000

       [ ...  4 years]

      year
age    2014  2015  2016  2017  2018
  all 3e+05 3e+05 3e+05 3e+05 3e+05
```

Note: we have to ignore the F and removals (catch, landings and discards) in 2018 as these have not been included in the projection and still hold their initial values.

```
plot(window(ple4_ssb, start=2000, end=2017))
```



Example 4: Relative catch target

The examples above have dealt with ABSOLUTE target values. We now introduce the idea of RELATIVE values. This allows us to set the target value RELATIVE to the value in another year.

We do this by using the `rel.year` column in the control object (the year that the target is relative to). The `val` column now holds the relative value, not the absolute value.

Here we set catches in the projection years to be 90% of the catches in the previous year, i.e. we want the catche in 2009 to be 0.9 * value in 2008 etc.

```
ctrl_rel_catch <- fwdControl(
    data.frame(year = 2009:2018,
           quantity = "catch",
           val = 0.9,
           rel.year = 2008:2017))
```

When we look at the control object we can see that an extra column, `rel.year`, appears:

```
ctrl_rel_catch
```

```
Target
   year quantity min val max rel.year
1  2009    catch  NA 0.9  NA     2008
2  2010    catch  NA 0.9  NA     2009
3  2011    catch  NA 0.9  NA     2010
4  2012    catch  NA 0.9  NA     2011
5  2013    catch  NA 0.9  NA     2012
6  2014    catch  NA 0.9  NA     2013
7  2015    catch  NA 0.9  NA     2014
8  2016    catch  NA 0.9  NA     2015
9  2017    catch  NA 0.9  NA     2016
10 2018    catch  NA 0.9  NA     2017


     min val max
  1   NA 0.9  NA
  2   NA 0.9  NA
  3   NA 0.9  NA
  4   NA 0.9  NA
  5   NA 0.9  NA
  6   NA 0.9  NA
  7   NA 0.9  NA
  8   NA 0.9  NA
  9   NA 0.9  NA
  10  NA 0.9  NA
```

We run the projection as normal:

```
ple4_rel_catch <- fwd(ple4_mtf, ctrl_rel_catch, sr = ple4_sr)
```

```
catch(ple4_rel_catch)
```

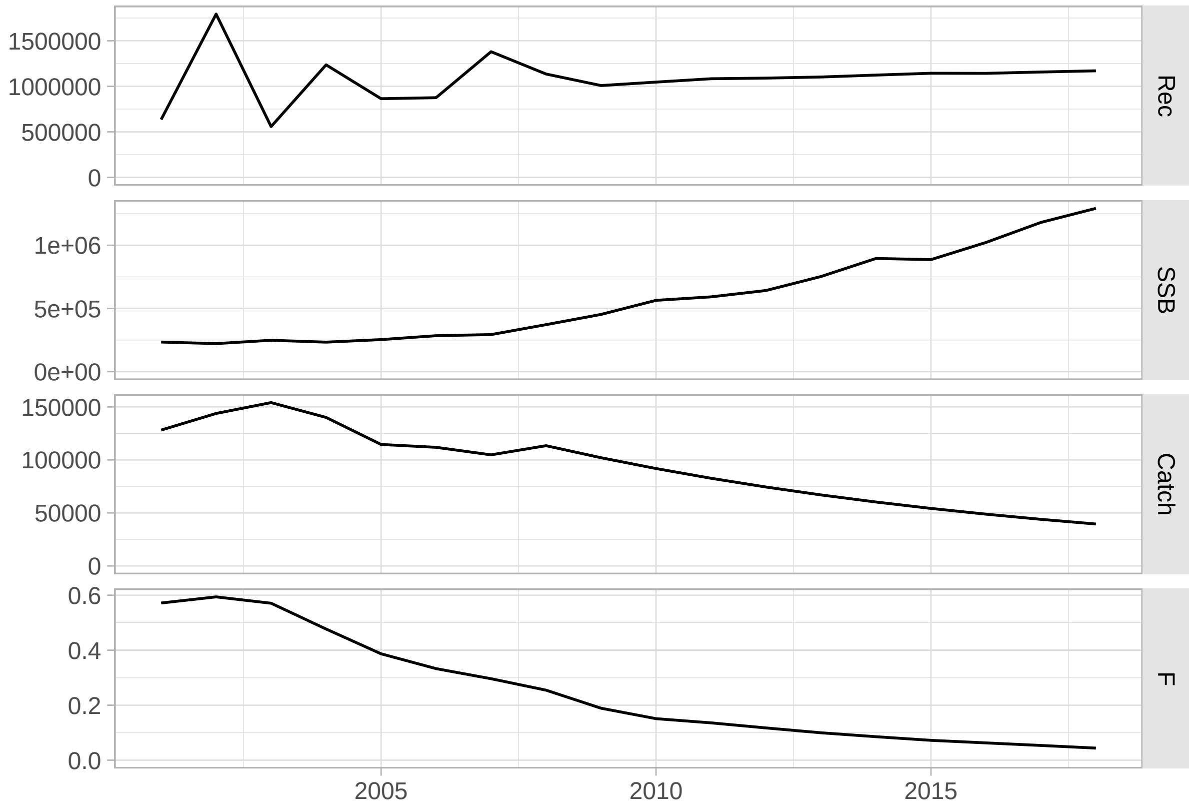
```
, , unit = unique, season = all, area = unique

     year
age   1957   1958   1959   1960   1961
  all  78360  88785 105186 117975 119541

      [ ...  61 years]
```

```
     year
age   2023 2024 2025 2026 2027
  all NA   NA   NA   NA   NA
```

```
catch(ple4_rel_catch)[,ac(2009:2018)] / catch(ple4_rel_catch)[,ac(2008:2017)]
```

```
An object of class "FLQuant"
, , unit = unique, season = all, area = unique

     year
age   2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
  all 0.9  0.9  0.9  0.9  0.9  0.9  0.9  0.9  0.9  0.9

units:  NA
```

```
plot(window(ple4_rel_catch, start = 2001, end = 2018))
```



This is equivalent to the catch example above (LINK TO EXAMPLE 2) but without using absolute values.

Example 5: Minimum and Maximum targets

In this Example we introduce two new things:

1. Multiple targets;

2. Targets with *bounds*.

Here we set an F target so that the future F = F0.1. However, we also don't want the catch to fall below a minimum level. We do this by setting a *minimum* value for the catch.

First we calculate F0.1 using **FLBRP** (see the **FLBRP** tutorial LINK TO FLBRP TUTORIAL):

```
f01 <- c(refpts(brp(FLBRP(ple4)))["f0.1","harvest"])
f01
```

```
[1] 0.1553
```

We'll set our minimum catch to be the mean catch of the last 3 years.

```
min_catch <- mean(catch(ple4_mtf)[,as.character(2006:2008)])
min_catch
```

```
[1] 110010
```

To make the control object we can bind together two data.frames, 1 for each target type. Note that we include a *min* = *NA* as a column of the F data.frame. This is necessary to bind it to the catch data.frame

```
ctrl_target <- rbind(
    f_df <- data.frame(
        year = 2009:2018,
        quantity = "f",
        val = f01,
        min = NA),
    catch_df <- data.frame(
        year = 2009:2018,
        quantity = "catch",
        val = NA,
        min = min_catch)
)
```

This looks sort of right but we need to order the data.frame so that the years are sequential and within each year, minimum / maximum targets come after the absolute one.

```
ctrl_target <- ctrl_target[order(ctrl_target$year),]
ctrl_target
```

	year	quantity	val	min
1	2009	f	0.1553	NA
11	2009	catch	NA	110010
2	2010	f	0.1553	NA
12	2010	catch	NA	110010
3	2011	f	0.1553	NA
13	2011	catch	NA	110010
4	2012	f	0.1553	NA
14	2012	catch	NA	110010
5	2013	f	0.1553	NA

	year	quantity	val	min
15	2013	catch	NA	110010
6	2014	f	0.1553	NA
16	2014	catch	NA	110010
7	2015	f	0.1553	NA
17	2015	catch	NA	110010
8	2016	f	0.1553	NA
18	2016	catch	NA	110010
9	2017	f	0.1553	NA
19	2017	catch	NA	110010
10	2018	f	0.1553	NA
20	2018	catch	NA	110010
Make	the con	trol object	:	

```
ctrl_min_catch <- fwdControl(ctrl_target)
```

What did we create (again, ignore the second table for the moment)? We can see that the *min* column has now got some data. The *max* column is still empty.

```
ctrl_min_catch
```

```
Target
   year quantity    min    val max
1  2009        f     NA 0.1553  NA
2  2009    catch 110010     NA  NA
3  2010        f     NA 0.1553  NA
4  2010    catch 110010     NA  NA
5  2011        f     NA 0.1553  NA
6  2011    catch 110010     NA  NA
7  2012        f     NA 0.1553  NA
8  2012    catch 110010     NA  NA
9  2013        f     NA 0.1553  NA
10 2013    catch 110010     NA  NA
11 2014        f     NA 0.1553  NA
12 2014    catch 110010     NA  NA
13 2015        f     NA 0.1553  NA
14 2015    catch 110010     NA  NA
15 2016        f     NA 0.1553  NA
16 2016    catch 110010     NA  NA
17 2017        f     NA 0.1553  NA
18 2017    catch 110010     NA  NA
19 2018        f     NA 0.1553  NA
20 2018    catch 110010     NA  NA
```

```
     min        val        max
  1          NA 1.5532e-01          NA
  2  1.1001e+05         NA          NA
  3          NA 1.5532e-01          NA
  4  1.1001e+05         NA          NA
  5          NA 1.5532e-01          NA
```

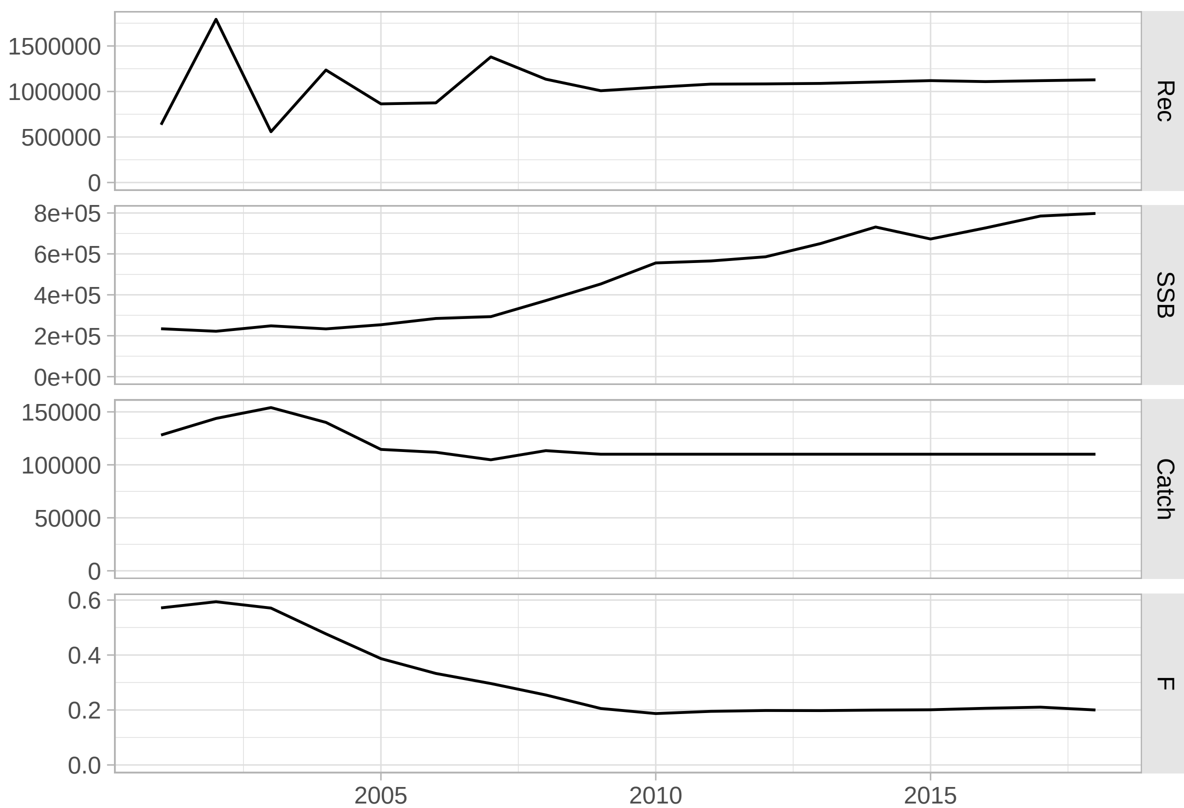
```
6  1.1001e+05         NA         NA
7          NA 1.5532e-01         NA
8  1.1001e+05         NA         NA
9          NA 1.5532e-01         NA
10 1.1001e+05         NA         NA
11         NA 1.5532e-01         NA
12 1.1001e+05         NA         NA
13         NA 1.5532e-01         NA
14 1.1001e+05         NA         NA
15         NA 1.5532e-01         NA
16 1.1001e+05         NA         NA
17         NA 1.5532e-01         NA
18 1.1001e+05         NA         NA
19         NA 1.5532e-01         NA
20 1.1001e+05         NA         NA
```

And project:

```
ple4_min_catch <- fwd(ple4_mtf, ctrl_min_catch, sr = ple4_sr)
```

What happens? The catch constraint is hit in every year of the projection. The projected F decreases but never hits the target F because the minimum catch constraint prevents it from dropping further.

```
plot(window(ple4_min_catch, start = 2001, end = 2018))
```



It is possible to also set a maximum constraint, for example, to prevent F from being too large.

Example 6 - Relative targets and bounds

In this example we use a combination of *relative* targets and *bounds*.

This kind of approach can be used to model a recovery plan. For example, we want to decrease F to F0.1 by 2015 (absolute target value) but catches cannot change by more than 15% each year (relative bound). This requires careful setting up of the control object. Again, we'll bind two data.frames.

We make a vector of the desired F targets using F0.1 we calculated above. We set up an F sequence that decreases from the current Fbar in 2008 to F01 in 2015, then F01 until 2018.

```
current_fbar <- c(fbar(ple4)[,"2008"])
f_target <- c(seq(from = current_fbar, to = f01, length = 8)[-1], rep(f01, 3))
f_target
```

```
 [1] 0.2405 0.2263 0.2121 0.1979 0.1837 0.1695 0.1553 0.1553 0.1553 0.1553
```

We set maximum annual change in catch to be 10% (in either direction).

```
rel_catch_bound <- 0.10
```

We make the control **data.frame** by joining a **data.frame** for the F target and one for the catch target. Note the use of the *rel.year*, *min* and *max* columns in the catch data.frame.

```
ctrl_target <- rbind(
    f_df <- data.frame(
        year = 2009:2018,
        rel.year = NA,
        quantity = "f",
        val = f_target,
        max = NA,
        min = NA),
    catch_df <- data.frame(
        year = 2009:2018,
        rel.year = 2008:2017,
        quantity = "catch",
        val = NA,
        max = 1 + rel_catch_bound,
        min = 1 - rel_catch_bound)
)
```

We have to reorder the **data.frame** to be in chronological order and for the absolute values to be before the minimum / maximum targets.

```
ctrl_target <- ctrl_target[order(ctrl_target$year),]
ctrl_target
```

	year	rel.year	quantity	val	max	min
1	2009	NA	f	0.2405	NA	NA
11	2009	2008	catch	NA	1.1	0.9
2	2010	NA	f	0.2263	NA	NA
12	2010	2009	catch	NA	1.1	0.9

	year	rel.year	quantity	val	max	min
3	2011	NA	f	0.2121	NA	NA
13	2011	2010	catch	NA	1.1	0.9
4	2012	NA	f	0.1979	NA	NA
14	2012	2011	catch	NA	1.1	0.9
5	2013	NA	f	0.1837	NA	NA
15	2013	2012	catch	NA	1.1	0.9
6	2014	NA	f	0.1695	NA	NA
16	2014	2013	catch	NA	1.1	0.9
7	2015	NA	f	0.1553	NA	NA
17	2015	2014	catch	NA	1.1	0.9
8	2016	NA	f	0.1553	NA	NA
18	2016	2015	catch	NA	1.1	0.9
9	2017	NA	f	0.1553	NA	NA
19	2017	2016	catch	NA	1.1	0.9
10	2018	NA	f	0.1553	NA	NA
20	2018	2017	catch	NA	1.1	0.9

Make the control object. The *min* and *max* columns now both have data:

```
ctrl_rel_min_max_catch <- fwdControl(ctrl_target)
ctrl_rel_min_max_catch
```

```
Target
   year quantity min    val max rel.year
1  2009        f  NA 0.2405  NA       NA
2  2009    catch 0.9     NA 1.1     2008
3  2010        f  NA 0.2263  NA       NA
4  2010    catch 0.9     NA 1.1     2009
5  2011        f  NA 0.2121  NA       NA
6  2011    catch 0.9     NA 1.1     2010
7  2012        f  NA 0.1979  NA       NA
8  2012    catch 0.9     NA 1.1     2011
9  2013        f  NA 0.1837  NA       NA
10 2013    catch 0.9     NA 1.1     2012
11 2014        f  NA 0.1695  NA       NA
12 2014    catch 0.9     NA 1.1     2013
13 2015        f  NA 0.1553  NA       NA
14 2015    catch 0.9     NA 1.1     2014
15 2016        f  NA 0.1553  NA       NA
16 2016    catch 0.9     NA 1.1     2015
17 2017        f  NA 0.1553  NA       NA
18 2017    catch 0.9     NA 1.1     2016
19 2018        f  NA 0.1553  NA       NA
20 2018    catch 0.9     NA 1.1     2017


     min     val     max
  1       NA 0.24046      NA
  2  0.90000      NA 1.10000
  3       NA 0.22627      NA
```

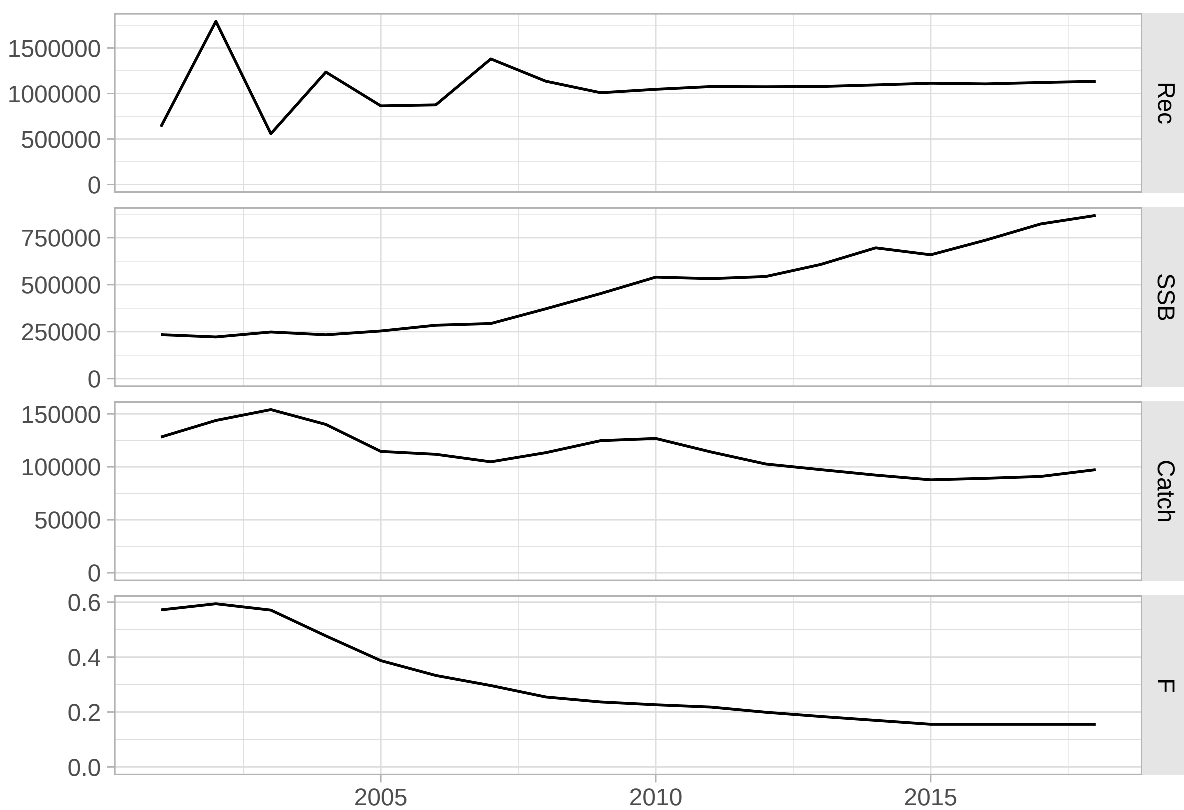
```
4  0.90000       NA 1.10000
5       NA 0.21208       NA
6  0.90000       NA 1.10000
7       NA 0.19789       NA
8  0.90000       NA 1.10000
9       NA 0.18370       NA
10 0.90000       NA 1.10000
11      NA 0.16951       NA
12 0.90000       NA 1.10000
13      NA 0.15532       NA
14 0.90000       NA 1.10000
15      NA 0.15532       NA
16 0.90000       NA 1.10000
17      NA 0.15532       NA
18 0.90000       NA 1.10000
19      NA 0.15532       NA
20 0.90000       NA 1.10000
```

Run the projection:

```
recovery<-fwd(ple4_mtf, ctrl=ctrl_rel_min_max_catch, sr=ple4_sr)
```

What happened? The F decreased and then remains constant, while the catch has changed by only a limited amount each year.

```
plot(window(recovery, start = 2001, end = 2018))
```



The bounds on the catch are operational in several of the years. They prevent the catch from increasing as well as decreasing too strongly, (allegedly) providing stability to the fishery.

```
catch(recovery)[,ac(2009:2018)] / catch(recovery)[,ac(2008:2017)]
```

```
An object of class "FLQuant"
, , unit = unique, season = all, area = unique

     year
age   2009    2010    2011    2012    2013    2014    2015    2016
  all 1.10000 1.01636 0.90000 0.90000 0.94825 0.94690 0.95171 1.01636
     year
age   2017    2018
  all 1.01975 1.07024

units:  NA
```

Projections with stochasticity

So far we have looked at combinations of:

- absolute target values;
- relative target values;
- bounds on targets, and
- mixed target types.

But all of the projections have been deterministic, that is they all have only one iteration. Now, we are going start looking at projecting with multiple iterations. This is important because it can help us understand the impact of uncertainty (e.g. in the stock-recruitment relationship).

fwd() is happy to work over iterations. It treats each iteration separately. "All" you need to do is set the arguments correctly.

There are two main ways of introducing iterations into fwd():

1. By passing in residuals to the stock-recruitment function (as another argument to *fwd()*);
2. Through the control object (by setting target values as multiple values)

You can actually use both of these methods at the same time. As you can probably imagine, this can quickly become very complicated so we'll just do some simple examples to start with.

Preparation for projecting with iterations

To perform a stochastic projection you need a stock object with multiple iterations. If you are using the output of a stock assessment method, such as *a4a*, then you may have one already. Here we use the *propagate()* method to expand the ple4 stock object to have 1000 iterations. We'll use the ten year projection as before (remember that we probably should change the assumptions that come with the *stf()* method).

```
niters <- 1000
ple4_mtf <- stf(ple4, nyears = 10)
ple4_mtf <- propagate(ple4_mtf, niters)
```

You can see that the 6th dimension, iterations, now has length 1000:

```
summary(ple4_mtf)
```

```
An object of class "FLStock"

Name: PLE
Description: Plaice in IV. ICES WGNSSK 2018. FLAAP
Quant: age
Dims:  age 	year	unit	season	area	iter
	10	71	1	1	1	1000	

Range:  min	max	pgroup	minyear	maxyear	minfbar	maxfbar 
	1	10	10	1957	2027	2	6	

catch         : [ 1 71 1 1 1 1000 ], units =  t 
catch.n       : [ 10 71 1 1 1 1000 ], units =  1000 
catch.wt      : [ 10 71 1 1 1 1000 ], units =  kg 
discards      : [ 1 71 1 1 1 1000 ], units =  t 
discards.n    : [ 10 71 1 1 1 1000 ], units =  1000 
discards.wt   : [ 10 71 1 1 1 1000 ], units =  kg 
landings      : [ 1 71 1 1 1 1000 ], units =  t 
landings.n    : [ 10 71 1 1 1 1000 ], units =  1000 
landings.wt   : [ 10 71 1 1 1 1000 ], units =  kg 
stock         : [ 1 71 1 1 1 1000 ], units =  t 
stock.n       : [ 10 71 1 1 1 1000 ], units =  1000 
stock.wt      : [ 10 71 1 1 1 1000 ], units =  kg 
m             : [ 10 71 1 1 1 1000 ], units =  m 
mat           : [ 10 71 1 1 1 1000 ], units =  
harvest       : [ 10 71 1 1 1 1000 ], units =  f 
harvest.spwn  : [ 10 71 1 1 1 1000 ], units =  
m.spwn        : [ 10 71 1 1 1 1000 ], units =  
```

Example 7: Stochastic recruitment

There are two arguments to *fwd()* that we haven't used yet:

1. *sr.residuals*
2. *sr.residuals.mult*

These are used for specifying the recruitment residuals (*sr.residuals*) and whether these residuals are multiplicative (*sr.residuals.mult*=TRUE) or additive (FALSE). In this example we'll use multiplicative residuals i.e. the recruitment values in projection = deterministic recruitment predicted by the SRR model * residuals. The residuals are passed in as an **FLQuant** with years and iterations. Here we make an empty **FLQuant** that will be filled with residuals.

```
multi_rec_residuals <- FLQuant(NA, dimnames = list(year=2009:2018, iter=1:niters))
```

We're going to use residuals from the stock-recruitment relationship we fitted at the beginning. We can access these using:

```r
residuals(ple4_sr)
```

```
, , unit = unique, season = all, area = unique

   year
age 1958     1959     1960     1961     1962    
  1 -0.33249 -0.13292 -0.22899 -0.15108 -0.50351

      [ ...  50 years]

   year
age 2013      2014      2015      2016      2017     
  1  0.282986  0.385725 -0.235863  0.072568  0.473244
```

These residuals are on a log scale i.e. log_residuals = log(observed_recruitment) - log(predicted_recruitment). To use these log residuals multiplicatively we need to transform them with *exp()*:

We want to fill up our *multi_rec_residuals* **FLQuant** by randomly sampling from these log residuals. We can do this with the *sample()* function. We want to sample with replacement (i.e. if a residual is chosen, it gets put back in the pool and can be chosen again).

First we get generate the samples of the years (indices of the residuals we will pick).

```r
sample_years <- sample(dimnames(residuals(ple4_sr))$year, niters * 10, replace = TRUE)
```

We fill up the **FLQuant** we made earlier with the residuals using the sampled years:

```r
multi_rec_residuals[] <- exp(residuals(ple4_sr)[,sample_years])
```

What have we got?

```r
multi_rec_residuals
```

```
An object of class "FLQuant"
iters:  1000 

, , unit = unique, season = all, area = unique

     year
quant 2009            2010            2011            2012           
  all 0.96993(0.506) 0.96993(0.495) 0.96993(0.488) 0.96099(0.387)
     year
quant 2013            2014            2015            2016           
  all 0.96993(0.495) 1.00595(0.476) 1.00595(0.514) 0.96993(0.477)
     year
quant 2017            2018           
  all 1.00595(0.520) 1.02471(0.471)

units:  NA 
```

It's an **FLQuant** of SRR residuals but what do those brackets mean? The information in the brackets is the Median Absolute Deviation, a way of summarising the iterations. We have 1000 iterations but don't want to see all of them - just a summary.

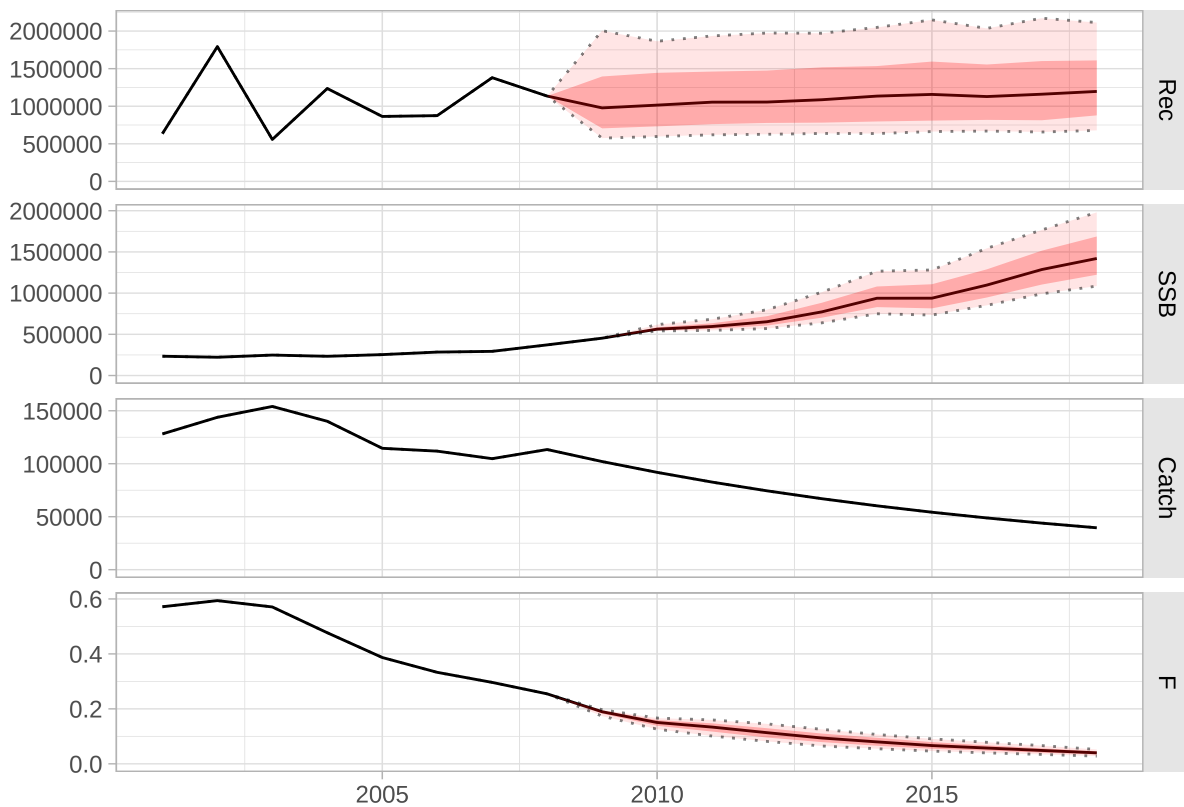
We now have the recruitment residuals. We'll use the *ctrl_catch* control object we made in Example 2.

with decreasing catch. We call *fwd()* as usual, only now we have *sr.residuals* and *sr.residuals.mult* arguments. This takes a little time (we have 1000 iterations).

```
ple4_stoch_rec <- fwd(ple4_mtf, ctrl = ctrl_catch, sr = ple4_sr, sr.residuals = multi_rec_residuals, sr
```

What just happened? We can see that now we have uncertainty in the recruitment estimates, driven by the residuals. This uncertainty feeds into the SSB and, to a lesser extent, the projected F and catch.

```
plot(window(ple4_stoch_rec, start = 2001, end = 2018))
```



We can see that the projected stock metrics also have uncertainty in them.

```
rec(ple4_stoch_rec)[,ac(2008:2018)]
```

```
iters:  1000

, , unit = unique, season = all, area = unique

   year
age 2008            2009             2010             2011
  1 1135050(     0)  978080(510283) 1014777(517962) 1054374(528951)
   year
age 2012
  1 1055789(442099)
```

```
      [ ...  1 years]

   year
age 2014            2015            2016            2017
  1 1135050(      0)  978080(510283) 1014777(517962) 1054374(528951)
   year
age 2018
  1 1055789(442099)
```

```
fbar(ple4_stoch_rec)[,ac(2008:2018)]
```

```
iters:  1000

, , unit = unique, season = all, area = unique

     year
age   2008             2009             2010             2011
  all 0.25465(0.00000) 0.18956(0.00881) 0.15037(0.01495) 0.13373(0.02223)
     year
age   2012
  all 0.11330(0.02465)

      [ ...  1 years]

     year
age   2014             2015             2016             2017
  all 0.25465(0.00000) 0.18956(0.00881) 0.15037(0.01495) 0.13373(0.02223)
     year
age   2018
  all 0.11330(0.02465)
```

```
ssb(ple4_stoch_rec)[,ac(2008:2018)]
```

```
iters:  1000

, , unit = unique, season = all, area = unique

     year
age   2008          2009          2010          2011
  all 371837(     0) 453027(     0) 562681(27467) 594845(46385)
     year
age   2012
  all 652657(80208)

      [ ...  1 years]

     year
age   2014          2015          2016          2017
  all 371837(     0) 453027(     0) 562681(27467) 594845(46385)
     year
age   2018
  all 652657(80208)
```

Example 8: stochastic target values

In this example we introduce uncertainty by including uncertainty in our target values. This example has catch as the target, except now catch will be stochastic.

We will use the ctrl_catch object from above (we make a copy):

```
ctrl_catch
```

```
Target
   year quantity min    val max
1  2009    catch  NA 102057  NA
2  2010    catch  NA  91851  NA
3  2011    catch  NA  82666  NA
4  2012    catch  NA  74400  NA
5  2013    catch  NA  66960  NA
6  2014    catch  NA  60264  NA
7  2015    catch  NA  54237  NA
8  2016    catch  NA  48814  NA
9  2017    catch  NA  43932  NA
10 2018    catch  NA  39539  NA


     min    val    max
  1      NA 102057     NA
  2      NA  91851     NA
  3      NA  82666     NA
  4      NA  74400     NA
  5      NA  66960     NA
  6      NA  60264     NA
  7      NA  54237     NA
  8      NA  48814     NA
  9      NA  43932     NA
  10     NA  39539     NA
```

```
ctrl_catch_iters <- ctrl_catch
```

Let's take a look at what else is in the control object:

```
slotNames(ctrl_catch_iters)
```

```
[1] "target"    "effort"    "trgtArray" "effArray"  "block"
```

The iterations of the target value are set in the *trgtArray* slot. This is the second table that gets printed when you call the control object.

```
ctrl_catch_iters@trgtArray
```

```
, , iter = 1
```

```
   min    val max
1   NA 102057  NA
2   NA  91851  NA
3   NA  82666  NA
4   NA  74400  NA
5   NA  66960  NA
6   NA  60264  NA
7   NA  54237  NA
8   NA  48814  NA
9   NA  43932  NA
10  NA  39539  NA
```

What is this slot?

```
class(ctrl_catch_iters@trgtArray)
```

```
[1] "array"
```

```
dim(ctrl_catch_iters@trgtArray)
```

```
[1] 10  3  1
```

It's a 3D array with structure: target no x value x iteration. It's in here that we set the stochastic projection values. Each row of the *trgtArray* slot corresponds to a row in the control **data.frame** we passed in.

Here we set 10 targets (one for each year in the projection), so the first dimension of *trgtArray* has length 10. The second dimension always has length 3 (for *min*, *val* and *max* columns). The third dimension is where the iterations are stored. This is currently length 1. We have 1000 iterations and therefore we need to expand *trgtArray* along the iter dimension so it can store the 1000 iterations.

Unfortunately, there is not a nice way of doing this. The simplest way is just to make a new array with the right dimensions. Note that we need to put in dimnames.

```
new_trgtArray <- array(NA, dim=c(10,3,niters), dimnames = list(1:10, c("min","val","max"),iter=1:niters
dim(new_trgtArray)
```

```
[1]   10    3 1000
```

Now we can fill it up with new data (our stochastic catch targets).

We need to generate random catch target data. This could come from a number of sources (e.g. MSY estimated with uncertainty). In this example we make it very simple, by using lognormal distribution with a fixed standard deviation of 0.3. We multiply the deterministic catch target values by samples from this distribution.

```
future_catch_iters <- ctrl_catch_iters@trgtArray[,"val",] * rlnorm(10 * niters, meanlog = 0, sdlog=0.3)
```

We fill up *trgtArray* with these values. We just fill up the *val* column (you can also set the *min* and *max* columns to set stochastic bounds).

```
new_trgtArray[,"val",] <- future_catch_iters
```

We put our new *trgtArray* into the control object:

```
ctrl_catch_iters@trgtArray <- new_trgtArray
```

We can see that now we have stochasticity in the target values.

```
ctrl_catch_iters
```

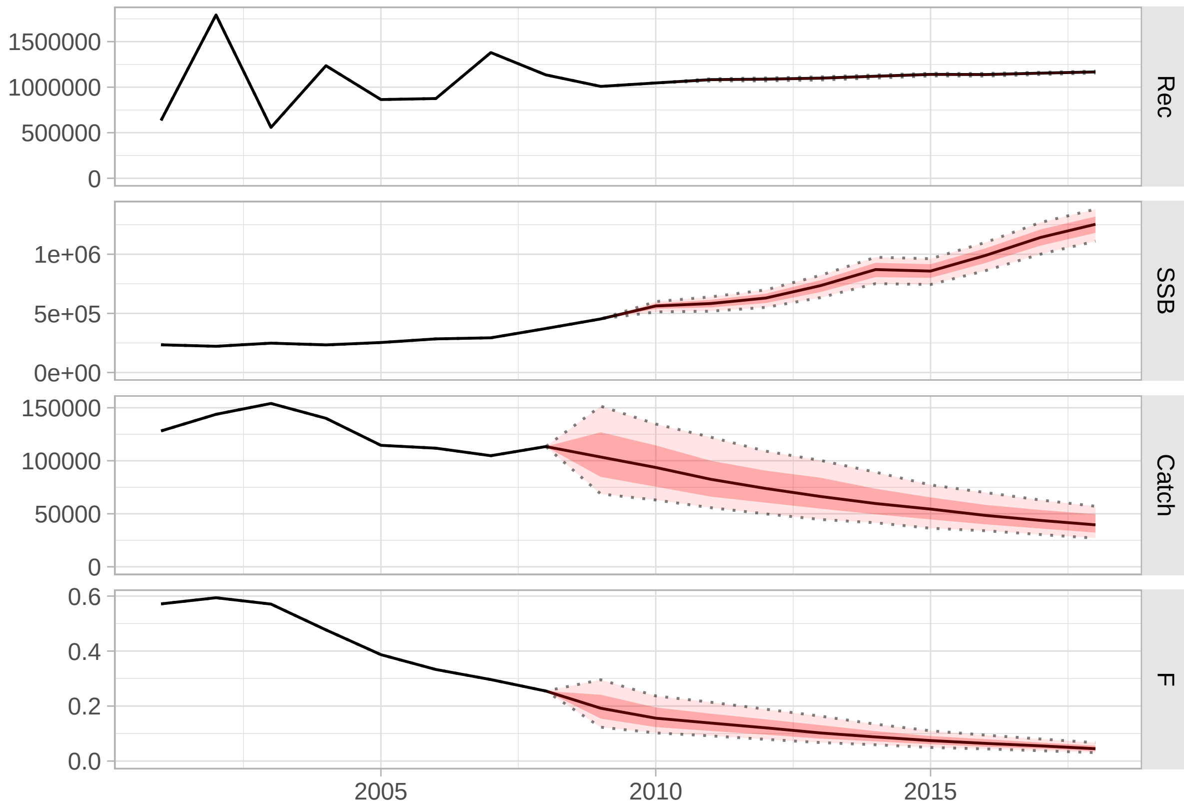
```
Target
   year quantity min    val max
1  2009    catch  NA 102057  NA
2  2010    catch  NA  91851  NA
3  2011    catch  NA  82666  NA
4  2012    catch  NA  74400  NA
5  2013    catch  NA  66960  NA
6  2014    catch  NA  60264  NA
7  2015    catch  NA  54237  NA
8  2016    catch  NA  48814  NA
9  2017    catch  NA  43932  NA
10 2018    catch  NA  39539  NA


     min           val           max
  1      NA(   NA) 103502(31044)     NA(   NA)
  2      NA(   NA)  93672(28603)     NA(   NA)
  3      NA(   NA)  82509(24980)     NA(   NA)
  4      NA(   NA)  73873(22275)     NA(   NA)
  5      NA(   NA)  66293(20989)     NA(   NA)
  6      NA(   NA)  59659(16935)     NA(   NA)
  7      NA(   NA)  54421(15150)     NA(   NA)
  8      NA(   NA)  48435(13472)     NA(   NA)
  9      NA(   NA)  43739(12763)     NA(   NA)
  10     NA(   NA)  39546(12281)     NA(   NA)
iter:  1000
```

We project as normal using the deterministic SRR.

```
ple4_catch_iters <- fwd(ple4_mtf, ctrl_catch_iters, sr = ple4_sr)
```

What happened?

```
plot(window(ple4_catch_iters, start = 2001, end = 2018))
```



The projected catches reflect the uncertainty in the target.

```
catch(ple4_catch_iters)[,ac(2008:2018)]
```

```
iters:  1000

, , unit = unique, season = all, area = unique

     year
age   2008          2009          2010          2011
  all 113397(    0) 103502(31044)  93672(28603)  82509(24980)
     year
age   2012
  all  73873(22275)

      [ ...  1 years]

     year
age   2014          2015          2016          2017
  all 113397(    0) 103502(31044)  93672(28603)  82509(24980)
     year
age   2018
  all  73873(22275)
```

Example 9: A projection with stochastic catch and recruiment

What is going on with recruitment in the results of the previous example?

```r
rec(ple4_catch_iters)[,ac(2008:2018)]
```

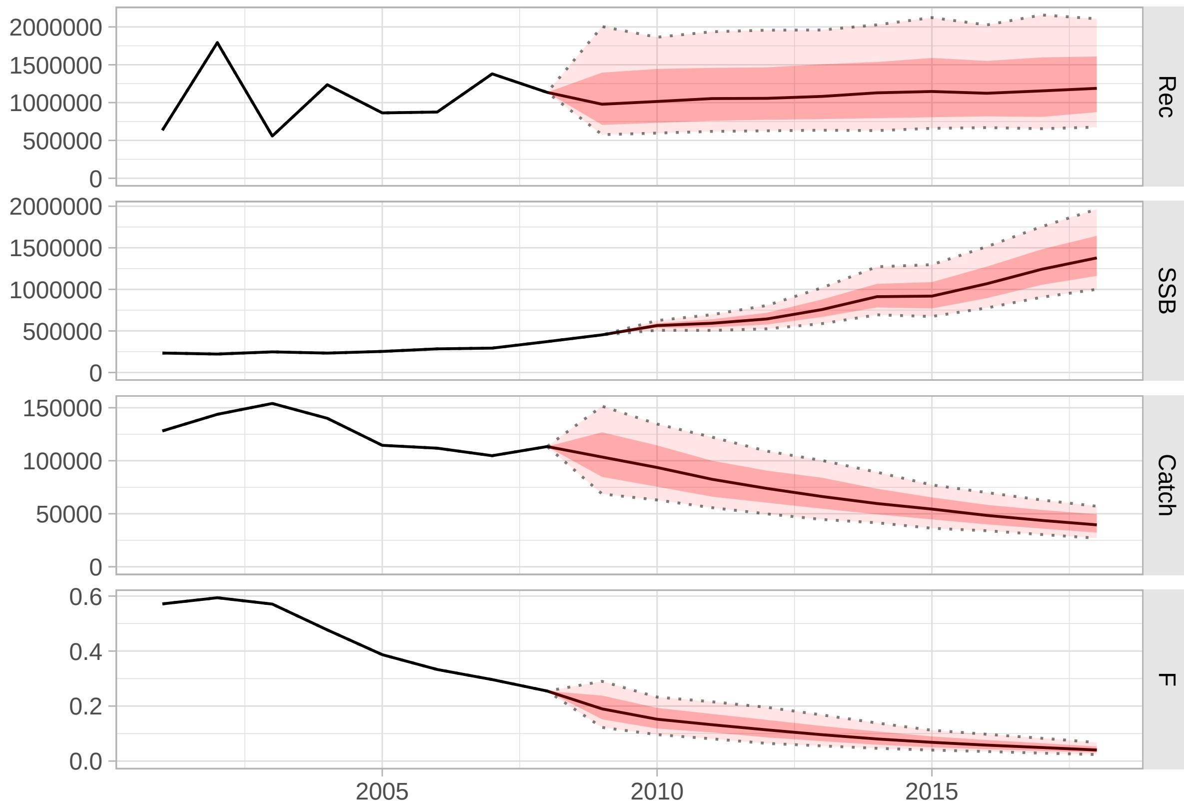
```
iters:  1000

, , unit = unique, season = all, area = unique

   year
age 2008          2009          2010          2011
  1 1135050(    0) 1008401(    0) 1046235(    0) 1082512( 8935)
   year
age 2012
  1 1087981(12436)

      [ ...  1 years]

   year
age 2014          2015          2016          2017
  1 1135050(    0) 1008401(    0) 1046235(    0) 1082512( 8935)
   year
age 2018
  1 1087981(12436)
```

Remember that here recruitment is not being driven by random residuals, it is only be driven by SSB. The recruitment in year Y is a result of the SSB in year Y-1. The SSB in year Y-1 is a result of the catch in year Y-2. So if catch is stochastic in 2009, we don't see the impact of the stochasticity on the recruitment until 2011. Even then the impact is small. This seems unlikely so we can also put in recruitment residuals (we already made them for Example 7).

```r
ple4_catch_iters <- fwd(ple4_mtf, ctrl_catch_iters, sr = ple4_sr, sr.residuals = multi_rec_residuals, s
```

What happened?

```r
plot(window(ple4_catch_iters, start = 2001, end = 2018))
```



The projected recruitment and catches are stochastic.

```
catch(ple4_catch_iters)[,ac(2008:2018)]
```

```
iters:  1000

, , unit = unique, season = all, area = unique

     year
age   2008          2009          2010          2011
  all 113397(    0) 103502(31044)  93672(28603)  82509(24980)
     year
age   2012
  all  73873(22275)

      [ ...  1 years]

     year
age   2014          2015          2016          2017
  all 113397(    0) 103502(31044)  93672(28603)  82509(24980)
     year
age   2018
  all  73873(22275)
```

```
rec(ple4_catch_iters)[,ac(2008:2018)]
```

```
iters:  1000
```

```
, , unit = unique, season = all, area = unique

   year
age 2008            2009            2010            2011
  1 1135050(     0)  978080(510283) 1014777(517962) 1053238(525454)
   year
age 2012
  1 1056372(462179)

      [ ...  1 years]

   year
age 2014            2015            2016            2017
  1 1135050(     0)  978080(510283) 1014777(517962) 1053238(525454)
   year
age 2018
  1 1056372(462179)
```

TO DO

Alternative syntax for controlling the projection

SOMETHING ON CALLING FWD() AND SPECIFYING TARGETS AS ARGUMENTS

Notes on conditioning projections

SOMETHING ON FWD WINDOW

References

More information

- You can submit bug reports, questions or suggestions on this tutorial at https://github.com/flr/doc/issues.
- Or send a pull request to https://github.com/flr/doc/
- For more information on the FLR Project for Quantitative Fisheries Science in R, visit the FLR webpage, http://flr-project.org.

Software Versions

- R version 3.5.1 (2018-07-02)
- FLCore: 2.6.9.9002
- FLash: 2.5.9
- FLBRP: 2.5.3
- FLAssess: 2.6.2
- **Compiled**: Tue Sep 4 11:50:41 2018

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Author information

Finlay Scott. European Commission, DG Joint Research Centre, Directorate D - Sustainable Resources, Unit D.02 Water and Marine Resources, Via E. Fermi 2749, 21027 Ispra VA, Italy. https://ec.europa.eu/jrc/