

TC: A MULTI-STOCK SPATIAL MANAGEMENT PROCEDURE FOR ATLANTIC BLUEFIN TUNA

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SUMMARY

Following operating model reconditioning, the multi-stock CMPs ('TC') were updated and tuned to development targets PGK 0.6 – 0.6 (eastern stock – western stock) (TC5) PGK 0.7 – 0.7 (TC6), LD15% 0.4 – 0.4, LD10% 0.4 - 0.4 for variants with 2-year (a) and 3-year (b) updates.

KEYWORDS

Management strategy evaluation, bluefin tuna, operating model, management procedure.

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Introduction

The MP approach to managing North Atlantic tuna provides an opportunity to move past the current assessment paradigm where management advice (which is necessarily by East / West area) is based on data that are also distinct by East / West area. Genetics, tagging and microconstituent data have long confirmed that there are at least two spawning stocks of Atlantic bluefin tuna, they exhibit extensive mixing in the Atlantic Ocean outside of their natal spawning grounds in the Gulf of Mexico and Mediterranean and they differ markedly in their magnitude (at unfished levels the Eastern stock is around 6-12 times larger than the Western stock). These observations suggest that if catch advice by area is to be based on estimates of vulnerable biomass in a given area, these should be responsive to varying augmentation from the stock originating from the other side of the ocean.

In this paper I describe a multi-stock, multi-area MP (TC) that uses spawning indices to estimate stock-specific vulnerable biomass which in conjunction with assumed rates of mixing is used to predict the vulnerable biomass of each stock in each area (Figure 1). These regional estimates of vulnerable biomass are combined with independent regional estimates derived from catch rate indices. Together these indices inform regional vulnerable biomass B , and fishing mortality rate F (since we also have observations of regional catches). TAC adjustments are made according to a novel harvest control rule that uses estimated fishing rate relative to FMSY (and optionally vulnerable biomass relative to BMSY) to locate the stock at approximately MSY levels. The harvest control rule is intended to be responsive with respect to fluctuations in stock-specific productivity, allowing for increased yields where production is high and throttling of TAC given periods of lower productivity.

Methods

The default CMP parameter values are provided in Table 1. Tuning parameter levels are provided in Table 2.

Data smoothing

In order to reduce noise in observations of both indices and catches, the MP uses a polynomial ('loess') smoothing function $S()$. Smoothed area (A) and stock (S) indices \tilde{I} are calculated from the raw observed indices I by area a and index type i , using the same smoothing parameter ω :

$$\begin{aligned}\tilde{I}_{a,i}^A &= S(I_{a,i}^A, \omega) \\ \tilde{I}_{a,i}^S &= S(I_{a,i}^S, \omega)\end{aligned}$$

The function is parameterized such that the approximate number of smoothing parameters is a linear function of the length of the time series. The effect of the ratio of smoothing parameters to length of the time series ω , is illustrated in Figure 1.

Vulnerable biomass and fishing rate estimation

A multi-stock, multi-area management procedure 'TC', was designed to provide TAC advice in a given time period t using Stock biomass indices (I^S) by stock s and Catch Rate Indices (I^A) by area a , calibrated to current stock assessments of vulnerable biomass B (estimates of catchability q for stock and area indices) (Figure 2). In order to, for example, interpret West area biomass in terms of Eastern stock biomass, an estimate of stock mixing is required $\theta_{s=East_stock, a=West}^{mix}$ that is the fraction of Eastern stock biomass that can be expected to be vulnerable to fishing in the West area. Where there are more than one spawning stock index ($n_{s,i} > 1$) or more than one area index ($n_{a,i} > 1$) overall biomass estimates were the mean of those from the multiple indices:

$$(1) \quad B_{a,t}^S = \frac{\sum_s \sum_i \tilde{I}_{s,i,t}^S q_{s,i}^S \theta_{s,i}^{mix}}{n_{s,i}}$$

$$(2) \quad B_{a,t}^A = \frac{\sum_s \sum_i \tilde{I}_{a,i,t}^A q_{a,i}^A}{n_{a,i}}$$

The q parameters are calibrated to 2016 estimates spawning biomass (by stock) θ_s^S , and vulnerable biomass (by area) θ_a^A :

$$(3) \quad q_s^S = \frac{\theta_{s,2016}^S}{I_{s,2016}^S}$$

$$(4) \quad q_a^A = \frac{\theta_{a,2016}^A}{I_{a,2016}^A}$$

The estimates of vulnerable biomass B arising from the calibrated indices can be used to estimate the fishing mortality rate using calculated TACs:

$$(5) \quad F_{a,t}^A = -\ln\left(1 - \frac{TAC_{a,t}}{B_{a,t}^A}\right)$$

$$(6) \quad F_{a,t}^S = -\ln\left(1 - \frac{TAC_{a,t}}{B_{a,t}^S}\right)$$

Combining inference from SSB and CPUE indices

Assessment estimates of vulnerable biomass at MSY (θ^{BMSY}) can be used to calculate current vulnerable biomass relative to $BMSY$, here inference from catch rate and spawning indices is equally weighted as the geometric mean:

$$(7) \quad \Delta_{a,t}^B = \exp\left(\frac{1}{2}\left[\ln\left(\frac{B_{a,t}^S}{\theta_{a,t}^{BMSY}^S}\right) + \ln\left(\frac{B_{a,t}^A}{\theta_{a,t}^{BMSY}^A}\right)\right]\right)$$

The same approach was used to combined estimates of F relative to $FMSY$:

$$(8) \quad \Delta_{a,t}^F = \exp\left(\frac{1}{2}\left[\ln\left(\frac{F_{a,t}^S}{\theta_{a,t}^{FMSY}^S}\right) + \ln\left(\frac{F_{a,t}^A}{\theta_{a,t}^{FMSY}^A}\right)\right]\right)$$

A harvest control rule for TAC adjustment based on estimates of $B/BMSY$ and $F/FMSY$

TACs in the following year are based on TAC in the previous time step multiplied by a factor $\varphi_{a,t}$:

$$(9) \quad TAC_{a,t+1} = TAC_{a,t} \varphi_{a,t}$$

where the factor $\varphi_{a,t}$ is determined by adjustments for fishing rate $\delta_{a,t}^F$ and stock status $\delta_{a,t}^B$:

$$(10) \quad \tilde{\varphi}_{a,t} = \delta_{a,t}^F \delta_{a,t}^B$$

The adjustment to F is the inverse of $F/FMSY$ ($\Delta_{a,t}^F$) where the magnitude of the adjustment is determined by β^F . The parameter α^F controls the target F level where $F/FMSY = 1$ and $B/BMSY = 1$. For example, at a value of 0.8, the MP deliberately aims to underfish at 80% of $FMSY$ when the stock is at $BMSY$ and current F is $FMSY$. Note that when $\alpha^F=1$ and $\beta^F = 1$ the F adjustment $\delta_{a,t}^F$ is the inverse of $\Delta_{a,t}^F$ and hence recommends $FMSY$ fishing rate (and depends on the assumption that biomass will be comparable at $t+1$) (Figure 3).

$$(11) \quad \delta_{a,t}^F = \alpha^F \exp\left(\beta^F \ln(1/\Delta_{a,t}^F)\right)$$

The adjustment according to biomass is exponentially related to the disparity between current biomass and BMSY. The term $|\Delta_{a,t}^B - 1|$ is the positive absolute difference (modulus). The magnitude of the adjustment for biomass is controlled by the parameter α^B while the (extent of the TAC change for biomass levels far from BMSY) is controlled by the exponent β^B . This is analogous to a traditional harvest control rule (e.g. ‘40-10’) and throttles fishing rates at low stock sizes to speed recovery while also increasing fishing rates at high stock sizes to exploit additional biomass (Figure 3). When $\alpha^B = 0$ there is no biomass adjustment and $\delta_{a,t}^B$ is invariant to β^B (e.g. Figure 3).

$$(12) \quad \delta_{a,t}^B = \begin{cases} \exp\left[(\alpha^B |\Delta_{a,t}^B - 1|)^{\beta^B}\right] & 1 < \Delta_{a,t}^B \\ \exp\left[-(\alpha^B |\Delta_{a,t}^B - 1|)^{\beta^B}\right] & \Delta_{a,t}^B \leq 1 \end{cases}$$

This generalized TAC harvest control rule can accommodate a wide range of control schemes of varying sensitivity to estimates of current exploitation rate and stock status (See Figures 4 and 5).

TAC adjustment limits

The maximum rate of TAC adjustment is determined by θ^{down} and θ^{up} and the minimum amount is controlled by θ^{min} :

$$(13) \quad \hat{\varphi}_{a,t} = \begin{cases} \theta^{down} & \tilde{\varphi}_{a,t} < \theta^{down} \\ \tilde{\varphi}_{a,t} & \theta^{down} < \tilde{\varphi}_{a,t} < (1 - \theta^{min}) \\ 1 & (1 - \theta^{min}) < \tilde{\varphi}_{a,t} < (1 + \theta^{min}) \\ \tilde{\varphi}_{a,t} & (1 + \theta^{min}) < \tilde{\varphi}_{a,t} < \theta^{up} \\ \theta^{up} & \theta^{up} < \tilde{\varphi}_{a,t} \end{cases}$$

For variant *a* CMPs with a 2-year update interval, the maximum downward adjustment θ^{down} is 10% for the first two CMP updates. For variant *b* CMPs with a 3-year update interval, the maximum downward adjustment is also 10% but for only the first CMP update.

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Tables

Table 1. The input data, parameters of the current default MPx management procedure. CMP parameters highlighted in yellow have been revised for the reconditioned operating models. CMP parameters highlighted in green are tuning parameters used to achieve the specified development tuning targets (Table 2).

Description		Value
<i>Biomass calculation</i>		
$I_{East_stock}^S$	Spawning stock biomass index for eastern stock	MED_LAR_SUV (#2), GBYP_AER_SUV_BAR (#4)
$I_{West_stock}^S$	Spawning stock biomass index for western stock	GOM_LAR_SUV (#3)
I_{East}^A	Vulnerable biomass catch rate index for eastern area	MOR_POR_TRAP (#5), JPN_LL_NEATL2 (#6)
I_{West}^A	Vulnerable biomass catch rate index for western area	JPN_LL_West2 (#10), US_RR_66_144 (#13)
θ_{East}^{BMSY}	Eastern area biomass at maximum sustainable yield	550 kt
θ_{West}^{BMSY}	Western area biomass at maximum sustainable yield	15 kt
θ_{East}^{FMSY}	Eastern area harvest rate at MSY	<i>tuned</i> (0.0585 - 0.0753)
θ_{West}^{FMSY}	Western area fishing mortality rate at MSY	<i>tuned</i> (0.006 - 0.0376)
$\theta_{East_stock,recent}^S$	Mean Vuln. biomass of eastern stock in 2015-2019	650 kt
$\theta_{West_stock,recent}^S$	Mean Vuln. biomass of western stock in 2015-2019	15 kt
$\theta_{East,recent}^A$	Mean Vuln. biomass in eastern area in 2015-2019	500 kt
$\theta_{West,recent}^A$	Mean Vuln. biomass in western area in 2015-2019	70 kt
$\theta_{West,East}^{mix}$	Fraction of western stock in eastern area	0.1
$\theta_{East,West}^{mix}$	Fraction of eastern stock in western area	0.05
<i>Harvest control rule</i>		
α^B	The magnitude of the adjustment for biomass relative to BMSY	0 (no biomass adjustment)
β^B	Exponent parameter controlling extent of the adjustment for biomass relative to BMSY	NA (given $\alpha^B = 0$)
α^F	Target fishing mortality rate (fraction of FMSY) at $F/FMSY = 1$ and $B/BMSY = 1$	1
β^F	The magnitude of the adjustment for fishing rate relative to FMSY	0.33
<i>Data smoothers</i>		
ω	The ratio of the No. polynomial smoothing parameters to the number of years of time series data. I.e. $loess(dat, enp.target = \omega \cdot n_t)$	0.15

Table 1. Continued.

Description		Value
<i>TAC adjustment limits</i>		
θ^{up}	The maximum fraction that TAC can increase	0.2
θ^{down}	The maximum fraction that TAC can decrease	0.3
θ^{min}	The minimum fractional change in TAC	0
θ_{East}^{TACmin}	Minimum TAC for the East area	0 kt
θ_{West}^{TACmin}	Minimum TAC for the West area	0 kt
θ_{East}^{TACmax}	Maximum TAC for the East area	100 kt
θ_{West}^{TACmax}	Maximum TAC for the West area	20 kt
$\theta_{West}^{TACmax_near}$	Near-term maximum TAC for the West area	10 kt
$\theta_{West}^{n_near}$	Western near-term period	10 years

Table 2. Parameter values for each of the eight TC CMP development tunings.

CMP tuning options (values are given in the order of western-eastern stocks)	Variant	Western Area harvest rate	Eastern Area harvest rate
		θ_{West}^{FMSY}	θ_{East}^{FMSY}
TC5: PGK 0.6 – 0.6	a	0.0376	0.0735
	b	0.0362	0.0708
	c	0.0365	0.0717
TC6: PGK 0.7 – 0.7	a	0.0316	0.0614
	b	0.0302	0.0585
	c	0.0303	0.0595
TC7: LD15% 0.4 - 0.4	a	0.0369	0.0753
TC8: LD10% 0.4 - 0.4	a	0.0060	0.0667

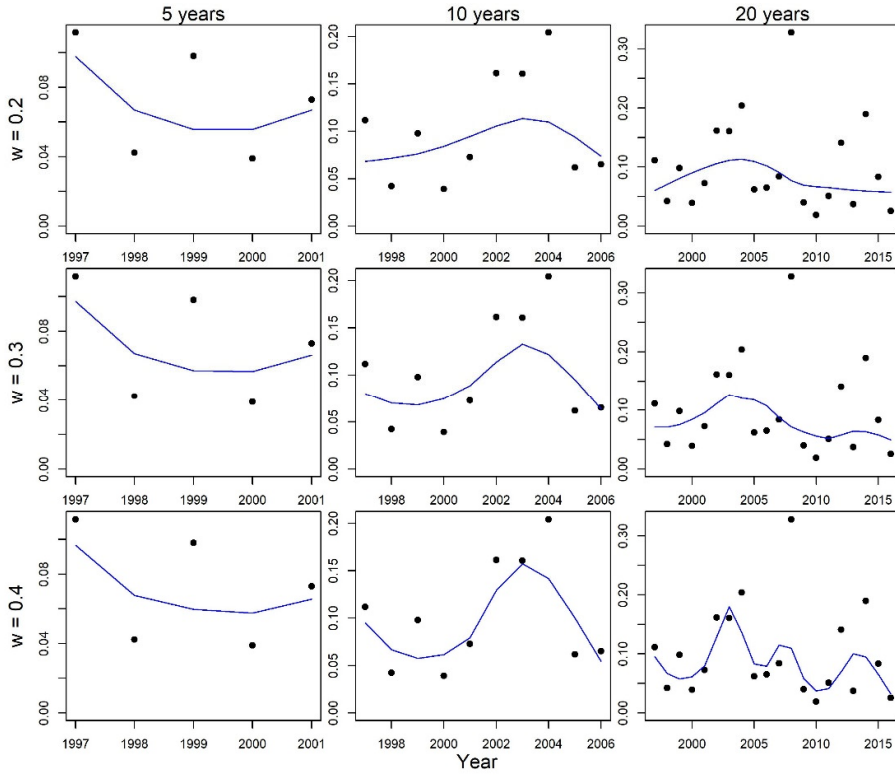


Figure 1. Effect of the smoothing parameter ω given time series of varying length.

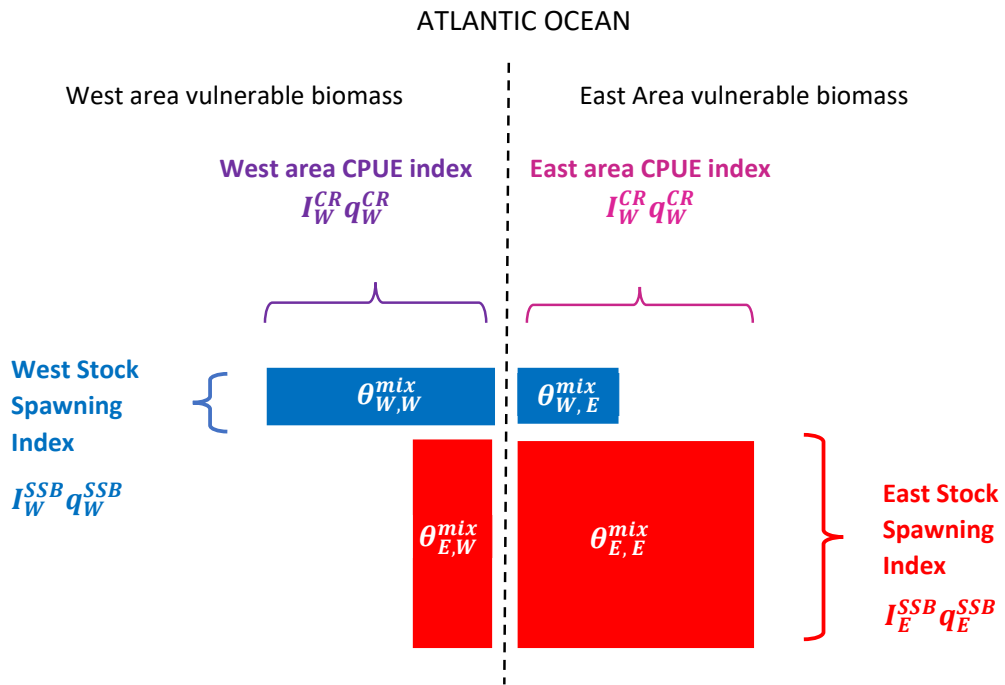


Figure 2. Regional vulnerable biomass estimation according to stock specific spawning indices and area-specific CPUE indices.

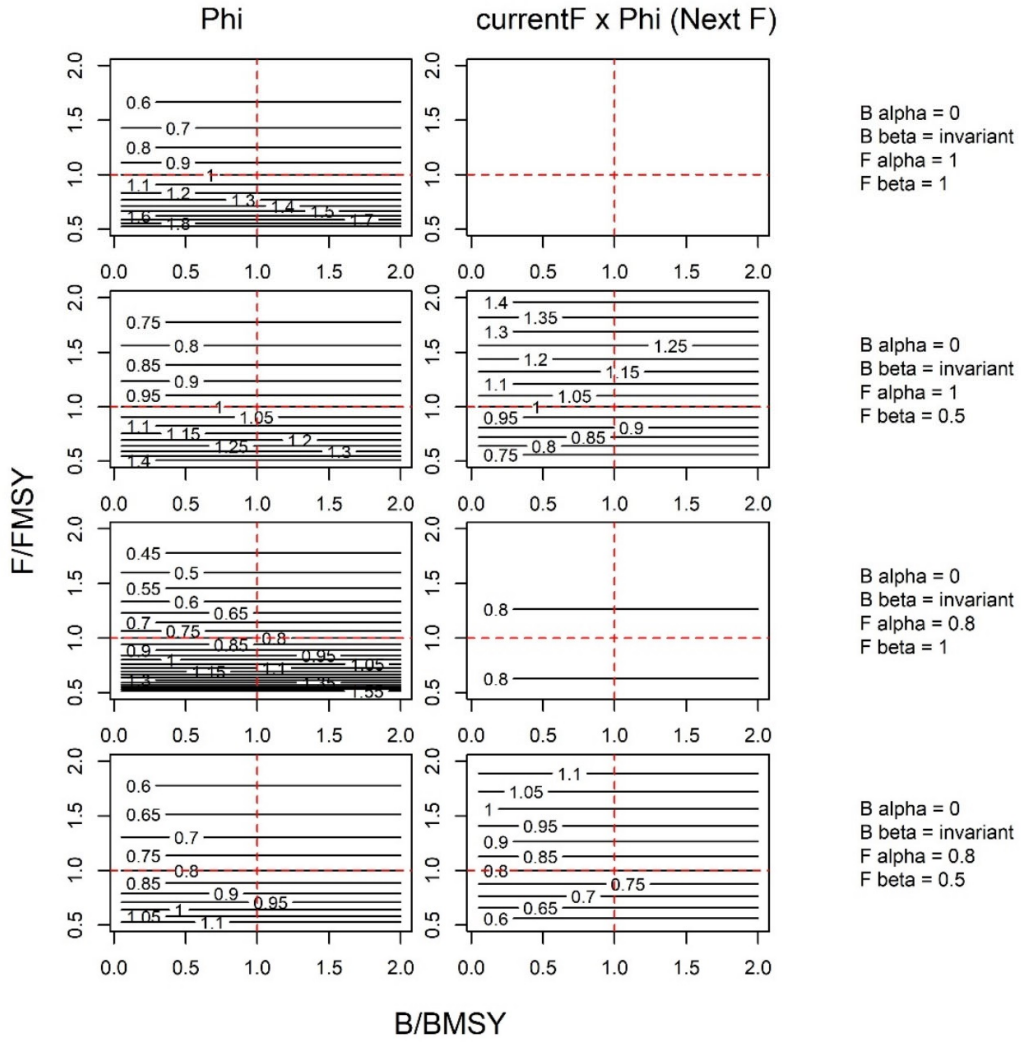


Figure 3. MP TAC adjustment based only on current fishing rate relative to FMSY ($\Delta_{a,t}^F$ only).

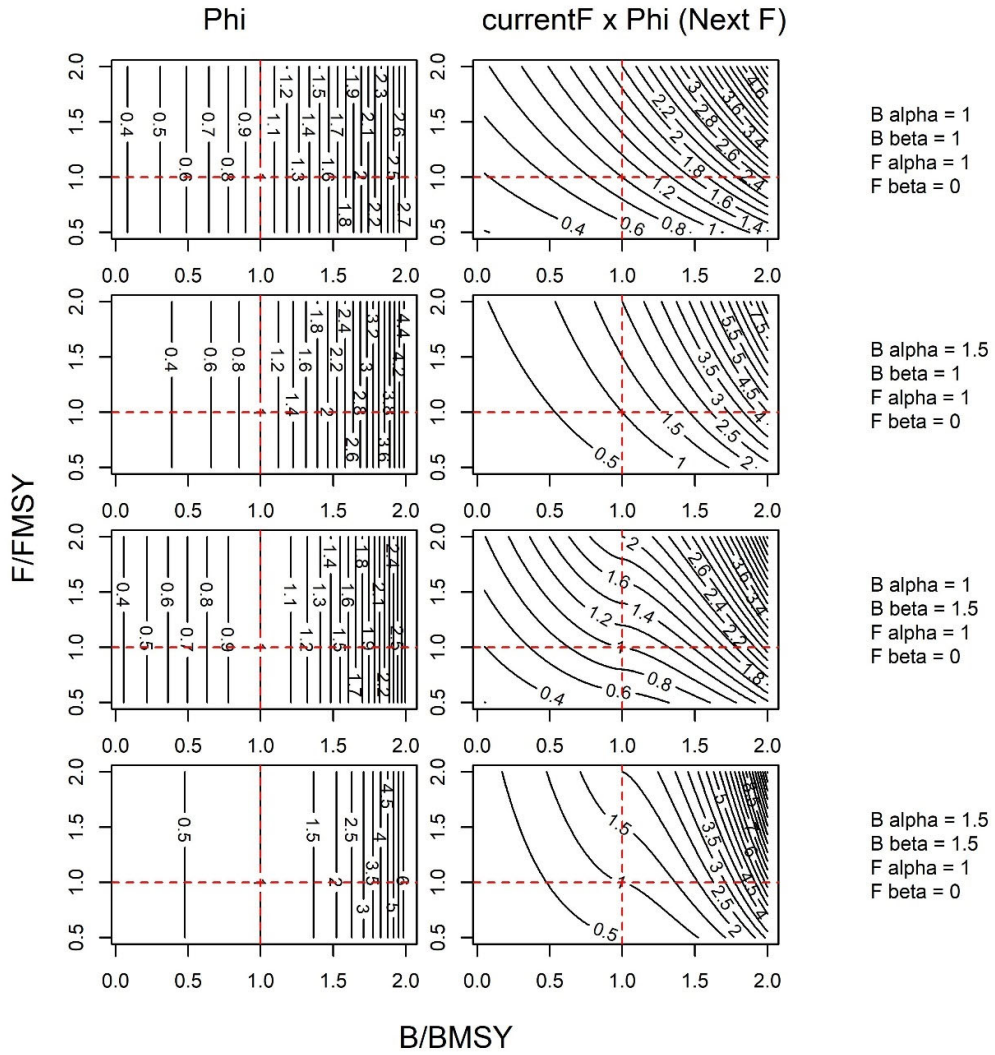


Figure 4. MP TAC adjustment based only on current biomass rate relative to BMSY ($\Delta_{a,t}^B$ only).

Appendix A. R Code for the TC CMP

```
MPx<-function(x, dset, AS, # simulation, dataset, stock number (1 is East, 2 is West)
  Balpha=0, Bbeta=1, Fbeta=0.33, # harvest control rule parameters (Balpha = 0 ignores the biomass component)
  i1CR=c(5,6), i1SUV=c(2,4), i2CR=c(10,13), i2SUV=3, # the indices used for i1 (East), i2 (West) TAC calculation
(CR is area and catch rates, SUV is stock and is surveys)
  theta=matrix(c(0.95,0.1,0.05,0.9), nrow=2), # assumed stock distribution matrix stock x area
  BMSYE=550, BMSYW=15, # assumed BMSY in east and west areas
  FMSYE=0.07, FMSYW=0.02, # !!! tuning parameters !!!
  BE=650, BW=15, BEa=500, BWa=70, # area and stock biomass assumed for in years 53-54
  maxDown=0.3, maxUp=0.2, mindelta=0, ## TAC change constraints
  minETAC=0, minWTAC=0, # min TAC constraints
  maxETAC=100, maxWTAC=20, # max TAC constraints
  maxWTACnear=10, wTACnear=10, # short term exception for setting max western TAC
  enp.mult=0.15, # smoothing parameter
  lastyrs=53:54){ # years or calibrating q

# Smoothing function for indices
smooth<-function(xx,plot=F,enp.mult,plotname=""){
  tofill<-!is.na(xx)
  xx[xx==0]<-1E3
  predout<-rep(NA,length(xx))
  dat<-data.frame(x=1:length(xx),y=log(xx))
  enp.target<-sum(tofill)*enp.mult
  out<-loess(y~x,dat=dat,enp.target=enp.target)
  predout[tofill]<-exp(predict(out))
  if(plot){
    plot(xx,type="p",xlab="x",ylab="y",main=plotname)
    lines(predout,col="#ff0000",lwd=2)
  }
  predout
}

# Extract index data and smooth using function above
thisyr<-length(dset[[1]]$Iobs[x,1,])
Iobs<-dset[[1]]$Iobs[x,,]
Iobs<-t(apply(Iobs,1,smooth,plot=F,plotname=x,enp.mult=enp.mult))

# Robustifying for missing index values: replicate previous observation if missing
fill<-is.na(Iobs[,thisyr])
Iobs[fill,thisyr]<-Iobs[fill,thisyr-1]

# Catchability calculations
q1SUV=BE/apply(Iobs[i1SUV,lastyrs],1,mean,na.rm=T)
q2SUV=BW/apply(Iobs[i2SUV,lastyrs,drop=F],1,mean, na.rm=T)
q1CR=BEa/apply(Iobs[i1CR,lastyrs],1,mean,na.rm=T)
q2CR=BWa/apply(Iobs[i2CR,lastyrs],1,mean,na.rm=T)

# Calculate biomass in the East area from eastern i1 and western i2 stock indices multiplied
# by catchability (q) and movement (theta)
BSUVE<-mean(Iobs[i1SUV,thisyr]*q1SUV)*theta[1,1]+
  mean(Iobs[i2SUV,thisyr]*q2SUV)*theta[2,1]

# Calculate biomass in the West area from eastern i1 and western i2 stock indices multiplied
# by catchability (q) and movement (theta)
BSUVW<-mean(Iobs[i1SUV,thisyr]*q1SUV)*theta[1,2]+
  mean(Iobs[i2SUV,thisyr]*q2SUV)*theta[2,2]

# Calculate biomass for East and West areas by multiplying area catch rate indices iCR by catchability (q)
BCRE<-mean(Iobs[i1CR,thisyr]*q1CR)
BCRW<-mean(Iobs[i2CR,thisyr]*q2CR)

# Get last TAC observation (y-1 works for all 2+ year intervals)
lastTACyr<-length(dset[[1]]$TAC[x,])-1
ETAC<-dset[[1]]$TAC[x,lastTACyr]/1E6
WTAC<-dset[[2]]$TAC[x,lastTACyr]/1E6
```

```

# Calculate implied Fs from TACs and the Biomass estimates
FSUVE<--log(1-ETAC/(ETAC+BSUVE))
FSUVW<--log(1-WTAC/(WTAC+BSUVW))
FCRE<--log(1-ETAC/(ETAC+BCRE))
FCRW<--log(1-WTAC/(WTAC+BCRW))

# Get TACs in the original scale (kg)
ETAC<-dset[[1]]$TAC[x,lastTACyr]
WTAC<-dset[[2]]$TAC[x,lastTACyr]

# A non linear power function for calculating TAC adjustment with respect to biomass and F
powdif<-function(x,z,g){
  x2<-(g*((x)^2)^0.5)^z
  x2[x<0]<-(-x2[x<0])
  x2
}

# geometric mean of Biomass status
dBE=exp(1/2*(log(BSUVE/BMSYE)+log(BCRE/BMSYE)))
dBW=exp(1/2*(log(BSUVW/BMSYW)+log(BCRW/BMSYW)))

# geometric mean of F status
dFE=exp(1/2*(log(FSUVE/FMSYE)+log(FCRE/FMSYE)))
dFW=exp(1/2*(log(FSUVW/FMSYW)+log(FCRW/FMSYW)))

# Depending on stock (AS) assign calculated variables to Frel, Brel and TAC
if(AS==1){ # If East area
  Frel<-dFE
  Brel<-dBE
  TAC<-ETAC
  maxTAC<-maxETAC*1E6
  minTAC<-minETAC*1E6
}else{ # If West area
  Frel=dFW
  Brel=dBW
  TAC=WTAC
  # West has an exception that it can have a max TAC in the short run
  if(thisyr<(56+wTACnear)){
    maxTAC=maxWTACnear*1E6
  }else{
    maxTAC<-maxWTAC*1E6
  }
  minTAC<-minWTAC*1E6
}

# Multipliers for calculating the TAC adjustment
Fresp<-exp(log(1/Frel)*Fbeta)
Bresp<-exp(powdif(Brel-1,Bbeta,Balpha))
TACadj2<-Bresp*Fresp

# Exception for short term TAC control (here for a 3-year variant)
if(thisyr<59){ # TAC update 1 is 57, update 2 is 59 - just one fixed update in the 3-year
  if(TACadj2>(1+maxUp))TACadj2=(1+maxUp)
  if(TACadj2<0.9)TACadj2=0.9 # this is changed
  if(TACadj2>(1-mindelta)&TACadj2<(1+mindelta))TACadj2=1
}else{
  if(TACadj2>(1+maxUp))TACadj2=(1+maxUp)
  if(TACadj2<(1-maxDown))TACadj2=(1-maxDown)
  if(TACadj2>(1-mindelta)&TACadj2<(1+mindelta))TACadj2=1
}

# return TAC subject to min-max constraints
max(minTAC,min(TACadj2*TAC,maxTAC))
}

```