Appendix 2: Model equations

The model was built using the Vensim software, produced by Ventana Systems, Inc. (www.vensim.com). Vensim PLE is freely available, and is required to read, modify, and run the model.

Immature PR Population= INTEG (
    births PR-maturation rate PR-immature PR harvested,initial CDH population*Initial Proportion PR*immature ratio)
thousand molluscs

Mature PR Population= INTEG (
    maturation rate PR-natural deaths PR-mature PR harvested,initial CDH population*Initial Proportion PR*(1-immature ratio))
thousand molluscs

Mature AT Population= INTEG (
    maturation rate AT-natural deaths AT-mature AT harvested,initial CDH population*(1-Initial Proportion PR)*(1-immature ratio))
thousand molluscs

Immature AT Population= INTEG (
    births AT-maturation rate AT-immature AT harvested,initial CDH population*(1-Initial Proportion PR)*immature ratio)
thousand molluscs

immature ratio = 0.1
Dmnl

stable CDH population with 15 boats=initial CDH population
thousand molluscs

population effect AT=surviving rate function (Total CDH AT/carrying capacity AT)
Dmnl

population effect PR=surviving rate function (Total CDH PR/carrying capacity PR)
Dmnl

Seri average boats=initial boats*(1-outsider boat percentage)+PULSE(5 , 100)*(more boats*(1-outsider boat percentage))
boat/Year
Average number of boats at start of model run; pulse at year 5 with more Seri boats for scenario testing

outsider average boats=initial boats*outsider boat percentage+PULSE(5 , 100)*(more boats*outsider boat percentage)
boat/Year
Number of outsider boats in fishery, with pulse at 25 years of more outsider boats

outsider boat percentage=IF THEN ELSE("Rule 3 On?", 0, 1)

final boats=15
boats/Year

"Stochastic Adult Lifetime?"=0
Dmnl

mature lifespan distribution AT=IF THEN ELSE("Stochastic Adult Lifetime?"=1, Pink Noise AT, 9)
years

more boats=final boats-initial boats

boats/Year [0,50,1]

"Rule 4 On?"=0
Dmnl

rule 4 PR immature harvest=IF THEN ELSE("Rule 4 On?"=1, 0, 1)
Dmnl
0 to turn rule on at 100%, 1 to turn rule off

fishing luck distribution=IF THEN ELSE("Stochastic Fishing Luck?"=1, Pink Noise FL, 1)
Dmnl

mature lifespan distribution PR=IF THEN ELSE("Stochastic Adult Lifetime?"=1,Pink Noise PR,12)
years

"Stochastic Fishing Luck?"=0
Dmnl

"Rule 3 On?"=0
Dmnl

boats to collapse=IF THEN ELSE((Total CDH Population/carrying capacity CDH)<0.1, (Seri average boats+outsider average boats), 0)
boat/Year

recovery=IF THEN ELSE(Total CDH Population>stable CDH population with 15 boats,1, 0)
Dmnl

fecundity rate AT=fecundity rate PR
Dmnl

Change in Pink Noise Fec=(White Noise Fec-Pink Noise Fec)/Correlation Time Fec
Dmnl

Standard Deviation Fec=5
Year

White Noise Fec=20*(White Noise AT/9)
Year

births AT=Mature AT Population*female percent*(fecundity rate AT/mature lifespan distribution AT)*population effect AT
thousand molluscs/Year

Correlation Time Fec=1
Year

Pink Noise Fec= INTEG (Change in Pink Noise Fec,Mean Fec)
Year

fecundity rate PR=20
Dmnl

Mean Fec=20
Year

White Noise PR=12*(White Noise AT/9)
Year

White Noise FL=Mean FL+
	(((Standard Deviation FL^2)*
	((2-(TIME STEP/Correlation Time FL)) / (TIME STEP/Correlation Time FL)))^0.5)*

RANDOM NORMAL(-Mean FL,Mean FL,0, 1, NOISE SEED)
Dmnl

Change in Pink Noise FL=(White Noise FL-Pink Noise FL)/Correlation Time FL
Dmnl/Year

Standard Deviation FL=0.5
Dmnl

Mean FL=1
Dmnl

Pink Noise FL= INTEG (Change in Pink Noise FL,Mean FL)
Dmnl

Correlation Time FL=0.25
Year

Change in Pink Noise AT=(White Noise AT-Pink Noise AT)/Correlation Time AT
Dmnl

Change in Pink Noise PR=(White Noise PR-Pink Noise PR)/Correlation Time PR
Dmnl

Mean AT=9
Year

Pink Noise AT= INTEG (Change in Pink Noise AT,Mean AT)
Year

Pink Noise PR= INTEG (Change in Pink Noise PR,Mean PR)

Year

White Noise AT=Mean AT+
(((Standard Deviation AT^2)*
((2-(TIME STEP/Correlation Time AT)) / (TIME STEP/Correlation Time AT)))^0.5)*
RANDOM NORMAL(-Mean AT,Mean AT+40,0, 1, NOISE SEED)
Year

natural deaths PR=Mature PR Population / mature lifespan distribution PR
thousand molluscs/Year

Correlation Time AT=1
Year

Correlation Time PR=1
Year

regrowth and density=regrowth rate CDH/"Total CDH Population/Carrying Capacity"
Dmnl

Standard Deviation PR=3
Year

Standard Deviation AT=2
Year

Mean PR=12
Year

rule 3 proportion of fishing effort for AT=1-OFT function in terms of PR(perceived relative abundance PR)

Dmnl

rule 3 proportion of fishing effort for PR=OFT function in terms of PR(perceived relative abundance PR)
Dmnl

to market=total CDH harvested in tons per year
tons/Year

Seri Harvet Rate=Seri harvest rate of AT+Seri harvest rate of PR
thousand molluscs/Year

total CDH harvested in tons per year= INTEG (annual total CDH harvested in tons-to market, 66)
tons/Year

Seri harvest rate of PR=Seri harvest capacity*rule 3 proportion of fishing effort for PR
thousand molluscs/Year

Seri harvest rate of AT=Seri harvest capacity*rule 3 proportion of fishing effort for AT
thousand molluscs/Year

immature PR harvested=((outsider harvest rate of PR+Seri harvest rate of PR)*fishing luck distribution*immature PR density*(1-rule 2 Percentage of Seagrass Coverage))*rule 4 PR immature harvest
thousand molluscs/Year

regrowth rate AT=births AT - natural deaths AT - mature AT harvested
thousand molluscs/Year

regrowth rate PR=births PR-natural deaths PR-mature PR harvested
thousand molluscs/Year

regrowth rate CDH=(births PR+births AT)-(natural deaths PR+natural deaths AT)-(mature AT harvested+mature PR harvested)
thousand molluscs/Year

births PR=Mature PR Population*female percent*(fecundity rate PR/mature lifespan distribution PR)*population effect PR
thousand molluscs/Year

mature AT density=Mature AT Population/carrying capacity CDH
Dmnl

mature PR density=Mature PR Population/carrying capacity CDH
Dmnl

OFT function in terms of PR(
[(0,0)-(1,1)],(0,0.05),(0.05,0.05),(0.3,0.05),(0.4,0.05),(0.5,0.12),(0.53,0.3),(0.57,0.58),(0.6,0.7),(0.66,0.8),(0.75,0.85),(1,0.85))
Dmnl

total immature CDH=Immature AT Population+Immature PR Population
thousand molluscs

Total CDH AT=Immature AT Population+Mature AT Population
thousand molluscs

maturation rate AT=Immature AT Population/time to mature AT
thousand molluscs/Year

immature AT density=Immature AT Population/carrying capacity CDH

Dmnl

NOISE SEED=10
Dmnl [0,1000]

immature PR density=Immature PR Population/carrying capacity CDH
Dmnl

time to mature AT=1
Year

mature PR harvested=(outsider harvest rate of PR+Seri harvest rate of PR)*fishing luck distribution*mature PR density*(1-rule 2 Percentage of Seagrass Coverage)
thousand molluscs/Year

immature AT harvested=((outsider harvest rate of AT+Seri harvest rate of AT)*immature AT density*fishing luck distribution*(1-rule 2 Percentage of Seagrass Coverage))*rule 4 AT immature harvest
thousand molluscs/Year

mature AT harvested=(outsider harvest rate of AT+Seri harvest rate of AT)*fishing luck distribution*mature AT density*(1-rule 2 Percentage of Seagrass Coverage)
thousand molluscs/Year

initial boats=15
boats/Year [0,80,1]

outsider fishing effort=Seri fishing effort
Year

initial AT harvested=23

tons/Year

tons PR harvested per year=DELAY1I(((immature PR harvested/number of immature PR per kg)+(mature PR harvested/number of mature PR per kg)), default delay, initial PR harvested)
tons/Year

tons AT harvested per year=DELAY1I(((immature AT harvested/number of immature AT per kg)+(mature AT harvested/number of mature AT per kg)), default delay, initial AT harvested)
tons/Year

initial PR harvested=14
tons/Year

Outsider harvest capacity=(outsider fishing effort*days per year*number of organisms caught per boat per day*outsider average boats)
thousand molluscs/Year

outsider harvest rate of AT=Outsider harvest capacity
thousand molluscs/Year

outsider harvest rate of PR=Outsider harvest capacity
thousand molluscs/Year

thousand PR harvested per year=mature PR harvested + immature PR harvested
thousand molluscs/Year

thousand AT harvested per year=immature AT harvested + mature AT harvested
thousand molluscs/Year

perceived relative abundance PR=SMOOTH(relative abundance PR,default delay)
Dmnl

default delay=1/12
Year

proportion immature in current AT harvest=IF THEN ELSE(thousand AT harvested per year>0,immature AT harvested/thousand AT harvested per year,0)
Dmnl

proportion immature in current PR harvest=IF THEN ELSE(thousand PR harvested per year>0,immature PR harvested/thousand PR harvested per year,0)
Dmnl

initial CDH population=23683
thousand molluscs

time to mature PR=2
Year

maturation rate PR=Immature PR Population/time to mature PR
thousand molluscs/Year

rule 1 days fished=1*Seri fishing effort
years

total mature CDH=Mature AT Population+Mature PR Population
thousand molluscs

annual total CDH harvested in tons=tons AT harvested per year+tons PR harvested per year
tons/Year

proportion AT of harvest=IF THEN ELSE(annual total CDH harvested in tons>0, tons AT harvested per year/annual total CDH harvested in tons, 0)
Dmnl

proportion of PR of harvest=IF THEN ELSE(annual total CDH harvested in tons>0, tons PR harvested per year/annual total CDH harvested in tons, 0)
Dmnl

natural deaths AT=Mature AT Population / mature lifespan distribution AT
thousand molluscs/Year

Seri harvest capacity=(rule 1 days fished*days per year*number of organisms caught per boat per day*Seri average boats)
thousand molluscs/Year
Maximum annual harvest for all Seri boats in the fishery.

actual proportion PR in current harvest=IF THEN ELSE((thousand AT harvested per year+thousand PR harvested per year)>0, thousand PR harvested per year/(thousand PR harvested per year+thousand AT harvested per year), 0)
Dmnl

relative abundance AT=1-relative abundance PR
Dmnl

Total CDH Population=Total CDH AT + Total CDH PR
thousand molluscs

Total CDH PR=Immature PR Population+Mature PR Population
thousand molluscs

days per year=365

days/Year

relative abundance PR=Total CDH PR/Total CDH Population
Dmnl

"Total CDH Population/Carrying Capacity"=Total CDH Population/carrying capacity CDH
Dmnl

Initial Proportion PR=2/3
Dmnl
Anecdotal evidence from Basurto (unpublished) suggests a PR:AT ratio of 2:1.

number of mature PR per kg=20
thousand molluscs/tons

number of immature PR per kg=RANDOM NORMAL (1,2,1.75,0.2,0)*number of mature PR per kg
thousand molluscs/tons

surviving rate function(
[(0,0)-
(1.5,0.6)],(0,0.5),(0.1,0.49),(0.2,0.48),(0.4,0.46),(0.6,0.42),(0.8,0.34),(0.9,0.25),(0.95,0.15),(1,0),(1.5,0),(2,0))
Dmnl

algae=0.06+0.06*PULSE(10, duration) *-decrease in seagrass
Dmnl
Percentage of seafloor covered by algae when algae is in season.

decrease in seagrass=0
Dmnl [0,1,0.25]

duration=200
years

number of organisms caught per boat per day=2.16
thousand molluscs/boat/day

"number of people/boat"=4
person/boat
Crew of one boat. Default in Seri community is 4; one diver plus three other crew members.

"Average organism per person/day"=0.54
thousand molluscs/person/day

number of mature AT per kg=30
thousand molluscs/tons

number of immature AT per kg=RANDOM NORMAL (0,2,1.75,0.2,0)*30
thousand molluscs/tons

rule 4 AT immature harvest=1
Dmnl
0 to turn rule on, 1 to turn rule off. There is no rule preventing the catch of immatures, but for the most part, divers catch very little numbers of immatures because they cannot see them! With no feedbacks or forcing rules, the percentage of immatures caught is equal to their percentage in the overal population, which varies between 20% and 30%. This seems about right; 30% is an upper bound.

Seri fishing effort=0.5
Year

eelgrass=0.22+0.22*PULSE(10, duration)*-decrease in seagrass

Dmnl
percentage of seafloor covered by eelgrass when eelgrass is in season. Commercial Seri fishers do not fish in the eelgrass.

rule 2 Percentage of Seagrass Coverage=PULSE TRAIN(0, 0.67, 1 , 1000)*eelgrass+PULSE TRAIN(0.67 , 0.33 , 1 ,1000)*algae
Dmnl
Field research by Torre-Cosio (2002) and Basurto (2008) reported that, during roughly 8 months of the year, the eelgrass Zostera marina covers 22% of the Infiernillo Channel's sea bottom, and in the remaining months of the year, the algae Caulerpa spp. covers about 6%.

female percent=0.5
Dmnl

carrying capacity CDH=24500
thousand molluscs

carrying capacity AT= carrying capacity CDH*(1-Initial proportion PR)
thousand molluscs

carrying capacity PR= carrying capacity CDH*Initial proportion PR
thousand molluscs

FINAL TIME = 100
Year

INITIAL TIME = 0
Year

TIME STEP = 0.02
Year