Supplementary material for

Projected shifts in 21st century sardine distribution and catch in the California Current.

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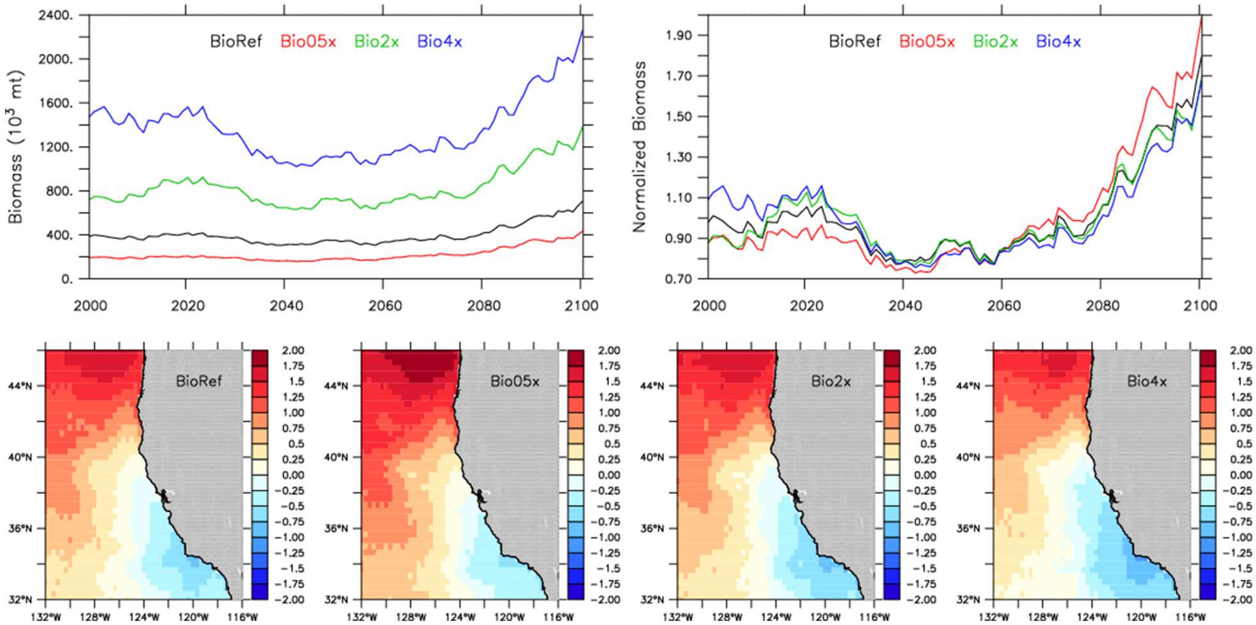
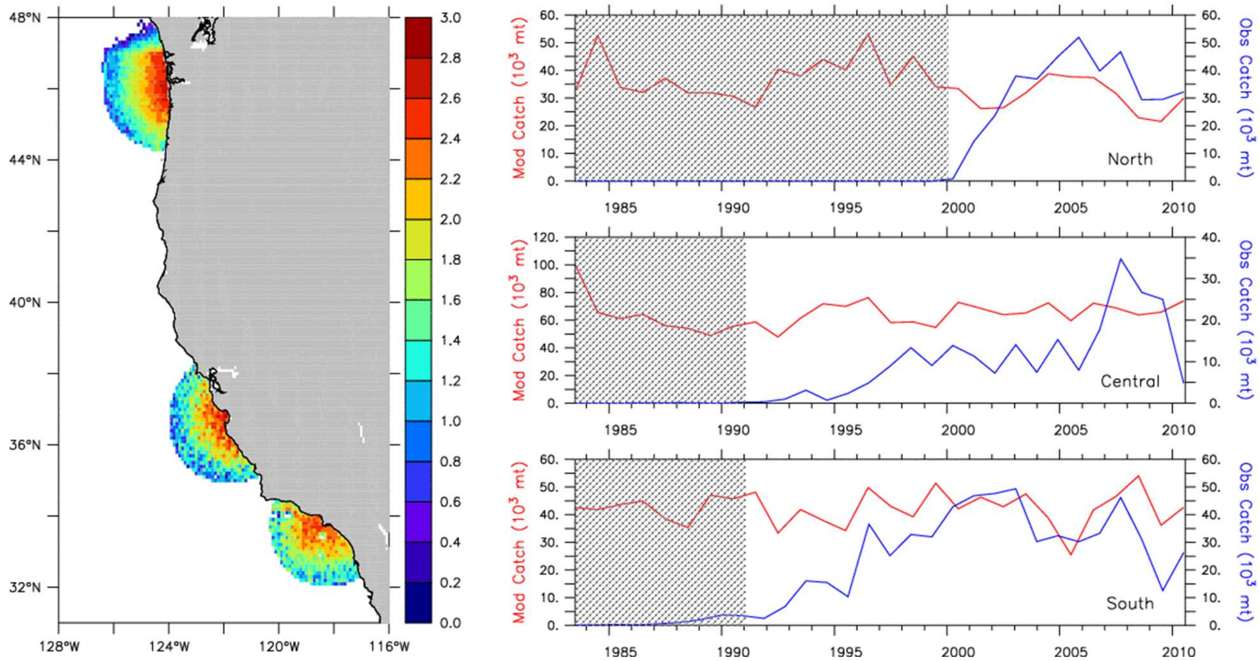
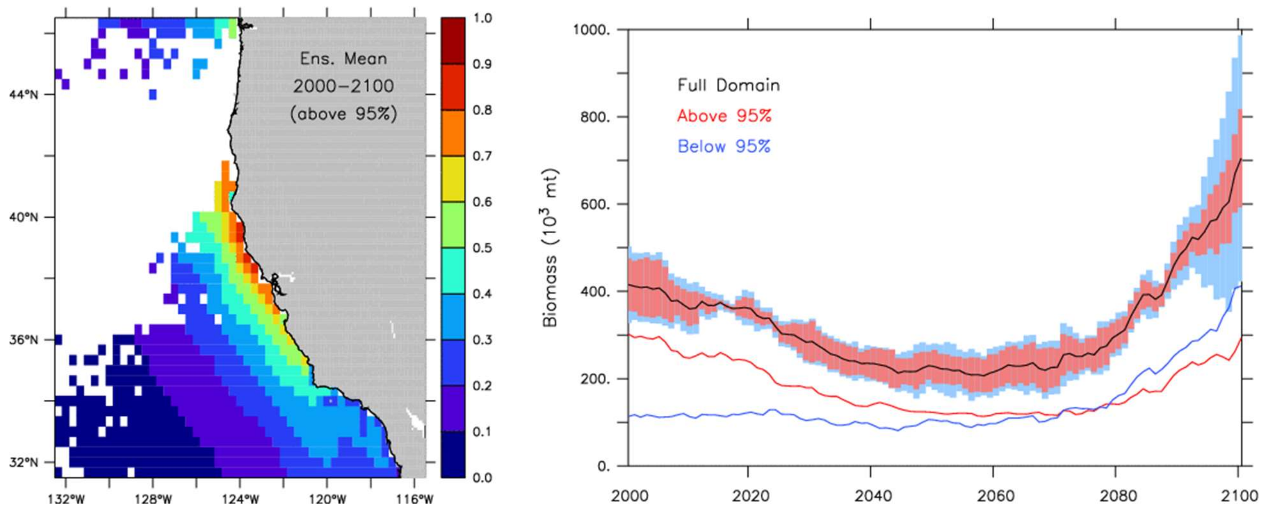


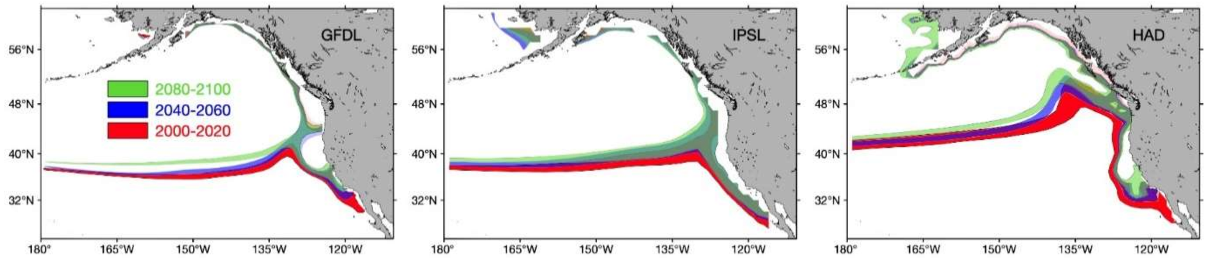
Supplementary Figure 1. Projected (GFDL) adult sardine population dynamics for different initial population biomasses. Top left: spawning stock biomass (10^3 metric tons). Top right: spawning stock biomass relative to 2000-2100 mean. Bottom: future (2080-2100) minus historical (2000-2020) adult biomass normalized by 2000-2100 mean. “BioRef” denotes the reference initial population biomass used in this study (~$400 \cdot 10^3$ metric tons), “Bio05x” denotes initial biomass of half the reference (~$200 \cdot 10^3$ metric tons), “Bio2x” denotes initial biomass of twice the reference (~$800 \cdot 10^3$ metric ton), “Bio4x” denotes initial biomass of 4 times the reference (~$1{,}600 \cdot 10^3$ metric ton).



Supplementary Figure 2. Historical sardine catch from fishing fleet model for 1983-2010. Left: annual mean catch per unit effort (log(CPUE)). Right: simulated (red) and observed (blue) catch (10^3 metric tons) for (from top to bottom) northern CCS (Astoria and Westport), central CCS (Monterey), and southern CCS (Long Beach). Observed catch is from Hill et al., 2010 and grayed out periods indicate times during which there were a moratorium, limited quotas, or no fishery.



Supplementary Figure 3. Projection robustness for sardine spawning stock biomass. Left: ensemble mean spatial biomass (10^3 metric tons) for 2000-2100 excluding locations (white shading) where GFDL, Hadley, and IPSL solutions are statistically different (95% confidence level). Right: Ensemble mean annual biomass (10^3 metric tons) based on the full domain (black), statistically identical locations (red), and statistically different locations (blue). Shading around the full domain ensemble mean indicate multi-model spread contributed by statistically identical (red) and different (blue) locations.



Supplementary Figure 4. Projections of the North Pacific Current (NPC) position for 2000-2020 (red), 2040-2060 (blue), and 2080-2100 (green) from GFDL (left), IPSL (center), and Hadley (right). The mean position of the NPC is defined as the region bounded by streamlines of the geostrophic currents that go poleward into the Gulf and Alaska and equatorward into the California Current.

Input Parameters for NPZ Model

```
! Light attenuation due to seawater [1/m].

       AttSW == 0.04d0

! Light attenuation due to phytoplankton, self-shading coefficient,
! [m2/millimole_N].

       AttPS == 0.02d0                     ! small biomass
       AttPL == 0.08d0                     ! large biomass

! Fraction of shortwave radiation that is photosynthetically active,
! [nondimensional].

     PARfrac == 0.43d0

! Phytoplankton photochemical reaction coefficient, initial slope of
! the P-I curve [1/(W/m2) 1/day].

     AlphaPS == 0.04d0                     ! small biomass
     AlphaPL == 0.04d0                     ! large biomass

! Phytoplankton photoinhibition coefficient, [1/(W/m2) 1/day].

      BetaPS == 1.0d-3                     ! small biomass
      BetaPL == 2.0d-3                     ! large biomass

! Phytoplankton maximum photosynthetic rate at 0 Celsius [1/day].

       VmaxS == 0.4d0                      ! small biomass
       VmaxL == 1.0d0                      ! large biomass

! Phytoplankton half saturation constant for Nitrate [millimole_N/m3].

       KNO3S == 0.3d0                      ! small biomass
       KNO3L == 3.0d0                      ! large biomass

! Phytoplankton half saturation constant for Ammonium [millimole_N/m3].

       KNH4S == 0.1d0                      ! small biomass
       KNH4L == 1.0d0                      ! large biomass

! Phytoplankton half saturation constant for Silicate [millimole_Si/m3].

        KSiL == 3.0d0                      ! large biomass

! Phytoplankton Ammonium inhibition coefficient [m3/millimole_N].

      PusaiS == 1.5d0                      ! small biomass
      PusaiL == 1.5d0                      ! large biomass
```

```
! Phytoplankton temperature coefficient for photosynthetic rate
[1/Celsius].

       KGppS == 6.93d-2                     ! small biomass
       KGppL == 6.93d-2                     ! large biomass

! Phytoplankton respiration rate at 0 Celsius [1/day].

      ResPS0 == 0.03d0                      ! small biomass
      ResPL0 == 0.03d0                      ! large biomass

! Phytoplankton temperature coefficient for respiration [1/Celsius].

      KResPS == 0.0693d0                    ! small biomass
      KResPL == 0.0693d0                    ! large biomass

! Phytoplankton ratio of extracellular excretion to photosynthesis
! [nondimensional].

      GammaS == 0.135d0                       ! small biomass
      GammaL == 0.135d0                       ! large biomass

! Phytoplankton mortality rate at 0 Celsius [m3/millimole_N 1/day].

      MorPS0 == 1.0d-2                      ! small biomass
      MorPL0 == 1.0d-2                      ! large biomass

! Phytoplankton temperature coefficient for mortality [1/Celsius].

      KMorPS == 6.93d-2                     ! small biomass
      KMorPL == 6.93d-2                     ! large biomass

! Zooplankton maximum grazing rate at 0 Celsius [1/day].

    GRmaxSps == 0.50d0                      ! small Zoo on small phy
    GRmaxSpl == 0.20d0                      ! small Zoo on large phy
    GRmaxLps == 0.10d0                      ! large Zoo on small Phy
    GRmaxLpl == 0.30d0                      ! large Zoo on large Phy
    GRmaxLzs == 0.10d0                      ! large Zoo on small Zoo
    GRmaxPpl == 0.30d0                      ! predator Zoo on large Phy
    GRmaxPzs == 0.00d0                      ! predator Zoo on small Zoo
    GRmaxPzl == 0.10d0                      ! predator Zoo on large Zoo

! Zooplankton temperature coefficient for grazing [1/Celsius].

       KGraS == 6.93d-2                     ! small biomass
       KGraL == 6.93d-2                     ! large biomass
       KGraP == 6.93d-2                     ! predator biomass

! Zooplankton half-saturation coefficient (squared) for ingestion used
! only when the Holling-type grazing formulation is activated
! [millimole_N/m3]^2.

      KPS2ZS == 0.10d0                      ! small Zoo on small Phy
```

```
      KPL2ZS == 0.20d0                    ! small Zoo on large Phy
      KPS2ZL == 0.10d0                    ! large Zoo on small Phy
      KPL2ZL == 0.20d0                    ! large Zoo on large Phy
      KZS2ZL == 0.50d0                    ! large Zoo on small Zoo
      KPL2ZP == 0.20d0                    ! predator Zoo on large Phy
      KZS2ZP == 0.50d0                    ! predator Zoo on small Zoo
      KZL2ZP == 0.80d0                    ! predator Zoo on large Zoo

! Zooplankton mortality rate at 0 Celsius [m3/millimole_N 1/day].

      MorZS0 == 6.0d-2                    ! small biomass
      MorZL0 == 6.0d-2                    ! large biomass
      MorZP0 == 8.0d-2                    ! predator biomass

! Zooplankton temperature coefficient for mortality [1/Celsius].

      KMorZS == 0.0693d0                  ! small biomass
      KMorZL == 0.0693d0                  ! large biomass
      KMorZP == 0.0693d0                  ! predator biomass

! Zooplankton assimilation efficiency [nondimemsional].

     AlphaZS == 0.70d0                    ! small biomass
     AlphaZL == 0.70d0                    ! large biomass
     AlphaZP == 0.70d0                    ! predator biomass

! Zooplankton growth efficiency [nondimensional].

      BetaZS == 0.30d0                    ! small biomass
      BetaZL == 0.30d0                    ! large biomass
      BetaZP == 0.30d0                    ! predator biomass

! Decomposition rates at 0 Celsius [1/day].

        Nit0 == 0.01d0                    ! NH4 nitrification
       VP2N0 == 0.08d0                    ! PON to NH4
       VP2D0 == 0.01d0                    ! PON to DON
       VD2N0 == 0.08d0                    ! DON to NH4
       VO2S0 == 0.02d0                    ! Opal to Silicate

! Temperature coefficients for decomposition [1/Celsius]

        KNit == 6.93d-2                   ! NH4 nitrification
        KP2D == 6.93d-2                   ! PON to DON
        KP2N == 6.93d-2                   ! PON to NH4
        KD2N == 6.93d-2                   ! DON to NH4
        KO2S == 6.93d-2                   ! Opal to Silicate

! Si:N ratio [millimole_Si/millimole_N].

        RSiN == 1.0d0

! Settling (sinking) velocities [m/day].
```

```
     setVPON == 20.0d0                      ! PON
    setVOpal == 20.0d0                      ! Opal

! Redfield Carbon:Nitrogen ratio [mole_C/mole_N] , {6.625d0}.

       RedCN == 6.625d0
```

Input Parameters for Sardine IBM

```
! Fish start and end of spawning season [yearday]

      Fspstr == 32.0d0
      Fspend == 182.0d0

! Min and max temperature for spawning season [C]

      FspTmin == 12.0d0
      FspTmax == 15.0d0

! Opt and s.dev. temperature for kinesis [C]

      FkinTopt == 13.0d0
      FkinTsdv == 3.0d0

! Opt and s.dev. p-value for kinesis [-]

      FkinPVopt == 0.85d0
      FkinPVsdv == 0.10d0

! Fish preference for ZS, ZL, ZP

      ZSpref_L == 1.0d0         ! larval stage
      ZLpref_L == 0.2d0         ! larval stage
      ZPpref_L == 0.0d0         ! larval stage
      ZSpref_J == 0.2d0         ! juvenile stage
      ZLpref_J == 1.0d0         ! juvenile stage
      ZPpref_J == 0.1d0         ! juvenile stage
      ZSpref_A == 0.1d0         ! adult stage
      ZLpref_A == 1.0d0         ! adult stage
      ZPpref_A == 0.5d0         ! adult stage

! Fish half saturation for ZS, ZL, ZP

      K_ZS_L == 0.02d0          ! larval stage
      K_ZL_L == 0.02d0          ! larval stage
      K_ZP_L == 0.00d0          ! larval stage
      K_ZS_J == 0.10d0          ! juvenile stage
      K_ZL_J == 0.10d0          ! juvenile stage
      K_ZP_J == 0.10d0          ! juvenile stage
      K_ZS_A == 0.10d0          ! adult stage
      K_ZL_A == 0.10d0          ! adult stage
      K_ZP_A == 0.10d0          ! adult stage

! Energy conversion from Zooplankton to Fish
! (CAL_ZF = CAL_Z/CAL_F = 2580/7775)

      Cal_Z == 3800.0d0
      Cal_F == 8000.0d0

! Fish consumption coefficient and exponent
```

```
       a_C_L == 0.24d0          ! larval stage
       a_C_J == 0.24d0          ! juvenile stage
       a_C_A == 0.24d0          ! adult stage
       b_C_L == 0.455d0         ! larval stage
       b_C_J == 0.455d0         ! juvenile stage
       b_C_A == 0.455d0         ! adult stage

! Fish maximum p-value

       pvalmax_L == 1.0d0       ! larval stage
       pvalmax_J == 1.0d0       ! juvenile stage
       pvalmax_A == 1.0d0       ! adult stage

! Fish respiration coefficient and exponent

       a_R_L == 3.3d-3          ! larval stage
       a_R_J == 3.3d-3          ! juvenile stage
       a_R_A == 3.3d-3          ! adult stage
       b_R_L == 0.15d0          ! larval stage
       b_R_J == 0.15d0          ! juvenile stage
       b_R_A == 0.15d0          ! adult stage

! Fish activity (if 0, then activity computed from swimming)

       activity_L == 0.0d0      ! larval stage
       activity_J == 0.0d0      ! juvenile stage
       activity_A == 0.0d0      ! adult stage

! Fish swimming coefficient and swimming speed

       d_R_L == 3.0d-3          ! larval stage
       d_R_J == 3.0d-3          ! juvenile stage
       d_R_A == 3.0d-3          ! adult stage
       Fswim_L == 3.0d0         ! larval stage
       Fswim_J == 3.0d0         ! juvenile stage
       Fswim_A == 3.0d0         ! adult stage

! Fish assimilation efficiency coefficient and exponent

       a_AE_L == 0.60d0         ! larval stage
       a_AE_J == 0.60d0         ! juvenile stage
       a_AE_A == 0.60d0         ! adult stage
       b_AE_L == 0.04d0         ! larval stage
       b_AE_J == 0.04d0         ! juvenile stage
       b_AE_A == 0.04d0         ! adult stage

! Fish assimilation efficiency maximum

       AEmax_L == 0.7d0         ! larval stage
       AEmax_J == 0.7d0         ! juvenile stage
       AEmax_A == 0.7d0         ! adult stage

! Temprature coefficients for bioenergetics
```

```
      te1_L == 10.0d0          ! larval stage
      te1_J == 10.0d0          ! juvenile stage
      te1_A == 10.0d0          ! adult stage
      te2_L == 12.0d0          ! larval stage
      te2_J == 12.0d0          ! juvenile stage
      te2_A == 12.0d0          ! adult stage
      te3_L == 16.0d0          ! larval stage
      te3_J == 16.0d0          ! juvenile stage
      te3_A == 16.0d0          ! adult stage
      te4_L == 22.0d0          ! larval stage
      te4_J == 27.0d0          ! juvenile stage
      te4_A == 27.0d0          ! adult stage

      xk1_L == 0.10d0          ! larval stage
      xk1_J == 0.10d0          ! juvenile stage
      xk1_A == 0.10d0          ! adult stage
      xk2_L == 0.98d0          ! larval stage
      xk2_J == 0.98d0          ! juvenile stage
      xk2_A == 0.98d0          ! adult stage
      xk3_L == 0.98d0          ! larval stage
      xk3_J == 0.98d0          ! juvenile stage
      xk3_A == 0.98d0          ! adult stage
      xk4_L == 0.01d0          ! larval stage
      xk4_J == 0.01d0          ! juvenile stage
      xk4_A == 0.01d0          ! adult stage

      cr_L == 3.0d-3           ! larval stage
      cr_J == 3.0d-3           ! juvenile stage
      cr_A == 3.0d-3           ! adult stage
      tr_L == 0.0d0            ! larval stage
      tr_J == 0.0d0            ! juvenile stage
      tr_A == 0.0d0            ! adult stage

! Weight (g) and length (mm) at first feeding

      Wffeed ==  1.53d-3
      Lffeed ==  6.0d0

! Weight (g) and length (mm) for transition from larva to juvenile

      WeightLJ ==  0.395d0
      LengthLJ ==  35.0d0

! Weight (g) and length (mm) for transition from juvenile to adult

      WeightJA ==  0.395d0
      LengthJA ==  35.0d0

! Coefficients for weight to length conversion

      aw2l_L == 5.4d-6         ! larval stage
      aw2l_J == 5.4d-6         ! juvenile stage
      aw2l_A == 5.4d-6         ! adult stage
```

```
      bw2l_L == 3.15d0         ! larval stage
      bw2l_J == 3.15d0         ! juvenile stage
      bw2l_A == 3.15d0         ! adult stage
      dSLk_L == 3.26d-3        ! larval stage
      dSLk_J == 3.26d-3        ! juvenile stage
      dSLk_A == 3.26d-3        ! adult stage
      dSLinf_L == 206.0d0      ! larval stage
      dSLinf_J == 206.0d0      ! juvenile stage
      dSLinf_A == 206.0d0      ! adult stage

! Coefficients for length to weight conversion

      al2w_L == 5.4d-6         ! larval stage
      al2w_J == 5.4d-6         ! juvenile stage
      al2w_A == 5.4d-6         ! adult stage
      bl2w_L == 3.15d0         ! larval stage
      bl2w_J == 3.15d0         ! juvenile stage
      bl2w_A == 3.15d0         ! adult stage

! Batch duration coefficient, exponent, and temperature

      abatch == 11.0d0
      bbatch == 0.015d0
      T0batch == 12.6d0
      apof == 5.0d0
      bpof == 0.015d0
      T0pof == 8.0d0

! Batch size parameters

      epg == 260.0d0
      eegg == 4500.0d0
      megg == 2.78d-4

! Breeeding strategy

      breed == 3.0d0

! Matrurity coefficients

      amature == -18.16d0
      bmature == 0.1195d0

! Weight perecentage

      pctxwt == 0.5d0

! Gain percentage

      pctgain == 0.5d0

! Fish yearly natural mortality
! Daily for eggs->juvenile; Yearly for adults
```

```
Nmort_E == 0.72d0          ! egg stage
Nmort_Y == 0.67d0          ! yolksac stage
Nmort_L == 0.13d0          ! larval stage
Nmort_J == 0.0055d0        ! juvenile stage
Nmort_A == 0.40d0          ! adult stage
```

Input Parameters for Fishing Fleet Model

```
! Maximum daily catch [kg]

      CatchMax == 30000.0d0

! Cost per hour of traveling [$]

      TravCost == 30.0d0

! Boat motoring speed [km/h]

      BoatVel == 20.0d0

! Catchability [-]

      Qcatch == 0.01d0

! Time to fish and process catch at a location, [hr]

      FishTime == 2.0d0

! Maximum numer of encounters with fish, [-]

      EncMax == 20

! Mean encounter rate (1.0 means boats see all fish in cell), [-]

      EncRate == 0.9d0

! Price for catch by port [$/kg], {0.5d0}.

      CatchPrice == 0.5d0 0.5d0 0.5d0 0.5d0
```