Online Supplementary Material: Biodynamics Model (BDM)

BDM Description

A modified Pella and Tomlinson (Pella and Tomlinson 1969) model has been used and fitted using ADMB (Fournier et al. 2012). It is a non-equilibrium model that fits to two time series of abundance, (i) standardised commercial fishing catch rates and (ii) standardised independent survey catch rates. The annual standardised commercial catch rate data spans 1975 until present and is adjusted for high grading and the influences of location, month, water depth and soak time using a linear model. Commercial catch rate information prior to 1975 is considered unreliable due to the questionable recording of effort and hence is omitted from the model. The annual independent survey catch rate data was collected using a standardised survey in deep water (same pots, bait, location and lunar cycle) and spans the period 1992 until present (see de Lestang et al. 2016 for full details). Data from this survey are averaged across locations using a linear model which also accounts for month, ocean swell and water depth. The Biodynamics model (BDM) also utilises four other data sources to help inform legal biomass and catch rate estimates:

- Commercial catch data since 1944. Recorded through statutory returns and adjusted for under reporting (de Lestang et al. 2016).
- Recreational catch data since 1987 (prior data is not available but recreational catch was considered negligible). Derived from survey estimates and adjusted for a number of biases (e.g. recall and response bias) (de Lestang et al. 2016).
- Puerulus settlement data from 1968, recorded through independent surveys (de Lestang et al. 2016).

- Bottom boundary layer water temperature (BBLWT) since 1992 derived from a ROMs oceanographic model for the period 2000 - 2014. The data series has been extended to match that of the standardised independent survey (discussed below).

The estimated biomass of the lobster population in a year (B_{t+1}) was derived from the biomass in the previous year (B_t), the additional biomass produced during the previous year (productivity), and the catch removed during that year (C_t) based on the equation:

$$B_{t+1} = B_t + \left(\frac{r}{p} B_t \left(1 - \left(\frac{B_t}{K} \right)^p \right) \right) R_t - C_t \ ,$$

where R_t is the puerulus-derived recruitment deviation, *r* is the growth rate, *K* is the virgin biomass level (carrying capacity) and *p* allows for asymmetry in the production curve.

The puerulus-derived recruitment deviation uses puerulus settlement data collected towards the centre of the fishery at Lancelin, Jurien, Dongara and Rat Island at the Abrolhos Islands. The data from the four sites is combined using a linear model to account for an incomplete data set (some months in some locations are missing) and spans 1968/69 until 2017/18. Projections of model biomass utilise average puerulus settlement levels of the most recent ten years (e.g. 2008/09 – 2017/18). Historic levels of puerulus settlement (i.e. pre 1968) are set to the average level of settlement for the entire time series (not inclusive of projections). Puerulus settlement is lagged four years to align with legal-size catch rates. The lag represents the average time taken for lobsters to grow from puerulus (~8.5 mm CL) to legal size (76 mm CL) (de Lestang et al. 2009). The standardised puerulus settlement data is converted to a proportion of the average of the index of known data (1968-current; i.e. does not include projections). The proportion is then transformed into a recruitment deviation (R_t) based on the equation:

$$R_t = \alpha \left(\frac{P_t}{\overline{P}_{1968-2017}} \right)^{\beta} ,$$

where P_t is the puerulus index in time t, $\overline{P}_{1968-2017}$ is the average level of observed puerulus settlement over the time series from 1968 to 2017 and α and β are parameters in the model. Based on this equation all historical deviations are zero.

Commercial catch rates are assumed to have been impacted by fishing efficiency over time (de Lestang et al. 2011). Previous estimates of this factor indicate that there has been a progressive 1-2% increase per year over the period 1970 until the end of input management controls (2009). Following the move to output management in 2010, fishing efficiency has been found to have decreased by around 20% in a single year before again starting to increase slowly (de Lestang et al., 2018). In the BDM, fishing efficiency is accounted for by a combination of five parameters, a compounding fishing efficiency and four catchability/selectivity parameters. The compounding fishing efficiency parameter is applied across two time periods (1970 –1992 and 1993 – 2009 as each has a unique catchability parameter. Prior to 1970 fishing efficiency increases were not considered as great therefore the compounding parameter was not applied. After the move to quota management, the influence of compounding fishing efficiency was again considered minor, therefore this parameter was not applied.

The four catchability/selectivity parameters in the model allow for step-wise changes in catchability and selectivity, and when combined with fishing efficiency, they allow for five specific time periods to have different patterns of efficiency, catchability and selectivity (selectivity allows for variation in the proportion of the stock defined as legal biomass from “all lobsters ≥ 76 mm CL excluding egg bearing females”) based on the equation;

$$K_y = \begin{cases} q_1 & y < 1970 \\ q_1 c^{(y-1970)} & 1970 < y < 1993 \\ q_2 c^{(y-1993)} & 1993 < y < 2010 \\ q_3 & 2010 < y < 2014 \\ q_4 & 2014 < y \end{cases},$$

where K_y is a vector of a combination of fishing efficiency, catchability and selectivity, specific for each fishing season and c is the fishing efficiency (creep) parameter. The five periods have been grouped for the following reasons:

- Prior to 1970. The fishery was still developing and little increase in fishing efficiency was evident. All lobsters > 76 mm could be taken (apart from reproductively active [egg bearing] females).
- 1970 – 1993. All lobsters > 76 mm could be taken (apart from reproductively active [egg bearing] females).
- 1993 – 2010. A greater proportion of the stock was protected, with the minimum gauge increased to 77 mm (November – February), and setose and maximum size (105 or 115 mm CL) females were protected.
- 2010 – 2014. The fishery moved to quota management which caused a marked change in fisher's behaviour and the minimum size was reduced again to 76 mm.
- Since 2014. Protection to maximum size females was removed and the taking of setose lobsters was allowed from May to October (only egg bearing females still protected).

The BDM estimated commercial catch rates using the equation:

$$\bar{U}_y = B_y K_y ,$$

and were compared to the observed standardised commercial catch rates (U_y) using the following equation:

$$\lambda_1 = \sum_{i=y}^{n} 1/(\hat{\sigma}_{K,i}\sqrt{(2\pi)})\mathrm{e}^{(-((U_y - \bar{U}_y)^2/(2\hat{\sigma}_{K,i}^2)))},$$

where λ_1 is the log likelihood and $\sigma_{K,i}$ is the standard deviation associated with the estimated commercial catch rates.

Catch rates from the independent survey are less susceptible to biases due to their standardised sampling design and therefore contained no changes in lobster selectivity or fishing efficiency. These surveys are however susceptible to variation in environmental conditions as they are only conducted over a short 10-day time period each year. Estimation of catch rates over longer time periods smooths out the influence of environmental variation and hence lessens their impact (e.g. commercial catch rates). The influence of ocean swells was corrected during the standardisation process (described above) as this factor varied within year and this contrast allowed for its impact to be determined and corrected for. Water temperature on the other hand did not vary within year and could therefore not be corrected using a linear model with year as a factor. The bottom boundary layer water temperature (BBLWT) has been incorporated to allow for temperature associated changes in catchability. A temporary measure for this data series has been derived from an oceanographic model (ROMs) developed by University of Western Australia for the Western Australia Coastline. The modelled data series however only covers the period 2000 – 2015. As such it was extended to match that of the IBSS (1992 – 2017) by using the average water temperature for years when data was not available. This is only temporary as it will be changed to direct observation data collected during the independent surveys using archival tags. Currently these data are being collated. Future projections of BBLWT are based on the long-term average from the ROMs model. The catchability parameter for the independent catch rates could therefore vary between years (I_y) in response to BBLWT. The independent catchability parameter was estimated using the equation;

$$I_y = \rho + \varphi BBLWT_y,$$

where ρ and ϕ are estimated parameters, with the independent catch rates estimated using the equation;

$$\bar{V}_y = B_y I_y \,,$$

which were compared to the observed standardised independent catch rates (V_y) using the following equation:

$$\lambda_2 = \sum_{i=y}^{n} 1/(\hat{\sigma}_{I,i}\sqrt{(2\pi)})\mathrm{e}^{(-((V_y - \bar{V}_y)^2/(2\hat{\sigma}_{I,i}^2)))} \,,$$

where λ_2 is the log likelihood and $\sigma_{I,i}$ is the standard deviation associated with the estimated independent catch rates.

The combined log likelihoods plus a penalty function ($\sum\left(\lambda_{K,i}\lambda_{I,i}\right) + pen$) were minimised using ADMB via the R2ADMB routine in R (R Core Team, 2016). The penalty was the sum of two functions, one which kept efficiency creep close to previous estimates of 2% pa and the other to keep a BBLWT parameter on a sensible scale. Estimation of all confidence intervals used the delta method on the Hessian matrix and derived quantities.

Maximum sustainable yield (MSY) was estimated from the model using the equation:

$$MSY = rB_0 \Big/ (p+1)^{((p+1)/p)} \,,$$

and harvest rate (H_y) estimated using the equation;

$$H_y = {C_y}\big/{B_y} \,.$$

BDM Diagnostics

Two diagnostics were produced to assess the appropriateness of the BDM in the replication of commercial and independent catch rates (actual and residual). The fit between observed and estimated catch rates were very good for the commercial cpue index (R^2 = 0.96; Fig. S1A,B) and slightly less accurate for the independent survey cpue index (R^2 = 0.76; Fig. S1C,D). The poorer fit to independent catch rates may be a combination of this index only being derived from the deeper water regions of the fishery (as the BDM encompasses all water depths of the fishery), and a lack of suitable catchability standardisation for the independent survey.

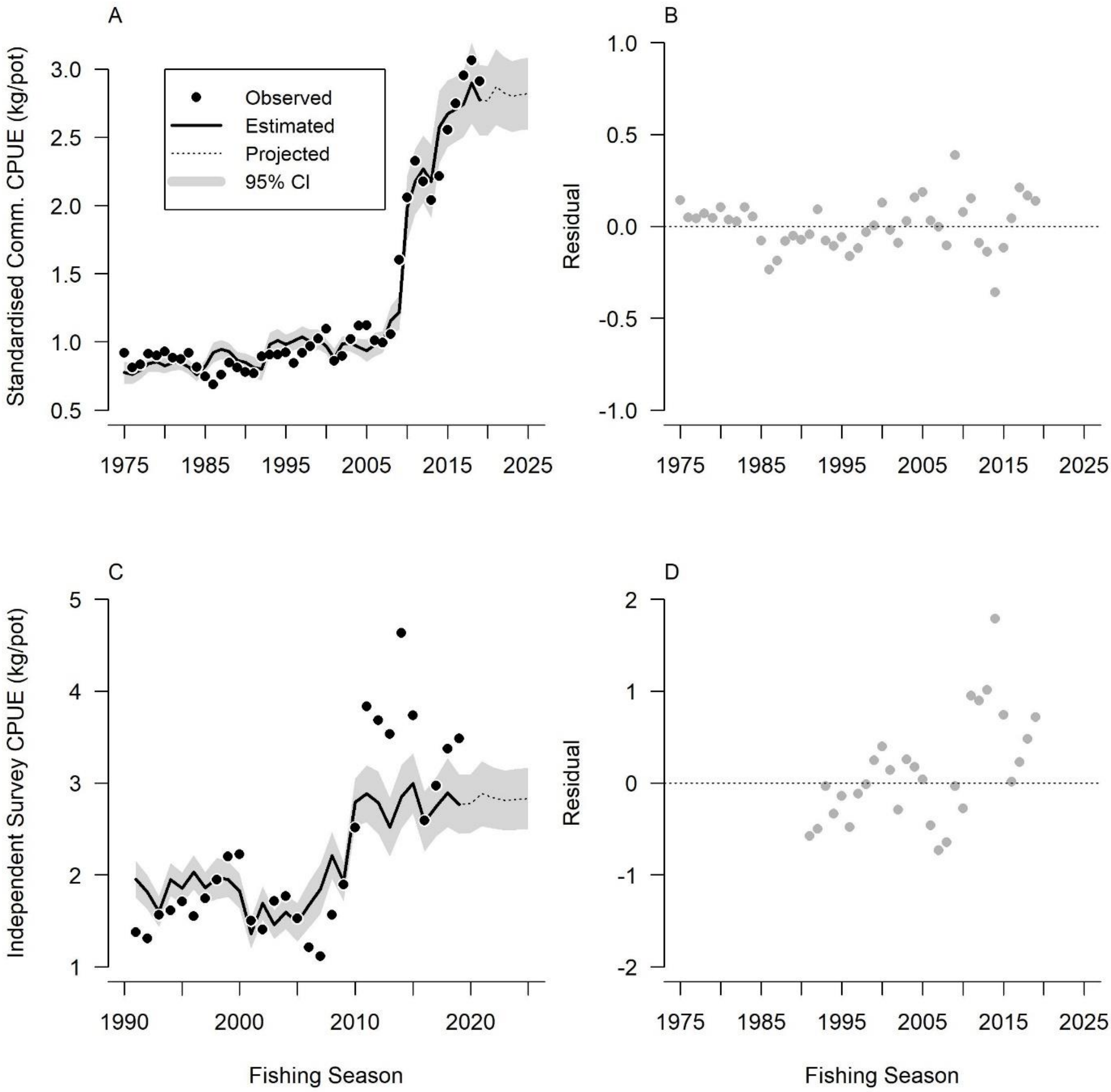

Fig. S1. Model fits to standardised commercial (A) and independent survey (C) catch rates, with respective residual plots between observed and predicted shown in B and D.

BDM Outputs

The BDM estimated MSY to be 11 621 t ± 269 t (1 SD), the initial virgin biomass to be 35 472 t ± 22157 t and efficiency creep to be 1.9% ± 1.1% pa. Biomass was estimated to have declined slowly from a virgin level to a low of about 15 000 t in the early 2000s (~40% of virgin) before increasing markedly until 2012, after which it levelled off at ~ 25 000 t (~ 70 % of virgin) (Fig. S2A). Exploitation rates have shown the opposite trend, increasing from ~ 35% in the 1960s to ~ 80% in the late 1990s and early 2000s, before declining rapidly to a low of ~ 25% in 2010, where they have remained subsequently (Fig. S2B).

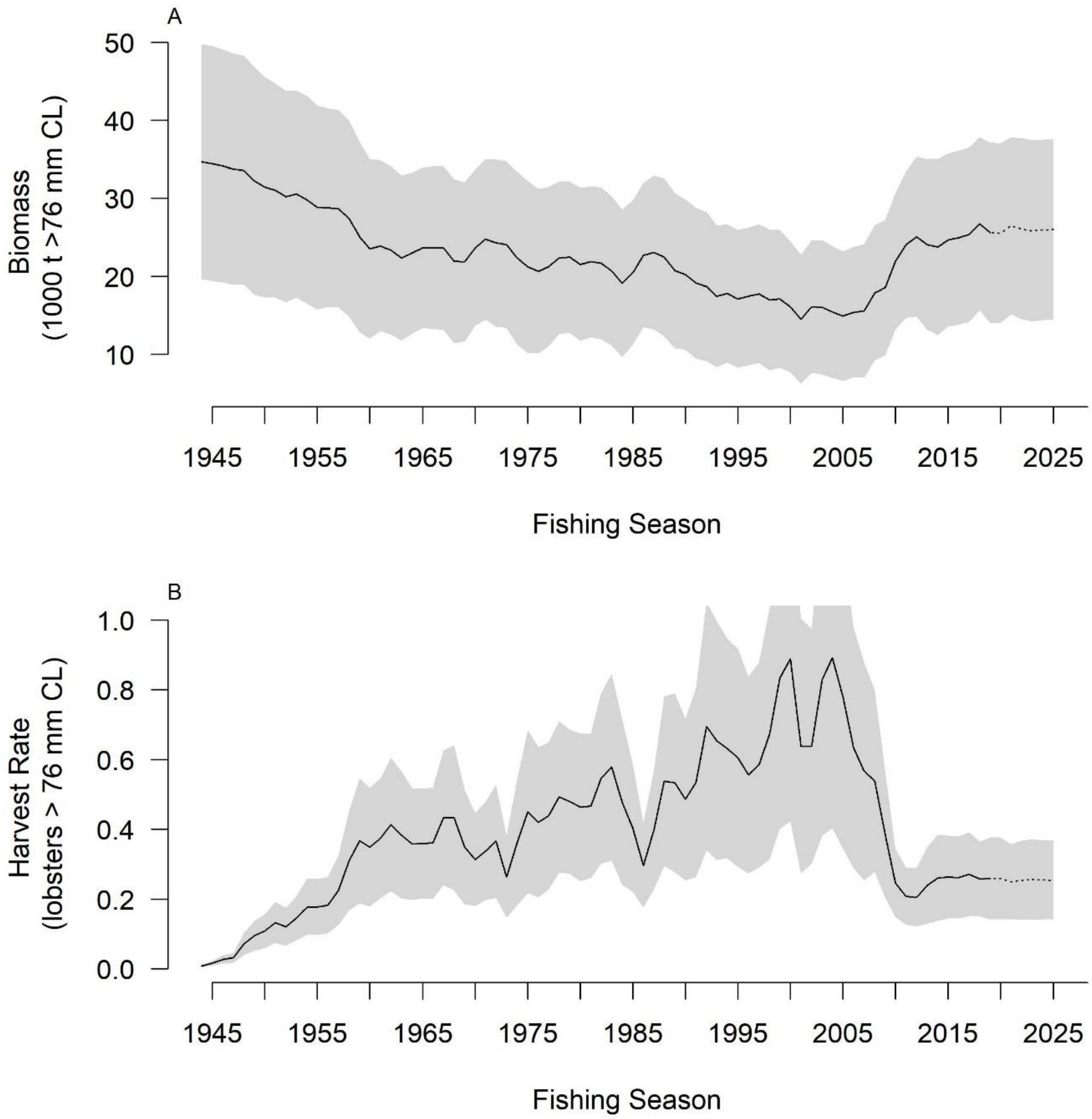

Fig. S2. Legal Biomass (A) and harvest rate (B) estimates from the BDM.

BDM References

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Fournier, D.A., Skaug, H.J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M.N., Nielsen, A., and Sibert, J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

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Methodology of Barrowman and Myers (1996)

This methodology breaks tag loss down into two separate components, initial tag shedding (ρ; instant loss due to poor technique or mortality) and chronic tag loss (ϕ), which is a constant rate of loss over time (*t*). The likelihood of tag (*T*) retention at a point in time ($R_T\left[t\right]$) is:

$$R_T\left[t\right] = \rho \, \mathrm{e}^{(-\phi t)}.$$

Since the two tagging trials (double tag [TT] and single tag/permanent mark [TP]) differed in the number of unique tags/marks (e.g. 1 and 2, respectively), the model needed to be designed with two separate components: one for fitting the TT dataset, where PTT and PT represent the probability of a lobster being recaptured with both or only one of the same tag, respectively. The other component was for the TP datasets, where PTP, PT and PP represent the probability of recapture with either both a tag and a pleopod marked, only a tag or only a pleopod marked, respectively. The equations used for the TT model were:

$$P_{TT}^{TT}[t] = R_T[t]^2,$$
$$P_T^{TT}[t] = 2R_T[t](1 - R_T[t]),$$

and for the TP model were:

$$P_{TP}^{TP}[t] = R_T[t]R_P[t],$$
$$P_T^{TP}[t] = R_T[t](1 - R_P[t]),$$
$$P_P^{TP}[t] = R_P[t](1 - R_T[t]).$$

For each model there were two (TT, $I = 2$) or three (TP, $I = 3$) states for recaptured lobsters, and for a recapture that occurs at time *t*, the probability that this occurs for observation *i* was;

$$P[t] = P_i[t] \Big/ \sum_{k=1}^{I} P_k[t],$$

and the negative log likelihood was; $\lambda = -\sum_{i=1}^{i} N_i \ln(P_i[t])$ where N_i is the number of lobsters returned in state *i*. The model was capable of fitting to either a single tag-loss experiment (e.g. TT or TP) or both simultaneously (both TT and TP) by combining the negative log-likelihoods from both components (e.g. $\lambda = \lambda_{TT} + \lambda_{TP}$).

Supplementary Table 1. Parameters and their assumed distributions used to initialise the Brownie Tag Recapture (BTR) and Individual Based Model (IBM).

Parameter	**Number**	**Model**	**Initial Value**	**Distribution**
Catchability q	12 month specific	BTR	1.0e-6	Log-normal
Catchability q	7 timestep specific	IBM	1.0e-6	Log-normal
M	1	BTR	0.0125	Uniform 0 - 1
Reporting Rate ς	1	IBM	0.2	Uniform 0 - 1
Migrate β	7 timestep specific	IBM	0.2	Uniform 0 - 1
Migrate α	7 area specific	IBM	70	Normal
Migrate σ	2 depth specific	IBM	10	Log-normal
Growth δ	8 area specific	IMB	2	Log-normal
Growth γ	8 area specific	IBM	70	Log-normal
Growth κ	8 area specific	IBM	3	Log-normal
Growth η	2 sex specific	IBM	0.2	Log-normal
Growth σ	1	IBM	0.2	Uniform 0 - 1
Tag loss ρ	1	IBM	0.8	Uniform 0 - 1
Tag loss ϕ	1	IBM	0.3	Uniform 0 - 1