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Analysis of paua (*Haliotis iris*) maturity and growth

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EXECUTIVE SUMMARY

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The analyses presented in this report investigate variability in paua growth and maturity within and among QMA, and evaluate the trade-offs between yield and spawning potential resulting from variation in these demographic characteristics and the MLS. All currently available paua growth and maturity data sets were included in these analyses, and while most of these data sets had been previously analysed this is the first attempt to synthesize the maturity and growth data and analyse all data sets simultaneously.

There is significant variability in the maturity-at-length relationship among the sites within each QMA, with the exception of the four sites sampled in PAU 5A. Although the maturity-at-length differences were significant, in many cases the magnitude of these differences was not large. For example, the range in length at 50% maturity was about 10 mm across the 13 sites in PAU 7.

The maturity analyses provide strong support for the hypothesis that maturation as a function of length is independent of sex. Also, shell length was not always the best predictor of the proportion mature, and for over half of the sites either shell width or shell height were better predictors of maturity.

Two models (Schnute model and inverse-logistic) were used to predict growth increments for the site-specific tag recapture data and both showed sensitivity to the models' formulation, in particular for sites where the range of tagged paua sizes was small. When the data were aggregated at the QMA level, this sensitivity disappeared.

Variability in predicted growth increments was large, both within and among QMA. At the site level, the predicted annual length increment for a 75 mm paua ranged from about 5 mm to 30 mm. At the QMA-level, the range was about 15 mm to 30 mm.

The parameters that define the variance of predicted growth increments are highly confounded and it was found that fixing or assuming commonality among some of them greatly improved model estimation. In particular, the parameter that allows for non-linearity in the variation around the mean growth curve was estimated more consistently when a single value, common to all data sets, was assumed. Estimation of this parameter had a strong effect on reducing the expansion of the variance of mean growth for larger predicted increments (smaller initial size), which had been suggested at the recent (2015) review of the paua stock assessment model.

To investigate local variation in population productivity and the trade-off between yield and reproductive potential associated with the MLS, maturity-at-length and growth parameters were linked for all sites where both types of data were available.

Yield per recruit and spawning per recruit analyses were conducted under the current MLS regime and for the current MLS plus and minus 10 mm. Given current MLS, instantaneous fishing mortality rates associated with $F_{40\%SPR}$ are highly variable, ranging from 0.12 for a D'Urville site to 1.0, the maximum rate evaluated, for a number of sites. Yields at $F_{40\%SPR}$ are only slightly reduced from the maximum, ranging from 81% to 100% of the maximum yield. For the Taranaki region of PAU 2, a 10 mm reduction of the current MLS of 85 mm would allow for some yield in the two locations (Cape Egmont and Opunake) that have no apparent yield at the current MLS.

For some of the sites, a 10 mm increase in the MLS results in higher maximum yield per recruit and yields at $F_{40\%SPR}$ (or only a slight reduction in yields). These are of course associated with higher fishing mortality rates. For some regions of the coast, local industry paua managers have instituted voluntary minimum harvest sizes that are greater than the government prescribed MLS. These have the potential to increase the reproductive of paua populations at some sites, but may also restrict fishing opportunities at others.

1. INTRODUCTION

This work addresses the objectives of the Ministry for Primary Industries (MPI) contract PAU2015-03. This contract was awarded to Trophia Ltd. and the work conducted by the author of this report. The research objectives of contract PAU2015-03 are:

1. To undertake a detailed analysis of all available paua length at maturity data to determine the level of variation between sampled populations.
2. To undertake a detailed analysis of all available paua growth (tag-recapture) data to determine the level of variation among sampled populations and to determine the duration between populations becoming mature and becoming available to the fisheries (attaining the MLS).

New Zealand paua are managed through a number of mechanisms including a minimum legal size (MLS) for commercial and recreational harvest. Setting an appropriate MLS is important to ensure paua are able to spawn and contribute to the future productivity of the populations prior to becoming vulnerable to fisheries. However, if the MLS is set too high slower growing paua may never attain the MLS, reducing utilisation opportunities for fishers. Setting an appropriate MLS requires evaluation of the trade-off of maintaining spawning potential and allowing for utilisation opportunities.

The current MLS for paua is 125 mm (shell length) throughout New Zealand, with the exception of the Taranaki region of PAU 2. The lower MLS for the Taranaki region (85 mm) is based on slower growth rates, smaller maximum size, and smaller size at maturity in this area (Naylor & Andrew 2000). In addition to the Taranaki region, there are other locations with slower-growing populations where the majority of individuals do not attain the MLS, however the distribution of these areas is not well known. Slower growing populations have been identified at Banks Peninsula (Naylor & Andrew 2000) and D'Urville Islands (McShane & Naylor 1995, Naylor & Andrew 2004), and recently fishers' local knowledge has been used to map coastal areas believed to contain stunted populations (Naylor & Fu 2016).

Over recent years MPI tendered a number of projects to document all maturation and growth (tag-recapture) studies for New Zealand paua, and to collate the available data into a database (Naylor & Fu 2016). Additional maturity samples were also collected from a number of Quota Management Areas (QMA) to extend the range of available samples so that variation in size-at-maturity within and between QMAs could be assessed (Naylor et al. 2017a; Naylor et al. 2017b). The growth and maturity data described in Naylor & Fu (2016) and the more recent maturity data reported in Naylor et al. (2017a, 2017b) were made available for the analyses described here. While most of these data have been previously analysed and reported on, the focus of this report is to investigate variability in maturation and growth among sites and determine the effect of that variability on spawning potential.

The work described in this report was presented to the Shellfish Working Group (SFWG) as it progressed, and recommendations from that group were incorporated in the analysis.

2. MATURITY ANALYSIS

2.1 Data

The paua maturity data used in these analyses include the samples described by Naylor & Fu (2016) and the more recent samples collected in 2015 and 2016 (Naylor et al. 2017a, 2017b) (see Table 1).

Each maturity sample generally comprises individuals measured at a single site over a short time interval however a few samples contain individuals measured over a wider temporal or geographical range (Table 1). At the extreme, the Chatham Islands (PAU 4) sample comprises paua sampled from 7 Statistical Areas which are combined to ensure an adequate sample size. For some sites, samples were collected at two distinct times and these are treated as distinct samples to allow evaluation of temporal differences in maturation rates (e.g. Opunake sampled in 1998 and 2015, Table 1).

All maturity samples include measurements of individual paua length (basal length) and assessed maturity (immature or mature), and most samples also have sex information. Some samples have additional information with individual paua height and paua width measured.

Paua sex and maturity are assessed through visual examination of the gonads. The classification system includes the categories: immature (no discernible gametes); just male (JM) and just female (JF) where gametes are visible and sexes distinguishable but the digestive gland is visible through the gonad; and mature male and mature female where the gametes surround the digestive gland. Paua classified as JM and JF have few gametes, contributing little to the reproductive output of the population and these categories have generally not been included with mature paua when assessing maturity-at-length (e.g. Naylor et al. 2016, Naylor & Andrew 2000b). Where detailed classification data are available, fish classified JM and JF are considered immature for these analyses. However detailed classification information is not available for all samples, with some only identifying individuals as immature or mature. McShane et al. (1996) report that they included fish classified as JM and JF (which they call "intermediate") with mature paua in their maturity-at-length analyses, so it is possible that historically there has been some inconsistency in the determination of maturity.

2.2 Analytical methods

A logistic model is used to describe the relationship between the probability of an individual being mature and length:

$$P_l = \left(1 + \exp\left(\frac{-\ln(19)(L_i - l_{50})}{l_\delta}\right)\right)^{-1} \qquad \text{Eqn. 1}$$

where L_i is the length of paua *i*, P_l is the probability that a paua of length L_i is mature, and the parameters l_{50} and l_δ are the length with 50% probability of being mature and the difference between l_{50} and the lengths with a 5% and 95% probability of being mature. A binomial probability distribution is assumed in fitting the maturity model, so the negative log-likelihood (ignoring the constant component) is given by:

$$-\ln(\mathbf{L}) = \sum_l -m_l \ln(P_l) - (n_l - m_l)\ln(1 - P_l)$$

where m_l is the number of mature paua of length *l* and n_l is the number of paua of length *l* in the sample. Note that for simplicity of presentation, the above equations do not include notation to identify individual samples (or sex, for sex-specific models), however unless explicitly stated otherwise the maturity model is fitted and parameters estimated for each sample.

The Akaike Information Criterion with correction for finite sample size (AICc) is used to select among alternative models used to describe the data. This statistic can be used to test whether more complex models are superior to simpler ones. The AICc for a model is given by:

$$AICc = 2(-\ln(\mathbf{L}) + k) + \frac{2k(k+1)}{N - k - 1}$$

where *k* is the number of parameters for the model and *N* is the total sample size $\left(N = \sum_l n_l\right)$. The model with the lowest AICc is the preferred model.

2.3 Sex-specific maturation

Sex information was available for most of the maturity samples, allowing an analysis of sex-specific maturation rates. For the 50 maturity samples, 46 had sex coded. Only the samples collected in the Taranaki region in 1998 did not identify sex. Naylor & Andrew (2000) report that the Taranaki samples had been sexed, but this information may have been lost in the archiving process (Reyn Naylor, NIWA, pers. comm.).

For each maturity sample, the maturity-at-length model was fitted separately to the data for males, the data for females, and the combined male and female data. Individuals where sex was coded as immature (i.e. unable to sex) were not included in these analyses so that the statistical comparisons of the sex-specific and sex-aggregated models was based on the same data sets. For each sample, AICc was used to select which model best represented that data. This statistic tests whether the more complex model (i.e. sex-specific maturation, with 2 additional parameters) is superior to a simpler model (sex-aggregated maturation).

For 39 of the 46 data sets, the AICc criterion selected the sex-aggregated maturation model over the sex-specific model (Table 2). For the remaining 7 data sets, there was no consistency in the sex that had higher proportions mature at a given length. Males and females each had higher l_{50}'s for 3 of the data sets and for one of the data sets (Waterfall) male and female l_{50}'s were similar but the l_{δ}'s differed (Table 2).

Considering basic biological principles, if length-specific maturation rates are different between the sexes one would expect the direction of the differences to be consistent across areas. Based on results presented here, AICc selecting the sex-aggregated model for most sites and no consistent differences for those sites where the sex-specific model was selected, sex-aggregated maturity models appear to provide an adequate description of the maturation process.

2.4 Replicate samples at site

For seven of the locations where maturity data were available, samples had been collected at two distinct times (Table 1). The maturity-at-length model was fitted to these replicate samples to ascertain if there are temporal differences in maturation rates. This analysis includes: 4 locations in the Taranaki region of PAU 2; Catlins West in PAU 5D; and Perano and Rununder in PAU 7. Based on the reported latitudes and longitudes where samples were collected, the distances between the replicate data sets ranged from less than 0.1 km (New Plymouth, Opunake, Puketapu) to about 18 km (Rununder, Table 3).

AICc was calculated for models fitted separately to each of the data sets and for models fitted to the replicate data sets combined. For 6 of the 7 sites, AICc selected the model fitted to the disaggregated data indicating significant differences in the replicate samples (Table 3). In all 6 cases, the length at 50% maturity was higher for the later (2013, 2015, 2016) samples than for the earlier (1996, 1998, 2001, 2005) samples. Differences in the length at 50% maturity ranged from 4.2 mm (Opunake) to 19.1 mm (New Plymouth). The earlier and later samples from Rununder were the only ones where AICc selected the combined sample as providing a more parsimonious fit to the maturity data.

Potential reasons for the differences in size-specific maturation rates for the replicate samples are unclear, but may be associated with differences in location or seasonal differences in sampling rather than actual temporal changes in length specific maturation.

2.5 Maturity by site and QMA

The maturity data provide strong support for the hypothesis that there are no sex-specific differences in paua maturation rates, so all further models investigated use sex aggregated data. These models can then include the data where sex is coded as immature (unable to sex) which extends the length range to include more small paua in the samples. This should provide better estimates of the maturity ogive. Additionally, the two data sets for Rununder were combined, as AICc indicated that the combined model was superior to the temporally separated data. The maturity-at-length model (Equation 1) was fitted to each individual sample and to the data aggregated at the QMA level.

Within some of the QMAs, in particular PAU 2, there is considerable variation in the maturation ogives among sites (Table 4, Figure 1). The PAU 2 samples tend to separate into 3 groups: the early

Taranaki data, the later Taranaki data, and the remainder of PAU 2. Paua in the Taranaki region have stunted growth (Naylor et al. 2016) and resulting lower length at 50% maturity than other regions. The Breaker Bay sample has l_{50} more similar to the later Taranaki samples than those for other areas of PAU 2 sites. The Waituna site in PAU 5B has much lower l_{50} than the remainder of PAU 5B sites, but this may be the result of the small sample size (Table 4) rather than a real difference.

Maturity models were also fit to the aggregate data for each QMA. The exception was PAU 2, where clear differences between the Taranaki region and other areas of PAU 2 and differences between the early and later Taranaki samples suggested that those distinctions are likely to represent real differences in size-specific maturation (Figure 2). For both PAU 4 and PAU 6 only one sample was available, so aggregate models were not fitted for those QMAs.

With the exception of PAU 5A, AICc selects the site-specific maturation models over the QMA-level models (Table 5). The differences in the AICc values are large, providing strong support for differences in maturation-at-length among sites within the QMA. For PAU 5A, the range in l_{50}'s among the four sites sampled is relatively small (91.3 to 96.3 mm).

2.6 Maturity relationships with alternative shell morphometrics

Shell morphometric measurements, in addition to length, were made for some of the maturity samples. These measurements included shell width and shell height. It has been suggested that the shell height-shell length ratio may be indicative of stunted populations (Saunders & Mayfield 2008) with a larger shell height relative to shell length in stunted populations. Also it is thought that as paua mature the shell height increases to accommodate the gonad, so mature paua may have a greater shell height for a given length than immature paua.

To investigate whether shell height may be useful for predicting paua maturity a non-linear relationship between shell height and shell length was fitted to all available observations to account for the observed increase in shell height with shell length. The fitted relationship was:

$$H_i = aL_i^{\,b} + \varepsilon_i \qquad \text{where } \varepsilon_i \sim N\left[0,\sigma^2\right] \qquad \text{Eqn. 2}$$

where H_i and L_i are the height and length of paua *i*, and *a* and *b* are estimated parameters (*a*= 0.09871, *b*=1.23007, Figure 3). Standardised residuals were calculated as, ε_i/σ and the mean standardised residual for mature paua, immature paua, and site are presented in Table 6.

If shell height increases as paua mature, the mean residual for mature paua should be larger than that for immature paua. For 17 of the 22 sites with shell height data, the mean residual for mature paua was greater than that for immature paua, suggesting that shell height does increase as paua mature (Table 6). In general, the differences were not large, averaging about 0.2 across all sites.

The site-specific standardised residuals tended to be larger than those between immature and mature paua, indicating considerable spatial variation in the shell length-height relationship (Table 6). No detailed morphometric samples were available from sites in the Taranaki region of PAU 2 which is known to have stunted paua populations. However there are samples from Banks Peninsula sites, an area that also has populations that do not grow to attain the MLS which suggests stunted growth (Naylor & Andrew 2000). The two samples from Banks Peninsula (Inside Akaroa and Scenery Nook) have the two largest site-specific mean residuals providing some support to the hypothesis that the shell height shell length relationship can be used to determine stunted populations.

To determine if the addition of shell height data increases the ability to predict maturity or if alternative morphometric measures are better than shell length in predicting maturity, a series of alternative maturity models were fitted to the data. These were:

$$P_l = \left(1 + \exp\left(\frac{-\ln(19)\left(L_i - l_{50}^d + \lambda\varepsilon_i\right)}{l_\delta^d}\right)\right)^{-1}$$

$$P_l = \left(1 + \exp\left(\frac{-\ln(19)\left(R_i - r_{50}\right)}{r_\delta}\right)\right)^{-1}$$

$$P_l = \left(1 + \exp\left(\frac{-\ln(19)\left(H_i - h_{50}\right)}{h_\delta}\right)\right)^{-1}$$

$$P_l = \left(1 + \exp\left(\frac{-\ln(19)\left(W_i - w_{50}\right)}{w_\delta}\right)\right)^{-1}$$

where L_i, H_i, W_i and R_i are the length, height, width and height-length ratio of paua *i*, respectively, ε_i is defined in equation 2, and P_l is the probability that paua *i* is mature. The parameters $l_{50}, h_{50}, w_{50},$ and r_{50} are the sizes with 50% probability of being mature, for their respective relationships. The parameters $l_\delta^d, h_\delta, w_\delta,$ and r_δ are the differences between the size at 50% maturity and the sizes with 5% and 95% probability of being mature. Note that the definitions of l_{50}^d and l_δ^d are for the case where ε_i is 0. The binomial probability distribution described in Section 2.2 is used in fitting the models.

AICc values for the base model (Eqn. 1, fitted only to individuals with the additional shell height and shell width measurements) and the difference between the base model AICc and alternative models AICc are given in Table 7. For the 23 samples that had shell height and width measurements, AICc selected the base model (maturation-shell length) in 10 cases, the maturation-shell height model in 6 cases and the maturation-shell width model in 7 cases (Table 7). There were no obvious regional patterns to which model provided the best fit to the data.

3. GROWTH

In addition to investigating site-specific variation in growth, the analyses presented here explore two of the recommendations from the 2015 paua stock assessment review, that is: growth curves should be fitted only to data from areas that dominate the catch; and to estimate a parameter that allows for non-linearity in the variation around the mean growth curve to see if this can control the expansion of the variation about the mean growth as initial length decreases (Butterworth et al. 2015).

3.1 Data

All available paua tag-recapture data were compiled and made accessible electronically under project PAU 2013-01. Data were available for 43 sites (Naylor & Fu, 2016), but 3 sites had fewer than 10 tag recaptures and those were excluded from these analyses. Also, some annualized growth increments were unrealistically large, and with agreement from the SFWG all individuals with growth increments of 40 mm/year or greater were excluded from these analyses (see discussion in Section 3.3).

The final data set comprised 2794 animals from 40 sites. All QMA with significant paua fisheries were represented, with the number of sites per QMA ranging from 2 to 11 (Table 8). In general, tagging occurred over a very short period (days), recaptures also occurred over a very limited period, and times-at-liberty were close to 1 year (Table 8). There were a few exceptions to this, for example

Seal Point in PAU 5D where tagging occurred in 1976, 1983, and 1996, and days-at-liberty ranged from 285 to 1259.

3.2 Models of growth increments

In recent years, three options for parameterizing growth increments as a function of initial length have been explored in the length-based paua stock assessment models (e.g. Fu 2016, Fu 2015, Fu 2014). These are: the von Bertalanffy model, termed the linear model in the paua assessment documentation; the exponential model, first described by Davies et al. (2001); and the inverse-logistic model (Haddon et al. 2008). The exponential and inverse-logistic models describe growth increments, but unlike the von Bertalanffy model, do not transform to true growth models because they do not account for deceleration in the growth rate as elapsed time (and size) increases. That is, the predicted length increment for an individual at liberty for two years would be twice that of an individual at liberty for one year, given the same initial size. In contrast, the von Bertalanffy and other growth models predict increments that account for decreased rates of growth as length increases.

Although not true growth models, the exponential and inverse-logistic growth increment models may provide better fits to tag-recapture data than other growth models because the shapes they encompass may better fit observed growth increments. In particular, when times-at-liberty are fairly consistent among all tag-recaptures in a data set the assumption that the growth rate depends only on initial size may not be a detriment in model fitting. If these growth increment models are incorporated into length-based stock assessment models to inform growth transition matrices, the critical consideration is that the time-at-liberty of the tag-recaptures is similar to the growth time-step in the stock assessment model. For paua, most of the tag-recaptures are from individuals at liberty for about one year which is consistent with the stock assessment time-step of one year, so the exponential and inverse-logistic growth increment models should perform adequately to inform growth.

The two models investigated in these analyses are the Schnute growth model (Schnute 1981) and the inverse-logistic growth increment model (Haddon et al. 2008). The Schnute model is a general four parameter growth model that incorporates the von Bertalanffy model as a special case. When formulated in terms of growth increments, the Schnute model has three estimable parameters, the same number as the inverse-logistic model. While the Schnute model does not contain the exponential growth increment model as a special case, it is capable of taking similar shapes to the exponential model.

The Schnute growth model, converted to growth increments for fitting tag-recapture data is given by (Baker et al. 1991, Quinn & Deriso, 1999):

$$\Delta L_i = -L_i + \left[L_i^{\gamma}\, e^{-\kappa t_i} + l_{\infty}^{\gamma}\left(1 - e^{-\kappa t_i}\right)\right]^{1/\gamma} + \varepsilon_i \qquad \varepsilon_i \sim N\left[0, \left(\sigma_i^t\right)^2\right] \qquad \text{Eqn. 3}$$

where ΔL_i is the expected increment of fish *i* with initial length L_i, t_i is the interval from the time of tagging to the time of recapture for fish *i* , and $l_{\infty}, \kappa,$ and γ are parameters of the growth curve. l_{∞} is the asymptotic mean length and γ is a shape parameter. When γ is equal to one, the Schnute growth model is equivalent to the von Bertalanffy growth model and κ is the Brody growth parameter. The variance of the expected growth increment, $\left(\sigma_i^t\right)^2$, is described in Section 3.3.

Francis (1995) recommends a re-parameterization of the Schnute growth increment model, using two parameters that represent the predicted growth increment at two specified lengths. For this form of the Schnute model, *galpha* $\left(g_{\alpha}\right)$ and *gbeta* $\left(g_{\beta}\right)$ are the expected growth increments at specified lengths *lalpha* $\left(l_{\alpha}\right)$ and *lbe*ta $\left(l_{\beta}\right)$. Typically *lalpha* and *lbeta* are selected to fall within the range of the data set being fitted as this can result in better performance in parameter estimation. For the *Francis* parameterization, κ and l_{∞} of equation 3 are replaced with:

$$\kappa = -\ln\left(1 - \frac{a' - b'}{l_\beta^{\gamma} - l_\alpha^{\gamma}}\right) \qquad l_\infty = \frac{l_\beta^{\gamma} - l_\alpha^{\gamma}\left(b'/a'\right)}{1 - \left(b'/a'\right)}$$

where $a' = \left(l_\alpha + g_\alpha\right)^{\gamma} - l_\alpha^{\gamma}$ and $b' = \left(l_\beta + g_\beta\right)^{\gamma} - l_\beta^{\gamma}$.

For comparison, the Schnute growth model was also parameterized in terms of the more common growth parameters, the Brody growth coefficient (κ) and the asymptotic maximum length (l_∞) (Equation 3). This formulation was first proposed by Baker et al. (1991) and is named the *Baker* parameterization here.

The Schnute growth model allows for negative growth increments, however predicted negative increments were truncated to 0.

The inverse-logistic growth increment model is given by (Haddon et al. 2008):

$$\Delta L_i = \frac{t_i\, g_m}{1 + \exp\left(\ln(19)\left(\frac{(L_i - f_{50})}{(f_\delta)}\right)\right)} + \varepsilon_i \qquad \text{where } \varepsilon_i \sim N\left[0, \left(\sigma_i^t\right)^2\right] \qquad \text{Eqn. 4}$$

where g_m is the asymptotic maximum growth increment in a unit time interval (generally defined as a year), f_{50} is the length with 50% of the maximum growth increment and f_δ is the difference between f_{50} and the lengths with 5% and 95% of the maximum growth increment. $\Delta L_i, L_i, t_i,$ and $\left(\sigma_i^t\right)^2$ are as defined for equation 3. For comparison with the *Baker* form of the Schnute model, the inverse-logistic model was parameterized in terms of *galpha* and *gbeta*, the predicted growth increments at lengths *lalpha* and *lbeta*. For this parameterization g_α and g_β are estimated in model fitting and f_δ and f_{50} are replaced with:

$$f_\delta = \frac{\ln(19)\left(l_\beta - l_\alpha\right)}{\ln\left(g_m/g_\beta - 1\right) - \ln\left(g_m/g_\alpha - 1\right)} \qquad f_{50} = l_\alpha - \frac{f_\delta \ln\left(g_m/g_\alpha - 1\right)}{\ln(19)}.$$

For both the *Baker* form of the Schnute model and inverse-logistic growth increment models *lbeta* is by definition greater than *lalpha* so for all plausible model fits *gbeta* is less than or equal to *galpha*. To ensure *gbeta* is never greater than *galpha* it was parameterized in terms of *galpha* and a parameter, *gdiff* (g_δ) :

$$g_\beta = g_d\, g_\alpha ,$$

and *gdiff* constrained to be between 0 and 1.

Similarly, to ensure the asymptotic maximum growth increment of the inverse-logistic model is always greater than *galpha* it was parameterized relative to *galpha* :

$$g_m = (1 + \omega)\, g_\alpha$$

and ω constrained to be positive. Note that the parameter that scales the maximum growth increment relative to *galpha* (ω) influences the shape (spread) of the inverse-logistic model and is named the inverse-logistic shape parameter.

The values of fixed parameters and bounds for estimated parameters are shown in Table 9 for all variants of the growth models fitted to the tag-recapture data. In some cases there are natural values for parameter bounds (i.e. positive values for *gshape*, 0 to 1 for *gdiff*). For other parameters the bounds were fairly broad as they were not intended to be restrictive, although where the data are relatively uninformative parameter estimates sometimes went to a bound.

A number of shapes that the inverse-logistic and Schnute growth models can accommodate are shown in Figure 4 for fixed values of *galpha*, *gbeta*, *lalpha*, and *lbeta* and a range of shape parameters. An example of the exponential growth increment model is also shown to demonstrate that the Schnute model can encompass many of the forms available to the exponential model.

3.3 Parameterizing variance of growth increments

The observed variability in tag-recapture growth increments results from individual growth variability as well as measurement and process error. When fitting tag-recapture data in length-based assessment models to inform growth transition matrices, it is important to distinguish among the components of variability in the observations so that simulated growth does not include measurement error effects. However, the effect of the variance components are often confounded so that it can be problematic to simultaneously estimate both process and measurement error parameters.

Parameterization of the variance of tag-recapture growth increments in the paua stock assessment model follows that used in the rock lobster stock assessment model (Haist et al. 2009), which is based on the approach suggested by Francis (1988). The observed variability in growth increments is parameterized as a function of process variability and observation error as follows:

$$\sigma_i^t = \sqrt{\left(\sigma_i^p\right)^2 + \left(\sigma^o\right)^2}$$

where σ_i^t and σ_i^p are the standard deviations of the total and process error for fish *i* respectively, and σ^o is the standard deviation of the observation error. The process error is further parameterized to be a constant proportion, *GCV* (ϕ), of the expected increment, truncated to a minimum value, *Gmin* $(\sigma^{\min})$ so that the variance does not tend to 0 as the predicted increment tends to 0. The smooth differentiable function for the standard deviation of predicted growth increment ΔL_i is:

$$\sigma_i^p = \left(\left(\phi\Delta L_i - \sigma^{\min}\right)\left(\frac{1}{\pi}\tan^{-1}\left(10^6\left(\phi\Delta L_i - \sigma^{\min}\right) + 0.5\right)\right)\right) + \sigma^{\min} . \qquad \text{Eqn. 4}$$

The paua stock-assessment model also allows a more complex form of the process variability where the variance of predicted increments are related to the predicted increments using a power function parameter *Gpow* (ψ):

$$\sigma_i^p = \left(\left(\phi\left(\Delta L_i\right)^{\psi} - \sigma^{\min}\right)\left(\frac{1}{\pi}\tan^{-1}\left(10^6\left(\phi\left(\Delta L_i\right)^{\psi} - \sigma^{\min}\right) + 0.5\right)\right)\right) + \sigma^{\min} . \qquad \text{Eqn. 5}$$

As described, the full version of the model describing the variance of growth increments is over parameterized with four separate variance components (*GCV, Gpow, Gmin,* and *Gobs*). For recent paua stock assessment analyses, three of the variance components (*Gpow, Gmin,* and *Gobs*) are generally fixed (Fu 2013, Fu 2014, Fu 2015) and *GCV* is estimated.

A number of initial growth model fits to the paua tag-recapture data investigated the parameterization of the variance of the predicted growth increments. As in the paua stock assessment some of the variance parameters were fixed, or they were estimated as a single parameter common among all tagging data sets. To allow estimation of parameters assumed to be the same for all sites the growth models were fit to all data sets simultaneously.

In addition to the assumption of a normal distribution for the length increment residuals (i.e. the ε_i of equations 3 and 4), some robust likelihood approaches were also examined. The robust approaches assumed mixture distributions whereby a normal distribution was contaminated with a small proportion of a Cauchy distribution. This mixture form for the robust likelihoods would be expected if the data sets contained a small amount of contamination from erroneous measurements which would result in a small proportion of extreme outliers. Francis (1988) proposed the mixture likelihood approach for dealing with outliers, but proposed a normal distribution contaminated with a small proportion of observations from a uniform distribution.

Initial explorations of the variance parameterization resulted in the following decisions: to remove some of the extreme observations (outliers) from the data set; to assume that observation error was negligible; and to assume that the ε_i were normally distributed. These decisions were based on a number of considerations.

The tag-recapture data sets generally suggest a fairly consistent growth pattern among individuals within a locality (Figure 5, Figure 6), although there are a few sites where it appears likely that a few observations were erroneously recorded (D'Urville site 1-B, D'Urville site 3-B, Figure 6). For the paua data sets, both the initial tagging and subsequent tag recaptures were done by trained scientists and technicians, and as a result the observation error appears to be minimal. It therefore seems reasonable to assume negligible observation error and remove extreme outliers from the data sets. The SFWG agreed that all observations with annualized length increments of 40 mm or greater be removed from the data set, as these were most likely to represent data recording errors (Figure 5, Figure 6).

A secondary reason for the simplifying assumptions of no observation error and normal distributions for growth increment residuals was that alternative, more complex, assumptions did not resolve the fundamental issues in fitting the growth increment data. That is, there was a strong tendency for the predicted variance of growth increments to be much larger than the observed variance for the larger predicted increments. This result suggests that estimation of the *Gpow* parameter may be important to obtain good fits to the observations. However, estimation of this additional parameter further aggravates the confounding of the growth variance parameters, which is somewhat balanced by fixing the observation variance to zero.

A simplified form of the variance parameterization used in the paua stock assessment model was developed. The primary change was that the minimum variance parameter (*Gmin*) was replaced with a constant, *Gconst* $\left(\sigma^{const}\right)$. With that change, the component of equation 5 that produces a smooth transition to *Gmin* as the predicted increment approaches 0 is not required. The alternative formulation is:

$$\sigma_i^p = \phi\left(\Delta L_i\right)^{\psi} + \sigma^{const} . \qquad \text{Eqn. 6}$$

Results from the two approaches (i.e. equation 5 and equation 6) should be quite similar as they become equivalent as *Gmin* and *Gconst* approach zero.

Even with the observation error fixed at 0, the three remaining parameters defining the variance of predicted growth increments remain highly confounded which can result in estimation problems. The approach adopted here to resolve this issue was to assume that *Gpow* and *Gconst* are the same at all sites, and estimate only the *GCV* parameters for each site. For comparison, the version of the variance parameterization used in recent paua stock assessments, was also fitted to the data. That approach fixes the parameters *Gobs*, *Gmin*, and *Gpow* at 0.25 mm, 1 mm, and 1, respectively. The alternative approach estimates two more parameters (*Gpow* and *Gconst*) than the stock assessment approach.

With the assumption of a normal distribution for the growth increment residuals, the negative log-likelihood for each sample (ignoring constants) is given by:

$$-\ln(\mathbf{L}) = \sum_i \left(\ln(\sigma_i^t) + 0.5\left(\frac{(L_{2,i} - L_i) - \Delta L_i}{\sigma_i^t} \right)^2 \right) \qquad \text{Eqn. 7}$$

where $L_{2.i}$ is the length at recapture for fish *i*. Note that for simplicity of presentation the negative log-likelihood does not include notation to denote the individual samples. However, the models are fitted simultaneously to data for all samples so that the common parameters, *Gconst* and *Gpow*, can be estimated.

The inverse-logistic growth model was fitted to the data for each site using both the stock assessment and the alternative form for parameterizing the variance of predicted length increments. Model fits for both variance parameterizations are shown in Figures 7 and 8.

In all cases the alternative approach fits the data as well or better than the stock assessment approach. The stock assessment variance approach consistently predicts larger variances for the larger increments predicted for fish at smaller initial sizes, although at some sites the difference between the two approaches is minimal (e.g. Egmont, Cape Campbell, Sandy Point, Figures 7 and 8). Where there are observations of paua tagged at smaller initial sizes, the distribution of observed growth increments are generally more consistent with the alternative variance parameterization (e.g. Ocean Beach, New Plymouth, Breaker Bay, Figures 7 and 8). For paua tagged at larger initial sizes where predicted growth increments are small, the two approaches generally result in similar variance intervals.

The primary reason that the alternative variance parameterization results in fits that are more consistent with the observed variability in length increments is that the *Gpow* parameter is estimated rather than fixed at 1. *Gpow* is estimated to be less than 1 so the variance of the predicted growth increment does not become too large as the predicted increment increases. For all further fits of growth increment models the alternative form of the variance parameterization is used.

3.4 Schnute versus inverse-logistic growth increment models

The inverse-logistic and the two forms of the Schnute growth model described in section 3.2 were fitted to each of the tag-recapture data sets using the alternative form for the variance of predicted length increments described in section 3.3. Fits were made simultaneously for all data sets so that only one *Gconst* and one *Gpow* variance parameter, assumed common to all data sets, were estimated. AICc, as described in Section 2.2, was the basis for selecting the preferred model for predicting growth increments.

Model parameter estimates and AICc values for the three model fits are given in Table 10. Predicted annual length increments for the inverse-logistic and *Baker* form of the Schnute growth model are shown in Figure 9 and Figure 10.

The AICc criterion selected the inverse-logistic model as the preferred growth increment model for 22 of the 40 sites (Table 10). For the remaining 18 sites, the *Bake*r parameterization of the Schnute model provided better fits in 11 cases and the *Francis* parameterization fit better in 7 cases. The differences in likelihood values for the two Schnute model parameterizations tend to be small, however in 6 cases they differed by more than a full likelihood unit. In some cases this may have been the result of a parameter at its bound (e.g. Mataikona, Inside Pigeon Bay), but that was not so for all cases with large differences in the likelihoods. Rather, it appears to show the general sensitivity of fitting the growth increment models – changes to initial parameter values, phases for estimating parameters, and different *lapha* and *lbeta* values all resulted in somewhat different model fits.

The three growth increment models resulted in somewhat different values for the parameters associated with the variance of growth increments (see table below). The inverse-logistic had the highest value for the average *GCV*, but this was compensated with the lowest values for the *Gconst* and *Gpow* parameters. The *Francis* parameterization of the Schnute growth model had the lowest *GCV* but also the highest values for *Gconst* and *Gpow*. These results indicate that the three variance parameters are highly conflated.

Values of the parameters defining the variance of growth increments for the inverse-logistic and Schnute growth models fitted to site-specific tag-recapture data:

Model	Mean *GCV*	*Gconst*	*Gpow*
Inverse-logistic	1.36	0.312	0.349
Schnute - *Francis*	0.88	0.970	0.433
Schnute- *Baker*	1.17	0.687	0.362

The predicted length increments for the inverse-logistic and Schnute growth models are generally quite similar over the range where there are data, but the Schnute model tends to predict higher increments at smaller sizes when there are no data (e.g. Mataikona, Wharekauri, Boat Harbour, Figure 9, Figure 10). Where there are observations over a broad range of initial sizes, predicted increments from the two models are generally similar (e.g. Ocean Beach, D'Urville site 1-B, Figure 10).

The variability in growth increments among the sampled sites is large, both within and among the QMA. The *galpha* parameter, the predicted annual length increment for a 75 mm paua (40 mm for the Taranaki region), ranges from approximately 5 mm (Inside Pigeon Bay, Table 10) to greater than 30 mm (Landing Bay, Big Bay and Glasgow West, Table 10). For PAU 7, the QMA with the most sampled sites (11), *galpha* ranges from approximately 10 mm to 30 mm (Table 10).

3.5 QMA-level growth

Paua stock assessments are currently conducted at the QMA level, so growth parameters estimated from tag-recapture data need to reflect the mean and variance of growth across the QMA, or at least the areas of the QMA that are regularly fished. Within each QMA there appears to be considerable spatial variability in paua growth. The available paua tag-recapture data were collected through a number of projects with differing objectives (Naylor & Fu, 2016), so these samples may not appropriately represent growth through the areas of the QMA that are fished regularly. The 2015 paua stock assessment review recommended that tag-recapture data be weighted by the amount of catch associated with each sampling site so that the resultant growth parameters would better reflect paua growth of the fished populations (Butterworth et al. 2015).

The inverse-logistic and Schnute growth models were fitted to all tag-recapture data within each QMA, weighting each sample by either the number of fish in the sample or weighting each sample by the relative amount of catch taken in its Statistical Area. The catch-weighting for each tag-recapture in Statistical Area *j* $\left(w_j\right)$ was calculated as:

$$w_j = \frac{C_j}{\sum_j C_j} \frac{\sum_j n_j}{n_j}$$

where C_j is the average catch in Statistical Area *j* (based on 2001 – 2013 PCELR catch data) and n_j is the number of tag-recapture observations in the Statistical Area. Note that the catch summation is only over Statistical Areas which have associated tag recapture data and the catch is set to 1 for Statistical Areas with no reported catch. The weights, average catches, and number of tag-recapture observations for each Statistical Area are given in Table **11**. The negative log-likelihood for the growth increment model fits to the tag-recapture data (ignoring constants) for each QMA is then:

$$-\ln\left(\mathbf{L}\right) = \sum_{k=1}^{n_k} w_j \sum_i \left(\ln\left(\sigma_i^t\right) + 0.5\left(\frac{\left(L_{2,i} - L_i\right) - \Delta L_i}{\sigma_i^t} \right)^2 \right)$$

where n_k is the number of tag-recapture samples in the QMA, *j* is the Statistical Area where the *k*th sample was taken, and w_j is the catch-weighting for the *j*th Statistical Area. The remaining notation is as in equation 7. For the *unweighted* fits, the Statistical Area weights $\left(w_j\right)$ are set to 1 so that each sample is weighted by the number of fish in the sample. Note that for ease of presentation, notation for QMA has not been included in the equations of this section. However, the data for all QMA are fitted simultaneously so that common variance parameters (*Gconst*, *Gpow*) can be estimated.

The *unweighted* and *catch-weighted* fits for the Schnute and inverse-logistic models are shown in Figures 11 and 12, respectively, and summary statistics presented in Table 12. In general the catch weighting has little influence on the fits, in particular through the length range where there are observations. The exceptions to this are for the PAU 4 Schnute model and the PAU 3 inverse-logistic model where the *catch-weighted* fits predict much larger growth increments for small paua where there are few or no observations. For the inverse-logistic growth model estimates of *GCV* are much higher for the unweighted fits than for the catch-weighted fits (Table 12). For the Schnute model the *GCV* parameters are only slightly higher for the unweighted fits and are intermediate between the inverse-logistic model unweighted and catch-weighted model estimates (Table 12).

Unlike the model fits to the individual samples, the QMA-level fits to the tag recapture data were not sensitive to the form of the Schnute model or to the specified values of *Lalpha* and *Lbeta*. The larger sample sizes and greater range of initial lengths for these samples results in greater stability in the growth parameter estimates.

Although parameter estimates appear to be relatively stable for the QMA-level growth models, some QMA have few paua tagged at small initial sizes and the growth models extrapolation of growth increments for small paua appears unrealistically large (i.e. Schnute model fits for PAU 2, PAU 3, PAU 4, PAU 5A, PAU 6, Figure 11; inverse-logistic model fits for PAU 3 and PAU 5A, Figure 12). The key parameter influencing the large predicted increments for small paua is the shape parameter, *gshape*. The value of this parameter is much larger for the QMA with unrealistic extrapolations of growth increments (Table 12).

An alternative formulation for the shape parameters of the inverse-logistic and Schnute growth increment models was investigated to force these parameters to be more similar across the QMA. For this parameterization, the QMA-specific shape parameters were defined as deviations from a common shape parameter:

$$\gamma_m = \gamma + d_m \qquad d_m : N\left[0,\left(\sigma_m^d\right)^2\right] \qquad \text{for the Schnute model}$$

$$\omega_m = \omega + d_m \qquad d_m : N\left[0,\left(\sigma_m^d\right)^2\right] \qquad \text{for the inverse logistic model}$$

where d_m is the QMA-specific deviation from the general *gshape* parameter for QMA *m*. The variance of the deviations from the common shape was set at 0.25. The selection of this value for the variance was *ad hoc*. It resulted in some of the more extreme shape parameter values moving closer to the mean, but did not force the parameters to be the same across QMA.

Results for the *shape-penalty* model fits to the tag recapture data are shown in Figure 11 for the Schnute growth model and in Figure 12 for the inverse-logistic model. These model fits used the catch weighting. For both Schnute and the inverse-logistic growth increment models, the addition of the shape penalty function decreases the predicted large increments for small paua in PAU 3 and in PAU 5A. The predicted growth increments for small paua tend to be less for the inverse-logistic model than the Schnute model because of that models asymptotic form. Based on negative log-likelihood values, the inverse-logistic growth increment model is preferred over the Schnute model for all QMA except the Taranaki region of PAU 2 and PAU 7 (Table 12). More tagging data for paua tagged at small initial sizes would be useful to fully describe the paua growth functions, in particular for PAU 3 and PAU 5A.

Variability in predicted growth increments among the QMA is large, with the inverse-logistic *galpha* parameter (predicted increment for a 75 mm paua) ranging from 7.3 mm (Taranaki region of PAU 2) to 49.2 mm (PAU 5A, Table 12) for the *catch-weighted* model fits. For the *shape-penalty* model fits this range is reduced; 9.8 mm (Taranaki region of PAU 2) to 29.7 mm (PAU 5B, Table 12).

For the Schnute growth model, the parameters defining the variance of growth increments are relatively consistent across the three formulations of the QMA-level growth models whereas for the inverse-logistic model the parameters change with model formulation (see table below). However, for all cases the *Gpow* parameter is larger than the values obtained when fitting the tag recovery data at the site level. This suggests that the expansion of the variance for larger growth increments may be greater at the QMA level than at the site level.

Values of the parameters defining the variance of growth increments for the inverse-logistic and Schnute growth models with alternative model structure fitted to QMA-aggregated data:

	Inverse-logistic			Schnute		
Model	Mean *GCV*	*Gconst*	*Gpow*	Mean *GCV*	*Gconst*	*Gpow*
Unweighted	1.71	0.116	0.411	0.957	1.118	0.550
Catch-weighted	0.49	1.564	0.749	0.808	1.167	0.599
Shape-penalty	0.66	1.301	0.676	0.858	1.109	0.589

The three parameters that define the variance of growth increments are highly confounded so it may be more useful to look at the actual variance associated with a range of growth increments. These are presented for the growth model fits for site-specific data and for the data aggregated at the QMA level (see table below). Although there is considerable variation in the parameters that define the variance of growth increments, the resulting standard deviation at specific growth increments are very similar among the various QMA-level growth model formulations. At the site-level, the standard deviations of growth increments are smaller than for the QMA-level data, in particular for larger increments.

The standard deviations of growth increments (1, 10, and 20 mm) for various formulations of the inverse-logistic and Schnute growth models:

	Inverse-logistic			Schnute		
Model	1	10	20	1	10	20
QMA unweighted	1.8	4.5	6.0	2.1	4.5	6.1
QMA catch-weighted	2.1	4.3	6.2	2.0	4.4	6.0
QMA shape-penalty	2.0	4.5	6.3	2.0	4.4	6.1
Site-specific	1.7	3.3	4.2	1.9	3.4	4.2

4. SPAWNING POTENTIAL AND YIELD

To investigate local variation in population productivity and the trade-off between yield and reproductive potential associated with an MLS, maturity-at-length and growth parameters were linked for all sites where both types of data are available. Where the same name was used to describe a location where growth and maturation data had been collected that was the basis for linking the data (Table 13). In a few cases maturity and growth samples were available from different sites within a Statistical Area and in these cases the maturity and growth parameters were also linked (e.g. Port Gore and Jackson in Statistical Area 736, Table 13). For the D'Urville area of PAU 7, one maturity sample was coded Statistical Area 766/767 and two Swamp Bay samples were coded Statistical Area 767 (Table 1). Maturity parameters were similar for these three samples (Table 4) so these samples were combined for the maturity estimates. In general the distance between the location of the linked maturity and growth samples was small, often a tenth of a kilometre or less, but in a few cases the distances were greater than four kilometres (Table 13).

4.1 Spawning potential from maturity to MLS

One measure of the effectiveness of the MLS in maintaining some spawning potential is the number of spawning events an average individual will have prior to becoming vulnerable to the fishery. A simple measure of this spawning potential is the number of years it takes to grow from the length where 50% of the population is mature to the MLS - a deterministic calculation. While this approach does not include the variability in length at maturity and individual variation in growth rates, it should provide a useful approximation to the average number of spawning events a paua can be expected to have prior to becoming vulnerable to the fishery.

For the Schnute growth model, the number of years from the length at 50% maturity (l_{50}) to the MLS (L_{MLS}) can be calculated by solving the following reconfiguration of equation 3 for time, *t*:

$$t = \frac{-\ln\left(\frac{\left((L_{MLS})^{\gamma} - (l_{\infty})^{\gamma}\right)}{\left((l_{50})^{\gamma} - (l_{\infty})^{\gamma}\right)}\right)}{\kappa}$$

where l_{50} is defined in equation 1 and $l_{\infty}, \gamma,$ and κ are defined in equation 3.

The inverse-logistic growth increment model does not have an analytical solution for the interval between two lengths. For this model the number of years from the length at 50% maturity to the MLS is estimated with step-wise annual increments beginning at the length of 50% maturity length and continuing until the MLS is achieved, with a linear interpolation for the final year when the MLS is reached mid-year. Annual increments were run for 30 years, and the length after 30 years taken as the maximum length because the inverse-logistic model has no analytical maximum length.

The number of years between the length at 50% maturity and the MLS is highly variable, ranging from 1.5 years for Rununder/Glasgow West to sites where the MLS is never attained (Table 14). In general, results based on the Schnute growth model are similar to those from the inverse-logistic model, a result that is expected given the two models predict similar growth over the range of lengths where there are observations. The variation in the number of years between 50% maturity and the MLS is considerable both among the QMA and within each QMA.

The estimated maximum length is generally higher for the inverse-logistic model than for the Schnute model (Table 14). Results from the Schnute model suggest that the MLS is not attained for 7 of the 24 sites with linked growth and maturity data whereas for the inverse-logistic model there are only 2 sites where the MLS is not attained. However, caution should be used in interpreting the site-specific maximum length estimates because for some sites no larger paua were tagged resulting in poorly determined maximum length estimates.

4.2 Yield per recruit and spawning per recruit

Yield per recruit and spawning stock biomass per recruit analysis is a useful way to evaluate the trade-off in yield and spawning potential resulting from alternative MLS values. A forward simulation approach was used for these calculations using length-transition matrices calculated from the Schnute growth model incorporating the variance of predicted growth increments. Fishing selectivity was assumed to be knife-edge at the MLS. Because growth and fishing occur throughout the year, results were found to be sensitive to the annual sequence of events (growth, fishing, spawning) when the simulations were conducted at an annual time-step. To minimize the sensitivity of results to the relative timing of growth and fishing, simulations were conducted with 4 time steps per year. The simulated annual sequence was then:

1. growth, recruitment, fishing
2. growth, fishing
3. growth, spawning, fishing
4. growth, fishing

The annual sequence was repeated over 40 years. Fishing mortality was based on the Baranov catch equation:

$$C_l = \frac{F_l}{F_l + M}\left(1 - \exp\left(-F_l - M\right)\right)$$

where C_l is the catch at length *l*, F_l is the fishing mortality at length *l*, and *M* is the natural mortality which was assumed to be length-independent and equal to 0.1. Catch and spawning stock biomass were summed across the 40 year simulation assuming a weight-length relationship with parameters a=2.592e-08 and b= 3.322 (Schiel & Breen 1991). Fishing mortality was evaluated over a range of values from 0 to 1, and assumed to be 0 for fish less than the minimum harvest size. Fish were recruited at a mean length of 30 mm with a variance of 10 mm. A number of alternative scenarios were also examined that varied: size and variance of recruitment length; number of time steps in a year; sequence of events through a year. Results were relatively insensitive to the alternative scenarios that were examined. Note that per recruit analyses were not conducted based on the inverse-logistic growth increment model because moving to four growth periods per year substantially changes the resulting annual growth.

Per recruit analyses were conducted for minimum harvest sizes (MHS) equal to the current MLS, the current MLS minus 10 mm, and the current MLS plus 10 mm.

The yield and spawning stock biomass per recruit resulting from alternative fishing mortality rates and MHSs are shown in Figure 13. Yields are expressed relative to the maximum obtained across all MHS and spawning stock biomass is relative to the unfished level. The MHS resulting in the highest yields differs among sites, and in some cases no harvest is attained without a decrease in the MLS (e.g. Cape Egmont, Opunake, Staircase, Table 15, Figure 13).

A potential biological reference point for managing paua fisheries, consistent with the New Zealand Harvest Strategy Standard, is $F_{40\%SPR}$. This reference point, the fishing mortality rate associated with a spawning biomass per recruit of 40% B_0, is the default B_{MSY} proxy for stocks with moderate productivity (New Zealand Ministry of Fisheries 2011).

For each site and MHS, the fishing mortality rate and resulting yield consistent with the $F_{40\%SPR}$ target are presented in Table 15. Yields are presented relative to the maximum across fishing mortality rates for each respective MHS. Given the current MLS regime, fishing mortality rates associated with $F_{40\%SPR}$ are highly variable, ranging from 0.12 for D'Urville Site 6 to 1.0, the maximum rate evaluated, for a number of sites. Yields at $F_{40\%SPR}$ are only slightly reduced from the maximum yield at the current MLS, ranging from 81% to 100% of the maximum yield. For the Taranaki region of PAU 2, a 10 mm reduction of the current MLS of 85 mm would allow for some yield in the two locations (Cape Egmont and Opunake) that have no apparent yield at the current MLS.

PAU 7, the QMA with the largest number of sites that have maturity and growth data, shows considerable variability in productivity among sites. For two sites in PAU 7, a 10 mm reduction in the MLS would result in considerably higher potential yields (Staircase and D'Urville Site 2, Table 15). For the remaining sites in PAU 7, a 10 mm change in the MLS would result in only minor changes in potential yields.

5. DISCUSSION

The analyses presented in this report investigate variability in paua growth and maturity within and among QMA, and evaluate the trade-offs between yield and spawning potential resulting from variation in these demographic characteristics and the MLS. All currently available paua growth and maturity data sets were included in these analyses, and while many of these data sets had been previously analysed (eg. McShane & Naylor, 1995; Naylor & Andrew, 2002; Naylor et al. 2006, 2016, 2017a, 2017b) this is the first attempt to synthesize the maturity and growth data and analyse all data sets simultaneously.

The maturity analyses provide strong support for the hypothesis that maturation as a function of length is independent of sex. That is, the proportion of male and female paua that are mature at a given length is the same within each site. Previous studies have tended to combine male and female paua when estimating maturation rates (e.g. Naylor & Andrew 2000; Naylor et al. 2017a), most likely because this allows immature paua that cannot be sexed to be included in the analysis. Results presented here provide support for that practice.

Shell length was not always the best predictor of the proportion mature, and for over half of the sites with more extensive morphometric data either shell width or shell height were better predictors of the proportion mature. There were no obvious features common to the sites where shell height or shell width provided stronger relationships with maturity. Given that the paua stock assessment model is length-based, the current practise of focussing on maturation at length is appropriate.

A small number of sites had samples collected at two periods, with between 8 and 18 years between the two sampling periods. For 6 of the 7 sites with replicate samples there were significant differences in the parameters describing maturity-at-length, with paua maturing at a larger size for the later samples. Whether this reflects a real change in the maturation process or if it was an artefact of how maturity is assessed is unclear. The later samples were all collected somewhat later in the year, and this could have affected the maturation assessments.

There is significant variability in the maturity-at-length relationship among sites within each QMA, with the exception of the four sites sampled in PAU 5A. To assess this "within QMA" variability in maturation, samples from the Taranaki region of PAU 2 were treated separately from the remainder of PAU 2 and the early and late Taranaki samples also treated as a separate group. Even when the PAU 2 samples were split into these three groups, there was significant variability among the samples within each of the groups. Although maturity-at-length showed significant differences within most QMA, in many cases the magnitude of these differences was not large. For example, the range in length at 50% maturity was about 10 mm across the 13 sites in PAU 7.

Two models were used to predict growth increments for the site-specific tag recapture data with the AICc criterion selecting the inverse-logistic model over the Schnute model as the preferred growth increment model for slightly more than half of the sites. For both models, growth parameter estimates for some of the sites were sensitive to the models' formulation (e.g. initial parameter values, values of *galpha* and *gdiff*). Generally this sensitivity was associated with sites where the range of tagged paua sizes was small, so the data sets were relatively uninformative about growth. When the data were aggregated at the QMA level, this sensitivity disappeared.

One of the useful aspects of analysing all tag-recapture data sets simultaneously is that features that are similar among sites are more readily identified and growth model parameters that are confounded can either be assumed to be the same or to be similar among sites, thus improving the consistency with which they can be estimated. In particular, the parameters that define the variance of predicted growth increments are highly confounded and it was found that fixing or assuming commonality among three of these parameters (*Gobs, Gconst, Gpow*) while estimating a fourth site-specific parameter (*GCV*) greatly improved model estimation.

Although the focus of this report is to investigate growth variability among sites, once the data was organized it was opportune to conduct some analyses with the data aggregated at the QMA level as they are used in paua stock assessments. As would be expected when combining data from sites with different growth, the variance of predicted growth increments increased for the QMA-level growth models. The proportional increase in the standard deviations of growth increments was much greater for large increments than for small increments.

A recent review of the paua stock assessment model (Butterworth et al. 2015) focussed considerable attention on the model's formulation of growth because for length-based models growth drives the model dynamics. Two recommendations from that review are investigated here. The first recommendation was that growth curves should be fitted only to data from areas that dominate the catch. To investigate the potential effect of this recommendation, growth models that weighted the tag-recovery observations by the relative amount of catch within each Statistical Area were fitted to the QMA-level data. In general, catch-weighting the data observations had little effect on estimated growth increments and where there was an effect the estimated growth increments increased.

The second stock assessment review recommendation investigated was to estimate a parameter that allows for non-linearity in the variation around the mean growth curve to see if that would control the expansion of the variation about the mean growth as initial length decreases. Because of strong confounding among growth variance parameters, the non-linearity parameter (*Gpow*) was assumed to be the same among all sites (for site-specific models) and among all QMA (for QMA-level models). When this parameter was estimated (rather than fixed at 1), it had a strong effect on reducing the expansion of the variance of mean growth for larger predicted increments (smaller initial size). This effect was greater at the site level than at the QMA level, as would be expected given that the QMAs encompass both slower and faster growing paua. Given parameter confounding, it may be prudent to fix the value of the *Gpow* parameter or to construct a tight parameter prior based on these results for the paua stock assessments.

Variability in predicted growth increments was large, both within and among QMA. At the site level (ignoring Taranaki sites), the predicted annual length increment for a 75 mm paua ranged from about 5 mm to 30 mm. At the QMA-level (ignoring the Taranaki region of PAU 2), the range was about 15 mm to 30 mm.

To investigate local variation in population productivity and the trade-off between yield and reproductive potential associated with the MLS, maturity-at-length and growth parameters were linked for all sites where both types of data were available. A simple measure, the number of years between maturity and the MLS, was calculated for all sites based on both the inverse-logistic and the Schnute growth models. Yield per recruit and spawning per recruit analyses were limited to the Schnute growth model parameters as the inverse-logistic model parameters can only be appropriately used with an annual time step and it was necessary to conduct those analyses with multiple time steps each year.

The number of years between the length at 50% maturity and the MLS is highly variable among sites, ranging from 1.5 years for Rununder/Glasgow West to sites where the MLS is never attained. For about one third of the sites that have both maturity and growth data, the MLS is not attained within 10 years of paua attaining maturity. That result is unlikely to reflect paua populations in general as samples from the Taranaki region of PAU 2 and the Banks Peninsula region of PAU 3, areas with known stunted or slow growing paua, were overrepresented in the sites that had both maturity and length data. Ignoring the samples from those regions, it appears that most paua populations will have at least 3 opportunities to spawn between maturity and becoming susceptible to the fisheries.

Yield per recruit and spawning per recruit analysis was conducted with four time steps per year, because results were sensitive to the timing of the annual sequence of growth, fishing, spawning and recruitment when an annual time step was used. Additional time steps minimized this problem by allowing paua to grow and become susceptible to fishing a number of times during the annual cycle. Given the current MLS regime, instantaneous fishing mortality rates associated with $F_{40\%SPR}$ are highly variable, ranging from 0.12 for a D'Urville site to 1.0, the maximum rate evaluated, for a number of sites. Yields at $F_{40\%SPR}$ are only slightly reduced from the maximum yield at the current MLS, ranging from 81% to 100% of the maximum yield. For the Taranaki region of PAU 2, a 10 mm reduction of the current MLS of 85 mm would allow for some yield in the two locations (Cape Egmont and Opunake) that have no apparent yield at the current MLS.

For some of the sites, a 10 mm increase in the MLS results in higher maximum yield per recruit and yields at $F_{40\%SPR}$ (or only a slight reduction in yields). These are of course associated with higher fishing mortality rates. For some regions of the coast, local industry paua managers have instituted voluntary minimum harvest sizes that are greater than the government prescribed MLS. These have the potential to increase the reproductive of paua populations at some sites, but may also restrict fishing opportunities at others.

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Table 1: Summary information for maturity samples including: QMA, site, Statistical Area(s), sample size (N), year(s), months (coded 1=January, 12=December), latitude and longitude. Note that where two latitudes and longitudes are given for a site these reflect the minimum and maximum of the sampling range. Note that for some samples latitude and longitude data is not available.

QMA	Site	Statistical Areas	N	Years	Months	Latitude	Longitude
PAU 2	Tora	223	115	2013	2	-41.487	175.574
PAU 2	Breaker Bay	237	118	1996	4, 6	-41.339	174.825
PAU 2	Terakirae	237	101	2013	3	-41.435	174.912
PAU 2	Pukerua Bay	238	96	2008	3	-41.030	174.882
PAU 2	Cape Egmont	240	107	1998	1	-39.277	173.751
PAU 2	Cape Egmont 2	240	91	2016	3	-39.248	173.770
PAU 2	Opunake	240	117	1998	1	-39.456	173.848
PAU 2	Opunake 2	240	131	2015	2	-39.457	173.847
PAU 2	Puketapu	240	109	1998	11	-39.520	173.915
PAU 2	Puketapu 2	240	115	2016	3	-39.519	173.914
PAU 2	New Plymouth	241	212	1998	1	-39.054	174.062
PAU 2	New Plymouth 2	241	115	2016	3	-39.054	174.061
PAU 2	Sponge Bay	244	104	2013	3	-38.707	178.049
PAU 2	Blackhead Pt	245	95	2013, 2015	3		
PAU 3	Okiwi Bay	302	118	2012	4	-42.223	173.857
PAU 3	Paparoa	302	101	2013	4	-42.236	173.848
PAU 3	Jorgies Rock	307	106	2012	4	-42.442	173.587
PAU 3	Motunau	318	117	2012	3	-43.064	173.080
PAU 3	Inside Akaroa	333	120	2012	12	-43.856	172.942
PAU 3	Scenery Nook	334	103	2012	12	-43.898	172.925
PAU 4	Chatham Island	405, 406, 407, 409, 425, 427, 419	96	1994	6	-44.045 -43.773	177.243 176.325
PAU 5A	Milford	F05	124	2012	2	-44.578	167.771
PAU 5A	Poison Bay	F07	120	2012	2	-44.662	167.625
PAU 5A	Woodhen Cove	F26	111	2016	2	-45.631	166.552
PAU 5A	Green Islets	F41	62	2012	8	-46.225	166.789
PAU 5B	Waterfall	S04	131	2014	12		
PAU 5B	Ruggedy	S13	123	2014	12		
PAU 5B	Waituna	S18	28	1994	6	-46.788	167.713
PAU 5B	Big Kuri	S56	120	2014	12		
PAU 5B	Shelter Pt	S65	93	2014	12		
PAU 5B	East Cape	S69	57	1995	2, 10	-47.014	168.225
PAU 5D	Catlins west 2	H12	103	2016	5	-46.666	168.991
PAU 5D	Catlins west	H14, H12, H13	79	1996, 2001	3, 11	-46.672 -46.648	169.026 169.224
PAU 5D	Catlins east	H14	142	2016	8	-46.652	169.223
PAU 5D	Moeraki	H43	114	2013	3	-45.367	170.866
PAU 6	Kahurangi	604	112	1994, 1995	1, 2	-40.811	172.173
PAU 7	Campbell	709	86	2013	9	-41.726	174.278
PAU 7	Staircase	714	42	1994	5	-41.377	174.070
PAU 7	Rununder	719	126	2013	9	-41.335	174.179
PAU 7	Rununder2	719, 721, 722	125	2005	1	-41.334 -41.272	174.195 174.266
PAU 7	Tory	725	127	2013	9	-41.215	174.309
PAU 7	Perano	726	112	2013	9	-41.198	174.365
PAU 7	Perano 2	727	118	2005	1	-41.187	174.374
PAU 7	Port Gore	736	123	2013	9		
PAU 7	Northern faces	737, 736,738, 745, 746, 748	302	1995	5	-41.050 -40.003	173.981 174.289
PAU 7	D'Urville	767, 766	136	1994	3	-40.746 -40.714	173.926 173.956
PAU 7	Swamp Bay North	767	106	2002	1	-40.747	173.935
PAU 7	Swamp Bay South	767	105	2002	1	-40.745	173.928
PAU 7	Lookout Bay East	771	102	2002	1	-40.738	173.873
PAU 7	Lookout Bay West	771	104	2002	1	-40.737	173.873

Table 2: Sample size (N) and parameter values $\left(l_{50}, l_{\delta}\right)$ for sex-specific and sex-aggregated maturity-at-length models, and AICc values for the sex-aggregated model and the combined male and female sex-specific models. The AICc for the preferred model fit (sex-specific or sex-aggregated) is indicated in bold.

		Sex-aggregated			Male			Females			AICc	
QMA	Site	N	l_{50}	l_{δ}	N	l_{50}	l_{δ}	N	l_{50}	l_{δ}	Sex-aggregated	Male + Female
PAU 2	Tora	96	91.7	8.0	48	92.7	2.0	48	87.8	13.9	31.1	**30.0**
PAU 2	Breaker Bay	101	69.3	12.6	49	67.5	17.7	52	71.0	8.1	**36.5**	40.1
PAU 2	Terakirae	82	89.6	16.7	38	93.6	13.8	44	86.0	18.6	**49.7**	51.8
PAU 2	Pukerua Bay	63	91.0	36.8	36	91.5	19.0	27	96.1	80.0	**84.9**	85.6
PAU 2	Cape Egmont 2	54	57.2	21.3	23	51.6	32.4	31	50.0	4.5	**13.7**	17.0
PAU 2	Opunake 2	74	65.1	19.5	24	65.4	28.7	50	65.2	15.9	**80.5**	83.9
PAU 2	Puketapu 2	80	69.2	14.8	37	66.3	20.4	43	70.7	10.9	**91.1**	93.5
PAU 2	New Plymouth 2	37	73.6	15.1	11	76.8	7.1	26	72.0	17.6	**40.6**	44.6
PAU 2	Sponge Bay	78	79.5	20.0	40	79.2	16.1	38	79.5	23.7	**40.0**	43.6
PAU 2	Blackhead Pt	81	93.1	13.7	41	94.2	15.8	40	92.2	7.5	**39.8**	42.1
PAU 3	Okiwi Bay	118	83.0	5.9	63	83.4	6.8	55	50.0	6.0	**11.3**	14.8
PAU 3	Paparoa	71	76.6	13.8	42	78.6	14.4	29	72.7	11.1	**38.4**	40.3
PAU 3	Jorgies Rock	101	87.7	9.8	52	88.4	10.3	49	86.7	8.5	**23.3**	27.3
PAU 3	Motunau	113	90.3	5.7	55	90.7	4.0	58	91.2	6.0	**15.2**	19.2
PAU 3	Inside Akaroa	108	88.3	6.4	51	87.4	5.1	57	89.1	6.7	**30.7**	34.1
PAU 3	Scenery Nook	97	86.8	14.5	52	91.1	9.0	45	83.9	18.7	**41.7**	44.1
PAU 4	Chatham Island	63	91.0	36.8	36	91.5	19.0	27	96.1	80.0	**84.9**	85.6
PAU 5A	Milford	107	90.2	10.7	53	85.9	15.6	54	93.2	5.4	56.9	**54.4**
PAU 5A	Poison Bay	102	93.4	9.0	57	94.5	4.9	45	88.1	16.4	41.0	**40.3**
PAU 5A	Woodhen Cove	100	91.4	14.6	64	87.9	17.9	36	98.9	6.1	34.0	35.3
PAU 5A	Green Islets	52	96.3	1.0	29	92.1	1.0	23	96.4	1.0	**4.3**	9.1
PAU 5B	Waterfall	80	95.5	13.6	37	96.8	19.3	43	95.0	1.0	40.6	**37.8**
PAU 5B	Ruggedy	101	100.1	25.2	40	103.9	24.9	61	96.6	27.1	**95.2**	97.5
PAU 5B	Waituna	23	50.0	80.0	14	50.0	72.0	9	71.3	51.4	**26.9**	33.1
PAU 5B	Big Kuri	87	97.2	11.4	50	96.7	10.6	37	97.6	12.2	**41.3**	45.5
PAU 5B	Shelter Pt	57	102.5	10.7	35	101.7	7.7	22	104.1	14.2	**42.0**	44.8
PAU 5B	East Cape	26	87.9	46.1	10	93.6	11.4	16	84.4	80.0	**38.9**	41.8
PAU 5D	Catlins west 2	89	91.8	6.0	44	91.2	8.7	45	93.0	1.0	**24.2**	26.6
PAU 5D	Catlins west	69	77.1	13.4	36	71.2	24.3	33	78.5	1.0	28.9	**27.2**
PAU 5D	Catlins east	134	82.9	8.5	65	84.5	6.9	69	80.8	10.3	**54.2**	55.6
PAU 5D	Moeraki	99	75.6	5.1	60	76.2	6.2	39	74.9	3.0	**31.2**	33.9
PAU 6	Kahurangi	76	115.4	33.9	24	111.8	26.0	52	118.1	39.8	**90.0**	94.1
PAU 7	Campbell	63	86.0	11.5	21	85.0	14.9	42	87.0	7.0	**24.9**	28.4
PAU 7	Staircase	20	91.1	11.7	8	89.2	6.6	12	95.3	3.5	**24.7**	29.7
PAU 7	Rununder	49	85.4	15.9	28	88.7	13.3	21	78.6	19.9	**38.1**	39.5
PAU 7	Rununder 2	112	89.5	13.9	63	92.2	7.8	49	65.1	49.2	63.8	**60.8**
PAU 7	Tory	78	92.3	8.4	43	92.4	7.7	35	92.3	9.3	**45.5**	49.9
PAU 7	Perano	72	93.2	14.3	37	94.1	11.9	35	92.2	16.6	**58.5**	62.4
PAU 7	Perano 2	112	88.8	8.1	60	89.7	6.4	52	87.1	10.2	**40.6**	43.6
PAU 7	Port Gore	84	98.8	8.4	6	96.0	1.0	78	98.9	8.6	**53.7**	58.9
PAU 7	Northern faces	234	80.2	35.1	121	71.0	36.3	113	88.0	27.2	294.4	**274.3**
PAU 7	D'Urville	107	89.6	14.2	62	89.4	15.5	45	89.9	12.7	**125.8**	130.0
PAU 7	Swamp Bay North	74	89.6	11.2	27	88.8	10.1	47	90.1	11.5	**64.1**	68.4
PAU 7	Swamp Bay South	82	89.6	5.4	43	90.2	5.8	39	89.1	4.3	**58.2**	61.3
PAU 7	Lookout Bay East	70	86.0	9.5	32	85.7	9.5	38	86.2	9.6	**61.8**	66.4
PAU 7	Lookout Bay West	89	81.9	18.2	45	81.8	26.1	44	82.7	11.2	**93.4**	95.2

Table 3: Parameter estimates (l_{50}, l_{δ}) for sites with maturity samples collected at two distinct times. Results are presented for the data treated as separate samples and for the samples combined. The months in which samples were collected are coded (1=January, 12=December), and year and sample size (N) presented. Distance (Dist.) is the distance between the location of the earlier and later sample collection sites. The AICc for the preferred model fit (samples separated or combined) is indicated in bold.

			Combined data sets			Data set 1 (earlier years)					Data set 2 (later years)					AICc	
QMA	Site	Dist. (km)	N	l_{50}	l_{δ}	Years	Month	N	l_{50}	l_{δ}	Years	Month	N	l_{50}	l_{δ}	Combined	Separate
PAU 2	Cape Egmont	3.65	198	69.9	9.1	1998	1	107	68.8	7.5	2016	3	91	75.8	7.8	105.8	**97.3**
PAU 2	New Plymouth	0.09	327	63.9	36.6	1998	1	212	56.9	20.0	2016	3	115	76.0	9.4	416.4	**317.9**
PAU 2	Opunake	0.10	248	69.5	11.4	1998	1	117	66.6	7.2	2015	2	131	70.8	11.8	184.0	**178.5**
PAU 2	Puketapu	0.09	224	64.5	19.2	1998	11	109	59.9	5.2	2016	3	115	71.8	14.8	234.6	**155.2**
PAU 5D	Catlins west	1.46	182	85.7	16.5	1996, 2001	3, 11	79	80.5	15.1	2016	5	103	93.2	7.7	109.0	**88.7**
PAU 7	Perano	1.36 -10.09	230	91.6	9.5	2005	1	118	89.0	7.8	2013	9	112	94.4	11.5	115.2	**106.4**
PAU 7	Rununder	2.74 -17.87	251	91.9	11.9	2005	1	125	92.6	11.2	2013	9	126	91.1	11.5	**136.1**	139.7

Table 4: Sample sizes (N), parameter values (l_{50}, l_{δ}) and AICc values by sample site for the maturity-at-length model fitted to all maturity and length data (including unsexed fish).

QMA	Site	Statistical Area	N	l_{50}	l_{δ}	AICc
PAU 2	Tora	223	115	92.5	7.3	33.8
PAU 2	Breaker Bay	237	118	74.1	13.9	70.3
PAU 2	Terakirae	237	101	91.8	12.7	54.7
PAU 2	Pukerua Bay	238	96	97.5	16.8	107.8
PAU 2	Cape Egmont	240	107	68.8	7.5	73.6
PAU 2	Opunake	240	117	66.6	7.2	59.3
PAU 2	Puketapu	240	109	59.9	5.2	31.9
PAU 2	Cape Egmont 2	240	91	75.8	7.8	23.7
PAU 2	Opunake 2	240	131	70.8	11.8	119.2
PAU 2	Puketapu 2	240	115	71.8	14.8	123.4
PAU 2	New Plymouth	241	212	56.9	20.0	269.7
PAU 2	New Plymouth 2	241	115	76.0	9.4	48.2
PAU 2	Sponge Bay	244	104	85.0	16.3	54.1
PAU 2	Blackhead Pt	245	95	94.8	12.8	46.5
PAU 3	Okiwi Bay	302	118	83.0	5.9	11.3
PAU 3	Paparoa	302	101	79.1	10.5	44.2
PAU 3	Jorgies Rock	307	106	89.3	8.2	25.7
PAU 3	Motunau	318	117	91.3	7.9	27.4
PAU 3	Inside Akaroa	333	120	88.9	5.5	33.6
PAU 3	Scenery Nook	334	103	89.1	12.2	46.8
PAU 4	Chatham Island	405	96	97.5	16.8	107.8
PAU 5A	Milford	F05	124	91.3	9.1	61.2
PAU 5A	Poison Bay	F07	120	94.1	8.5	44.9
PAU 5A	Woodhen Cove	F26	111	94.9	10.7	39.5
PAU 5A	Green Islets	F41	62	96.3	1.0	4.3
PAU 5B	Waterfall	S04	131	99.2	10.5	54.1
PAU 5B	Ruggedy	S13	123	103.4	28.1	124.6
PAU 5B	Waituna	S18	28	75.3	50.9	38.3
PAU 5B	Big Kuri	S56	120	99.6	9.2	51.8
PAU 5B	Shelter Pt	S65	93	103.8	9.1	48.3
PAU 5B	East Cape	S69	57	97.5	22.8	57.6
PAU 5D	Catlins west 2	H12	103	93.2	7.7	39.3
PAU 5D	Catlins west	H14	79	80.5	15.1	49.4
PAU 5D	Catlins east	H14	142	83.5	8.3	58.9
PAU 5D	Moeraki	H43	114	76.6	6.5	43.0
PAU 6	Kahurangi	604	112	115.3	25.3	98.5
PAU 7	Campbell	709	86	86.7	9.8	26.2
PAU 7	Staircase	714	42	93.5	7.7	29.5
PAU 7	Rununder	719	251	91.9	11.9	136.1
PAU 7	Tory	725	127	92.4	8.0	46.0
PAU 7	Perano	726	112	94.4	11.5	65.4
PAU 7	Perano 2	726	118	89.0	7.8	41.0
PAU 7	Port Gore	736	123	99.1	8.2	56.5
PAU 7	Northern faces	737	302	85.3	22.3	357.4
PAU 7	D'Urville	767	136	91.0	11.9	141.9
PAU 7	Swamp Bay	767	106	89.5	11.4	70.7
PAU 7	Swamp Bay	767	105	89.6	5.3	58.4
PAU 7	Lookout Bay East	771	102	86.2	8.6	63.2
PAU 7	Lookout Bay	771	104	83.5	15.5	102.8

Table 5: Sample sizes (N), parameter values (l_{50}, l_{δ}) and AICc values for maturity-at-length models fitted to QMA-wide data (for PAU 2, subsets of the QMA data), and the summed AICc values for maturity-at-length models fitted by site within the QMA (or sub-sets of PAU 2). For each QMA or QMA-subset, the lower AICc value (preferred model) is highlighted.

					AICc	
QMA	Sites	N	l_{50}	l_{δ}	Sites combined	Sites summed
PAU 2	All but Taranaki	629	87.5	23.9	476.4	**367.2**
PAU 2	Taranaki - 1998	545	60.9	16.8	548.9	**434.5**
PAU 2	Taranaki -2015, 2016	452	72.5	11.8	320.3	**314.5**
PAU 3	All	665	85.2	12.5	220.3	**189.1**
PAU 5A	All	417	93.0	9.4	**147.5**	149.8
PAU 5B	All	552	99.5	21.4	437.3	**374.7**
PAU 5D	All	438	81.4	15.4	248.2	**190.7**
PAU 7	All	1714	89.3	15.5	1355.6	**1195.1**

Table 6: Summary of statistics for the standardised height-length residuals including: the mean residuals for immature paua; for mature paua; for the site; and the difference between the mean residuals for mature and immature paua).

				Mean height-length residual			
QMA	Site	Statistical Area	N	Immature	Mature	Mature – Immature	Site
PAU 2	Tora	223	115	0.03	0.25	0.21	0.20
PAU 2	Terakirae	237	99	0.17	0.13	-0.03	0.14
PAU 2	Sponge Bay	244	94	0.40	0.72	0.32	0.64
PAU 2	Blackhead Pt	245	90	-0.56	-0.84	-0.29	-0.78
PAU 3	Okiwi Bay	302	116	0.67	0.51	-0.16	0.52
PAU 3	Motunau	318	117	-0.51	0.13	0.64	0.09
PAU 3	Inside Akaroa	333	120	0.13	0.97	0.83	0.78
PAU 3	Scenery Nook	334	103	0.28	1.24	0.95	1.10
PAU 5A	Milford	F05	124	0.00	0.68	0.68	0.50
PAU 5A	Poison Bay	F07	120	-0.14	0.14	0.28	0.06
PAU 5A	Green Islets	F41	52	0.08	-0.34	-0.42	-0.29
PAU 5B	Waterfall	S04	130	-0.34	-0.24	0.09	-0.29
PAU 5B	Ruggedy	S13	121	-0.85	-0.68	0.17	-0.75
PAU 5B	Big Kuri	S56	116	-0.56	-0.80	-0.23	-0.71
PAU 5B	Shelter Pt	S65	91	-1.01	-0.80	0.20	-0.92
PAU 5D	Catlins west 2	H12	103	-0.17	-0.04	0.13	-0.06
PAU 5D	Moeraki	H43	112	0.58	0.60	0.02	0.60
PAU 7	Campbell	709	85	0.20	0.28	0.08	0.25
PAU 7	Rununder	719	124	0.24	0.77	0.53	0.39
PAU 7	Tory	725	122	-0.21	0.07	0.29	-0.12
PAU 7	Perano	726	111	-0.39	-0.30	0.09	-0.35
PAU 7	Port Gore	736	116	-0.42	-0.20	0.22	-0.31

Table 7: AICc for the base maturity model (maturity-at-length), and the difference in AICc between the base model and alternative maturity models, by sampling site. The alternative maturity models are described in the text, and the lowest AICc (preferred model) is indicated with bold values.

					Base model AICc – alternative model AICc				
QMA	Site	Statistical Area	N	AICc base model	Base	Length + residual	Height/Length Ratio	Height	Width
PAU 2	Tora	223	115	33.8	0	2.1	64.2	-3.2	**-7.0**
PAU 2	Terakirae	237	99	54.7	0	2.1	62.6	2.7	**-1.0**
PAU 2	Sponge Bay	244	94	54.1	0	2.1	31.8	4.4	**-1.8**
PAU 2	Blackhead Pt	245	90	46.4	0	2.1	47.3	**-6.3**	1.4
PAU 3	Okiwi Bay	302	116	11.3	**0**	2.1	12.8	6.5	4.7
PAU 3	Motunau	318	117	27.4	0	2.1	13.7	**-3.7**	1.0
PAU 3	Inside Akaroa	333	120	33.6	**0**	2.1	67.5	21.1	4.8
PAU 3	Scenery Nook	334	103	46.8	0	2.1	16.0	**-3.8**	5.8
PAU 5A	Milford	F05	124	61.2	0	2.1	40.3	**-1.5**	9.6
PAU 5A	Poison Bay	F07	120	44.9	0	2.1	64.0	6.2	**-0.9**
PAU 5A	Green Islets	F41	52	4.3	**0**	2.3	34.8	5.9	4.9
PAU 5B	Waterfall	S04	130	54.1	0	2.1	75.6	**-9.0**	10.3
PAU 5B	Ruggedy	S13	121	124.6	**0**	2.1	23.1	0.2	2.3
PAU 5B	Big Kuri	S56	116	51.8	**0**	2.1	90.1	6.8	0.5
PAU 5B	Shelter Pt	S65	91	48.1	0	2.1	51.1	-1.3	**-3.3**
PAU 5D	Catlins west 2	H12	103	39.3	0	2.1	54.4	4.1	**-4.3**
PAU 5D	Catlins east	H14	142	58.9	**0**	2.1	80.3	17.8	1.5
PAU 5D	Moeraki	H43	112	43.0	**0**	2.1	74.2	9.2	4.8
PAU 7	Campbell	709	85	26.2	**0**	2.2	74.4	8.6	0.6
PAU 7	Rununder	719	124	61.7	**0**	2.1	55.2	1.4	3.4
PAU 7	Tory	725	122	36.3	0	2.1	88.1	12.1	**-4.6**
PAU 7	Perano	726	111	65.4	0	2.1	56.4	**-6.3**	-0.6
PAU 7	Port Gore	736	116	56.1	**0**	2.1	72.2	14.7	0.1

Table 8: Summary information for tag releases and recoveries, including latitude, longitude, Statistical Area, year(s) and coded month(s) (January=1, December =12) of release and number of recoveries (N) and days at liberty.

QMA	Site	N	Statistical Area	Latitude	Longitude	Year(s)	Month(s)	Days at Liberty
PAU 2	Mataikona	30	208	-40.687	176.347	1999	10	338 – 346
PAU 2	Breaker Bay	189	237	-41.339	174.827	1991, 1992	6 , 7, 8, 9, 10	62 – 784
PAU 2	Turakirae	44	237	-41.431	174.909	2000	6	408
PAU 2	Egmont	40	240	-39.277	173.751	1998	1	375
PAU 2	Opunake	17	240	-39.456	173.848	1998	2	375
PAU 2	New Plymouth	80	241	-39.054	174.062	1998	1	300
PAU 3	Inside Pigeon Bay	17	326	-43.656	172.914	1998	11	398
PAU 3	Outside Pigeon Bay	19	326	-43.624	172.932	1998	11	399 - 400
PAU 3	Inside Akaroa	83	333	-43.865	172.946	1998	11	399
PAU 3	Scenery Nook	66	334	-43.899	172.925	1998	11	401
PAU 4	Waitangi West	120	411	-43.782	-176.837	2001	11	363
PAU 4	Wharekauri	31	415	-43.707	-176.574	2001	11	362
PAU 4	Ascots	20	425	-44.017	-176.384	2009	4	439
PAU 4	The Horns	36	435	-44.114	-176.633	2001	11	363
PAU 4	Sandy Point Pitt Is.	61	443	-44.274	-176.158	2009	4	428
PAU 5A	Poison Bay	135	F07	-44.667	167.633	2000	5	381
PAU 5A	Landing Bay	73	F34	-45.999	166.504	2000	11	369
PAU 5A	Red Head	91	F36	-46.074	166.566	2000	11	369
PAU 5B	Christmas Village	78	S07	-46.751	167.983	2000	1	364
PAU 5B	Waituna	132	S18	-46.789	167.713	1995, 1996	5, 7	214–289
PAU 5B	Port Adventure	51	S65	-47.067	168.172	2000	1	363
PAU 5B	Ocean Beach	70	S70	-46.978	168.184	2000	1	363
PAU 5D	Boat Harbour	116	H14	-46.654	169.194	2001	3	266
PAU 5D	Catlins East	61	H16	-46.630	169.315	2001	3	265
PAU 5D	Roaring Bay	36	H26	-46.447	169.812	1987, 1988	1, 9, 11, 12	249–851
PAU 5D	Papatowai	24	H32	-45.570	169.478	1977, 1978, 1988	3, 8	243–1036
PAU 5D	Seal Pt	37	H33	-45.899	170.638	1976, 1983, 1996	1, 2, 3, 8	285–1259
PAU 6	Big Bay	37	604	-40.872	172.128	1996	1	271–383
PAU 6	Otukoroiti	113	604	-40.811	172.173	1995	2	346–348
PAU 7	Cape Campbell	10	709	-41.725	174.279	2003	8	384–878
PAU 7	Staircase	48	714	-41.386	174.066	1992	8	634
PAU 7	Glasgow West	58	721	-41.307	174.238	2000	4	334–335
PAU 7	Smokey Bay	67	728	-41.125	174.389	2000	5	294
PAU 7	Jackson	211	736	-41.000	174.306	2000	4	337
PAU 7	D'Urville site 1-B	102	766	-40.727	173.948	1993	7	242
PAU 7	D'Urville site 2-H	105	766	-40.727	173.936	1993	7	241
PAU 7	D'Urville site 3-B	144	766	-40.713	173.957	1993	7	237
PAU 7	D'Urville site 4-H	51	766	-40.714	173.953	1993	7	239
PAU 7	D'Urville site 5-B	46	767	-40.745	173.925	1993	7	238
PAU 7	D'Urville site 6-H	45	767	-40.747	173.935	1993	7	237

Table 9: Parameter values or parameter bounds for all parameters used in the growth increment models:

Parameter name	Parameter symbol	Bounds or fixed value	Model or data set where used
galpha	g_α	1, 50	inverse-logistic, *Francis*
gdiff	g_d	0, 1	inverse-logistic, *Francis*
gshape (Schnute)	γ	0.001, 40	*Francis*, *Baker*
gshape (inverse-logistic)	ω	0.001, 40	inverse-logistic
Brody growth coefficient	κ	0.001, 1	*Baker*
Linf	l_∞	50, 400	*Baker*
lalpha	l_α	40	Taranaki region (site-specific models only)
lalpha	l_α	75	All site-specific models and Taranaki QMA-level models
lbeta	l_β	75	Taranaki region (site-specific models only)
lbeta	l_β	125	All site-specific models and Taranaki QMA-level models
GCV	ϕ	0.01, 2	both variance formulations
Gmin	$\sigma^{\min}$	1 mm	stock assessment variance formulation
Gconst	σ^{const}	0.01, 5	alternative variance formulation
Gobs	σ^o	0.25	stock assessment variance formulation
Gobs	σ^o	0	alternative variance formulation
Gpow	ψ	1	stock assessment variance formulation
Gpow	ψ	0, 10	alternative variance formulation

Table 10: Summary of estimated parameter values for the inverse-logistic and 2 forms of the Schnute growth increment models. Parameter values at bounds are noted by a *. The lowest AICc value (preferred model) is shown in bold.

			Inverse-logistic					Schnute - *Francis* parameterization					Schnute – *Baker* parameterization				
QMA	Locality	N	AICc	*galpha*	*gdiff*	*gshape*	*GCV*	AICc	*galpha*	*gdiff*	*gshape*	*GCV*	AICc	*K*	*Linf*	*gshape*	*GCV*
PAU 2	Breaker Bay	189	696.51	23.64	0.35	0.20	1.37	697.37	24.98	0.28	1.13	0.87	**696.31**	0.43	144.90	1.12	1.16
PAU 2	Egmont	40	104.19	10.14	0.27	0.77	0.84	102.00	10.12	0.15	0.79	0.42	**101.53**	0.30	81.00	0.82	0.62
PAU 2	Mataikona	30	**62.89**	16.25	0.02	0.001*	1.39	69.58	32.77	0.00*	40*	1.08	64.52	0.16	117.41	17.45	1.30
PAU 2	New Plymouth	80	223.87	16.97	0.24	0.12	1.04	223.43	16.32	0.26	0.52	0.59	**223.06**	0.51	86.00	0.52	0.82
PAU 2	Opunake	17	36.74	9.61	0.13	0.001*	0.92	33.89	23.93	0.06	4.79	0.31	**33.84**	0.47	79.02	3.91	0.55
PAU 2	Turakirae	44	**168.51**	24.15	0.29	0.25	1.57	168.89	25.65	0.18	3.09	1.02	172.48	0.25	143.42	3.29	1.32
PAU 3	Inside Akaroa	83	**244.25**	19.36	0.05	0.31	1.66	245.53	21.09	0.00*	10.36	1.13	244.37	0.10	122.07	9.36	1.43
PAU 3	Inside Pigeon Bay	17	40.21	4.70	0.01	14.93	1.12	42.85	5.40	0.00*	14.88	0.66	**36.68**	0.07	97.88	10.95	1.08
PAU 3	Outside Pigeon	19	40.38	10.79	0.00	0.001*	1.66	51.21	19.14	0.00*	40*	1.52	**35.54**	0.41	97.96	40*	2*
PAU 3	Scenery Nook	66	191.66	14.90	0.11	40*	1.35	**188.74**	19.05	0.16	20.48	0.81	192.89	0.00	185.77	7.51	1.11
PAU 4	Ascots	20	62.25	15.74	0.29	40*	1.00	**62.05**	18.66	0.21	7.25	0.56	62.36	0.001*	341.12	4.90	0.80
PAU 4	Sandy Point Pitt	61	**197.11**	17.79	0.55	0.05	1.04	201.64	19.42	0.38	0.47	0.65	201.65	0.35	150.97	0.47	0.89
PAU 4	The Horns	36	123.92	14.33	0.33	0.06	1.21	122.97	15.71	0.09	0.001*	0.73	**122.88**	0.44	128.59	0.01	0.98
PAU 4	Waitangi West	120	**488.29**	13.96	0.28	0.01	2*	495.15	15.56	0.06	0.001*	1.52	494.13	0.44	127.38	0.00	1.87
PAU 4	Wharekauri	31	**97.89**	19.54	0.24	0.04	1.20	105.21	22.27	0.13	1.92	0.83	105.09	0.32	135.99	2.48	1.11
PAU 5A	Landing Bay	73	242.71	31.10	0.30	0.69	1.34	**242.31**	33.22	0.19	5.69	0.84	242.40	0.02	196.07	6.49	1.11
PAU 5A	Poison Bay	135	**439.59**	12.00	0.22	0.06	1.76	439.90	18.37	0.05	4.87	1.21	440.99	0.17	130.37	4.29	1.53
PAU 5A	Red Head	91	**290.41**	19.50	0.45	0.11	1.42	290.49	26.06	0.22	3.43	0.94	290.97	0.17	154.23	3.68	1.21
PAU 5B	Christmas Village	78	**326.72**	30.98	0.31	0.37	1.65	332.82	29.57	0.18	0.82	1.15	332.63	0.70	135.69	0.76	1.50
PAU 5B	Ocean Beach	70	269.25	22.94	0.31	0.30	1.34	265.79	22.42	0.12	0.001*	0.83	**265.41**	0.64	130.43	0.00	1.12
PAU 5B	Port Adventure	51	**182.98**	24.31	0.22	0.04	1.47	191.09	25.26	0.06	0.00	0.98	195.00	0.42	133.93	2.49	1.39
PAU 5B	Waituna	132	**414.21**	14.79	0.50	0.05	1.40	416.05	15.61	0.29	0.001*	0.89	414.86	0.30	144.89	0.39	1.16
PAU 5D	Boat Harbour	116	277.79	25.22	0.50	0.07	0.84	**270.88**	28.36	0.29	1.88	0.40	270.92	0.36	150.89	1.90	0.61
PAU 5D	Catlins East	61	221.54	23.04	0.33	0.81	1.58	221.24	21.44	0.23	2.30	1.04	**220.75**	0.24	146.06	2.37	1.34
PAU 5D	Papatowai	24	96.17	21.02	0.35	1.45	1.43	**93.18**	19.94	0.34	2.82	0.84	93.25	0.09	180.25	2.77	1.11
PAU 5D	Roaring Bay	36	**152.28**	14.80	0.65	40*	1.53	154.87	15.73	0.79	1.71	1.06	155.01	0.15	189.25	0.98	1.39
PAU 5D	Seal Pt	37	147.54	16.00	0.50	0.02	1.84	140.01	22.00	0.27	0.06	1.22	**138.90**	0.51	140.18	0.43	1.58
PAU 6	Big Bay	37	**112.10**	50*	0.04	0.20	1.93	112.56	33.16	0.01	17.76	1.37	113.08	0.01	137.37	17.71	1.61
PAU 6	Otukoroiti	113	**436.88**	10.88	0.27	0.07	2*	440.66	11.91	0.13	1.35	1.44	441.15	0.26	130.95	0.32	1.75
PAU 7	Cape Campbell	10	44.34	18.80	0.33	0.07	1.06	**40.99**	20.20	0.22	0.001*	0.48	41.36	0.52	136.13	0.03	0.67
PAU 7	D'Urville site 1-B	102	**268.85**	8.84	0.30	0.56	1.03	269.49	8.62	0.01	0.45	0.58	269.46	0.22	125.32	0.41	0.81
PAU 7	D'Urville site 2-H	105	**331.66**	19.34	0.16	0.77	1.09	337.15	17.15	0.00*	2.02	0.68	336.55	0.41	120.80	1.69	0.92
PAU 7	D'Urville site 3-B	144	**497.38**	18.34	0.17	0.09	1.28	500.60	16.98	0.22	0.001*	0.82	500.60	0.42	136.23	0.01	1.09
PAU 7	D'Urville site 4-H	51	**181.30**	13.91	0.15	0.05	1.42	181.66	13.27	0.17	0.001*	0.93	181.74	0.31	133.67	0.20	1.21
PAU 7	D'Urville site 5-B	46	**145.44**	9.76	0.41	40*	1.31	145.57	9.32	0.45	3.31	0.82	145.61	0.00	397.11	2.95	1.08
PAU 7	D'Urville site 6-H	45	162.00	12.32	1*	30.68	1.46	160.42	12.72	1.00*	0.001*	0.93	**160.42**	0.09	400*	0.17	1.21
PAU 7	GlasgowWest	58	**198.81**	30.69	0.47	0.11	1.06	205.18	30.67	0.34	0.26	0.69	205.05	0.67	147.05	0.25	0.94
PAU 7	Jackson	211	644.49	25.72	0.21	0.54	1.28	**643.93**	26.20	0.11	5.22	0.80	644.42	0.18	138.75	5.04	1.06
PAU 7	Smokey Bay	67	**217.94**	28.63	0.25	0.29	1.35	218.82	32.79	0.13	8.34	0.88	219.11	0.001*	262.53	7.53	1.14
PAU 7	Staircase	48	**176.43**	13.96	0.15	0.31	1.23	178.86	17.28	0.00*	3.55	0.79	178.51	0.26	124.21	3.31	1.07

Table 11: Total catch (PCELR, 2002 – 2013), number of tag recoveries, and weight factor used in catch-weighted QMA-level model fits, by QMA and Statistical Area. The Taranaki region of PAU 2 is identified by "(T)" and the remainder of PAU 2 is identified by "(O)". Statistical Areas with no recorded PCELR catch are assigned a catch of 1.

QMA	Statistical Area	Number of recoveries	Total catch	Catch weighting
PAU 2 (T)	240	57	1	1.202
PAU 2 (T)	241	80	1	0.856
PAU 2 (O)	208	30	1	0.674
PAU 2 (O)	237	233	12	1.042
PAU 3	326	36	230	0.016
PAU 3	333	83	6 468	0.195
PAU 3	334	66	67 356	2.550
PAU 4	411	120	104 008	0.198
PAU 4	415	31	117 510	0.866
PAU 4	425	20	191 368	2.187
PAU 4	435	36	142 507	0.905
PAU 4	443	61	187 834	0.704
PAU 5A	F07	135	50 882	0.727
PAU 5A	F34	73	59 154	1.563
PAU 5A	F36	91	44 980	0.953
PAU 5B	S07	78	40 350	1.731
PAU 5B	S18	132	33 347	0.845
PAU 5B	S65	51	14 155	0.929
PAU 5B	S70	70	11 073	0.529
PAU 5D	H14	116	28 798	0.378
PAU 5D	H16	61	51 859	1.293
PAU 5D	H26	36	99 049	4.185
PAU 5D	H32	24	200	0.013
PAU 5D	H33	37	245	0.010
PAU 6	604	150	1	1.000
PAU 7	709	10	55 997	8.305
PAU 7	714	48	115 403	3.566
PAU 7	721	63	179 754	4.232
PAU 7	728	67	171 336	3.793
PAU 7	736	211	22 077	0.155
PAU 7	766	402	35 228	0.130
PAU 7	767	91	21 627	0.352

Table 12: Parameter estimates for the *unweighted*, *catch-weighted* and *shape-penalty* fits for the inverse-logistic and Schnute growth models by QMA. PAU 2 is separated into two sub-areas, and the Taranaki region identified by "(T)" and the remainder of PAU 2 by "(O)".

		Inverse-logistic					Schnute				
QMA	N	-ln(L)	*galpha*	*gdiff*	*gshape*	*GCV*	-ln(L)	*K*	*Linf*	*gshape*	*GCV*
Unweighted											
PAU 2 (T)	137	219.3	7.7	0.10	0.99	1.41	213.1	0.37	84.8	0.91	0.66
PAU 2 (O)	263	516.6	26.8	0.66	0.10	1.55	535.3	0.24	146.4	3.02	0.87
PAU 3	185	288.9	16.8	0.35	0.22	1.84	290.2	0.11	122.0	4.99	1.08
PAU 4	278	533.0	16.3	0.82	0.03	1.74	540.5	0.38	137.7	0.00	0.99
PAU 5A	299	570.0	44.2	0.32	182.84	2.00	569.2	0.00	299.2	6.08	1.19
PAU 5B	331	633.6	27.9	0.70	0.06	1.56	646.3	0.56	134.3	0.54	0.87
PAU 5D	274	496.1	19.7	0.88	0.01	1.57	486.8	0.40	147.0	0.00	0.79
PAU 6	150	268.8	11.2	0.82	0.01	1.91	271.5	0.20	130.9	2.11	1.12
PAU 7	892	1802.5	16.0	0.83	0.03	1.83	1800.5	0.31	144.2	0.16	1.04
Catch-weighted											
PAU 2 (T)	137	219.0	7.3	0.10	1.04	0.37	212.3	0.36	84.3	0.89	0.59
PAU 2 (O)	263	513.4	26.4	0.69	0.08	0.36	526.5	0.27	146.2	2.61	0.70
PAU 3	185	260.4	35.4	0.18	44.76	0.37	260.0	0.00	212.3	7.70	0.62
PAU 4	278	322.3	17.7	0.75	0.06	0.45	324.7	0.30	139.9	1.04	0.76
PAU 5A	299	566.0	49.2	0.33	44.76	0.66	565.9	0.00	300.3	6.24	1.00
PAU 5B	331	653.9	29.9	0.69	0.07	0.45	667.1	0.58	134.6	0.78	0.79
PAU 5D	274	523.0	18.0	0.89	0.02	0.39	524.6	0.34	150.5	0.00	0.67
PAU 6	150	268.3	10.8	0.86	0.00	0.64	271.4	0.19	131.1	2.15	1.01
PAU 7	892	2010.1	15.7	0.95	0.00	0.75	1990.9	0.38	146.2	0.00	1.13
Shape-penalty											
PAU 2 (T)	137	228.6	9.8	0.01	0.08	0.58	212.4	0.33	85.0	1.15	0.62
PAU 2 (O)	263	513.3	26.0	0.70	0.07	0.50	527.5	0.32	145.1	2.00	0.73
PAU 3	185	265.4	14.6	0.49	0.07	0.55	269.1	0.22	119.7	1.58	0.72
PAU 4	278	322.3	17.7	0.75	0.06	0.60	324.9	0.29	140.4	1.21	0.79
PAU 5A	299	570.1	18.6	0.75	0.07	0.85	571.5	0.18	153.0	1.89	1.08
PAU 5B	331	653.6	29.7	0.70	0.06	0.60	667.5	0.54	135.2	1.09	0.83
PAU 5D	274	524.6	18.2	0.83	0.05	0.52	531.0	0.23	159.6	0.70	0.72
PAU 6	150	270.2	14.2	0.65	0.05	0.83	271.6	0.23	130.6	1.27	1.05
PAU 7	892	2024.1	17.6	0.84	0.03	0.97	1994.5	0.31	149.0	0.79	1.19

Table 13: Sites with linked maturity and growth data. The Taranaki region of PAU 2 is identified by “(T)” and the remainder of PAU 2 by “(O)”. Sites are linked based on site name, or in some cases by Statistical Area. The three D’Urville maturity samples are all coded as Statistical Areas 766 and 767, so maturity parameters were estimated for the three samples combined. The distance between the site(s) where maturity and growth data were collected is measured from the reported latitude and longitudes of the samples. In some cases a range in latitude and longitude were reported for the maturity data in which case distance shows the range in distance between the two data sources.

	Maturity data		Growth data		
QMA	Site	Statistical Area	Site	Statistical Area	Distance (km)
PAU 2 (O)	Terakirae	237	Turakirae	237	0.51
PAU 2 (O)	Breaker Bay	237	Breaker Bay	237	0.17
PAU 2 (T)	Cape Egmont	240	Egmont	240	0.00
PAU 2 (T)	Cape Egmont 2	240	Egmont	240	3.61
PAU 2 (T)	New Plymouth	241	New Plymouth	241	0.00
PAU 2 (T)	New Plymouth 2	241	New Plymouth	241	0.09
PAU 2 (T)	Opunake	240	Opunake	240	0.00
PAU 2 (T)	Opunake 2	240	Opunake	240	0.14
PAU 3	Inside Akaroa	333	Inside Akaroa	333	1.05
PAU 3	Scenery Nook	334	Scenery Nook	334	0.11
PAU 5A	Poison Bay	F07	Poison Bay	F07	0.84
PAU 5B	Waituna	S18	Waituna	S18	0.08
PAU 5B	Shelter pt	S65	Port Adventure	S65	
PAU 5D	Catlins west	H14, H12, H13	Boat Harbour	H14	2.36 – 12.99
PAU 7	Campbell	709	Cape Campbell	709	0.14
PAU 7	Port Gore	736	Jackson	736	
PAU 7	D'Urville, Swamp Bay N & S	766,767	D'Urville site 1	766	1.59 – 2.89
PAU 7	D'Urville, Swamp Bay N & S	766,767	D'Urville site 2	766	2.22 – 2.38
PAU 7	D'Urville, Swamp Bay N & S	766,767	D'Urville site 3	766	0.14 – 4.59
PAU 7	D'Urville, Swamp Bay N & S	766,767	D'Urville site 4	766	0.25 – 4.31
PAU 7	D'Urville, Swamp Bay N & S	766,767	D'Urville site 5	767	0.24 – 4.32
PAU 7	D'Urville, Swamp Bay N & S	766,767	D'Urville site 6	767	0.76 – 4.07
PAU 7	Staircase	714	Staircase	714	1.05
PAU 7	Rununder 2	719, 721, 722	Glasgow West	721	4.54 – 4.68

Table 14: The number of years between the length at 50% maturity (L_{50}) and the minimum legal size (MLS) and the maximum length estimated for the Schnute and Inverse-logistic growth increment models by site.

				Years to MLS		Maximum Length	
QMA	Site	MLS	L_{50}	Schnute	Inverse-logistic	Schnute	Inverse-logistic
PAU 2 (O)	Breaker Bay	125	74.1	2.9	3.5	144.9	163.7
PAU 2 (O)	Turakirae	125	91.8	3.0	3.2	143.4	159.5
PAU 2 (T)	Cape Egmont	85	68.8	-	6.3	81.0	106.5
PAU 2 (T)	Cape Egmont 2	85	75.8	-	4.2	81.0	107.6
PAU 2 (T)	New Plymouth	85	56.9	6.8	5.4	86.0	102.7
PAU 2 (T)	New Plymouth 2	85	76.0	4.6	3.2	86.0	103.5
PAU 2 (T)	Opunake	85	66.6	-	-	79.0	84.5
PAU 2 (T)	Opunake 2	85	70.8	-	-	79.0	84.6
PAU 3	Inside Akaroa	125	88.9	-	27.2	122.1	125.9
PAU 3	Scenery Nook	125	89.1	15.7	15.8	185.8	134.9
PAU 5A	Poison Bay	125	94.1	9.1	9.3	130.4	136.7
PAU 5B	Waituna	125	75.3	4.7	4.6	144.9	158.7
PAU 5B	Shelter Pt/Port Adventure	125	103.8	2.6	3.5	133.9	142.6
PAU 5D	Catlins west/Boat Harbour	125	80.5	2.3	2.3	150.9	170.3
PAU 7	Cape Campbell	125	86.7	3.1	4.0	136.1	151.3
PAU 7	Staircase	125	93.6	-	11.5	124.2	136.6
PAU 7	Rununder 2/Glasgow West	125	91.9	1.5	1.5	147.1	176.3
PAU 7	Port Gore/Jackson	125	99.1	3.8	3.8	138.8	155.1
PAU 7	D'Urville 1/Swamp Bay	125	90.1	21.8	10.2	125.3	145.8
PAU 7	D'Urville 2/Swamp Bay	125	90.1	-	7.8	120.8	144.6
PAU 7	D'Urville 3/Swamp Bay	125	90.1	3.9	7.8	136.2	138.2
PAU 7	D'Urville 4/Swamp Bay	125	90.1	5.6	11.9	133.7	133.1
PAU 7	D'Urville 5/Swamp Bay	125	90.1	6.8	7.2	397.1	168.2
PAU 7	D'Urville 6/Swamp Bay	125	90.1	2.6	2.8	400.0	459.8

Table 15: Summary of yield and spawning stock biomass per recruit results for minimum harvest sizes of the current MLS and the current MLS plus and minus 10 mm for sites that have both maturity and growth data. For each minimum harvest size, Ymax is the maximum yield that is obtained at a fishing mortality rate of Fmax, F40% is the fishing mortality rate that results in 40% of the unfished spawning stock biomass and Y40% is the yield (expressed as a fraction of the Ymax for the respective minimum harvest size) obtained when fishing at F40%. The highest yield generated from the alternative minimum harvest sizes is shown in bold.

			MLS - 10 mm				MLS				MLS + 10 mm			
QMA	Site	MLS	Ymax	Fmax	Y40%	F40%	Ymax	Fmax	Y40%	F40%	Ymax	Fmax	Y40%	F40%
PAU 2 (O)	Breaker Bay	125	0.160	0.53	0.85	0.15	0.171	0.98	0.84	0.19	**0.173**	1.00	0.89	0.33
PAU 2 (O)	Turakirae	125	0.156	0.64	0.83	0.15	**0.164**	1.00	0.84	0.21	0.153	1.00	0.97	0.70
PAU 2 (T)	Cape Egmont	85	**0.020**	1.00	0.82	0.24	0.000	-	-	-	0.000	-	-	-
PAU 2 (T)	Cape Egmont 2	85	**0.020**	1.00	0.71	0.15	0.000	-	-	-	0.000	-	-	-
PAU 2 (T)	New Plymouth	85	**0.033**	1.00	0.82	0.18	0.028	1.00	1.00	1.00	0.000	-	-	-
PAU 2 (T)	New Plymouth 2	85	**0.033**	1.00	0.73	0.13	0.028	1.00	0.95	0.65	0.000	-	-	-
PAU 2 (T)	Opunake	85	**0.029**	1.00	0.80	0.23	0.000	-	-	-	0.000	-	-	-
PAU 2 (T)	Opunake 2	85	**0.029**	1.00	0.77	0.20	0.000	-	-	-	0.000	-	-	-
PAU 3	Inside Akaroa	125	**0.078**	1.00	1.00	1.00	0.000	-	-	-	0.000	-	-	-
PAU 3	Scenery Nook	125	**0.073**	1.00	1.00	1.00	0.046	1.00	1.00	1.00	0.019	1.00	1.00	1.00
PAU 5A	Poison Bay	125	**0.108**	1.00	0.87	0.27	0.084	1.00	1.00	1.00	0.000	-	-	-
PAU 5B	Waituna	125	0.114	0.58	0.86	0.16	**0.120**	1.00	0.88	0.24	0.115	1.00	0.98	0.73
PAU 5B	Shelter Pt/Port Adventure	125	0.149	0.95	0.80	0.16	**0.152**	1.00	0.83	0.25	0.012	1.00	1.00	1.00
PAU 5D	Catlins west/Boat Harbour	125	0.178	0.44	0.85	0.14	0.189	0.70	0.85	0.17	**0.198**	1.00	0.86	0.24
PAU 7	Cape Campbell	125	0.133	0.70	0.84	0.17	**0.140**	1.00	0.85	0.24	0.118	1.00	1.00	1.00
PAU 7	Staircase	125	**0.099**	1.00	0.89	0.35	0.004	1.00	1.00	1.00	0.000	-	-	-
PAU 7	Rununder 2/Glasgow West	125	0.185	0.49	0.83	0.14	0.197	0.74	0.81	0.16	**0.208**	1.00	0.81	0.21
PAU 7	Port Gore/Jackson	125	**0.144**	1.00	0.82	0.16	0.142	1.00	0.88	0.31	0.099	1.00	1.00	1.00
PAU 7	D'Urville 1/Swamp Bay	125	**0.054**	1.00	0.99	0.90	0.025	1.00	1.00	1.00	0.000	-	-	-
PAU 7	D'Urville 2/Swamp Bay	125	**0.096**	1.00	0.89	0.38	0.000	-	1.00	1.00	0.000	-	-	-
PAU 7	D'Urville 3/Swamp Bay	125	0.113	0.88	0.84	0.18	**0.116**	1.00	0.88	0.32	0.079	1.00	1.00	1.00
PAU 7	D'Urville 4/Swamp Bay	125	**0.093**	1.00	0.86	0.21	0.089	1.00	0.96	0.64	0.002	1.00	1.00	1.00
PAU 7	D'Urville 5/Swamp Bay	125	0.082	0.70	0.90	0.15	**0.083**	1.00	0.93	0.26	0.079	1.00	1.00	1.00
PAU 7	D'Urville 6/Swamp Bay	125	0.175	0.19	0.94	0.11	0.186	0.22	0.93	0.12	**0.199**	0.26	0.93	0.14

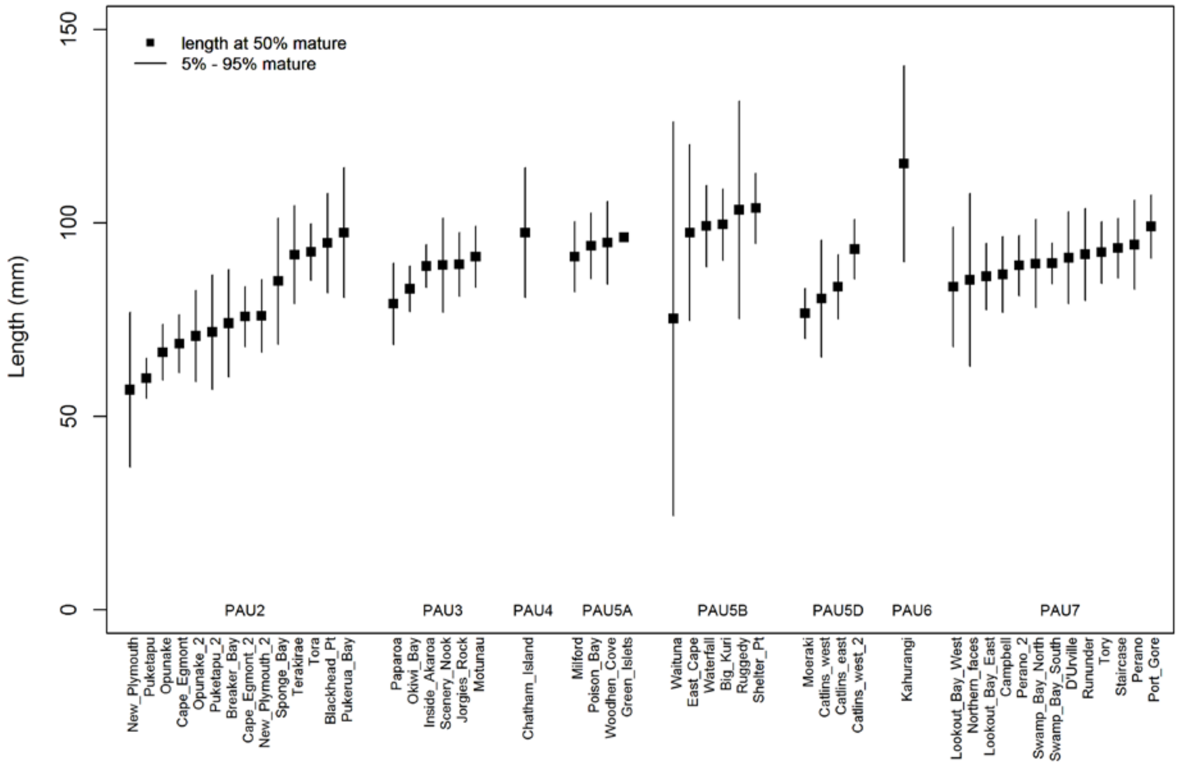

Figure 1: Lengths at 50% maturity and the range for length at 5% to 95% maturity by sampling site within each QMA.

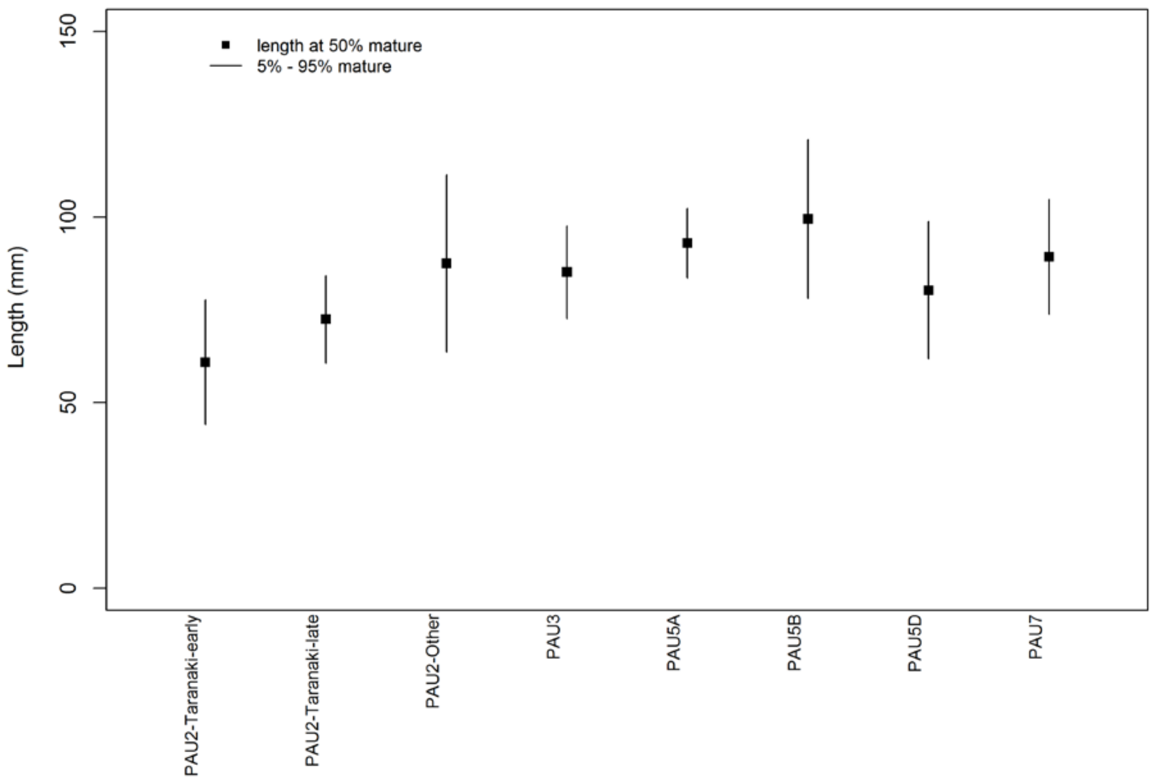

Figure 2: Lengths at 50% maturity and the range for lengths at 5% to 95% maturity by QMA. Note that PAU 2 has been split into early and late Taranaki samples and other sites in PAU 2. PAU 4 and PAU 6 are not shown because they contain only a single sample.

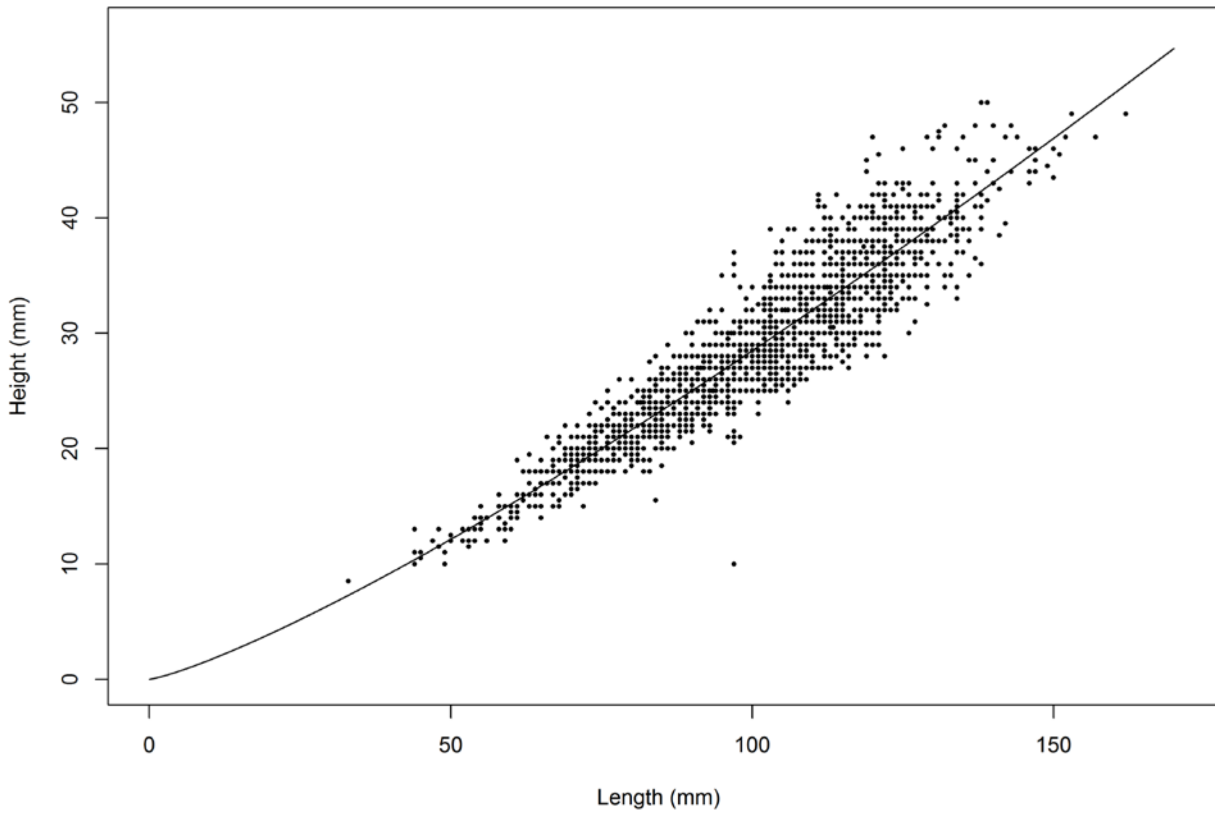

Figure 3: Height versus length for individual paua and the non-linear relationship fitted to the data.

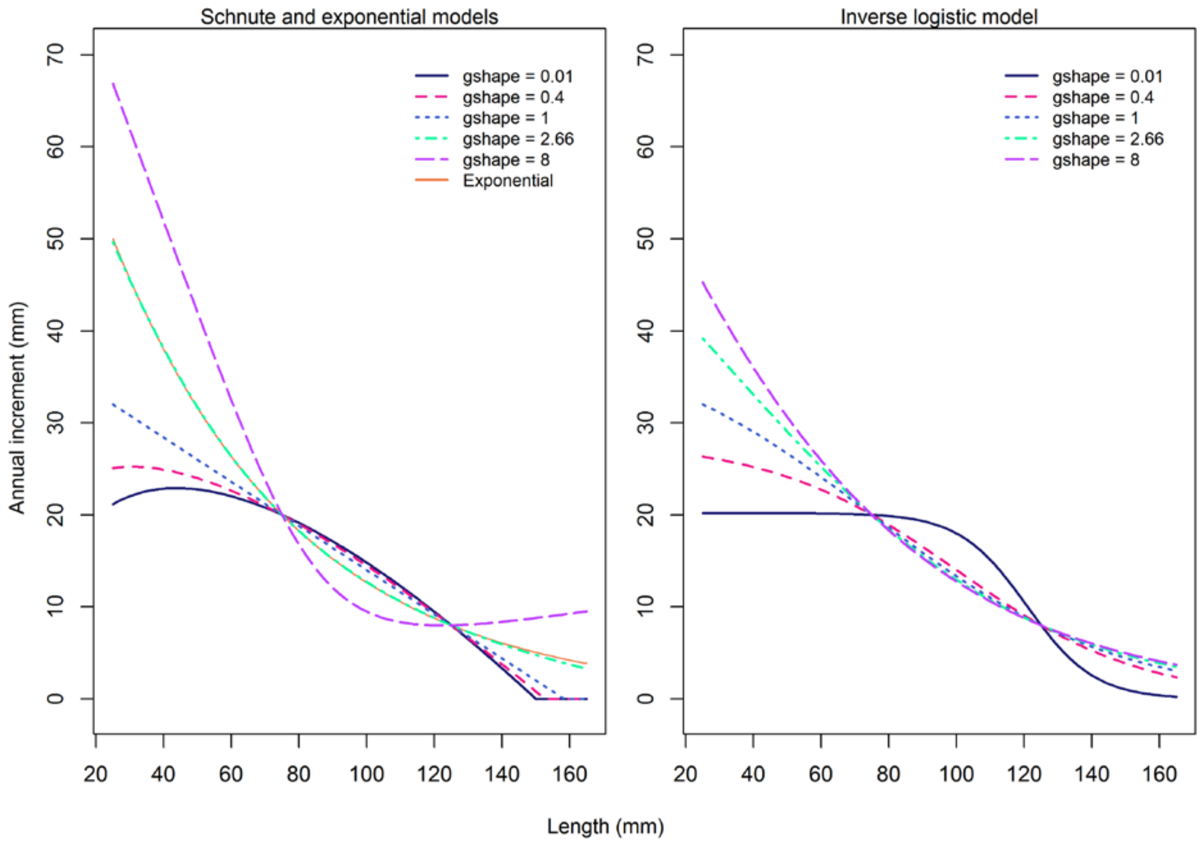

Figure 4: Examples of predicted growth increments for the Schnute, exponential and inverse-logistic growth models with fixed *galpha* and *gbeta* parameters $\left(l_\alpha = 75, l_\beta = 125, g_\alpha = 20, \text{ and } g_\beta = 8\right)$ and a range of *gshape* values. The exponential growth increment model is fully defined by the *galpha* and *gbeta* parameters.

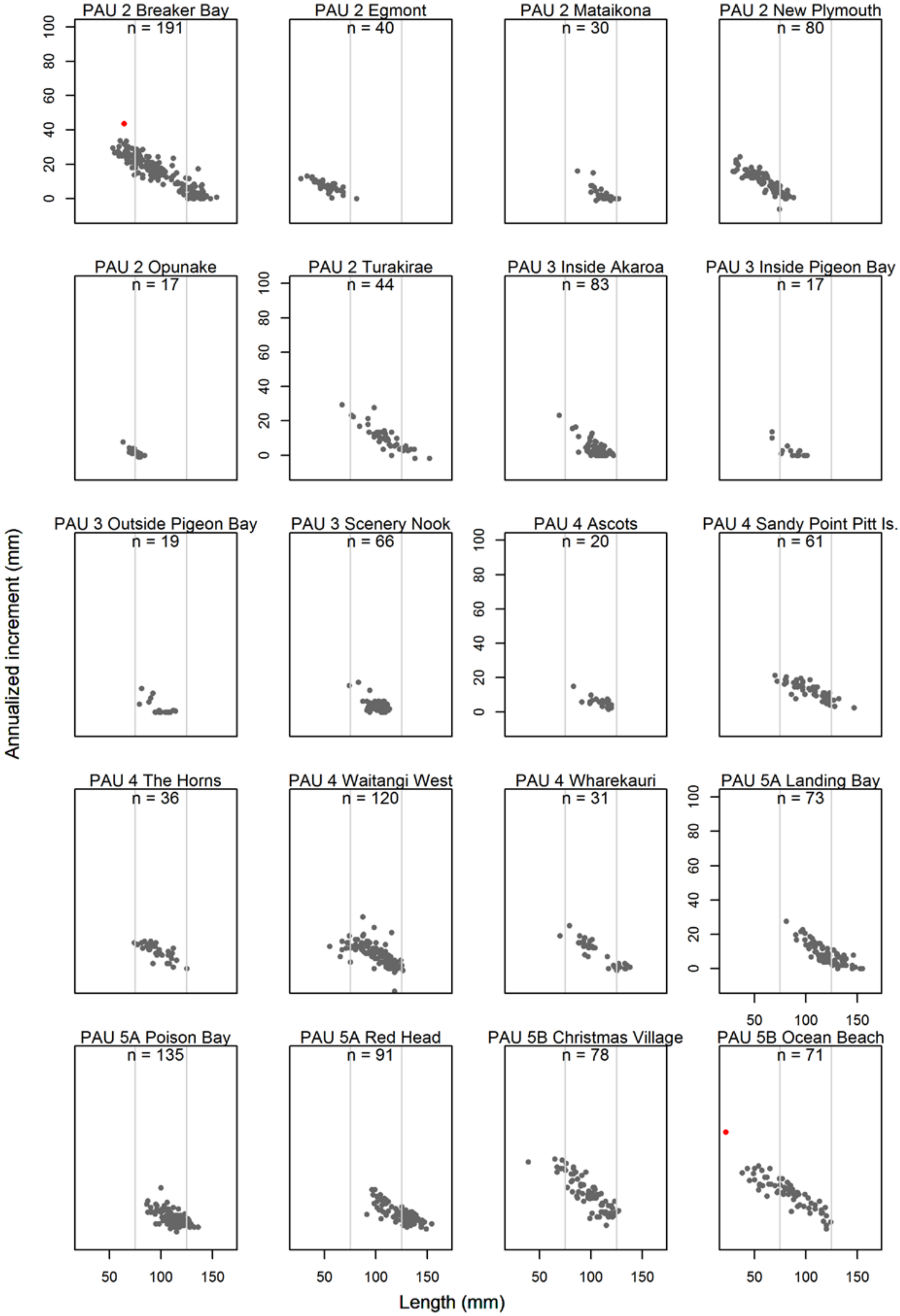

Figure 5: Observed length increments (adjusted to annual estimates) versus initial length by tagging site. Annualized increments of 40 or greater are shown in red.

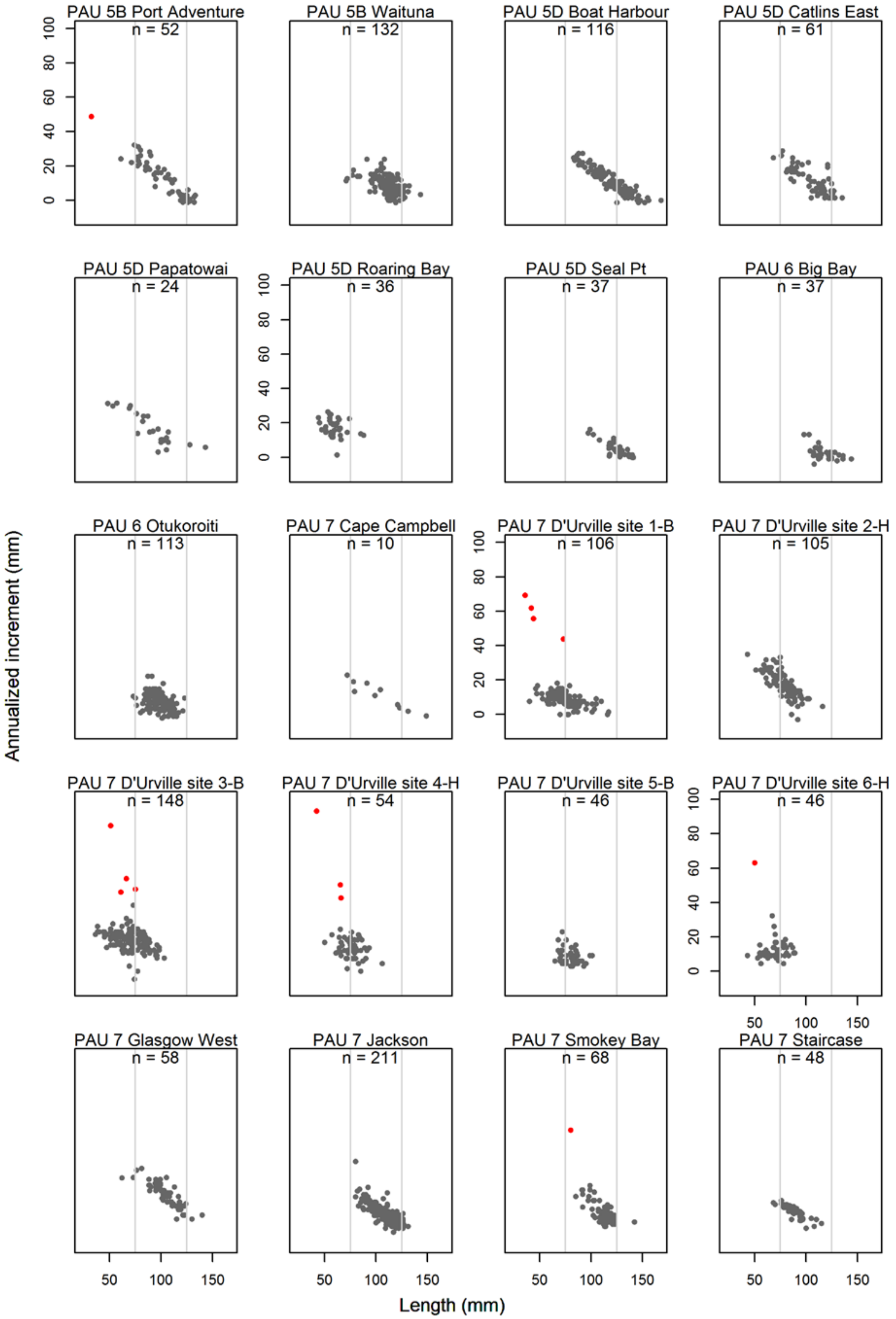

Figure 6: Observed length increments (adjusted to annual estimates) versus initial length by tagging site. Annualized increments of 40 or greater are shown in red.

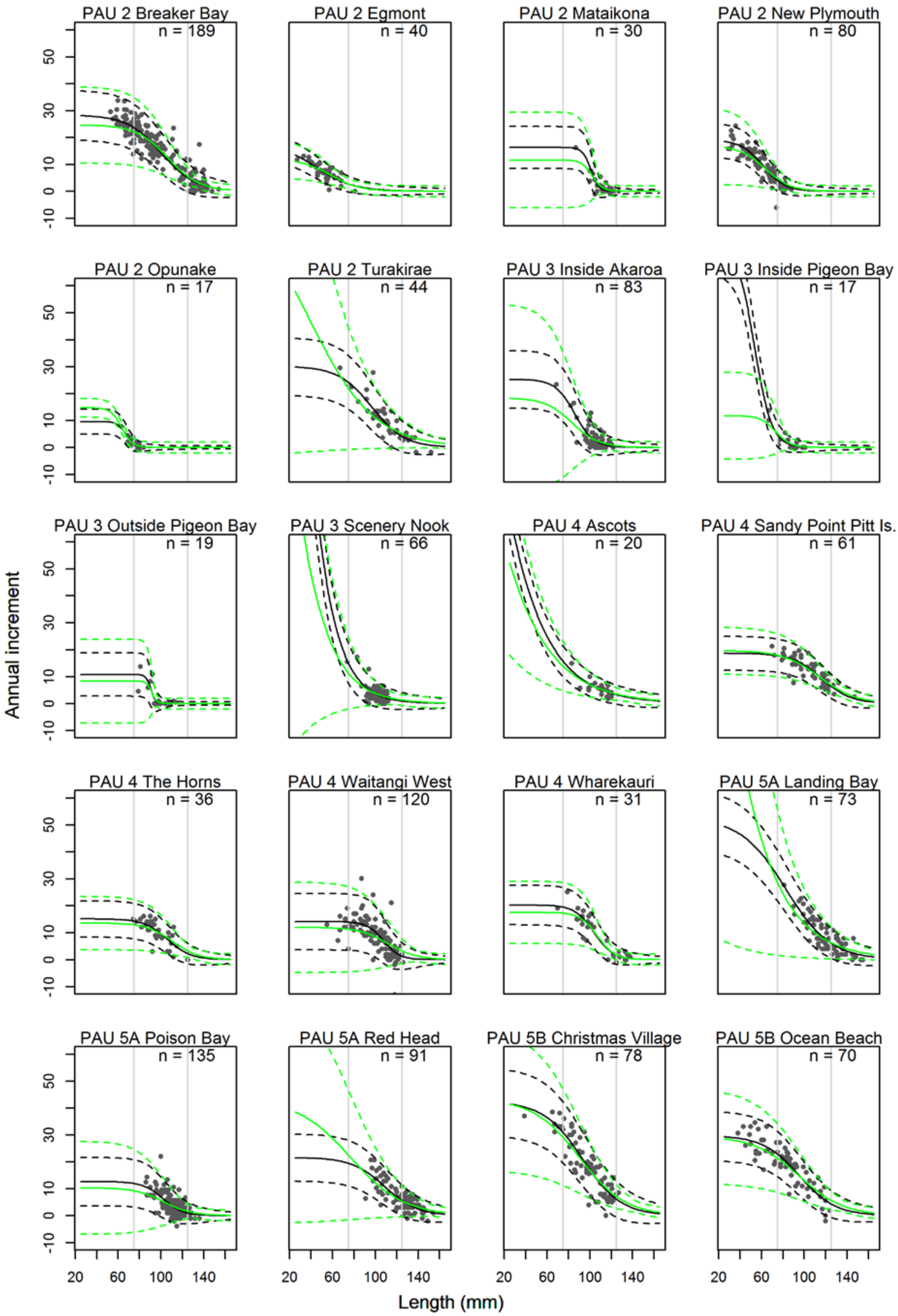

Figure 7: Predicted annual growth increments from fitting the inverse-logistic growth model under two alternative parameterizations for the variance of the growth increment: the paua stock assessment parameterization (green lines) and a proposed alternative parameterization (grey lines). The solid line shows the predicted growth increment and the dashed lines show the 95% limits in the range of the predicted increment.

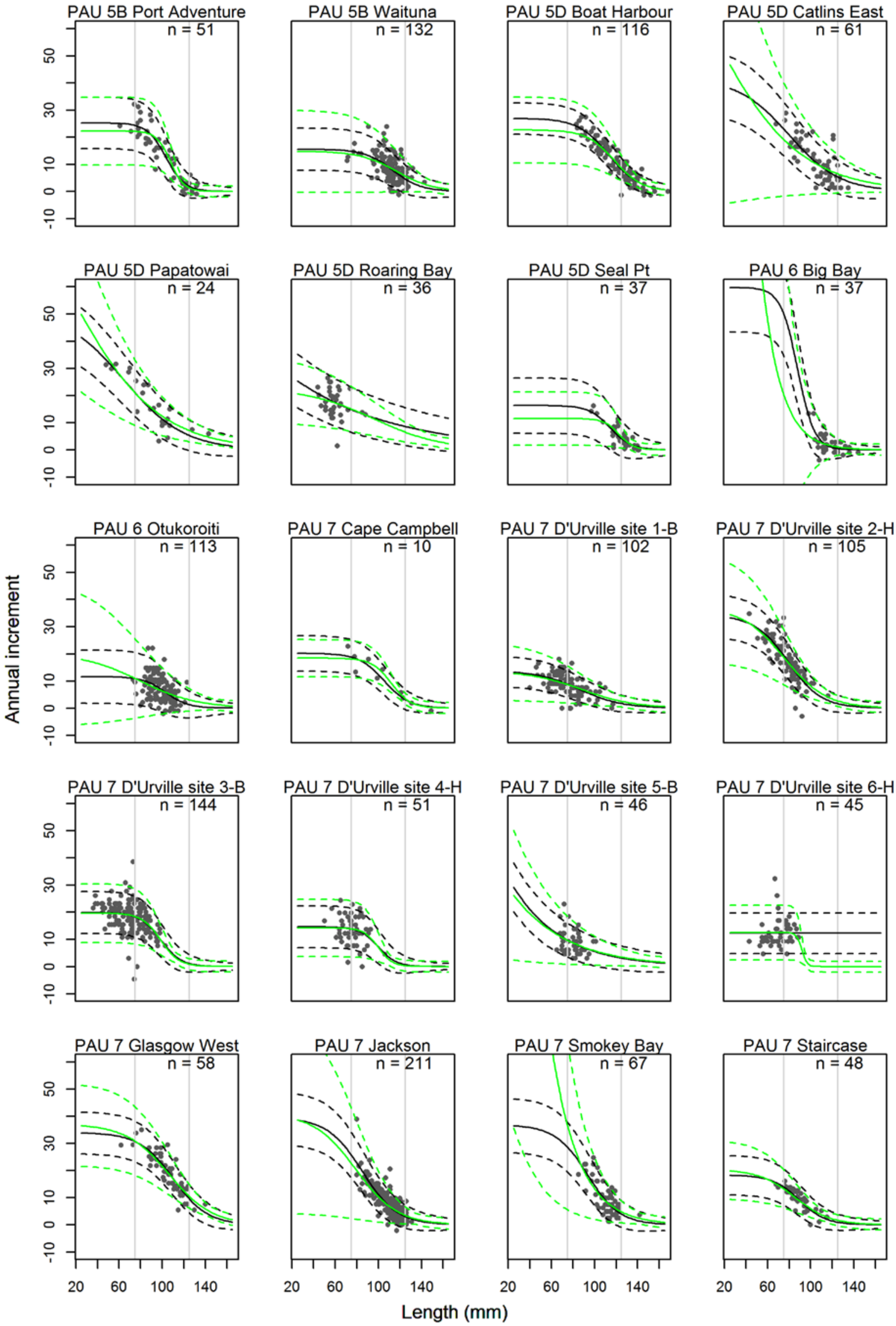

Figure 8: Predicted annual growth increments from fitting the inverse-logistic growth model under two alternative parameterizations for the variance of the growth increment: the paua stock assessment parameterization (green lines) and a proposed alternative parameterization (grey lines). The solid line shows the predicted growth increment and the dashed lines show the 95% limits in the range of the predicted increment.

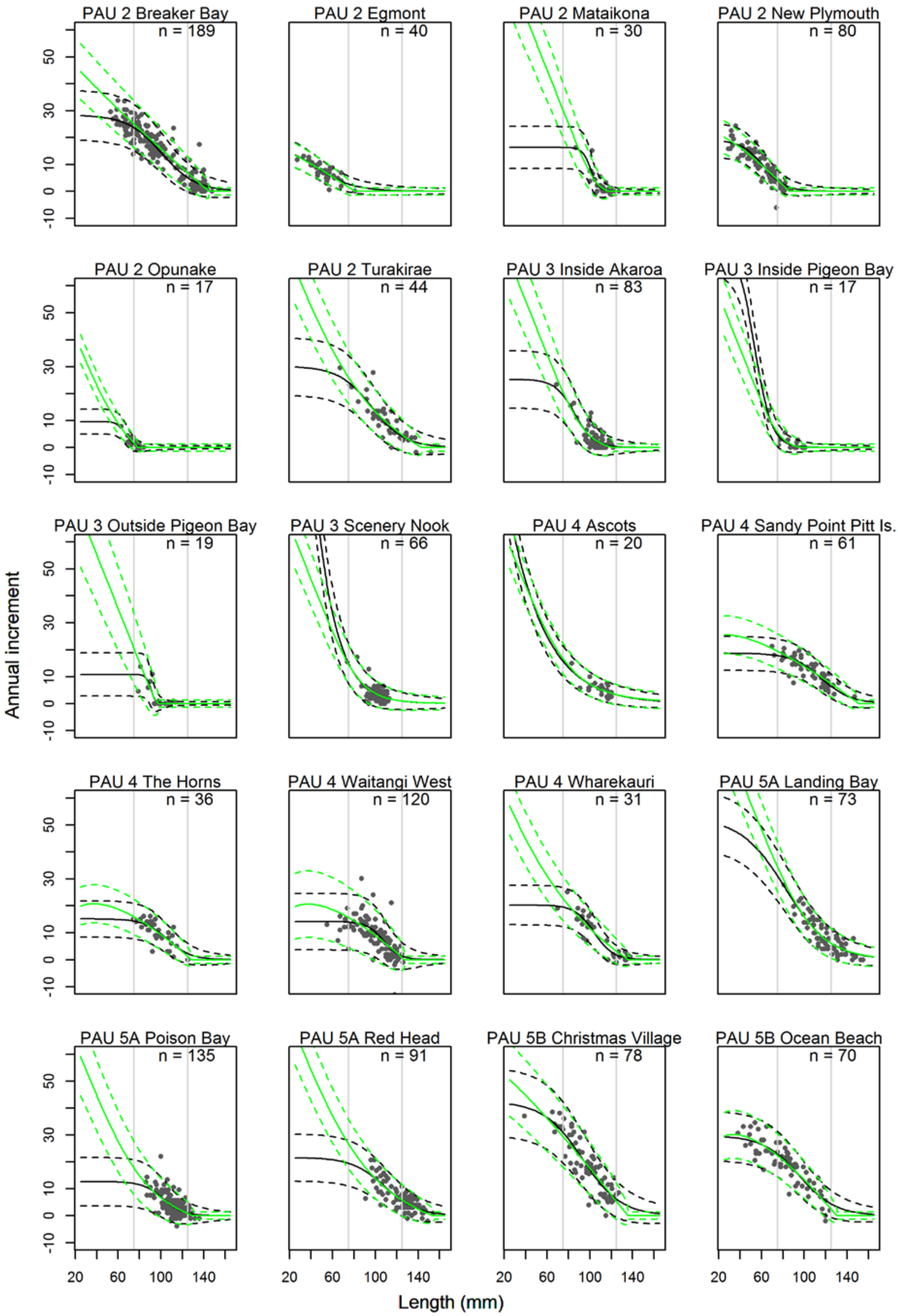

Figure 9: Predicted annual growth increments from fitting the inverse-logistic (grey lines) and Schnute (green lines) growth models to tag recapture data by site. The solid line shows the predicted growth increment and the dashed lines show the 95% limits in the range of the predicted increment.

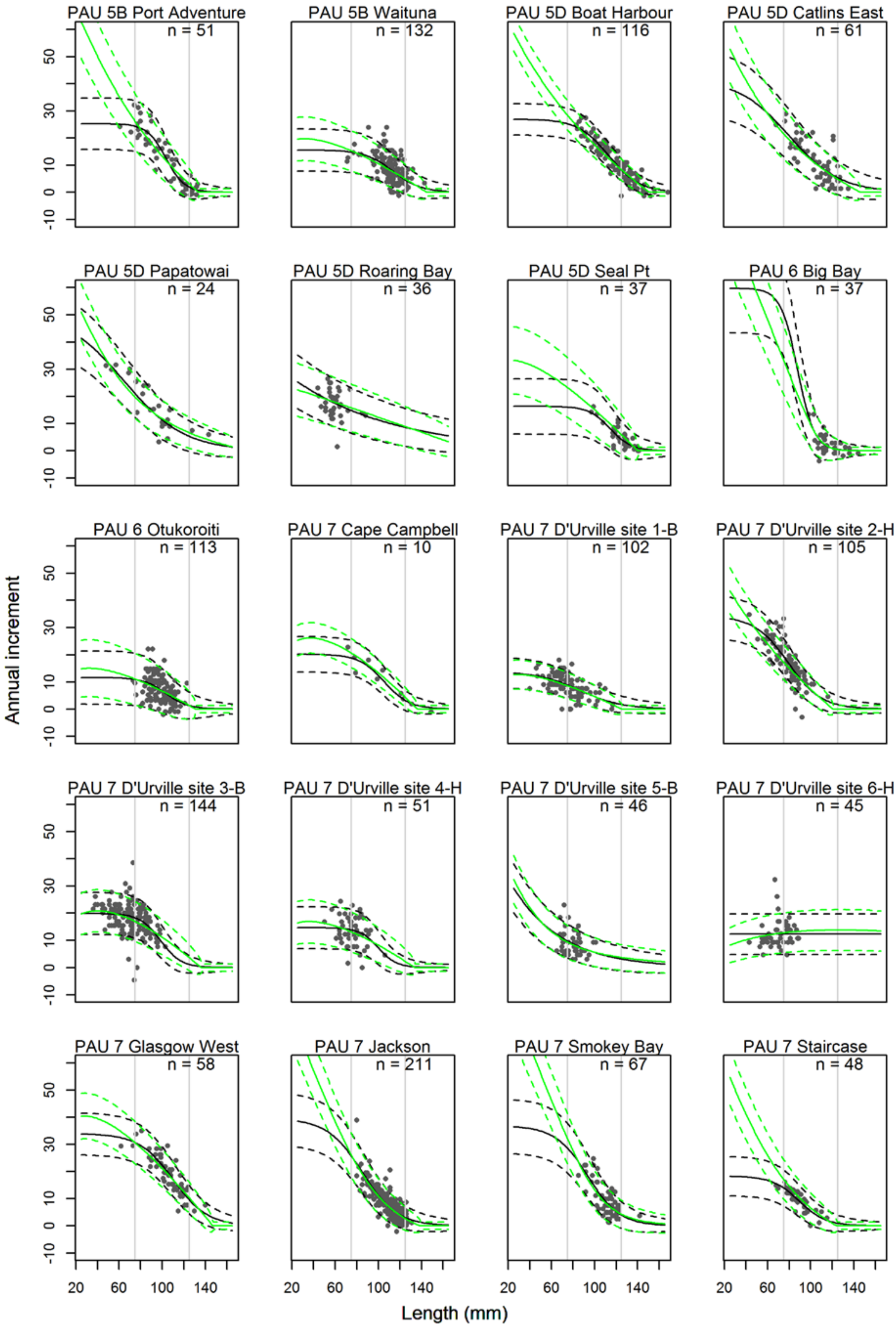

Figure 10: Predicted annual growth increments from fitting the inverse-logistic (grey lines) and Schnute (green lines) growth models. The solid line shows the predicted growth increment and the dashed lines show the 95% limits in the range of the predicted increment.

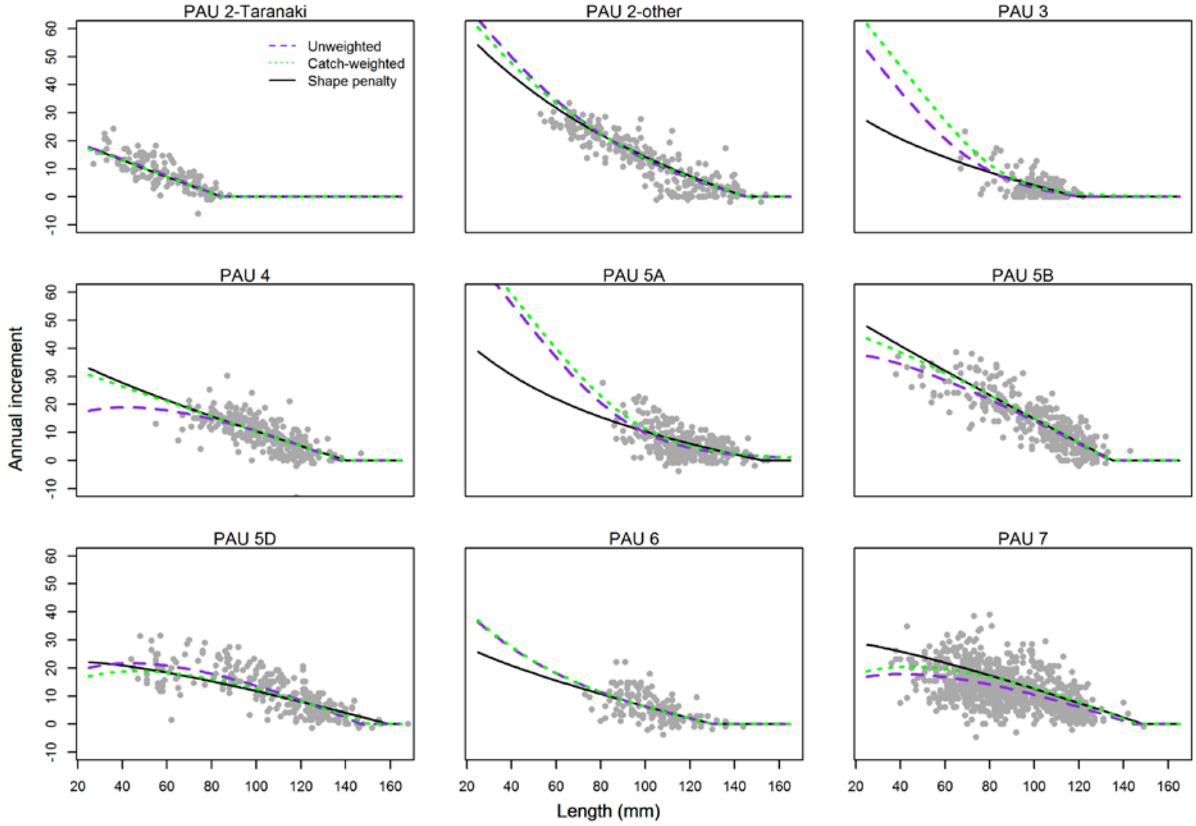

Figure 11: Predicted annual growth increments from three alternative fits of the Schnute growth model to tag recapture data aggregated by QMA. The alternative versions are: unweighted data, catch-weighted data, and a model with a penalty function on the *gshape* parameter.

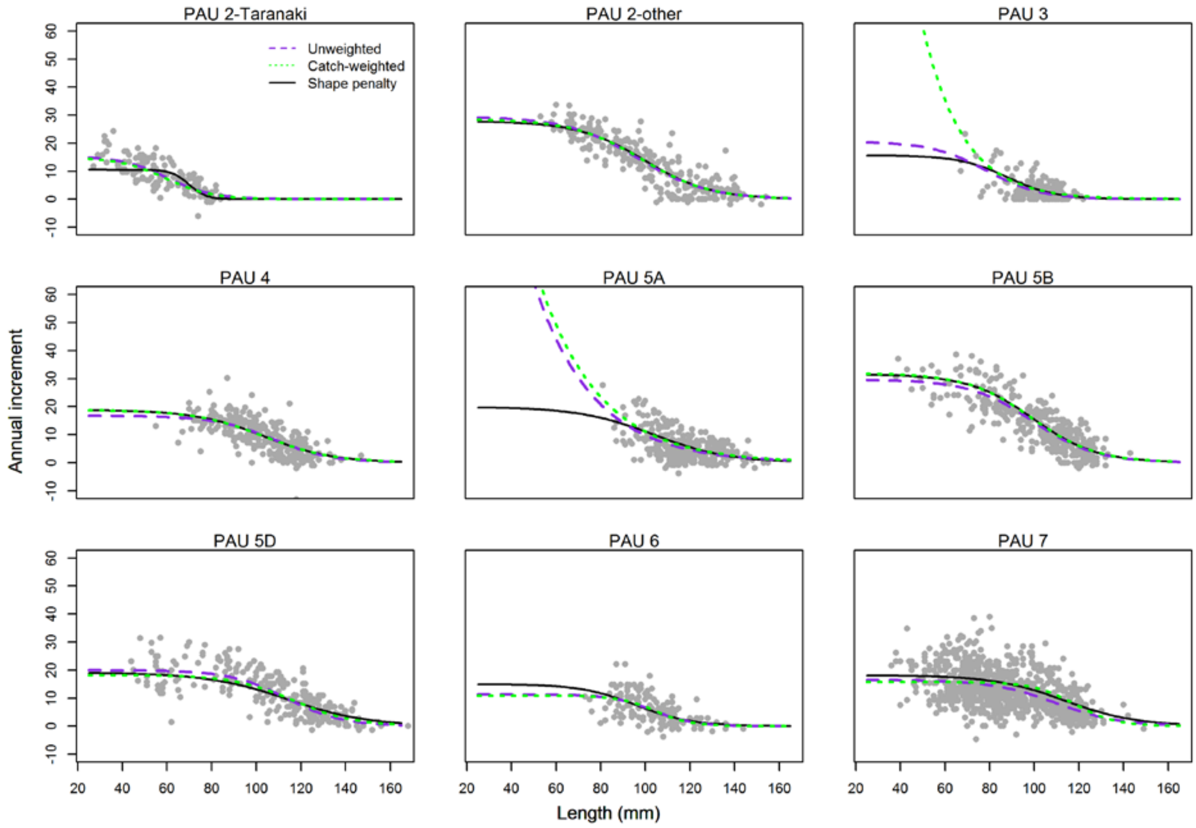

Figure 12: Predicted annual growth increments from three alternative fits of the inverse-logistic growth model to tag recapture data aggregated by QMA. The alternative versions are: unweighted data, catch-weighted data, and a model with a penalty function on the *gshape* parameter.

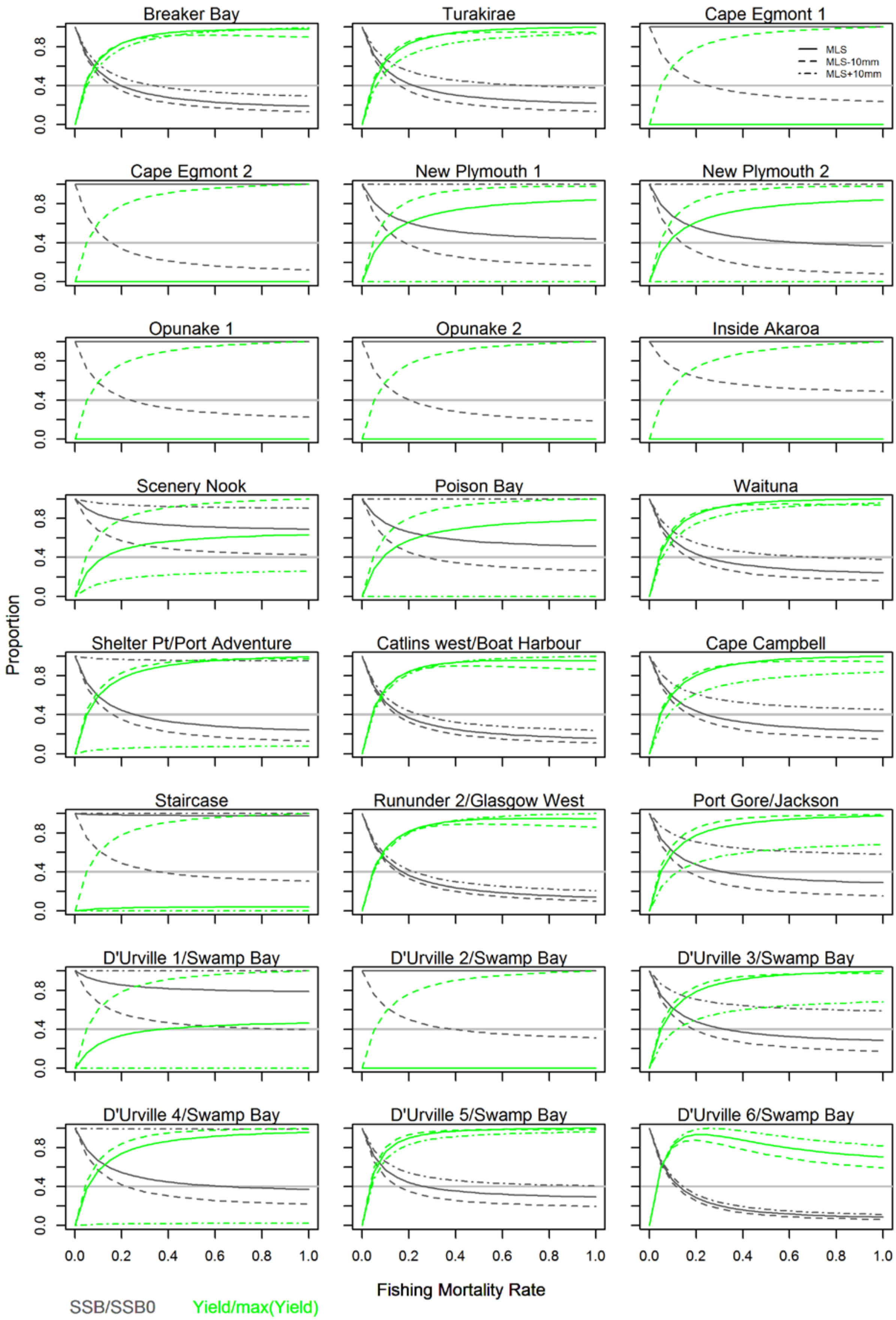

Figure 13: Yield per recruit and spawning stock biomass per recruit (both relative to their maximum) versus fishing mortality rate for minimum harvest sizes equal to the current MLS and 10 mm greater or less than the MLS.