Estimates of population status of humpback chub (*Gila cypha*) in the Grand Canyon based on a length-based mark-recapture assessment model.

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Abstract

A length-structured population model that incorporates mark-recapture data was developed to estimate abundance of humpback chub (*Gila cypha*) in the Grand Canyon between 1989 and 2011. The model was fit to observations on catch-at-length and capture-recapture data from sampling programs that employed a variety of gear types including electrofishing, tramel netting, and hoop nets. Previous assessment models were age-based and have been shown to produce biased estimates of recent recruitment estimates. The age-structured model was also limited to data on fish that were greater than 150mm total length; the minimum size required for tagging. The length-structured model developed here makes no assumptions about age of individual fish and is also fit to catch-at-length data for fish that are too small to tag. Model outputs are based the number of fish greater than a specified size, or in a fixed size interval, there are no age-based results.

Contents

1 Introduction

In this report, I develop a length-structured mark-recapture model (hereafter, LSMR) where the accounting system for population numbers is based purely on length. The model is a statistical catch-at-length model, where the initial length distribution and recruitment each year are treated as latent variables to be estimated by fitting the model to a series of catch-at-length observations take over a period of time. A separable function is developed to estimate the year and size effect in observed catch-at-length data. The statistical nature of the model is very similar to that of Fournier and Archibald (1982), but is based on catch-at-length rather than catch-age data. The model is also fit to length-based capture-recapture data, where the growth and survival of tagged animals is updated at each time step and the predicted ratio of marked and unmarked fish-at-length is used to estimate the length-based recapture rates.

2 Methods

There are two major methodological components in this length-based model: (1) the development of an individual based model (IBM) for simulating a capture recapture program, and (2) a statistical catch-at-length mark-recapture model to estimate the number of individual fish in each length-class in each sampling year. A detailed description of the IBM simulation model is provided in the appendix; in short, this simulation model generates a matrix of the number of fish captured-at-length, a matrix of the number of newly marked fish released-at-length, and a matrix of marked fish recaptured-at-length. The remained of this section is a detailed analytical description of the statistical catch-at-length model used to estimate the abundance-at-length of humpback chub in the Grand Canyon.

The following is a description of the analytical model for the length-structured mark-recapture model (hereafter, LSMR) used in this assessment. I present the analytical model in the form of a table (Table 1) where the order in which model equations are presented also represent the order in which the calculations proceed in the computer code. Equations presented in each table are referenced, for example, as (T1.1), where the T1 refers to Table 1, and the .1 refers to the first equation in that table. The LSMR model was implemented in AD Model Builder (Fournier et al., 2011), and the template code is available in the appendix of this document as well as a Git code repository (`https://code.google.com/p/lsmr-project/`). The description of the Length-Structured Mark-Recapture (LSMR) model is broken down into: input data, estimated parameters, dynamics of numbers-at-length, capture probability, and negative log-likelihoods and prior densities.

The following notation is used to define the dimensions of various variables. Vector quantities are designated with an an arrow ($\vec{x}$) or with a single subscript, and matrix is denoted by boldface uppercase letters ($\mathbf{X}$) and where two subscripts are shown denotes the element specific calculation. Higher dimensional arrays are indicated by normal upper case letters with 3 or more subscripts.

2.1 Input data

The model dimensions consists of time intervals (year indexed by i) and length intervals (index by j, T1.1). Capture-recapture data for the humpback chub have been collected on an annual basis since May 1, 1989, and the latest capture record in this analysis is February 27, 2012. The principle input data for LSMR consists of model dimensions (e.g., years, length intervals Λ), a matrix of catch-at-length data $\mathbf{C}$ for each year, the number of new marks released-at-length $\mathbf{M}$, and the number of recaptured marks-at-length $\mathbf{R}$.

2.1.1 Processing length frequency data

At the time of writing this report, there were a total of 81,812 records in the database for humpback chub, of which 35,696 are unique individuals (some of which may occur in the database only once). Details on the construction of Tables 4–10 can be found in Appendix

C. In short, the length composition and mark-recapture information, along with summary statistics about the number of trips, days fished and other units of effort were obtained.

The length composition of the newly marked and recaptured individuals each year were compiled in tables (Appendix C) and bar charts to characterize recruitment and growth of newly marked and previously marked HBC, respectively.

2.2 Estimated parameters & parametric functions

An array of estimated parameters (T1.5) is denoted by Θ and consists of $9 + (2I - 1) + J$ unknowns, where I is the total number of time steps (years) and J is the total number of length intervals.

Natural mortality is a function of length (T1.6), where the natural mortality at the asymptotic length M_∞ is estimated from the data. Note that in (T1.6) the estimated natural mortality rate is confounded with asymptotic length l_∞ which is also an estimated parameter along with the von Bertalanffy growth coefficient k. Selectivity is also assumed to be a parametric function of length (T1.7) where l_x and g_x represent length-at-50% vulnerability and the standard deviation of the logistic function, respectively.

2.3 Growth transition

The growth parameters are used to calculate a vector of growth increments $\vec{\Delta}$ assuming von Bertalanffy growth (T1.8). An additional parameter β is used to characterize the variability in annual growth increments for individual fish. The asymptotic length l_∞ is defined as the average asymptotic length for a population of fish. It is assumed in (T1.8) that individuals greater than l_∞ continue to grow at a much reduced rate k; this is accomplished by exponentiating the growth increment equation $((l_\infty - x_j)(1 - \exp(-k\tau)))$, adding 1.0, and taking the natural logarithm ensuring that (T1.8) remains positive for all positive values of l_∞, k, and Λ.

The model assumes that the distribution of size transitions from length bin x_j to subsequent length bins x'_j follows a gamma distribution (T1.9). The mean of this function is denoted by the growth increment (Δ_j) and a variance equal to $\Delta_j \beta$. Each row of the size transition matrix $\mathbf{P}$ is normalized to sum to 1.0, and $\mathbf{P}_{j,j'} = 1.0$ when $j = j' = J$, where J is the number of length intervals (i.e., individuals in the last length interval represent a plus group).

There is also an alternative to jointly estimating a size transition matrix based on mark recapture data. A series of size transition matrices based on annual growth increments for humpback chub captured and recaptured in the subsequent year was also constructed. Details are outlined in Appendix D.

2.4 Size distribution of new recruits

Newly recruiting individuals at each time step are assumed to have a distribution of lengths that follows a gamma distribution (T1.10), where $\vec{p}$ represents the probability of a new recruit being in size interval x_j. Two parameters (μ and σ) corresponding to the mean and the coefficient of variation of the gamma distribution, respectively, are jointly estimated in the model. Note that the vector $\vec{p}$ is also normalized to sum to 1.0.

2.5 Initial states

A matrix of the total numbers-at-length in a given time step is denoted by $\mathbf{N}$, and the total number of marked individuals at large is denoted by $\mathbf{T}$, (T1.11). To initialize the vector of numbers-at-length in the initial year ($i = 1$), a J by J matrix of recruits prior to the initial year $\mathbf{R}$ is constructed using (T1.12), where $\ddot{R}$ and $\vec{\eta}$ is an estimated scaler and vector respectively. Note that the additional constraint of $\sum_j \eta_j = 0$ is also required to properly estimate the scaler $\ddot{R}$.

The initial numbers-at-length in the initial year is based on the recursive equation defined by (T1.13). This recursion occurs J times where the initial recruits in the first iteration survive at a rate $\exp(-\vec{m})$ and then grow based on the size transition matrix $\mathbf{P}$. In the second recursion, the next vector of new recruits is added and the survival and growth repeats. Note that if $\vec{\eta} = 0$, then a stable size distribution is set up based on the natural mortality, size transition and initial recruitment. The addition of $\vec{\eta}$ allows for a no stable size distribution to be set up in the initial year.

2.6 Dynamics of numbers-at-length

The size transition matrix $\mathbf{P}$ is the key component when modelling a population using length and not age. First, a matrix of annual recruits distributed over size intervals based on $\vec{p}$ is constructed in (T1.14), where $\bar{R}$ is the average recruitment over all years except the initial year, $\vec{\nu}$ is a vector of annual recruitment deviates. The vector of numbers-at-length in the next time step τ is given by (T1.15), where $\vec{R}_i$ is the corresponding row of recruitment from (T1.14).

2.7 Capture probability

Capture probability of fully selected fish at each time step is an unknown parameter to be estimated from the data. A total of $I + 1$ capture probability parameters are estimated (T1.16), where $\bar{f}$ is a scaler and $\vec{\zeta}$ is a vector of annual deviates with the constraint $\sum_i \zeta_i = 0$.

2.8 Predicted captures and recaptures

Predicted captures of unmarked and marked fish are based on the average number of fish available over each time step. The total number of marked and unmarked fish captured at each time step τ is denoted by $\hat{C}$, and in (T1.17) no additional mortality associated with handling and tagging unmarked fish was assumed. Handling mortality could easily be incorporated into the catch equations, however, it is completely confounded with the capture probability and in this case not estimable without additional information. The predicted number of recaptured individual fish ($\mathbf{R}$) is based on the same catch equation T1.18 and an estimate of the total number of tags at large ($\mathbf{T}$). For the initial time step, the total number of tags at large is $\mathbf{T} = 0$, as no fish have been tagged. For time steps greater than 1, the total number of tags at large is based on the recursive survival, growth and recruitment of newly marked animals ($\mathbf{M}$). This recursive equation is defined by (T1.20), where it is assumed that tagged and untagged individuals have the same natural mortality rate and size transition matrix. The number of newly marked fish at each time step is based on the difference between the total catch and number of recaptured fish in the total catch (T1.19).

2.9 Residuals & negative log likelihoods

Information for global scaling is a function of the total number of fish captured, the capture probability and the mark rate.

$$0.5\sum_{i=1}^{I}\ln\left[2\pi(\epsilon+0.1/I)\right]+I\ln(\tau)-\sum_{i=1}^{I}\ln\left[\exp\left\{\frac{-(o_i-p_i)^2}{2\pi(\epsilon_i+0.1/I)\tau^2}\right\}+0.01\right] \qquad (1)$$

3 Results

3.1 Sampling effort

The database provided for this project contains only records in which humpback chub (HBC) were captured, therefore summary statistics regarding effort for hoop nets and tramel nets are regarded as incomplete because sets that did not capture HBC were not included in these data.

Sampling intensity was greatest in the early 1990s and more recently in the mid to late 2000s, with a peak of 24 trips in 1993 with roughly 174 days fishing on the river (Table 3). The vast majority of humpback chub sampled are captured in hoop nets, and although these data do not include sets with zero catch, trends in the ratio of hoop net catch to hoop net sets has been increasing since about 2005 (Table 3).

3.2 Length composition

The length composition of all 81,812 records is summarized in Figure 1 where the area of each bubble is proportional to the number of fish measured in that length interval. Note that individual fish may appear more than once in each year as these data summarize the total number of humpback chub captured and measured in a calendar year. Prior to 1999, individuals less than 150 mm were rarely entered into the database and there are no records of recapturing fish tagged prior to 1999 that were less than 140 mm total length. Starting sometime in 1999, individuals >100 mm TL and less than 150 mm were being marked as there have been recoveries associated with these individuals (see panels 1999 and later in

Table 1: Data, parameters, and analytical procedures for the length-based mark-recapture model.

INDEXES, DATA & CONSTANTS		
index for time, index for length interval	i, j	(T1.1)
time step	τ	(T1.2)
set of midpoints of length intervals	$\Lambda = \{x_1, \ldots, x_J\}$	(T1.3)
catch, new marks, recaptures	$\mathbf{C}, \mathbf{M}, \mathbf{R}$	(T1.4)
PARAMETERS & DERIVED VARIABLES		
estimated parameters	$\Theta = \{\ddot{R}, \bar{R}, \bar{f}, M_\infty, l_\infty, k, \beta, \mu, \sigma, l_x, g_x, \vec{\eta}, \vec{\nu}, \vec{\zeta}\}$	(T1.5)
mortality-at-length	$\vec{m} = \dfrac{M_\infty l_\infty}{\Lambda}$	(T1.6)
selectivity-at-length	$\vec{s} = \dfrac{1}{1 + \exp(-(\Lambda - l_x)/g_x)}$	(T1.7)
growth increment	$\vec{\Delta} = \ln(\exp[(l_\infty - \Lambda)(1 - \exp(-k\tau))] + 1)$	(T1.8)
length transition probability	$\mathbf{P}_{j,j'} = \displaystyle\int_{x_{j'}-x^*}^{x_{j'}+x^*} \frac{x_{j'}^{(\Delta_j/\beta - 1)} e^{x_{j'}/\beta}}{\beta^{\Delta_j/\beta}\Gamma(\Delta_j/\beta)} dx_{j'},$	
	$\displaystyle\sum_{j'=1}^{J} P_{j,j'} = 1$	(T1.9)
length distribution of recruits	$\vec{p} = \dfrac{1}{\Gamma(a)b^a}\Lambda^{a-1}\exp(-\Lambda/b), \quad a = \dfrac{1}{\sigma^2}, b = \mu/a$	(T1.10)
total numbers, marked numbers	$\mathbf{N}, \mathbf{T}$	(T1.11)
INITIAL STATES ($i = 1$)		
recruits-at-length prior to 1989	$\mathbf{R} = \ddot{R}\exp(\vec{\eta})(\vec{p})^T$	(T1.12)
initial numbers-at-length	$\vec{N}_i^{j+1} = \vec{N}_i^{j}\exp(-\vec{m})\mathbf{P} + \vec{R}_j$	(T1.13)
DYNAMIC STATES ($i > 1$)		
new recruits	$\mathbf{R} = \bar{R}\exp(\vec{\nu})(\vec{p})^T$	(T1.14)
Numbers-at-length	$\vec{N}_{i+\tau} = \vec{N}_i\exp(-\vec{m}\tau)\mathbf{P} + \vec{R}_i$	(T1.15)
Capture probability	$f_i = \bar{f}\exp(\zeta_i)$	(T1.16)
Catch-at-length	$\hat{C}_{i,j} = \dfrac{N_{i,j} f_i s_j (1 - \exp(-m_j\tau))}{m_j\tau}$	(T1.17)
Recapture-at-length	$\hat{R}_{i,j} = \dfrac{T_{i,j} f_i s_j (1 - \exp(-m_j\tau))}{m_j\tau}$	(T1.18)
New marks-at-length	$\hat{M}_{i,j} = \hat{C}_{i,j} - \hat{R}_{i,j}$	(T1.19)
Tagged numbers-at-length	$\vec{T}_{i+\tau} = \vec{T}_i\exp(-\vec{m}\tau)\mathbf{P} + \vec{\hat{M}}_i$	(T1.20)

Table 2: caption

RESIDUALS

Total catch numbers

$$\delta_i = \ln\left(\sum_j C_{i,j}\right) - \ln\left(\sum_j \hat{C}_{i,j}\right) \qquad \text{(T2.1)}$$

NEGATIVE LOG LIKELIHOODS

total catch

$$\ell_1(\Theta) = 0.5I\left[\ln(2\pi) + \ln(\sigma)\right] + \sum_{i=1}^{I} \frac{\delta_i^2}{2\sigma^2} \qquad \text{(T2.2)}$$

Table 3: Number of trips, days fished, unique sets, hoop and tramel net sets, other gears, catch of humpback chub in hoop nets and tramel nets, and the corresponding arithmatic CPUE for each gear. Note that these CPUE trends should not be used as a relative abundance index because zero catch of HBC have been excluded from the effort data.

Year	Trips	Days	Sets	Hoop	Tramel	Other	Hoop Ct	Tramel Ct	Hoop CPUE	Tramel CPUE
1989	2	29	256	182	82	−8	560	321	3.08	3.91
1990	4	38	150	82	64	4	473	140	5.77	2.19
1991	14	177	1370	976	352	42	3978	711	4.08	2.02
1992	19	172	2104	1731	322	51	4740	636	2.74	1.98
1993	24	174	1941	1473	374	94	6313	876	4.29	2.34
1994	8	133	1032	962	70	0	2997	239	3.12	3.41
1995	7	84	543	511	32	0	2190	118	4.29	3.69
1996	2	34	105	65	34	6	113	72	1.74	2.12
1997	3	38	91	48	41	2	58	153	1.21	3.73
1998	8	51	188	165	17	6	377	58	2.28	3.41
1999	9	47	201	169	19	13	392	54	2.32	2.84
2000	12	56	618	546	58	14	1150	81	2.11	1.40
2001	7	58	1381	1215	167	−1	4003	233	3.29	1.40
2002	9	61	1057	1048	6	3	3346	10	3.19	1.67
2003	15	94	1053	950	14	89	2058	27	2.17	1.93
2004	19	115	1083	734	29	320	1621	49	2.21	1.69
2005	17	119	1323	914	103	306	1919	174	2.10	1.69
2006	19	120	1221	995	31	195	3442	58	3.46	1.87
2007	13	74	1413	1079	144	190	4352	225	4.03	1.56
2008	14	208	2655	1145	0	1510	4838	0	4.23	
2009	10	235	5059	1466	0	3593	7706	0	5.26	
2010	11	99	2568	1266	31	1271	5294	71	4.18	2.29
2011	5	218	3009	1099	0	1910	5376	0	4.89	
2012	1	35	89	0	0	89	0	0		

Figure 7). In 2001, a large number of fish between the 100-150mm length interval were captured and tagged (Figure 1). Similarly, starting in 2009 a large number of fish in the 100-150mm length interval have been tagged. Unfortunately, there are no clear modes of numbers-at-length that appear to progress through the size distribution over time; however, these data were obtained from a variety of sampling gears in a variety of locations and do not represent a standardized sampling program that would allow for monitoring of strong/weak cohorts progressing through the size composition data.

The majority of humpback chub are sampled through the months of April-June and in the fall in September-October (Table 4). Also, the majority of humpback chub are sampled using primarily hoop nets and less so with tramel nets (Table 5). In an attempt to reduce the level of confounding associated with the many different gear types that sample humpback chub, the length composition data was partitioned into two general gear types: (1) hoop nets, ranging in diameter from 2' to 4' with and without bait, and (2) tramel nets of various lengths. Catch-at-length data by year for hoop nets is shown in Figure 2. In the initial years (1989-1990), there are very few recaptures as the marked proportion in the population was relatively low; in subsequent years the marked proportion recaptured increases. Sampling effort was very low in 1996-1998, resulting in very few fish captured. As time progresses the number of newly marked large fish (greater than 300mm) decreases as most of these individuals were marked in previous years.

Far fewer humpback chub have been captured in tramel net gear in comparison to hoop-nets, and this is largely due the less frequent use of tramel nets. Similar patterns in the mark rates were also obtained with the tramel net catch (Figure 3). Since 1994, tramel net effort for catching humpback chub has been greatly reduced (Table 3). In 2001, the number of tramel net sets with non-zero catches of humpback chub increased to 167 sets, with a very large recapture proportion for fish greater than 300mm. This observation is also consistent with the large recapture proportion of >300mm fish in the hoop net sets in 2001. Similarly, in 2007, 225 humpback chub were caught in 144 non-zero tramel net sets and the majority of these fish were less than 250mm and never previously marked (Figure 3). Again, this is also consistent with the large number of unmarked fish less than 250mm captured in hoop nets in 2007.

3.3 Annual growth rates from capture-recapture information

Parameters for the von Bertalanffy growth model were estimated from the annual growth increment data, where the data were restricted to measured individuals recaptured in the subsequent year (Figure 8). The fitted growth model assumed a measurement error with a standard deviation equal to 9.14 mm. This measurement error was based on the standard deviation in total length of individuals captured multiple times within a 20-day period (roughly the duration of a sampling trip). Quantile regressions on the raw annual growth increment data (Figure 8) indicate a steeper, more negative, slope in recent years. Or in other words, annual growth rates have been increasing in recent years.

Estimated growth parameters based on the annual growth increment data are shown in Figure 4. Sample sizes between 1995 and 1999 were extremely small and are reflected in the

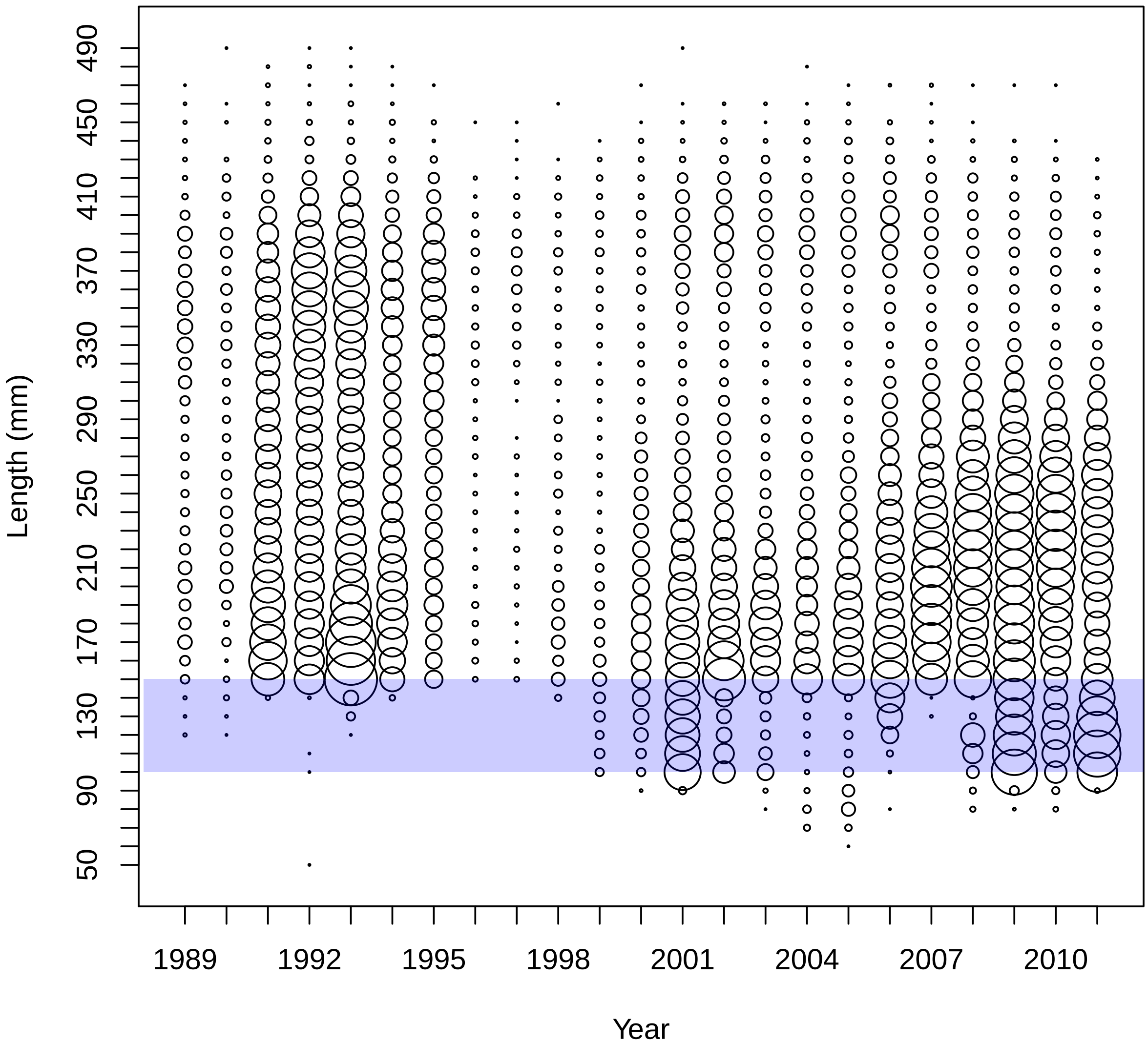

Figure 1: Length frequency by year for all gear types. Area of circle is proportional to abundance of measured fish, shaded region represents the 100-150 mm size interval.

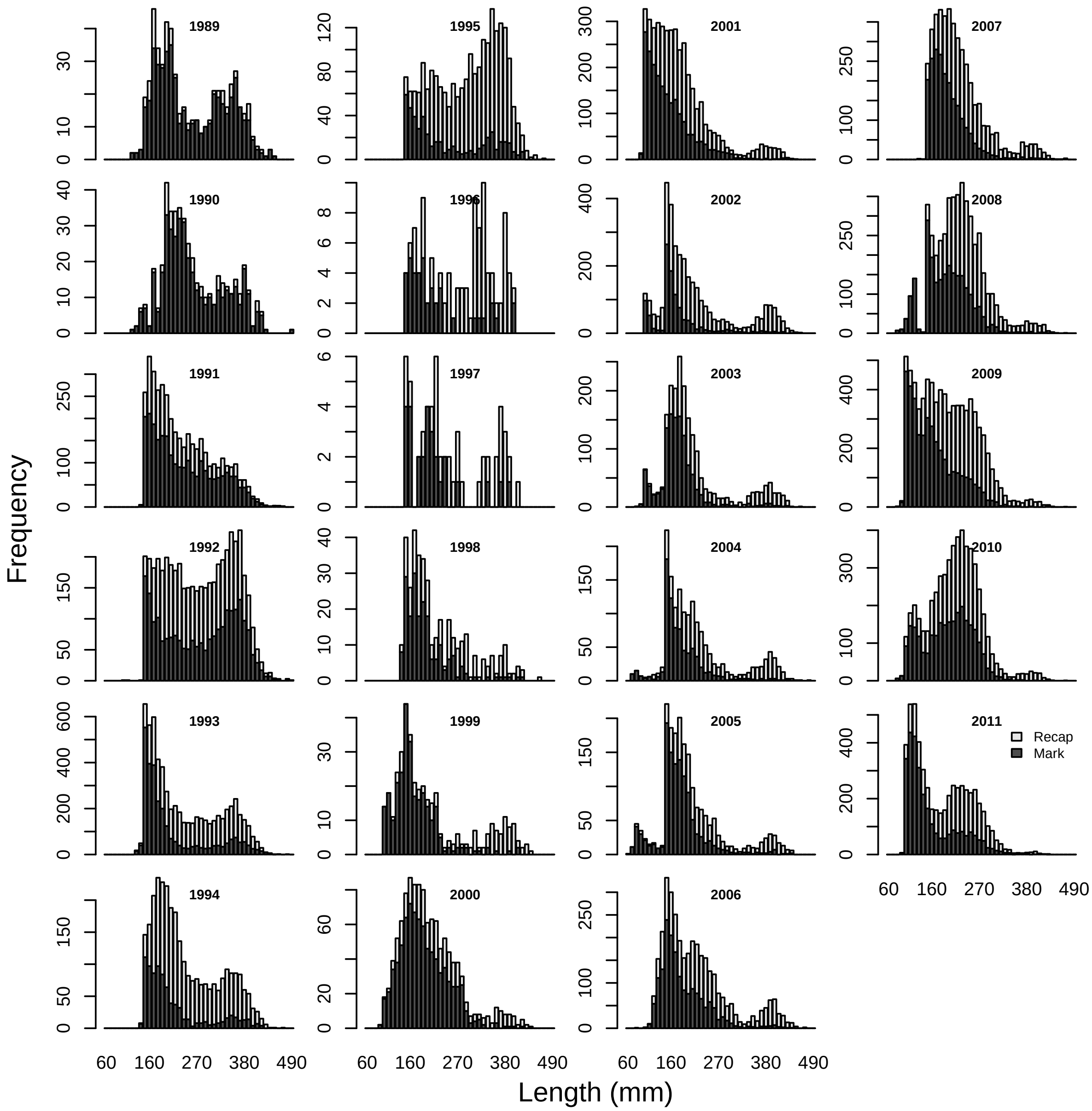

Figure 2: Annual initial-capture and mark (dark bars) and recapture (light bars) history of HBC using hoop nets (all sizes & bait) in the LCR and COR reaches from 1989 to 2011.

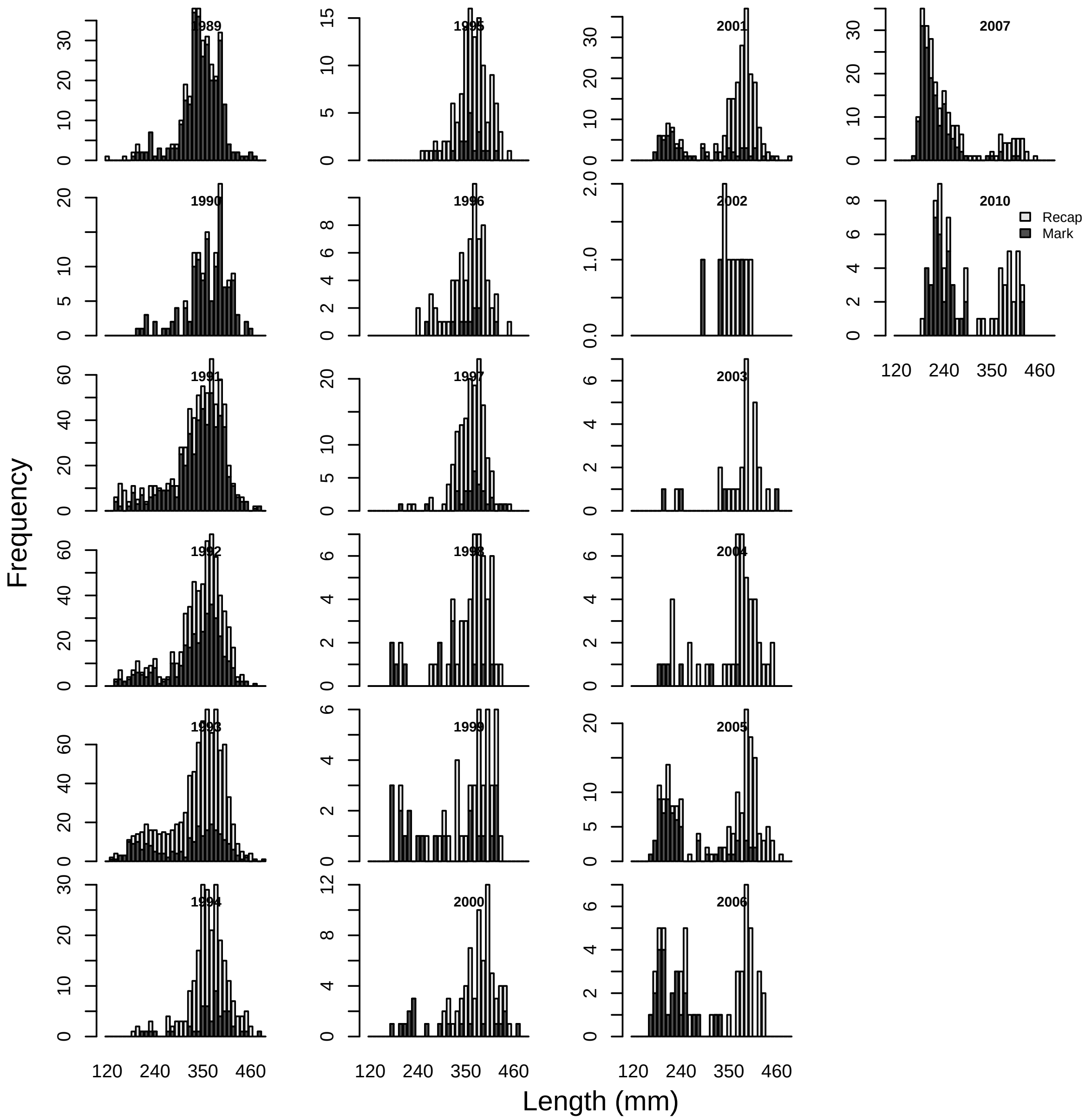

Figure 3: Annual capture and recapture history of HBC using tramel nets of all sizes in the LCR and COR reaches from 1989 to 2011.

Table 4: Number of fish measured by year and month, sampled by all gears in all reaches of both the LRC and COR.

	MONTH												
YEAR	1	2	3	4	5	6	7	8	9	10	11	12	(all)
1989	0	0	0	0	887	0	0	0	0	0	0	0	887
1990	0	0	0	408	125	0	0	0	0	43	42	0	618
1991	79	3	135	9	285	394	1624	1054	536	291	200	176	4786
1992	168	340	781	1293	493	1181	369	145	144	290	267	0	5471
1993	117	153	1132	759	1359	822	953	1093	270	228	250	239	7375
1994	154	201	296	658	707	410	198	154	152	129	128	55	3242
1995	226	231	383	915	476	83	0	0	2	0	0	0	2316
1996	0	2	20	96	47	6	0	0	27	0	0	0	198
1997	0	0	7	42	114	18	0	0	32	0	0	0	213
1998	0	0	1	234	47	36	39	65	5	18	0	0	445
1999	20	0	0	210	52	18	0	0	62	56	53	0	471
2000	20	0	0	418	21	271	2	44	20	333	151	13	1293
2001	0	0	1	37	491	1347	9	163	85	1180	929	0	4242
2002	0	4	0	980	1066	0	20	0	789	502	0	0	3361
2003	16	16	48	599	434	0	55	13	293	694	21	0	2189
2004	18	25	51	760	353	23	27	15	166	542	32	0	2012
2005	23	12	44	515	207	285	93	19	799	476	0	0	2473
2006	24	35	160	1098	921	679	179	56	270	317	0	0	3739
2007	0	0	2	937	1545	900	10	0	805	569	0	0	4768
2008	0	5	3	1265	1735	528	1020	195	718	928	0	0	6397
2009	0	0	6	1225	4180	2267	551	168	895	1323	443	245	11303
2010	0	0	2	0	1466	2882	523	14	1043	708	0	0	6638
2011	0	0	0	0	2796	2537	127	128	544	1042	63	49	7286
2012	28	61	0	0	0	0	0	0	0	0	0	0	89
(all)	893	1088	3072	12458	19807	14687	5799	3326	7657	9669	2579	777	81812

Table 5: Number of fish captured by gear type listed in the GCMRC database for each year.

				YEAR						
YEAR	ANGL	DIP	ELEC	GILL	HOOP	PA	SEINE	TRAP	(all)	NA
1989	6	0	0	321	560	0	0	0	887	0
1990	2	0	3	140	473	0	0	0	618	0
1991	4	0	44	711	3978	0	11	1	4786	37
1992	3	0	68	636	4740	0	24	0	5471	0
1993	2	0	80	876	6313	0	102	1	7375	1
1994	1	0	1	239	2997	0	2	1	3242	1
1995	1	0	7	118	2190	0	0	0	2316	0
1996	0	0	4	72	113	0	9	0	198	0
1997	0	0	2	153	58	0	0	0	213	0
1998	0	0	5	58	377	0	4	1	445	0
1999	0	0	17	54	392	0	1	7	471	0
2000	0	0	6	81	1150	0	55	1	1293	0
2001	5	0	1	233	4003	0	0	0	4242	0
2002	0	0	5	10	3346	0	0	0	3361	0
2003	0	1	102	27	2058	0	1	0	2189	0
2004	2	0	108	49	1621	226	0	0	2012	6
2005	0	0	228	174	1919	152	0	0	2473	0
2006	0	0	138	58	3442	100	1	0	3739	0
2007	0	0	9	225	4352	181	1	0	4768	0
2008	3	0	8	0	4838	1527	21	0	6397	0
2009	0	0	6	0	7706	3589	0	2	11303	0
2010	3	0	0	71	5294	1269	0	0	6638	1
2011	0	0	0	0	5376	1910	0	0	7286	0
2012	0	0	0	0	0	89	0	0	89	0
(all)	32	1	842	4306	67296	9043	232	14	81812	46

uncertainty in estimates of asymptotic length and k. The median estimate of l_∞ over the entire time series is 373.4 mm with a standard deviation of 28.88 mm. The overall median estimate of k is 0.246 with a standard deviation of 0.106. In 2005, the median estimate of k (0.536) was more than twice as large as the overall median estimate owing to the a number of individual fish that were less than 100 mm in 2004 having a growth increment of more than 100 mm in a single year (Figure 8, year 2005 panel).

Estimated growth transition matrices based on the estimated growth parameters from the annual growth increment data are shown in Figure 5. In addition to the transition matrix based, this Figure also has a 1:1 reference line and the corresponding maximum likelihood estimate of l_∞ as a reference to judge differences in the annual length transition matrices. Starting 2001, growth rates of fish less than 150 mm increased markedly relative to the growth increments observed in the 1990s. The implications of this increased growth rate in a length-based model would have significant impacts on annual recruitment estimates if growth was assumed to be constant. The length transition matrices shown in Figure 5 provide an alternative input into the length structured mark recapture model (LSMR), where length-transition matrices are estimated externally.

References

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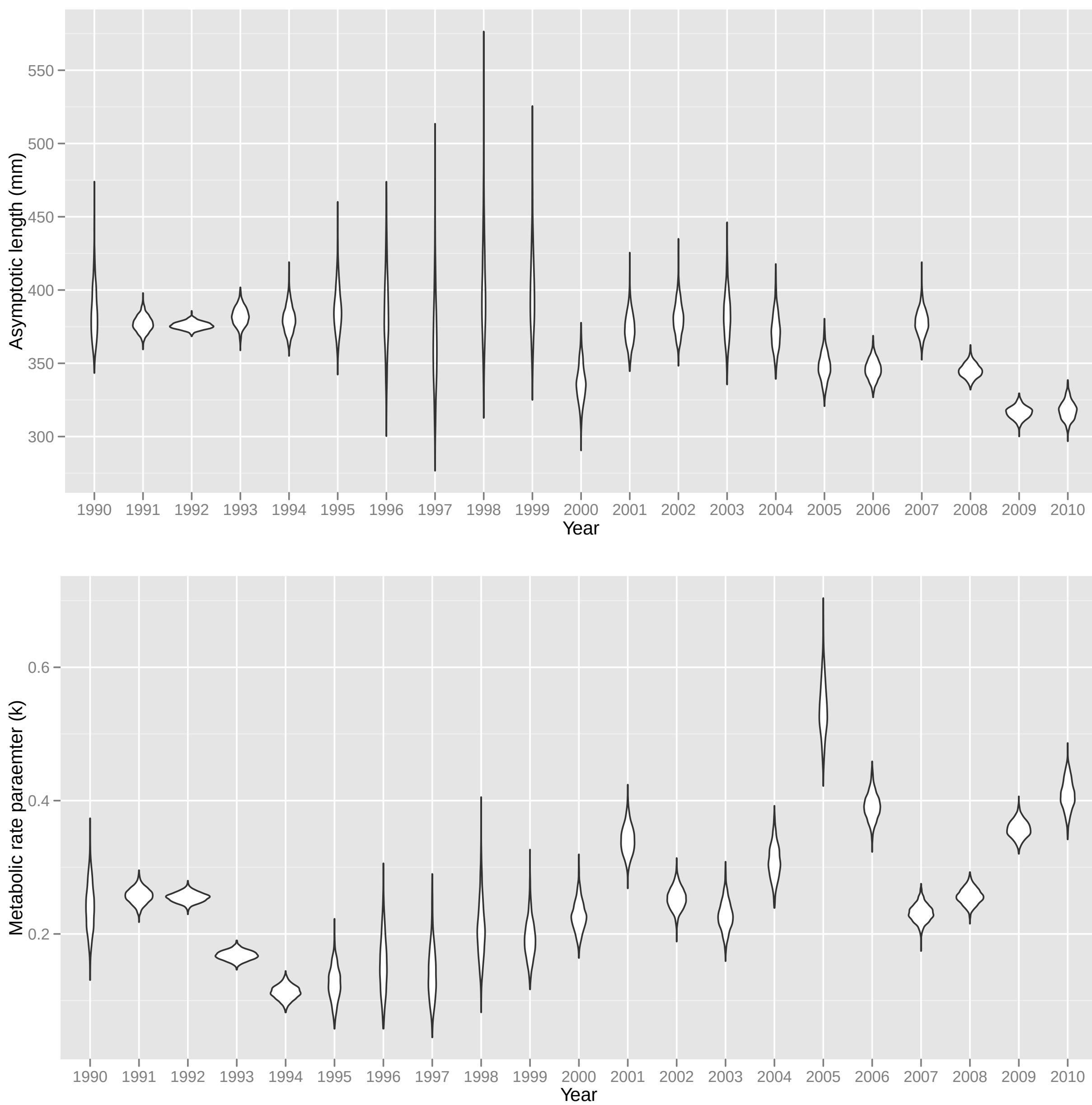

Figure 4: Violin plots of the marginal posterior distributions for annual estimates of asymptotic length (l_∞, top panel) and the von Bertalanffy metabolic rate parameter (k).

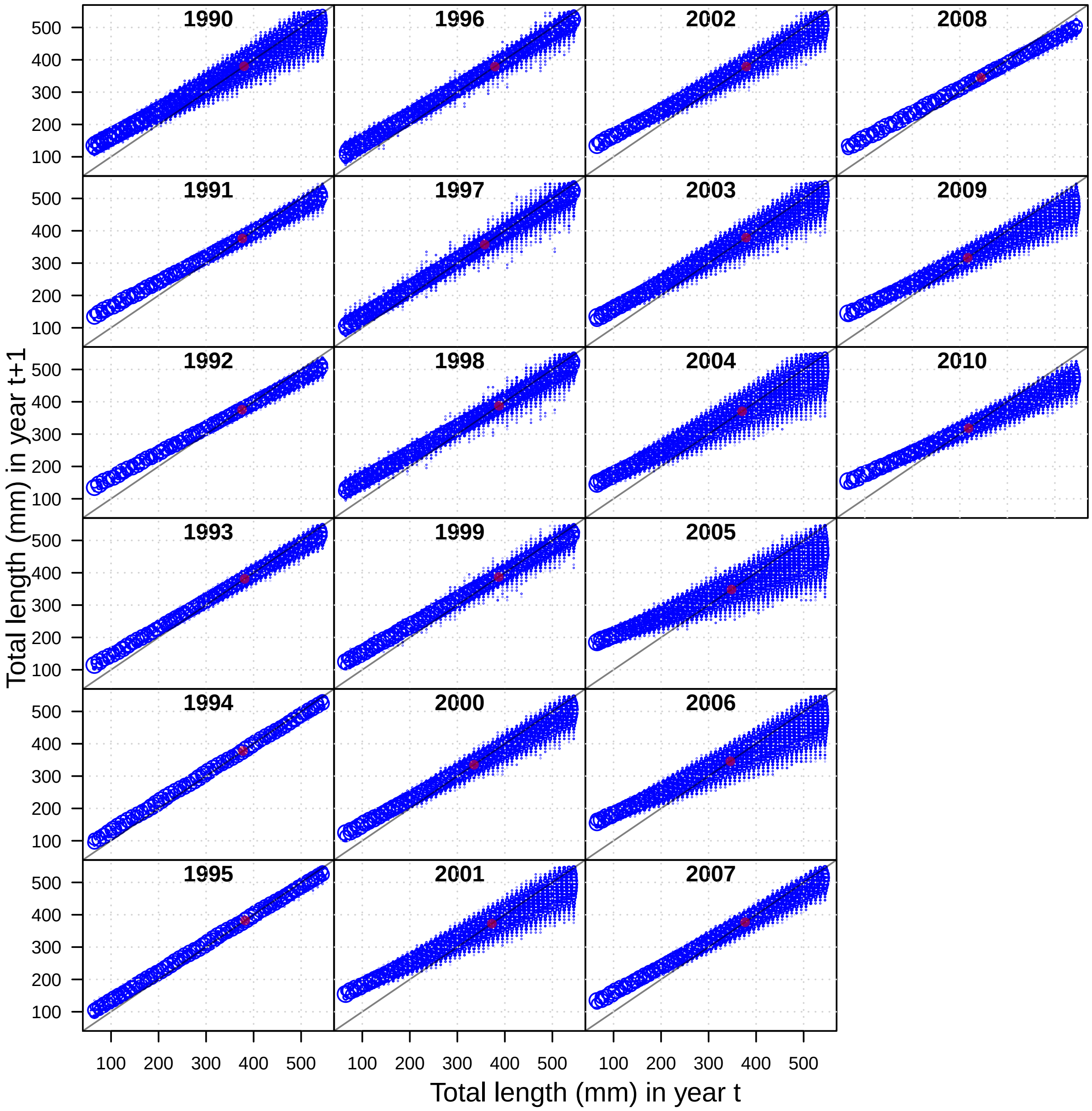

Figure 5: Annual length transition matrixes based on the annual growth increment data. The area of each bubble is proportional to the transition probability from year t to year $t+1$, the diagonal black line is the 1:1 slope, and the red circle corresponds to the maximum likelihood estimate of l_∞. Each matrix is based on parametric uncertainty in the estimated von Bertalanffy growth parameters as well as measurement errors.

A Work plan

The following outlines a work plan for the assessment of abundance for humpback chub. The objective is to develop a much more flexible length-based model that can be used to explore alternative hypotheses about natural mortality rates, cumulative effects of release mortality for intensive sampling periods, and to potentially integrate other sources of environmental variations such as the effects of turbidity on capture probability and recruitment variation.

Analytical approach

I will develop a statistical catch-at-length model in the AD Model Builder software and additions R-scripts for manipulating data and summarizing model results. Input data for the model will consist of a matrix of the total catch-at-length in 5 to 10 mm size intervals for all years, a matrix of the number of marks released by size and year, a matrix of the number of marks recaptured by size and year, and a three dimensional array of the number of marks recaptures by size for each tag-cohort released (optional).

Estimated parameter will include: natural mortality rate, growth parameters, a vector of the initial numbers in each length interval, and a vector of age-0 recruits each year. Propagation of the numbers-at-length to the next time step will be based on a size-transition matrix, which is a function of the growth parameters and variation in growth. Observation models will include a probability of capturing an animal of a given length each year, the probabilities of capturing a marked and unmarked animal of a given length, and optionally the probability of recapturing a specific tag-cohort of a given length. These predicted observations will be compared with the empirical data using a negative binomial likelihood function. The negative binomial model is more suitable here because it can account for over-dispersed data and accommodate zero observations in cases where there is sparse information.

Detailed work plan

Major components of the project

The following is list of milestones for this project. Each of these items will be expanded upon in the section on project details.

1. Data acquisition and processing.
2. Development of an operating model for simulating data with known parameter values.
3. Development of a length-based assessment model to be fitted to data on capture and recapture information by length interval.
4. Simulation testing; exploring the precision and bias of the assessment model in jointly estimating recruitment, size-specific capture probability, and growth and natural mortality using simulated data sets.

5. Application of the length-based model to the HBC data.

6. Quantifying uncertainty in model parameters and estimates of recruits using Markov Chain Monte Carlo methods to integrate the joint posterior distribution.

7. Report & presentation to the Technical Working Group.

Project details

Data acuisition & processing The necessary data required to conduct the analysis will require information from the following fields in the GCMRC database: FISHNO, TRIP_ID, DATES, RM, RIV, TL, TAGNO. The following SQL statement was used in a previous study to extract the necessary information. Note that the following code has been modified to obtain all fish lengths, not just those greater than 150 mm.

```
--****
--All
--****

CREATE OR REPLACE VIEW FISH.V_ASMR_2009_ALL
(
    FISHNO,
    TRIP_ID,
    DATES,
    RM,
    RIV,
    TL,
    TAGNO
)
AS
SELECT "CAPTURE_ID" fishno, "TRIP_ID" trip_id, "START_DATE" dates,"START_RM" rm,"RI
       FROM FISH.CAPTURE_HISTORY_20091211_0832
      WHERE SPECIES_CODE = 'HBC'
      AND (
        (RIVER_CODE = 'COR' AND START_RM >= 57 AND START_RM <= 68.5)
        OR RIVER_CODE = 'LCR'
        )
      AND START_DATE >= TO_DATE('04/01/1989', 'MM/DD/YYYY')
      AND TOTAL_LENGTH >= 00
```

An R-script will be developed for post processing of the data to assign the length capture and recapture information into discrete length intervals for assembling input data into the assessment model.

Operating model An individual based model will be developed to generate simulated data sets with known natural mortality rates, recruitment vectors, growth rates and capture probabilities. The pseudo code for the operating model is as follows:

1. Specify a vector of absolute recruitment from 1950-2011.
2. For each individual recruit in each year apply the following procedure:
   (a) boolean trail for survival, if the animal survives then go to (b) else, individual died and restart at step 2.
   (b) boolean trail for capture:
      i. Captured: obtain length of fish, if greater than 150mm then tag and release fish, go.
      ii. Recaptured: obtain length of fish, goto step (a).
      iii. Not captured: goto step (a).
3. Store information about individual capture history and length into simulated database.

The above algorithm is intended to generate the exact data that is currently collected in the HBC monitoring program. Specific details about factors that affect capture probability and survival would be incorporated into the boolean probabilities defined in 2a and 2b.

Length-based assessment model A statistical length-based assessment model is similar in nature to a statistical catch-age model in that numbers-at-age, or in this case, numbers-at-length are propagated forward in time. The previous Age-Structured Mark-Recapture Model (ASMR) was dependent on catch-age information; age data for HBC were inferred from an analytical age-length key (i.e., based on inferences about growth, not empirical age-length data). Estimates of uncertainty were overly precise due to the pre-processing of the data to be used with ASMR. The length-based model makes no such inferences about the age of individual fish and is based strictly on the length observation data.

In a length based model, individuals in a given length interval are propagated in time by redistributing these individuals into new length bins based on a length transition probability (Fig **??**). The length transition probability is a function of growth and the time interval between sampling events. The graphical example in Fig **??** does not account for mortality over time, its only meant to show the transition of individuals from one length bin to subsequent length bins.

Simulation testing The purpose of simulation testing is to (i) demonstrate that the model is able to estimate the model parameters given perfect information and satisfying all of the model assumptions, (ii) examine precision and bias in parameter estimates when faced with observation, process, and structural errors, and lastly (iii) to examine the

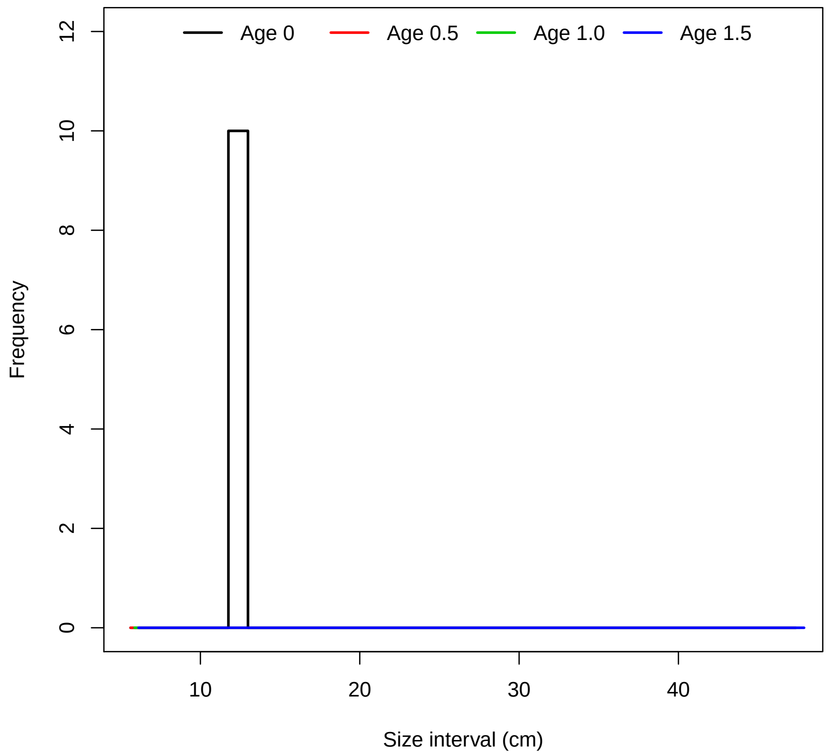

Figure 6: A graphical example of a length-based transition. Starting with 10 age-0 individuals, these 10 would then be distributed to the age-0.5 distribution distribution. The age-0.5 distribution then transitions to the age-1.0 distribution and so on.

estimability, bias, and precision of model parameters when underlying structural assumptions are not met. Simulation testing will be conducted to examine the ability to jointly estimate recruitment, capture probability, growth and natural mortality in a reliable and unbiased manner.

Application to the HBC data The length-based assessment model will then be applied to the length-based capture and recapture data for the humpback chub monitoring program. Model outputs will include estimates of recruits (and associated uncertainty), estimated model parameters (and uncertainty). It is anticipated that more reliable estimates of recruits will be available with the length based model because the model is not limited to length information that is greater than 150mm, as is the case in the ASMR model.

Quantifying uncertainty Estimates of uncertainty will jointly consider uncertainty in the mark-recapture data, growth and mortality. To do so the joint posterior distribution of the data will be constructed numerically using a Markov Chain Monte Carlo procedure (using the Metropolis Hastings algorithm implemented in AD Model Builder). Uncertainty in model parameters as well as outputs will be cast in the form of marginal posterior densities.

Report and presentation This is original research and the methods outlined for a length-based model that incorporates growth increment data from a mark recapture program has not been previously published to my knowledge. Ideally these results will be disseminated in the primary literature, but will also be presented to the Technical Working Group and be available as a technical report (e.g., USGS Open File Report). Also source code, scripts, and documentation will be hosted on an open source repository with version control. The intention here is to create a repository for continued development of the software and to document the historical changes over time.

B Individual based model for simulating the dynamics and sampling of humpback chub in the Grand Canyon

B.1 Introduction

The following is a detailed description of the simulation model that was used for simulating the population dynamics and data collection programs for humpback chub in the Grand canyon. We first describe in detail the life-history trajectory of an individual fish: the survival probability, growth, and capture history and provide the documented code to implement this process. I then describe the data structures that resemble a databased of individual capture histories for both tagged and untagged fish. The individual based model (IBM) is then used to estimate the fate and capture histories of a known number of recruits starting life at a 40mm length interval.

The simulation model was constructed using R (R Development Core Team, 2009). The algorithm populates three matrixes that contain the total number of fish captured in year t at length interval x, the total number of newly marked fish, and a matrix of the total number of recaptured individuals. At each time step the fish is alive, information on length and age is stored along with information on capture history, the tag number if the fish was large enough to tag.

B.2 R-code

```
## -------------------------------------------------------------- ##
## Simulation model for humpback chub                              ##
## Author: Steven Martell                                          ##
## DATE: September 26, 2011                                        ##
## Contact: martell.steve@gmail.com                                ##
##                                                                 ##
## FUNCTIONS:                                                      ##
##   - .ibm => given N recruits returns list with the capture      ##
##             history of each recruit. It also fills the          ##
##             global variables C M and R for the assessment       ##
##             model.                                              ##
##   - .runIBM Loops over syr:nyr and applies the .ibm function##
##             to each of Rt recruits.                             ##
##                                                                 ##
##                                                                 ##
## -------------------------------------------------------------- ##


## -- Required libraries --------------------------------------- ##
require( PBSmodelling )
require( Hmisc )
require( ggplot2 )
```

```r
## -- Simulation controls ------------------------------------ ##

# Model Dimensions
syr     <- 1950     #initial year
nyr     <- 2011     #final year
dt      <- 1.0      #time step
tmax    <- 50/dt    #max longevity index (50 yrs)
dyr     <- seq(syr, nyr, by=dt)
xbin    <- seq(3, 55, by=1)

# Growth (units in cm)
lmin        <- 4
lmin.sig    <- 0.4
m.linf      <- 0.08
linf        <- 40   #Asymptotic length (cm)
k           <- 0.18 #Growth coefficient

# Selectivity
lh          <- 10   #length @ 50% selectivity
gamma       <- 1.5  #std in selectivity

sample.yrs  <- seq(1989, 2011, by=dt)
fishing     <- dyr %in% sample.yrs
min.size    <- 15.0 #minimum size for tagging (15 cm)



# Parameter vector for the IBM model
THETA <- list( lmin=lmin,
               lmin.sig=lmin.sig,
               m.linf=m.linf,
               lh=lh,
               gamma=gamma )

set.seed(999)
iclr <- rev(topo.colors(length(syr:nyr),0.5))
Rt<-floor(rlnorm(length(syr:nyr), log(300), 0.9))
h1 <- 0.04
h2 <- 0.20
t  <- min(sample.yrs)
T  <- max(sample.yrs)
pr <- 1
Et <- h1+(h2-h1)*cos(0.5+(sample.yrs-t)/(T-t)*pr*pi)^2
#Et<-runif(length(sample.yrs), 0.05, 0.2)  #Effort

# Global objects for storing data
fish.id     <- 0    #Unique id for individual fish
tag.id      <- 0    #Unique tag no. for individual
# Total catch, marked, recap, unmarked by year at length interval
C   <- matrix(0,nrow=length(sample.yrs), ncol=length(xbin))
M   <- matrix(0,nrow=length(sample.yrs), ncol=length(xbin))
```

```
R    <- matrix(0,nrow=length(sample.yrs), ncol=length(xbin))

## ------------------------------------------------------------ ##




## ------------------------------------------------------------ ##
## PROCEDURES                                                   ##
## ------------------------------------------------------------ ##


.ibm <- function( Nt, jyr, THETA )
{
    #ARGUMENTS:
        #Nt    = Number of recruits from cohort
        #jyr   = brood year (year the cohort was age-0)
        #THETA = a list of simulation parameters for the ibm.

    #RETURNS:
        #df    = a list w records of capture date, len,  tag.no

    with(THETA, {
        #jyr <- syr+(ii-1)
        ## indexs i = individual; j=time

        ## Calculate length & mortality for time j.
        lj <- linf*(1.-exp(-k*dt*1:tmax))
        mj <- m.linf*linf/lj

        ## Draw initial recruit size (gamma).
        scale   <- (lmin.sig)^2/lmin
        shape   <- lmin/scale
        li <- rgamma(Nt, shape, 1/scale)


        ## Growth trajectory
        growth <- function ( li )
        {
            linf.i <- rnorm(1, linf, 0.1*linf)
            li+(linf.i-li)*(1-exp(-k*1:tmax*dt))
        }
        L <- sapply(li, growth)

        ## Survival trajectory
        ## S is a list of lengths of individuals at
        ## the time they were alive.
        survival <- function ( lj )
        {
            sj <- exp(-m.linf*linf/lj*dt)
```

```
    pj <- rbinom(tmax, 1, sj)
    nj <- which.min(pj)
    return(lj[1:nj])
}
S <- apply(L, 2, survival)


## Capture history
pcap <- function ( lj )
{
    #Arg: lj is the length at times j
    #Algorithm:
    #-1. determine index for sampling time periods (fyr)
    #-2. determine capture probability at sampling times
    #-3. if captured fish > 150 mm then assign a tag no.
    if(!is.null(lj))
    {
        # 1. Index for sampling time periods (fyr)
        n   <- length(lj)
        d1  <- which(dyr==jyr)  #min index of dyr for jyr
        d2  <- min(d1+n-1, length(dyr))
        jj  <- d1:d2
        iyr <- dyr[jj]            #years alive
        fyr <- fishing[jj]        #years fished fyr==1


        ## Did not survive into sampling years
        if(length(iyr[fyr])==0) return(NULL)

        # -2. Selectivity at time of sampling
        len <- (lj[1:length(jj)])[fyr]
        iyr <- iyr[fyr]
        # TODO Add annual effort to sj capture probability
        eyr <- findInterval(iyr, sample.yrs)
        #print(cbind(sample.yrs[eyr],Et[eyr]))
        sj  <- Et[eyr]*plogis(len, lh, gamma)

        cj  <- rbinom(length(sj), 1, sj)
        rid <- which(cj==1)  #row index for capture
        if(length(rid)==0) return(NULL) #never captured

        tmp <- c(iyr[rid], len[rid],
             tag.no=rep(NA,length=length(rid)))
        tmp <- matrix(tmp, ncol=3)


        # -3. Assign tag.id if greater than 150 mm
        if(max(tmp[,2])>=min.size)
        {
            tag.id <<- tag.id + 1
        }
```

```
                tmp[len[rid]>=min.size, 3] <- tag.id

                # -4. Populate global variables with catch history
                tt <- findInterval(tmp[,1],sample.yrs)
                xx <- findInterval(tmp[,2],xbin)
                for(i in 1:length(tt))
                    C[tt[i], xx[i]] <<- C[tt[i], xx[i]] + 1

                #print(cbind(tmp,sample.yrs[tt],xbin[xx],tmp[,3]))

                # - Newly marked fish into matrix M
                im   <- !is.na(tmp[,3])
                if(sum(im)>0) #fish was large enough to tag
                {
                    it <- min(which(im))
                    iy <- findInterval(tmp[it,1],sample.yrs)
                    ix <- findInterval(tmp[it,2],xbin)

                    #print(cbind(tmp, sample.yrs[iy],xbin[ix]))
                    M[iy, ix] <<- M[iy, ix] + 1

                    ir <- which(im)[-1]
                    ry <- findInterval(tmp[ir,1],sample.yrs)
                    rx <- findInterval(tmp[ir,2],xbin)
                    for(i in 1:length(ry))
                        R[ry[i], rx[i]] <<- R[ry[i], rx[i]] + 1
                }

                return(tmp)
            }
        }
        P <- sapply(S, pcap)
        return(P)
    })
}

.runIBM <- function()
{
    j <- 1
    A <- NULL
    for(i in syr:nyr)
    {
        A <- c(A, .ibm(Rt[j], i, THETA))
        j <- j+1
    }
    return(A)
}

.writeLSMRdata <- function()
{
        # This function writes the data file for LSMR model
```

```
        fn <- "simLSMR.dat"
        C  <- cbind(floor(sample.yrs),sample.yrs%%1*4+1,C)
        M  <- cbind(floor(sample.yrs),sample.yrs%%1*4+1,M)
        R  <- cbind(floor(sample.yrs),sample.yrs%%1*4+1,R)

        write("#Simulated data from HBCsim.R", fn)
        write("#Model Dimensions", fn, append=T)
        write("#Years, timestep", fn, append=T)
        write(c(range(sample.yrs), dt), fn, append=T)
        write("#Array dimensions(C, M, R)", fn, append=T)
        write(dim(C), fn, append=T)
        write("#Number of length intervals", fn, append=T)
        nbin=length(xbin)+1
        write(nbin, fn, append=T)
        write("#Length intervals (cm)", fn, append=T)
        write(c(xbin,xbin[nbin-1]+diff(xbin[(nbin-2):(nbin-1)])), fn, append=T)

        write("#Catch at length by period", fn, append=T)
        write("#Year, Period, Count ...", fn, append=T)
        write.table(C, fn, append=T, col.names=F, row.names=F)
        write("#Number Marked at length by period", fn, append=T)
        write("#Year, Period, Count ...", fn, append=T)
        write.table(M, fn, append=T, col.names=F, row.names=F)
        write("#Number Recaptured at length by period", fn, append=T)
        write("#Year, Period, Count ...", fn, append=T)
        write.table(R, fn, append=T, col.names=F, row.names=F)

        write("#End of file", fn, append=T)
        write(999, fn, append=T)

        file.copy(fn, "../ADMB/srcLSMR/simLSMR.dat", overwrite=TRUE)
}

## ------------------------------------------------------------ ##
## MAIN                                                         ##
## ------------------------------------------------------------ ##
#A  <- .ibm(1000, 1980, THETA)
A <- .runIBM()
.writeLSMRdata()

## ------------------------------------------------------------ ##

par(mfcol=c(6, 4), las=1, mar=c(2, 2, 1, 1), oma=c(3, 3, 1, 1))
for(i in seq(1,length(sample.yrs)-1/dt,by=1/dt))
{

        ut <- colSums(C[i:(i+3),]-M[i:(i+3),]-R[i:(i+3),])
        mt <- colSums(M[i:(i+3),])
        rt <- colSums(R[i:(i+3),])
        tmp <- rbind(ut, mt, rt)
```

```r
    barplot(tmp,names.arg=xbin, xlab=""
    ,ylab="", main=sample.yrs[i], col=1:3)
}
mtext(c("Length (cm)","Frequency"),
    c(1, 2), outer=T, las=0, line=1)
```

C Processing mark-recapture by length information

The following description details how the raw data from the GCMRC database was used to construct the tables of data used in this assessment. The raw data obtained from Glenn Bennet (`gbennet@usgs.gov`) contained the following fields:

```
CAPTURE_ID SPECIES_CODE    TRIP_ID     START_DATETIME START_RM RIVER_CODE TOTAL_LENGTH TH_ENCOUNTER_RANKING GEAR_CODE
      1496          HBC LC20000417 4/17/2000 17:15:00       NA        LCR          380                20397        HS
        48          HBC LC20000417 4/18/2000 16:10:00       NA        LCR          285                49293        HS
        49          HBC LC20000417 4/18/2000 16:10:00       NA        LCR          219                49220        HS
       100          HBC LC20000417  4/18/2000 8:06:00       NA        LCR          170                49255        HS
       156          HBC LC20000417 4/17/2000 18:20:00       NA        LCR          325                49238        HS
       241          HBC LC20000417 4/18/2000 17:15:00       NA        LCR          214                49309        HS
```

The `TH_ENCOUNTER_RANKING` field is a unique number for each individual marked fish and occurs in the database one or more times depending on the number of recapture events for that individual, this is also referred to as the `TAGNO`. At the time of writing this report, there were a total of 81,812 records in the database for humpback chub, of which 35,696 are unique individuals (some of which may occur in the database only once). These data were first imported into R (R Development Core Team, 2009), the year and month was then extracted from the `START_DATETIME` field and appended to the data frame. Next the total length of measured humpback chub were assigned to corresponding 10mm size intervals ranging from 50mm to 600mm. Note that the R-code for manipulating the database can be found in subsection C.1.

There are 110 unique `GEAR_CODE`s in the database; these gear codes were classified into 12 gear groups, of which tramel nets (GILL) and hoop nets (HOOP) were used to reconstruct the marks and recaptures at length.

The last step in constructing the data frame (see the function `get.DF`) was to assign initial marks and recapture event to each of the records. To do so, the data frame was ordered by date and tag number in ascending order and all duplicate occurrences of `TAGNO` were assigned a boolean TRUE value. The additional columns added to the data frame was necessary to extract the total number of fish caught by month in each year (Table 4), and the total number fish captured each year by specific gear types (Table 5).

Key input data to the LSMR assessment model is the number of marked fish released (by size class) and the number of recaptured fish (by size class) in subsequent sampling events by specific gear types. To construct these data, an R-function (`tableMarks`) was developed to construct Tables 7–10. I only consider marks and recaptures from the hoop nets and gillnet (tramel nets) sampling gears in this analysis, as these two gear types were responsible for sampling the majority of humpback chub in the system.

C.1 R-Code for Database manipulation

```
# ——————————————————————————————————————————————————————————— #
# R-script for creating summary data for LSMR
# based on the data-based extraction from GCMRC
# Author: Steven Martell
# Date: May, 2012
# LOCATION: MAUI
#
# DESCRIPTION OF ROUTINES:
#   get.DF: reads csv file with raw data, appends YEAR MONTH TAGNO TL columns
#
#   getGrowthIncrement: extracts initial tag length and most recent recapture
#                       length information from DF, at-least 1-year at large
#
#   getCapturesByLength: extacts capture history by length interval at each time
#                        step.
```

Table 6: Number of fish captured by length by all gear types listed in the GCMRC database for each year.

LI	YEAR																						
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
50	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	11	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	15	45	1	0	7	2	6	0
90	0	0	0	0	0	0	0	0	0	0	0	2	14	0	5	7	35	0	0	10	21	13	6
100	0	0	0	1	0	0	0	0	0	0	17	18	327	118	65	5	23	2	0	37	514	117	393
110	0	0	0	1	0	0	0	0	0	0	24	24	304	97	40	6	15	10	0	95	465	180	538
120	3	1	0	0	1	0	0	0	0	0	17	47	286	56	22	9	17	71	0	140	424	201	539
130	2	2	0	0	18	0	0	0	0	0	28	57	297	50	25	11	9	153	2	10	334	165	403
140	3	7	5	2	54	8	0	0	0	10	30	71	289	76	34	20	13	213	1	3	371	132	304
150	19	8	268	221	684	147	76	6	6	43	45	83	280	447	166	229	248	345	245	333	436	132	239
160	24	2	353	215	585	163	63	9	5	26	37	91	281	382	216	162	218	310	333	257	424	213	162
170	47	18	318	194	618	209	62	7	1	44	22	89	283	259	208	116	204	267	371	201	359	235	159
180	34	7	270	211	450	235	62	8	2	39	23	88	240	233	264	141	215	210	394	238	399	278	148
190	31	19	296	188	400	229	88	10	3	35	20	88	259	222	208	106	190	168	401	259	385	283	159
200	46	43	262	213	295	224	65	3	5	30	19	64	190	167	159	102	165	176	415	349	322	325	211
210	42	35	215	193	216	189	82	5	4	11	16	67	164	151	125	122	124	198	374	352	345	362	247
220	28	37	176	188	235	182	76	2	7	13	20	65	118	135	97	94	81	192	328	354	347	390	239
230	21	35	168	201	205	139	66	4	3	17	6	50	129	97	51	74	79	171	291	385	346	409	246
240	17	34	152	161	156	105	61	4	2	4	3	52	81	80	32	54	68	162	258	338	329	361	231
250	14	25	180	156	153	82	49	4	2	17	5	44	65	62	25	40	50	131	206	299	368	358	221
260	13	23	153	156	154	74	71	2	2	12	5	39	59	41	23	29	61	122	147	229	324	313	232
270	15	15	144	152	177	81	58	6	5	10	6	38	53	36	16	24	31	78	150	257	271	244	183
280	12	15	171	167	177	70	67	5	1	12	4	30	41	41	15	27	23	70	92	155	245	178	154
290	14	14	140	160	170	72	74	4	0	15	4	16	30	35	17	14	14	51	86	101	183	121	102
300	22	12	126	174	155	64	98	3	1	1	4	9	22	26	9	10	15	55	65	101	129	71	85
310	40	13	131	191	175	72	80	10	4	8	8	11	11	16	5	8	10	32	69	72	89	46	51
320	37	18	137	223	215	68	90	12	8	5	2	9	14	13	8	10	6	15	26	42	65	32	38
330	59	27	157	244	207	89	113	14	14	7	6	8	10	19	6	10	14	10	28	34	39	20	19
340	54	25	147	255	259	109	113	10	15	7	7	10	19	20	20	18	17	16	20	20	20	10	17
350	54	20	149	287	292	116	151	8	14	10	10	8	34	27	27	23	18	28	18	18	22	11	5
360	59	30	151	292	329	116	133	9	23	6	10	20	39	49	33	30	15	18	16	19	19	20	6
370	40	17	133	313	242	105	137	13	23	15	9	14	53	44	35	34	37	45	50	20	15	24	5
380	36	31	108	231	236	90	135	15	26	18	17	18	57	86	52	49	40	54	38	33	23	21	7
390	50	35	108	181	187	73	103	12	18	8	11	15	64	84	60	58	57	76	43	25	26	31	8
400	21	9	72	123	145	46	52	7	8	6	15	20	46	77	38	43	51	81	44	25	18	24	11
410	8	17	38	77	90	37	43	2	7	10	7	7	43	51	35	32	38	36	32	19	18	25	4
420	5	15	21	49	49	22	28	3	1	4	8	8	24	36	25	20	25	36	23	22	7	11	2
430	4	4	12	16	20	10	11	0	1	1	4	6	8	15	15	7	15	17	12	6	7	4	2
440	4	0	8	18	11	5	2	0	1	0	1	5	4	8	4	8	12	12	2	3	2	1	0
450	3	2	7	7	5	7	5	1	1	0	0	1	2	3	1	5	5	5	2	1	0	0	0
460	2	1	3	3	6	2	0	0	0	1	0	0	1	2	2	1	2	0	1	0	0	0	0
470	1	0	4	1	1	1	1	0	0	0	0	1	0	0	0	0	1	2	3	1	1	1	0
480	0	0	2	3	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
490	0	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Table 7: Number of new marks released by year and size interval (HOOP).

LI	YEAR																						
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	11	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	15	41	1	0	7	2	6	0
90	0	0	0	0	0	0	0	0	0	0	0	2	12	0	5	7	30	0	0	10	16	13	5
100	0	0	0	1	0	0	0	0	0	0	14	17	277	97	64	4	21	2	0	37	462	92	343
110	0	0	0	0	0	0	0	0	0	0	18	21	235	53	36	6	13	9	0	95	412	146	437
120	2	1	0	0	0	0	0	0	0	0	10	34	206	14	21	2	15	54	0	140	370	142	423
130	2	2	0	0	15	0	0	0	0	0	21	38	182	9	23	6	9	111	2	10	246	118	311
140	3	6	1	1	40	7	0	0	0	8	24	48	159	8	31	13	11	130	1	1	244	75	215
150	16	7	204	169	553	111	59	4	4	29	44	64	142	264	136	181	193	239	203	289	304	73	165
160	18	2	211	141	395	97	47	5	4	18	33	72	123	185	160	123	150	205	257	194	275	121	109
170	34	17	187	95	389	86	39	4	0	30	17	67	130	115	154	79	133	168	280	130	222	120	76
180	29	6	152	102	232	97	28	4	2	18	16	63	99	76	156	77	139	114	267	137	193	154	58
190	28	17	161	64	200	84	39	5	2	22	18	59	82	40	123	45	115	84	218	151	162	148	58
200	33	33	160	68	124	64	23	2	4	18	14	46	54	38	72	41	91	76	195	173	110	156	72
210	35	29	117	70	69	39	12	3	3	6	10	44	54	28	56	48	51	87	154	154	120	158	87
220	25	27	97	73	56	37	16	2	2	6	14	40	38	12	30	36	30	77	137	147	116	181	77
230	11	32	90	65	39	32	16	3	1	10	5	32	39	18	21	20	26	65	104	147	106	197	82
240	15	31	89	52	28	14	6	0	2	3	1	35	33	10	8	12	17	46	81	116	101	160	67
250	9	21	105	51	26	14	9	0	0	6	2	27	21	7	8	13	20	58	66	99	95	148	80
260	11	17	78	65	34	3	12	1	0	7	1	24	21	5	4	8	13	45	41	64	77	136	68
270	12	12	69	55	38	8	7	0	1	1	2	24	18	6	1	7	9	19	28	68	66	102	52
280	8	10	104	61	29	8	5	0	0	4	2	25	16	7	4	6	7	25	22	42	50	71	49
290	10	8	82	49	26	10	6	0	0	2	2	10	14	11	4	1	6	17	17	16	23	33	24
300	11	10	64	67	28	5	8	0	0	0	0	3	12	8	2	2	3	11	11	22	22	23	21
310	20	8	63	72	38	6	5	1	0	1	1	4	3	4	1	2	2	5	9	16	17	12	14
320	19	12	66	83	39	8	10	1	0	0	1	5	3	4	0	3	1	3	2	5	4	10	11
330	17	10	70	87	34	10	13	1	0	0	0	2	2	3	0	3	3	1	4	5	8	3	6
340	14	12	78	114	49	16	20	0	1	1	2	0	2	1	6	3	3	4	3	2	3	4	6
350	19	11	69	113	66	20	25	2	0	0	0	0	2	5	1	2	1	3	4	2	2	1	0
360	25	13	69	115	74	17	9	1	0	1	1	3	1	3	2	1	3	1	1	3	3	2	1
370	16	8	44	131	53	12	16	0	1	1	0	0	0	7	3	3	2	4	6	2	0	2	1
380	12	18	44	97	55	13	16	0	0	1	0	1	2	5	6	1	2	4	1	2	0	0	1
390	12	11	33	82	40	14	15	0	1	1	1	1	0	3	6	3	4	5	4	4	2	0	0
400	6	2	19	42	25	4	7	2	0	0	0	1	1	5	2	3	7	7	3	0	0	1	1
410	3	6	12	29	21	7	4	0	0	1	2	0	1	2	2	1	0	3	3	2	0	0	1
420	2	5	6	17	15	4	7	0	0	1	0	1	3	4	1	1	1	2	2	2	0	0	1
430	1	1	2	7	2	0	0	0	0	0	0	0	1	0	2	2	1	1	1	1	1	0	0
440	3	0	1	7	2	1	0	0	0	0	0	0	0	1	0	0	2	1	0	0	0	1	0
450	1	0	3	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
460	0	0	2	2	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
470	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
480	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
490	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8: Number of recaptured marks by year and size interval (HOOP).

LI	YEAR																						
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	5	0	0	0	5	0	1
100	0	0	0	0	0	0	0	0	0	0	0	1	50	21	1	1	2	0	0	0	51	25	50
110	0	0	0	1	0	0	0	0	0	0	0	2	69	44	4	0	2	1	0	0	53	34	101
120	0	0	0	0	0	0	0	0	0	0	1	5	80	42	1	7	2	17	0	0	54	59	116
130	0	0	0	0	3	0	0	0	0	0	3	14	115	41	2	5	0	42	0	0	88	47	92
140	0	1	4	0	9	1	0	0	0	2	6	14	130	68	3	7	2	83	0	2	126	57	89
150	3	1	55	32	102	35	16	0	2	11	0	14	138	183	23	43	28	93	41	40	131	59	74
160	6	0	129	56	168	65	15	1	1	8	2	15	158	197	49	32	36	95	74	56	149	92	53
170	12	1	119	87	209	121	23	3	0	12	4	16	153	144	50	30	45	83	89	69	135	115	83
180	5	1	112	95	182	138	33	0	0	17	3	20	139	157	103	59	62	79	114	100	206	124	90
190	1	2	115	114	181	144	49	4	1	12	2	21	171	181	85	57	47	71	147	103	223	134	101
200	9	9	93	131	150	158	41	0	0	10	2	15	130	129	81	57	56	89	188	173	212	165	139
210	5	5	82	117	128	149	69	2	1	4	5	19	100	123	68	70	47	105	192	194	225	201	160
220	1	7	72	105	156	144	60	0	4	6	4	22	72	123	66	51	39	108	172	207	230	201	162
230	3	3	65	124	145	104	50	1	1	7	1	14	86	79	29	53	40	95	175	238	240	203	164
240	1	1	46	97	111	90	55	2	0	1	1	17	43	70	23	41	40	109	161	222	228	197	164
250	2	4	60	99	112	68	39	4	2	11	2	17	42	55	17	27	23	68	129	200	273	203	141
260	1	4	64	87	102	71	57	0	1	5	2	14	37	36	19	17	40	74	98	163	247	174	164
270	0	2	62	90	125	69	50	3	2	8	4	14	34	30	14	13	19	58	114	188	205	141	131
280	0	3	50	91	128	60	60	3	1	7	1	5	25	34	11	19	12	43	64	112	195	106	105
290	0	2	41	101	123	59	67	3	0	11	1	5	12	23	12	12	6	32	68	85	160	84	78
300	1	1	28	91	106	56	88	1	0	1	2	4	8	18	7	7	9	43	53	79	107	48	64
310	1	0	34	87	109	63	73	8	0	6	6	4	8	12	2	4	6	25	59	56	72	34	37
320	2	4	23	105	130	51	74	6	1	1	1	3	7	9	8	6	3	11	23	37	61	21	27
330	4	4	40	108	122	68	96	9	2	6	2	4	6	14	4	6	6	8	24	29	31	16	13
340	2	1	15	97	147	76	86	4	1	3	4	7	11	17	13	9	10	10	16	18	17	6	11
350	4	0	21	127	144	66	112	2	0	7	9	3	17	20	24	18	9	24	12	16	20	9	5
360	2	2	28	110	168	69	108	1	2	1	6	9	21	45	24	19	6	15	14	16	16	16	5
370	0	3	17	112	120	72	108	2	3	6	6	10	33	36	22	18	16	35	38	18	14	17	4
380	2	1	17	73	96	47	104	8	3	9	11	7	27	79	31	31	22	41	33	29	23	18	6
390	5	1	13	56	85	40	77	4	1	1	7	7	26	80	36	40	26	57	35	21	24	25	8
400	1	0	5	44	53	27	41	1	0	2	9	6	24	71	22	31	21	57	36	25	17	20	10
410	1	3	6	22	35	19	29	0	1	3	2	2	22	48	22	20	17	29	24	17	18	20	3
420	1	1	3	13	14	11	15	0	0	2	2	4	13	32	19	12	12	26	16	20	7	8	1
430	0	0	2	5	8	6	8	0	0	0	3	2	3	15	9	1	6	12	9	5	6	4	2
440	0	0	1	6	4	0	2	0	0	0	1	1	2	7	1	3	4	11	2	3	2	0	0
450	0	0	0	2	1	0	4	0	0	0	0	0	1	3	0	1	0	4	1	1	0	0	0
460	0	0	1	1	1	0	0	0	0	1	0	0	0	1	1	1	0	0	1	0	0	0	0
470	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	2	2	1	1	1	0
480	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
490	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 9: Number of new marks released by year and size interval (GILL).

LI	YEAR																			
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2010
120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
140	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150	0	0	4	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	2	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
180	0	0	2	3	10	0	0	0	0	2	3	1	2	0	0	0	3	2	9	0
190	1	0	8	5	9	0	0	0	0	1	0	0	6	0	0	1	9	4	31	0
200	2	1	3	6	10	0	0	0	1	0	2	1	5	0	1	1	7	4	26	4
210	2	1	7	5	6	1	0	0	0	1	1	1	6	0	0	1	9	1	19	3
220	2	3	3	4	9	1	0	0	0	0	2	2	7	0	0	0	7	2	15	7
230	7	0	6	6	8	1	0	0	0	0	0	3	3	0	0	0	6	3	8	6
240	1	2	7	8	5	1	0	0	0	0	1	0	3	0	1	1	5	1	13	2
250	3	0	9	1	4	0	0	0	0	0	1	0	1	0	0	0	0	2	6	5
260	1	1	9	2	4	0	0	1	1	0	0	1	1	0	0	0	0	0	5	3
270	3	1	9	3	2	1	0	0	0	0	0	0	1	0	0	0	0	1	3	0
280	3	2	11	10	5	1	1	0	0	0	1	0	0	0	0	0	3	1	2	1
290	3	4	6	4	4	0	0	0	0	2	0	1	3	1	0	0	0	0	1	2
300	9	0	25	9	5	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0
310	15	4	20	18	2	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
320	14	2	34	17	12	2	1	1	0	3	0	0	2	0	0	0	1	1	0	0
330	37	10	25	23	10	1	0	0	3	0	0	0	0	1	0	0	2	1	0	0
340	36	11	40	19	18	1	2	1	1	0	0	1	1	0	1	0	0	0	1	0
350	26	8	45	24	13	6	2	1	3	0	0	0	3	0	0	0	1	0	1	0
360	29	14	38	32	16	6	5	1	3	0	2	1	2	0	0	0	1	0	0	0
370	20	5	52	36	19	3	1	2	6	1	0	0	1	0	0	1	3	0	2	0
380	20	10	37	30	16	9	3	2	4	0	1	0	3	1	0	0	0	0	0	0
390	30	20	42	22	14	4	1	0	3	1	1	1	3	0	0	0	3	0	0	0
400	14	7	37	13	11	5	1	0	1	0	0	0	1	0	0	0	2	0	1	0
410	4	7	15	11	9	5	0	0	2	1	1	0	3	0	0	0	2	0	1	0
420	2	8	11	8	6	2	1	1	0	0	3	1	0	0	0	0	0	0	0	2
430	2	3	6	2	3	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0
440	1	0	4	2	1	1	0	0	1	0	0	2	0	0	0	0	0	0	0	0
450	1	2	4	2	2	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
460	2	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
470	1	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
480	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
490	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 10: Number of recaptured marks by year and size interval (GILL).

LI	YEAR																			
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2010
120	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
140	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150	0	0	2	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	10	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	1	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
190	1	0	3	2	4	1	0	0	0	0	0	0	0	0	0	0	2	1	4	1
200	2	0	2	5	4	2	0	0	0	2	1	0	1	0	0	0	2	1	5	0
210	0	0	3	1	9	0	0	0	0	0	0	0	3	0	0	0	5	0	9	0
220	0	0	1	4	10	0	0	0	1	0	0	0	1	0	0	4	1	0	3	1
230	0	0	5	3	8	2	0	0	1	0	0	0	1	0	1	0	2	0	4	3
240	0	0	4	4	11	0	0	2	0	0	0	0	2	0	0	0	4	2	3	2
250	0	0	1	3	10	0	1	0	0	0	0	0	1	0	0	0	0	3	5	2
260	0	0	0	1	11	0	1	0	0	0	1	0	0	0	0	2	1	1	3	0
270	0	0	3	1	12	3	1	3	2	1	0	0	0	0	0	0	0	0	5	1
280	1	0	3	5	11	1	1	2	0	1	0	0	0	0	0	1	1	0	4	0
290	1	0	5	6	15	3	1	1	0	0	1	0	1	0	0	0	0	0	0	2
300	1	0	3	6	15	3	2	1	1	0	1	2	1	0	0	1	1	0	1	0
310	4	1	8	14	23	3	2	1	4	1	1	2	0	0	0	0	1	1	1	0
320	2	0	11	18	32	7	5	3	7	1	0	1	2	0	0	0	0	0	1	1
330	1	2	16	23	36	10	4	4	9	1	4	2	2	0	2	0	0	0	0	1
340	2	1	11	23	43	16	5	5	12	3	1	2	5	2	0	1	2	0	0	0
350	4	1	10	21	59	24	12	3	11	3	1	4	12	1	1	1	4	1	1	1
360	2	1	14	32	62	23	11	6	17	4	1	6	13	1	1	1	3	0	1	1
370	4	0	15	31	47	18	12	9	13	6	3	3	18	1	1	6	7	3	4	4
380	1	2	10	27	62	21	12	5	19	7	5	10	25	0	2	7	7	3	4	3
390	2	2	16	18	43	15	9	8	13	5	2	5	34	1	7	5	19	7	4	5
400	0	0	10	20	49	10	3	4	7	4	6	12	20	1	0	4	16	5	4	2
410	0	1	5	15	24	6	9	2	4	5	2	5	16	0	5	4	13	0	4	5
420	0	1	1	9	13	5	5	2	1	1	3	2	8	0	2	2	4	3	5	1
430	0	0	1	2	6	4	3	0	0	1	1	3	3	0	0	1	3	2	2	0
440	0	0	2	3	4	3	0	0	0	0	0	2	2	0	1	1	5	0	0	0
450	0	0	0	0	1	4	1	1	1	0	0	1	0	0	0	2	3	0	1	0
460	0	0	0	0	4	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0
470	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
480	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
490	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0

```
#
#   tableCaptures: extracts the monthly captures each year
#
#   tableGear: extacts the number of HBC capture each year by gear type.
#
#   tableLf: extracts the catch at length (10 mm bins) each year.
#
#   tableMarks: marks released and recaptured by GILL and HOOP nets
# ———————————————————————————————————————— #
require(ggplot2)
# require(hacks) #deprecated
source("../read.admb.R")
require(reshape)
require(Hmisc)
require(PBSmodelling)
dfile    <- "raw2012data.csv"
xbin     <- seq(50, 600, by=10)
seas     <- seq(1,12,by=3)

# ———————————————————————————————————————— #
# Read data file and create data.frame object for use. Returns (DF)
# ———————————————————————————————————————— #
get.DF   <- function(dfile)
{
    DF         <- read.csv(dfile, header=T)
    t1         <- as.POSIXct(strptime(as.character(DF$START_DATETIME), "%m/%d/%Y"))
    DF$DATE    <- t1
    DF$YEAR    <- as.numeric(format(DF$DATE,"%Y"))
    DF$MONTH   <- as.numeric(format(DF$DATE,"%m"))
    DF$TAGNO   <- DF$TH_ENCOUNTER_RANKING
    DF$TL      <- DF$TOTAL_LENGTH
    DF$XI      <- xbin[findInterval(DF$TL, xbin)]
    DF$QTR     <- findInterval(DF$MONTH, seas)

    # Read in Gear codes and convert to Gear Group
    gearType   <- read.table("gearCode.txt", header=T, sep="\t")
    gid        <- pmatch(DF$GEAR_CODE, gearType[,1], duplicates.ok=TRUE)
    DF$GROUP   <- gearType[gid, 2]

    # Sort data frame by date the tagno,  add recapture field
    DF         <- DF[order(DF$DATE, DF$TAGNO), ]
    DF$RECAP   <- duplicated(DF$TAGNO)


    return (DF)
}

# ———————————————————————————————————————— #
# Construct growth increment data.frame for estimating growth using Laslett model.
# ———————————————————————————————————————— #
getGrowthIncrement <- function(DF)
```

```
{
    fnGI      <- function(idNum)
    {
        sDF  <- subset(DF,DF$TAGNO==idNum, select=c(DATE,TL,YEAR,RIVER_CODE))
        if(dim(sDF)[1]==1)  return(NULL)
        sDF  <- sDF[order(sDF[,1]),]
        ni   <- dim(sDF)[1]
        dt   <- as.integer(sDF[ni, 1] - sDF[1, 1]) # days at large
        if(dt<=365 || dt>730 ) return(NULL)        # at least 1-year at liberty
        l1   <- sDF[1 , 2]                         # length at tagging
        l2   <- sDF[ni, 2]                         # length at recapture
        yr   <- sDF[1 , 3]                         # release year
        tl   <- sDF[1 , 4]                         # release location
        dl   <- (l2-l1)/(dt/365.25)                # annual growth increment
        return (c(yr, tl, l1, l2, dt, round(dl, 2)))
    }
    idNum    <- unique(DF$TAGNO)
    TRdata   <- data.frame()
    for(i in idNum) TRdata <- rbind(TRdata, fnGI(i))
    colnames(TRdata) <- c("YEAR","RIVER","L1","L2","DT","DL")

    TRdata <- na.omit(TRdata)        #Remove missing recapture measurements
    ii <- which(TRdata$DL <= -10)    #Remove records with growth increments < -5 mm
    #TRdata$RIVER[TRdata$RIVER==1] <- "COR"
    #TRdata$RIVER[TRdata$RIVER==2] <- "LCR"
    return(as.data.frame(TRdata[-ii, ]))
}

# ------------------------------------------------------------------------------ #
# Annual growth increment data based on captures and recaps in subsequent year.
# ------------------------------------------------------------------------------ #
annualGrowthIncrement <- function(DF)
{
    # Goal: for each year compute the length-at-capture & growth increment into
    #       the following year.
    # PSEUDOCODE:
    # - get vector of unique years.
    # - find unique individuals recaptured year i and year i+1
    # - get TL from each capture event

    ATR    <- data.frame()
    iyr    <- unique(DF$YEAR)
    for(i in iyr)
    {
        iDF  <- rbind(subset(DF,DF$YEAR==i), subset(DF, DF$YEAR==i+1))
        iDF  <- iDF[order(iDF$TAGNO, iDF$DATE), ]
        irc  <- unique(iDF$TAGNO[duplicated(iDF$TAGNO)])

        for(j in irc)
        {
            ijDF <- subset(iDF, iDF$TAGNO==j)
```

```
        nj    <- dim(ijDF)[1]
        dt    <- as.integer(ijDF$DATE[nj] - ijDF$DATE[1])
        l1    <- ijDF$TL[1]
        l2    <- ijDF$TL[nj]
        loc   <- ijDF$RIVER_CODE[1]
        ATR   <- rbind(ATR, c(YEAR=i, RIVER=loc, TAGNO=j, l1=l1, l2=l2, dt=dt))
      }
    }
    colnames(ATR)=c("YEAR","RIVER","TAGNO","l1","l2","dt")
    return(ATR)
}


# ---------------------------------------------------------------------------- #
# Get captures & recaptures by length interval
# ---------------------------------------------------------------------------- #
getCaptureByLength <- function(DF)
{
    xbin     <- seq(50, 600, by=5)
    nbin     <- length(xbin)
    nyr      <- length(unique(DF$YEAR))
    ctx      <- matrix(0, nrow=nyr, ncol=nbin-1)
    fnCH     <- function(idNum)
    {
        sDF <- subset(DF, DF$TAGNO==idNum, select=c(YEAR,MONTH,RIVER_CODE,TL))
        sDF <- cbind(sDF, RECAP=FALSE)
        sDF <- sDF[order(sDF$YEAR,sDF$MONTH),  ]
        sDF <- sDF[!duplicated(sDF,MARGIN=c(1,2)),]

        sDF$RECAP[-1] <- TRUE

        sDF$TL  <- factor(sDF$TL, levels=xbin)
        t_TL    <- table(sDF$TL)
        ctx     <- ctx + t_TL
        return(sDF)
    }
}

# ---------------------------------------------------------------------------- #
# Table of monthly captures by year
# ---------------------------------------------------------------------------- #
tableCaptures <- function(DF)
{

    # Table of total HBC captures by MONTH~YEAR
    names(DF) <- toupper(names(DF))
    DFm       <- melt(DF, id=c("YEAR","MONTH"), na.rm=F)
    tx        <- cast(DFm,YEAR~MONTH,length,subset=variable=="TL"
                      ,margins=c("grand_row","grand_col"))
    fn        <- "../../TABLES/LSMR/tableCaptureNumbers.tex"
    cap       <- "Number of fish measured by year and month, sampled by all gears
```

```
                  in all reaches of both the LRC and COR."
    cgrp        <- c("", "MONTH")
    ncgrp       <- c(1, 13)
    d1          <- latex(tx, file=fn, rowname=NULL, caption=cap
                    , size="footnotesize", cgroup=cgrp, n.cgroup=ncgrp
                    , label="table:Captures")

}

# ---------------------------------------------------------------------- #
# Table of annual captures by gear type
# ---------------------------------------------------------------------- #
tableGear <- function(DF)
{
    names(DF) <- toupper(names(DF))
    DFm         <- melt(DF, id=c("YEAR","GROUP"), na.rm=FALSE)
    tx          <- cast(DFm,YEAR~GROUP,length, subset=variable=="TL"
                        ,margins=c("grand_row","grand_col"))
    fn          <- "../../TABLES/LSMR/tableCaptureGear.tex"
    cap         <- "Number of fish captured by gear type listed in the"
    cap         <- paste(cap, " GCMRC database for each year.")
    cgrp        <- c("", "YEAR")
    ncgrp       <- c(1, 10)
    d1          <- latex(tx, file=fn, rowname=NULL, caption=cap
                    , size="footnotesize", cgroup=cgrp, n.cgroup=ncgrp
                    , label="table:Gear")

}

# ---------------------------------------------------------------------- #
# Table of number of TRIP_IDs and CPUE per year
# ---------------------------------------------------------------------- #
tableEffort <- function(DF)
{
    names(DF) <- toupper(names(DF))
    DFm         <- melt(DF, id=c("YEAR","GROUP"), na.rm=FALSE)
    tx          <- cast(DFm,YEAR~., function(x) length(unique(x))
                        ,subset=variable=="TRIP_ID", margins=TRUE )
    td          <- cast(DFm, YEAR~., function(x) length(unique(x))
                        ,subset=variable=="DATE", margins=TRUE )
    tn          <- cast(DFm, YEAR~GROUP, function(x) length(unique(x))
                        ,subset=variable=="START_DATETIME"
                        ,margins=TRUE )
    tl          <- cast(DFm, YEAR~GROUP, length, subset=variable=="TL"
                        ,margins=TRUE)

    # Effort table
    Effort      <- cbind(tx, td[,-1],tn[,c(10, 6, 5)]
                        ,tn[,10]-rowSums(tn[,c(6, 5)]) , tl[,c(6,5)]
                        ,round(tl[,c(6,5)]/tn[,c(6,5)], 2))
    colnames(Effort) <- c("Year","Trips","Days","Sets","Hoop"
```

```
                        ,"Tramel","Other","Hoop Ct","Tramel Ct"
                        ,"Hoop CPUE","Tramel CPUE")

    fn          <- "../../TABLES/LSMR/tableEffort.tex"
    cap         <- "Number of trips,  days fished,  unique sets,
                  hoop and tramel net sets,  other gears,  catch of humpback
                  chub in hoop nets and tramel nets,  and the corresponding
                  arithmatic CPUE for each gear.  Note that these CPUE trends should
                  not be used as a relative abundance index because zero catch of HBC
                  have been excluded from the effort data."
    d1          <-latex(Effort[-25,], file=fn, caption=cap
                    , label="table:Effort", size="scriptsize", rowname=NULL)
}


# ---------------------------------------------------------------------------- #
# Table of annual captures by gear type
# ---------------------------------------------------------------------------- #
tableLf <- function(DF)
{
    names(DF) <- toupper(names(DF))
    DFm         <- melt(DF, id=c("YEAR","XI","GROUP"), na.rm=TRUE)
        tx          <- cast(DFm,YEAR~XI,length, subset=variable=="TL")
    rtx         <- cast(DFm,YEAR~XI|GROUP,length, subset=variable=="TL")
    gear        <- c("GILL", "HOOP") # Add gear group here to plot results

    plotBubbles(t(tx[,c(-1,-48)]),xval=1989:2011,yval=sort(unique(DF$XI,na.rm=T))
                    , size=0.15, hide0=TRUE, frange=0.01
                    , xlab="Year", ylab="Length (mm)")
    rect(1988,100,2013,150,col=colr(4,0.2),border=NA)
    fig         <- "../../FIGS/LSMR/fig:CaptureLFbubbles.pdf"
    dev.copy2pdf(file=fig)

    fn          <- "../../TABLES/LSMR/tableCaptureLF.tex"
    cap         <- "Number of fish captured by length by all gear types
                  listed in the GCMRC database for each year."
    cgrp        <- c("", "YEAR")
    ncgrp       <- c(1, 22)
    LI          <- t(tx)
    d1          <- latex(LI,file=fn, caption=cap
                     , size="tiny",cgroup=cgrp, n.cgroup=ncgrp
                     , lable="table:Lf")
    # use sed to make sideways table
    sed.exp <- paste("sed -i~ 's/table/sidewaystable/g' ", fn)
    system(sed.exp)

        return(rtx)
}

# ---------------------------------------------------------------------------- #
# Table of marks released and recaptured each year (RECAP=FALSE)
```

```
# ------------------------------------------------------------------------------------------ #
tableMarks <- function(DF)
{
    names(DF) <- toupper(names(DF))
    DFm       <- melt(DF, id=c("YEAR","MONTH","XI","RECAP","GROUP"), na.rm=TRUE)
    tx        <- cast(DFm,YEAR~XI~RECAP|GROUP, length, subset=c(variable=="TL"), fill=0)
    gear      <- c("GILL", "HOOP") # Add gear group here to plot results

    # Barplots of marks released and recaptured.
    fn.plot <- function(x)
    {
        par(mfcol=c(6, 4), mar=c(0.5, 1, 0.5, 1), oma=c(4, 4, 1, 1))
        n   <- dim(x)[1]
        for(i in 1:n)
        {
            if(!i%%6 || i==n)par(xaxt="s") else par(xaxt="n")
            if(i==n)lgdtxt=c("Mark", "Recap") else lgdtxt=NULL
            barplot(t(x[i, , ]), xlim=c(0, length(xbin))
                    , legend.text=lgdtxt
                    , args.legend=list(bty="n", cex=0.75))
            title( main=rownames(x)[i],    font.main=2, cex.main=0.75, line=-1)
        }
        mtext(c("Length (mm)","Frequency"),side=c(1, 2), outer=T, line=2)

        fig=paste("../../FIGS/LSMR/fig:MarksAtLength",gear[jj],".pdf", sep="")
        print(fig)
        jj<<-jj+1
        dev.copy2pdf(file=fig)
    }

    event     <- c("Mark", "Recapture")
    cap       <- c("Number of new marks released by year and size interval "
                 , "Number of recaptured marks by year and size interval ")
    fdir      <- "../../TABLES/LSMR/"
    cgrp       <- c("YEAR")


    fn.write <- function(x)
    {
        for(i in 1:2)
        {
            ncgrp <- c(dim(x)[1])
            pcap  <- paste(cap[i], "(", gear[jj], ").", sep="")
            fi    <- paste(fdir,"table:",event[i],":", gear[jj],".tex", sep="")
            LI    <- t(x[, , i])
            d1    <- latex(LI, file=fi, caption=pcap, size="tiny"
                     , cgroup=cgrp, n.cgroup=ncgrp
                     , label=paste("table:",event[i],"_",gear[jj], sep="")
                     )

            # use sed to replace table with sidewaystable
```

```
            sed.exp <- paste('sed -i~ "s/table/sidewaystable/g" ', fi)
            system(sed.exp)
        }
        jj <<- jj+1
        print(jj)
    }

    ii = names(tx) %in% gear
    jj          <<-1
    lapply(tx[ii], fn.plot)
    jj         <<- 1
    lapply(tx[ii], fn.write)

        return(tx)
}
# ------------------------------------------------------------------------ #
# Create LSMR datafile
# ------------------------------------------------------------------------ #
write.LSMRdatafile <- function(DF, ...)
{
        dfn <- "../../ADMB/srcLSMR/HBC2011qtr.dat"
        gr  <- c("HOOP", "GILL")

        # Melt dataframe
        DFm <- melt(DF, id=c("YEAR","MONTH","QTR","TRIP_ID","RECAP","XI","GROUP"), na.rm=T
        
        # Cast DFm to extract Catch-at-length,  Marks-at-length
        C   <- cast(DFm,YEAR + QTR~XI|GROUP,length,subset=variable=="TL", add.missing=TRUE)
        M   <- cast(DFm[DFm$RECAP==FALSE, ], YEAR+QTR~XI|GROUP, length, subset=variable=="T
        R   <- cast(DFm[DFm$RECAP==TRUE, ], YEAR+QTR~XI|GROUP, length, subset=variable=="TI
        E   <- cast(DFm, YEAR+QTR~GROUP, function(x) length(unique(x)),subset=variable=="ST
        E   <- E[1:92, ]
        # Plot the data to be used
        plot.b <- function(X)
        {
                yr <- seq(1989, 2011.75, by=0.25)
                plotBubbles(t(X[,-1:-2]),xval=yr,yval=colnames(X[,-1:-2]), prettyaxis=TRUE
                           , hide0=T,size=0.15,frange=0.01,cpro=FALSE,powr=1
                           , xlab="Year", ylab="Size class (Total Length mm)")
        }
        graphics.off()
        quartz(width=9,height=6.5)
        plot.b(C$HOOP); dev.copy2pdf(file="../../FIGS/LSMR/DATA/fig:Hoop_C.pdf", width=9, 
        plot.b(M$HOOP); dev.copy2pdf(file="../../FIGS/LSMR/DATA/fig:Hoop_M.pdf", width=9, 
        plot.b(R$HOOP); dev.copy2pdf(file="../../FIGS/LSMR/DATA/fig:Hoop_R.pdf", width=9, 

        plot.b(C$GILL); dev.copy2pdf(file="../../FIGS/LSMR/DATA/fig:Gill_C.pdf", width=9, 
        plot.b(M$GILL); dev.copy2pdf(file="../../FIGS/LSMR/DATA/fig:Gill_M.pdf", width=9, 
        plot.b(R$GILL); dev.copy2pdf(file="../../FIGS/LSMR/DATA/fig:Gill_R.pdf", width=9, 

        # Effort
```

```
    barplot(rbind(E$HOOP,E$GILL), beside=T,names.arg=paste(yr)
            , xlab="Year", ylab="Effort (number of sets)",
            , legend.text=c("Hoop","Tramel net"), args.legend=list(x="top", bty="n") )
    dev.copy2pdf(file="../../FIGS/LSMR/DATA/fig:Effort.pdf", width=9, height=6.5)

    # Get index for gears
    ic  <- names(C) %in% gr
    im  <- names(M) %in% gr
    ir  <- names(R) %in% gr
    ie  <- names(E) %in% gr

    # Ensure R matrix and M matrix have the same dimensions at C
    ii  <- colnames(C$HOOP) %in% colnames(R$HOOP)
    tmp <- C$HOOP; tmp[, ii] <- R$HOOP; tmp[, !ii] <- 0; R$HOOP <- tmp
    ii  <- colnames(C$GILL) %in% colnames(R$GILL)
    tmp <- C$GILL; tmp[, ii] <- R$GILL; tmp[, !ii] <- 0; R$GILL <- tmp



    write("#Data for HBC 1989:2011", file=dfn)
    write("#syr, nyr, dt", file=dfn, append=TRUE)
    write(c(1989, 2011, 1/4), file=dfn, append=TRUE)
    write("#Number of gears",file=dfn, append=TRUE)
    write(length(gr), file=dfn, append=TRUE)
    xbin = as.numeric(colnames(C$HOOP)[-1:-2])/10  #units cm
    write("#nbin", file=dfn, append=TRUE)
    write(length(xbin), file=dfn, append=TRUE)
    write("#xbin", file=dfn, append=TRUE)
    write(xbin, file=dfn, append=TRUE)

    write("#Array dimensions (rows,  cols) for each gear in (C M R)", file=dfn, append=
    write.table(matrix(unlist(lapply(C[ic],dim)),nrow=2,byrow=TRUE),file=dfn,row.names=

    # effort data (# of sets)
    write("#Number of sets by gear for each time step", file=dfn, append=TRUE)
    lapply(E[ie], write, file=dfn, append=TRUE)

    #order is GILL then HOOP
    write("#Captures by year (row) and length (col)", file=dfn, append=TRUE)
    lapply(C[ic],write.table,file=dfn,row.names=F,col.names=F, quote=F,append=T)

    write("#Marks by year (row) and length (col)", file=dfn, append=TRUE)
    lapply(M[im],write.table,file=dfn,row.names=F,col.names=F, quote=F,append=T)

    write("#Recaps by year (row) and length (col)", file=dfn, append=TRUE)
    lapply(R[ir],write.table,file=dfn,row.names=F,col.names=F, quote=F,append=T)

    write("#End of file", file=dfn, append=TRUE)
    write(999, file=dfn, append=TRUE)

}
```

```
# ---------------------------------------------------------------------------- #
# Read in data frames and obtain tag-recapture data
# ---------------------------------------------------------------------------- #
if(!exists("DF")) DF <- get.DF(dfile)
if(!exists("TR"))
{
    TR <- getGrowthIncrement(DF)
    print(head(TR))
    TR <- TR[order(TR$YEAR,TR$RIVER),]
    write(dim(TR)[1],file="HBC_Tag_RecaptureII.dat")
    write(c("#YEAR","RIVER","L1","L2","DT","DL"), ncol=6,
            file="HBC_Tag_RecaptureII.dat", append=TRUE)
    write.table(TR,file="HBC_Tag_RecaptureII.dat",row.names=F,
            col.names=F, append=TRUE)

    fig="../../FIGS/LSMR/fig:GrowthIncrements.pdf"
    plot.gi(TR, file=fig)
}
if(!exists("ATR"))
{
    ATR  <- annualGrowthIncrement(DF)
    O    <- na.omit(ATR[ATR$dt>365, -3])
    O$dl <- round((O$l2-O$l1)/(O$dt/365.25), 2)

    print(head(O))
    fn  <- "HBC_Annual_GI.dat"
    write(dim(O)[1], file=fn)
    write(c("#YEAR","RIVER","l1","l2","dt","dl"), ncol=6, file=fn, append=TRUE)
    write.table(O, file=fn, row.names=FALSE, col.names=FALSE, append=TRUE)

    fig <-"../../FIGS/LSMR/fig:AnnualGrowthIncrements.pdf"
    plot.atr(O, file=fig)
}

# ---------------------------------------------------------------------------- #
# Plotting routines
# ---------------------------------------------------------------------------- #
plot.gi <- function(TR, file=NULL,  ...)
{
    p<-ggplot(TR,aes(L1,DL))
    p<-p + geom_point(aes(colour=factor(RIVER), levels=2),alpha=0.5)
    p<-p + stat_quantile(alpha=0.7, col="black")+facet_wrap(~YEAR)
    p<-p + labs(x="Release Length (mm)", y="Annual growth increment (mm)")
    p<-p + labs(colour="River")+theme_grey(base_size =  12, base_family = "")
    if(!is.null(file))
        dev.copy2pdf(file=file)

    return(p)
}
```

```
plot.atr <- function(ATR, file=NULL, ...)
{
    O     <- ATR[ATR$dt>365, ]
    O$gi  <- (O$l2-O$l1)/(O$dt/365.25)
    p     <- ggplot(O, aes(l1, gi))
    p     <- p + geom_point(aes(color=factor(RIVER), levels=2), alpha=0.5)
    p     <- p + stat_quantile(alpha=0.7, col="black") + facet_wrap(~YEAR)
    p     <- p + labs(colour="River")+theme_grey(base_size = 12, base_family = "")
    p
    if(!is.null(file))
        dev.copy2pdf(file=file)

    return(p)

}
```

D Size Transition Matrix from Mark-Recapture data

There is an alternative method for independently constructing annual length transition matrix based on individual capture-recapture information that incorporates both parametric uncertainty and measurement error. The alternative method of constructing length-based transition matrices can be used as an alternative to internally estimating growth parameters, rather than jointly estimating them and introducing addition parameter confounding. This method was recently described by Hillary (2011). In short, the method first estimates von Bertalanffy growth parameters based on the length-at-release and growth increment information, growth parameters are then sampled from the joint posterior distribution, and for each posterior sample measurement error is then added to the predicted growth increment from x_j to $x_{j'}$ and the overlap between $(x_{j'} - x^*) \cap (x_{j'} + x^*)$ is calculated. To numerically approximate the length transition matrix, 1,000 samples from the joint posterior distribution are used to construct 1,000 length-transition matrixes $(P_{j,j'})$ and the mean values from the 1000 matrixes are used as the length transition matrix.

Growth parameters were estimated based on growth increment data from individual fish that were captured and recaptured in the subsequent year only. Initially, growth increment data based on length-at-tagging and the most recent capture event was used (i.e., the longest time at liberty) were going to be used; but, upon further inspection of the raw data there is evidence of changes in growth rates over time (see increasing negative slopes in Figure 7). To minimize the impact of changing growth rates, the growth increment data were based only on individuals that were captured and recaptured in the subsequent calendar year (Figure 8), hereafter referred to as annual growth increment data.

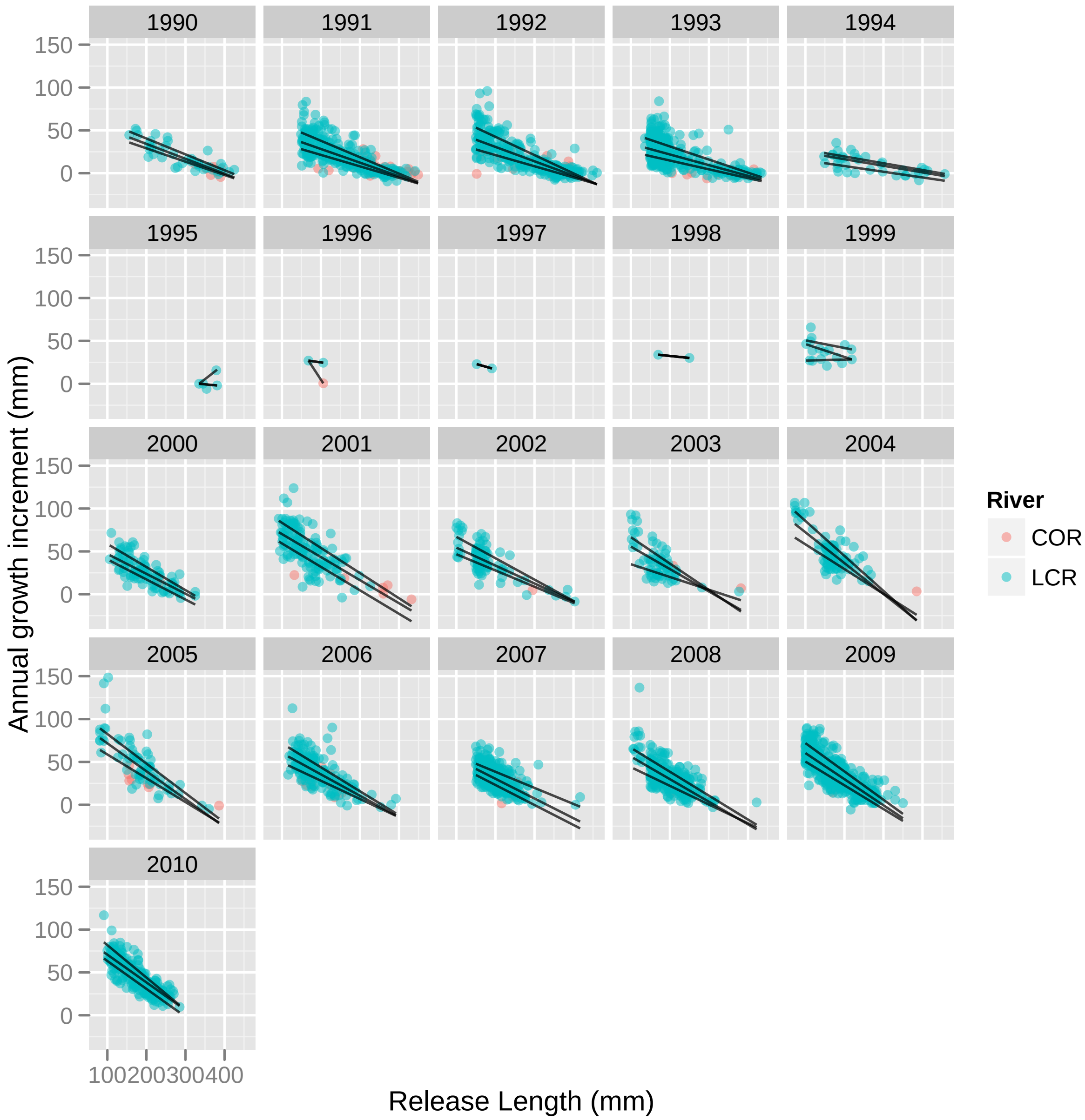

Figure 7: Growth increments by tag year for individually tagged humpback chub that have been at large for at least 1 year. Recapture events could have occurred in either river. Fitted lines correspond to the 5, 50 and 95 percentiles of the data.

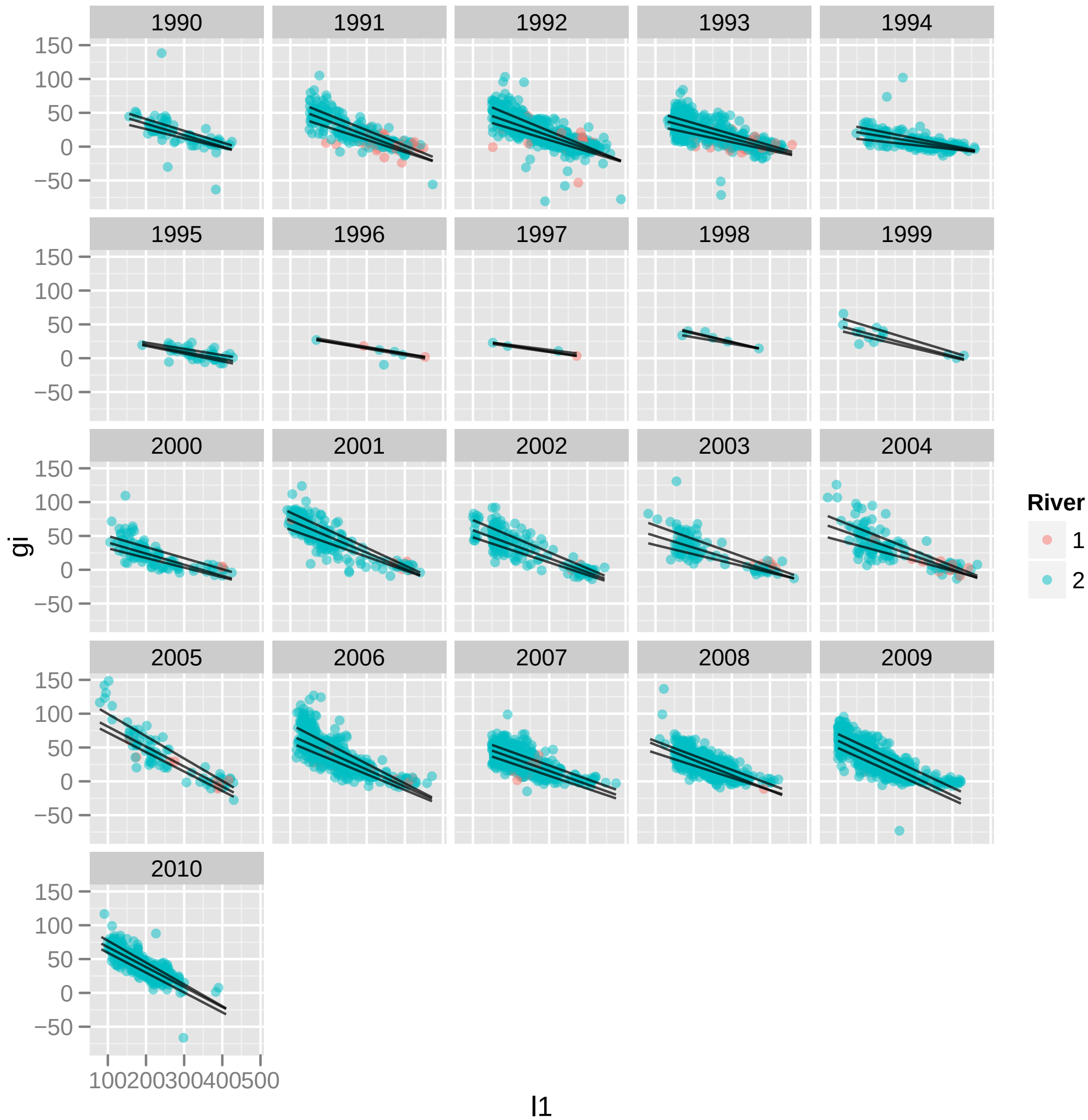

Figure 8: Annual growth increments of humpback chub of all fish captured and recaptured in the following year. River 2 corresponds to fish tagged in the Little Colorado River, River 1 the Colorado River. Fitted lines correspond to the 5, 50 and 95 percentiles of the data.