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ESTIMATES OF EASTERN NORTH PACIFIC GRAY WHALE CALF PRODUCTION 1994-2021

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Estimates of eastern North Pacific gray whale calf production 1994-2021

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INTRODUCTION

Eastern North Pacific gray whales *(Eschrichtius robustus)* migrate annually between foraging grounds in the arctic and wintering grounds in Baja California (Rice and Wolman 1971). Females give birth in protected lagoons in Baja California and migrate north with their calves in the spring of each year. Shore-based counts of female gray whales accompanying their calves (i.e. mother-calf pairs) have been conducted annually from the Piedras Blancas Light Station in central California since 1994. Survey methods were evaluated in detail at the outset of the study (Perryman et al. 2002) and both survey methods and the analytical approach used to estimate total annual calf production have remained consistent since 1994 (Weller and Perryman 2019). This report presents a new Bayesian modeling approach to estimate annual calf production of ENP gray whales that more fully accounts for uncertainty during unsampled periods. Here we provide estimates of calf production for the 1994-2021 period using the Bayesian approach and compare them to estimates using the previous methods.

METHODS

Calf count data used here were collected between 1994-2021 using standardized methods and processed to be consistent with previous analyses (Perryman et al. 2002;Weller and Perryman 2019). Briefly, a rotating pair of observers conducted counts of mother-calf pairs from a shore station during a watch period of, typically, a maximum of 12 hours per day. Watches were shut down for poor weather (rain, fog, etc.), visibility or sea conditions, resulting in total daily effort frequently below the maximum of 12 hours. The annual survey was not conducted in 2020 due to COVID-19 but was completed in 2021 under COVID staffing restrictions, including a three-person rather than four-person observer rotation during some weeks. During periods when the three-person rotation was in place, the maximum survey effort in a given day was capped at 9 hours rather than the typical 12 hours for a four-person rotation.

Perryman et al. (2002) determined that: (a) the number of calves passing offshore and outside of the range of shore-based observers was negligible (data from aerial surveys) and (b) the passage rates of mother-calf pairs were consistent between daytime and nighttime periods (based on infrared sensors). Independent replicate counts from two different shore-based observation stations conducted over seven consecutive years (1994-2000) suggested a detection probability of 0.889 (SE 0.06375) (Perryman et al. 2002). All of these assumptions were maintained for the present study. Raw data were processed to reflect the total number of calves passing within four 3-hour periods per day, and the total survey effort per 3-hour period following Weller and Perryman (2019).

Previous analyses of calf production used direct corrections for detection probability and effort to generate total calf production estimates. For example, if 2 calves were observed passing during a 3-hour period, that would be corrected for detection probability by dividing the total observed calves 0.889, for a total estimate of 2.247 calves for that 3-hour period. The detection probability-corrected calf counts were then summed for each 1-week period. Then, to account for both the portions of 3-hour watches that were terminated by poor conditions, and the unobserved night and weekend periods, the weekly total counts were multiplied by the number of hours in a week (168) divided by the total weekly effort. In 2016, for example, 22 calves were counted during the third week of survey effort (April 12-16). This was corrected to 24.747 calves to account for detection probability. There were 39.6 total hours of survey effort during that week, so the final estimate was 24.747 * (168/39.6) = 104.99. The same calculation was made for each week of the survey, and summed across weeks for a total calf estimate. Variance was incorporated via Taylor series expansion from the variance in estimated detection probability, the number of survey days, and the variance in the corrected total number of animals passing per 3-hour period (Weller and Perryman 2019).

In the present study, a Bayesian model was used to more fully account for uncertainty associated with detection probability, effort and unsampled periods. In addition, we estimate a passage rate that varies by week, which then helps inform the undetected calf estimates from unsampled periods. The model is based on a binomial sampling process,

$$Obs_i \sim binomial(True_i, p_i)$$

Where *Obs* is the number of calves observed during each 3-hour survey period *i* (including unobserved nights and weekends), *True* is the number of calves that actually pass during each 3-hour survey period *i*, and *p* is the effort-corrected detection probability for each survey period. We calculated *p* as,

$$p_i = \hat{p} * \frac{effort_i}{3}$$

$$\hat{p} \sim normal(0.889, 0.06375)$$

where $\hat{p}$ is the detection probability estimated by Perryman et al. (2002), and *effort* is the number of hours of reported effort in each 3-hour survey period *i*. Detection probability is therefore scaled by the proportion of time within a 3-hour survey period that observers are on watch. We make the assumption that, for example, if observers are only on watch for 1.5 out of 3 hours, then the probability of detecting a whale that passes during the 3-hour period is 0.889 * 1.5/3 = 0.4445. Similarly, nights and weekends are broken into 3-hour periods, each of which has 0 sightings and 0 effort. Any missing watch periods, either due to poor conditions or observer limitations during the 2021 survey that was impacted by COVID, were also logged as having 0 sightings and 0 effort. The detection probability during unobserved periods is therefore 0. Finally, we use a Poisson distribution to estimate the mean passage rate of whales within each 3-hour period during a given week,

$$True_i \sim Poisson(\lambda_{wk_i})$$

where λ is the mean passage rate for each week, and *wk* is the week during which survey period *i* occurred. This allows the estimated true number of whales passing during an unobserved 3-hour period to be informed by the mean passage rate during observed periods within the same week, with associated uncertainty. Finally, the total number of calves throughout the study period is calculated as

$$Total = \sum_i True$$

or the estimated true number of calves passing in each 3-hour period, summed across all periods *i*.

In some years, a survey was concluded mid-week after three consecutive days of 0 sightings of calves. In these cases, we populated the remainder of the final week with 0 sighting and 0 effort survey periods to maintain consistency across weeks. Migration start and end dates differed across years, and therefore the number of weeks surveyed were not consistent across years, but were instead designed to capture the full northbound migration from start to finish.

RESULTS

The annual variability in calf production estimates using the updated model closely followed the trends in previous calf production estimates (Table 1 and see Figure 1). However, updated estimates were consistently higher than previous estimates (mean 9.7% increase, SD 3.7%) (Figure 1 and Figure 2). In all cases, both the median and upper credible interval (CI) of the updated estimate were higher than the respective previous best estimate and upper CI from the same year. In all but two years (1995 and 1996) the same was true of the lower CI. Due to the aforementioned staffing limitations, the 2021 survey had the fewest effort hours (n = 353) of any year, but not the lowest calf counts (n = 76). Despite the reduced survey effort, the credible intervals and coefficient of variation of the 2021 calf production estimate were in line with previous years. In general, estimates with lower mean values had higher coefficients of variation compared to estimates with higher mean values, as the standard deviation was smaller in absolute terms but greater in relation to the mean values (Table 1 and see Figure 1).

DISCUSSION

The estimate for total calf production in 2021 using the updated Bayesian model was 380 (95% CI 296 – 493) and is among the lowest calf production estimates on record. While slightly higher than the 2019 calf production estimate (354; 95% CI 278-450), it appears that reproductive rates have remained depressed for the past three years. Two previous periods of low calf production also lasted for 3-4 years each (1999-2001 and 2007-2010), suggesting that the current pattern may be typical of ENP gray whale population dynamics. Two of the three recorded periods of low calf production have coincided with Unusual Mortality Events (UMEs; 1999-2000 and 2019-2021) and corresponding declines in abundance of over 20% (Stewart and Weller 2021). This suggests that the factors driving or mediating ENP gray whale fecundity and mortality rates may be similar.

Given the almost identical trend in updated calf production estimates as compared with estimates using the previous estimation method, we do not anticipate this new approach leading to substantial reinterpretations of calf production estimates for management purposes. However, it is noteworthy that the updated method led to, on average, a roughly 10% increase in calf production estimates (Figure 2a). We posit that this was due to how the unobserved periods were handled in the two approaches. Whereas the previous method simply applied the mean number of observed calves per hour of survey effort to the entire unobserved period within each week, the updated model allows the true number of calves during unobserved periods to vary throughout the entire range of uncertainty around the weekly mean passage rates, (λ_{wk}). This may have allowed the updated model to consider more extreme values of possible numbers of calves during unsampled periods, thereby slightly increasing the overall estimates. We would not expect the same to be true for the lower bounds (i.e. widening the credible intervals rather than increasing overall estimates) because the number of observed calves presents a minimum number of true calves passing in a 3-hour period. This is reflected in the estimates of λ_{wk}, which are generally slightly right skewed with more extreme values on the upper end of the distribution (Figure 3). Consequently, by incorporating the full range of uncertainty from λ_{wk}, the estimates of true number of calves during unobserved periods are likely to be higher than those obtained by simply applying the mean number of calves per hour to all unsampled periods, as in the previous approach.

There are two main advantages to the updated calf production model. The first is the implementation of a binomial sampling process, which explicitly includes detection probability and weekly changes in calf passage rates. This allows us to propagate the uncertainty associated with previous estimates of detection probability, as well as variability in calves detected per watch period, throughout the model and into unobserved periods. We argue that this provides a more complete accounting of the uncertainty associated with the extensive unobserved periods that make up more than half of each annual survey. Second, the use of a Bayesian framework provides posterior distributions of calf production estimates that lend themselves easily to projection studies that are frequently used to support the management of wildlife, while at the same time allowing for probabilistic interpretation that is essential in management settings (Dorazio and Johnson 2003; Ellison 2004).

Future work could attempt to create a modeling framework that combines all survey years into a single model, drawing on data from all years to inform a typical migration curve, similar to Durban et al. (2015). This would be most useful in cases where a complete survey was not possible due to logistical constraints or unanticipated interruptions, and the inclusion of many years of data would allow those gaps to be estimated based on an average migratory curve. The main challenge to that approach is the highly variable shape of the migratory curve of northbound mother-calf pairs across years (Figure 3). As long as the full migratory period is captured by the survey, the updated model described here provides a highly flexible approach that allows for deviations from an expected migratory pattern while still informing passage rates during unsampled periods by drawing on observed passage rates at weekly intervals.

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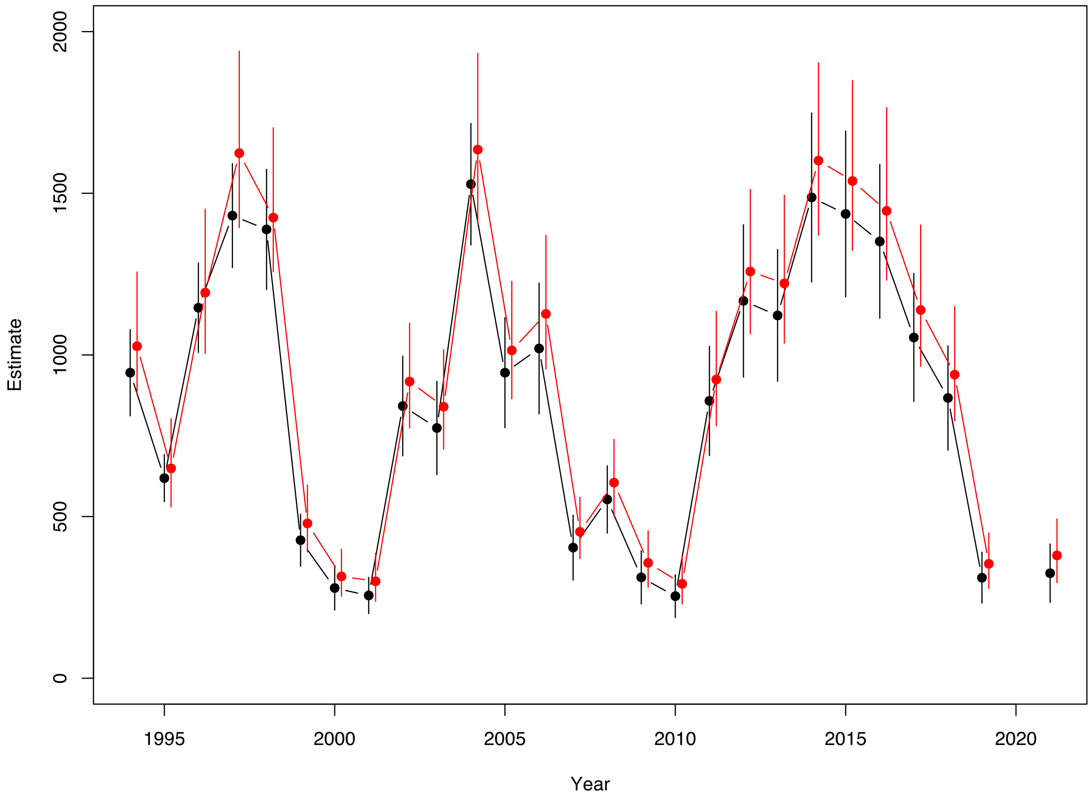

Figure 1. Annual estimates of eastern North Pacific gray whale calf production with associated 95% CIs using the previous estimation method (black) and updated model described in this report (red). Black points represent the best-estimate from the previous approach, and black bars represent the 95% confidence intervals around the mean estimate. Red points represent the median value of the Bayesian posterior distributions for each annual estimate and red bars represent the 95% Bayesian credible intervals.

Table 1. Eastern North Pacific gray whale calf production 1994-2021 with comparisons of previous and updated estimates.

Year	Hours Survey Effort	Number Female-Calves	Previous Estimate	Previous Confidence Intervals	Previous Coefficient of Variation (%)	Updated Estimate (Median)	Updated Credible Intervals	Updated Coefficient of Variation (%)
1994	712	320	945	811 - 1079	7.22	1027	881 - 1257	9.43
1995	559	168	619	546 - 692	6.01	649	530 - 803	10.82
1996	657	384	1146	1007 - 1285	6.17	1193	1004 - 1451	9.57
1997	594	493	1431	1270 - 1592	5.73	1624	1394 - 1940	8.76
1998	552	442	1388	1202 - 1574	6.83	1425	1257 - 1703	8.23
1999	731	141	427	346 - 508	9.63	479	390 - 598	11.21
2000	532	96	279	211 - 347	12.47	315	254 - 399	11.91
2001	541	87	256	200 - 312	11.16	300	237 - 387	12.60
2002	567	302	842	688 - 996	9.33	918	774 - 1098	9.11
2003	626	268	774	630 - 918	9.50	840	708 - 1016	9.49
2004	575	453	1528	1340 - 1716	6.28	1635	1405 - 1933	8.49
2005	660	341	945	775 - 1115	9.20	1014	864 - 1228	9.21
2006	518	285	1020	818 - 1222	10.13	1127	957 - 1370	9.47
2007	459	114	404	304 - 504	12.67	453	370 - 560	11.02
2008	495	171	553	449 - 657	9.60	605	502 - 739	10.09
2009	459	86	312	230 - 394	13.44	357	282 - 456	12.37
2010	486	71	254	187 - 321	13.36	292	230 - 376	13.05
2011	500	246	858	689 - 1027	10.04	924	781 - 1135	9.70
2012	435	330	1167	931 - 1403	10.31	1258	1065 - 1512	9.17
2013	483	311	1122	918 - 1326	9.28	1221	1036 - 1494	9.61
2014	529	429	1487	1226 - 1748	8.97	1601	1370 - 1904	8.84
2015	522	404	1436	1179 - 1693	9.12	1538	1323 - 1849	8.87
2016	436	367	1351	1113 - 1589	8.98	1446	1231 - 1765	9.08
2017	406	267	1054	856 - 1252	9.59	1139	965 - 1402	9.74
2018	468	243	867	706 - 1028	9.50	939	795 - 1150	9.57
2019	471	85	311	232 - 390	12.91	354	278 - 450	12.63
2021	353	76	325	235 - 415	14.18	380	296 - 493	12.92

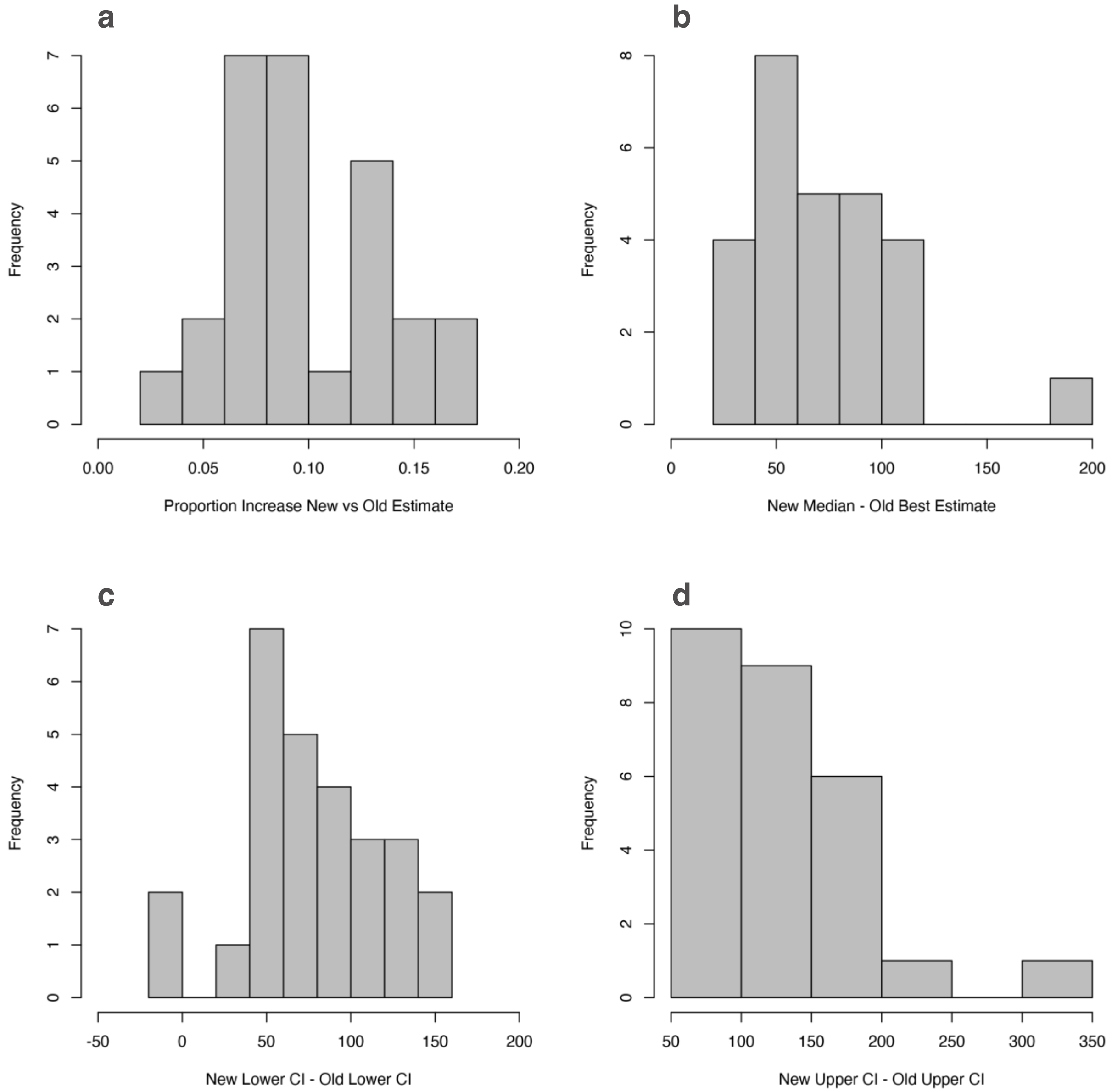

Figure 2. Comparisons of annual estimates from the previous estimation method and the updated model. (a) The proportion increase of the new model median estimates versus the respective previous best estimates. (b) The raw differences between updated annual median estimates and their respective previous best estimates. (c) The raw differences between the lower bound of 95% confidence intervals in updated versus previous estimates. (d) The raw differences between the upper bound of 95% confidence intervals in updated versus previous estimates.

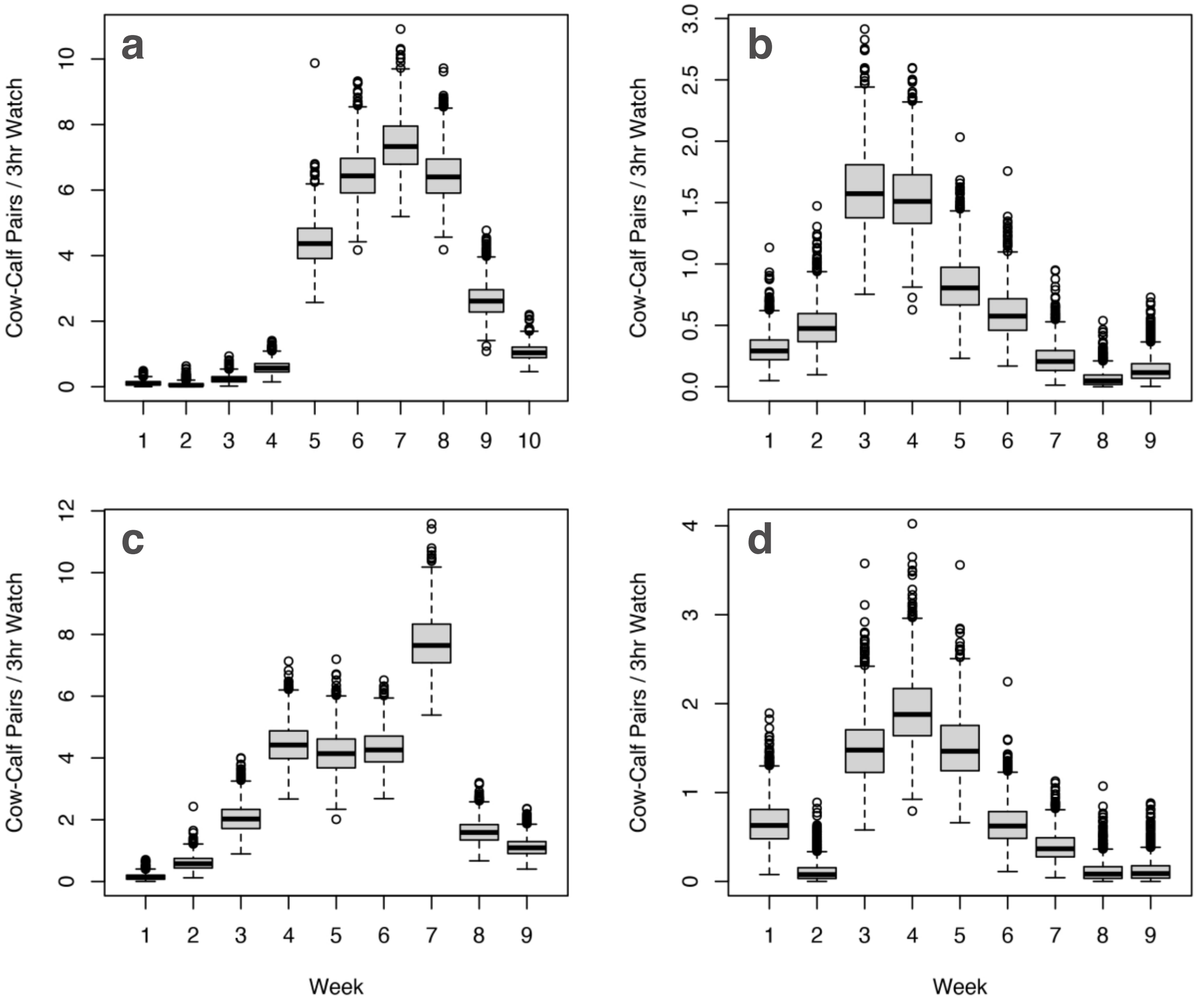

Figure 3. Examples of weekly mean passage rates, or the model-estimated true number of mother-calf pairs passing during each 3-hour watch period for each week of the survey (λ_{wk}). (a) 1997, (b) 2000, (c) 2016, (d) 2021. Note the differences in y axis scales, and the variable migration curve shapes between years. Week numbers are relative to each annual survey and do not necessarily reflect the same start or end dates between years.