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Fishery-Independent Indices of Abundance for Gag (*Mycteroperca microlepis*) in the Northeastern Gulf of Mexico, with Intrinsic Habitat Quality Controlled and Contrasted

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Fishery-independent annual indices and trends of gag abundance for 2001 through 2012 were developed using an approach that controls the effects of intrinsic habitat quality at sampling sites. MacCall's Basin Model (1990) was the population theory from which predictions about indices of abundance were derived. The applicability of that model to gag was established by Lindberg et al. (2006) through experiments confirming density-dependent habitat selection (DDHS), i.e. the ecological process driving population patterns in MacCall's model. Based on those and more recent results, we offer several pertinent predictions and implications:

1. For reef habitat patches of the ***highest*** intrinsic habitat quality:
   a. Gag abundances should remain high, even at low overall stock levels, thus contributing to hyperstability in CPUE;
   b. In a declining stock, the rate of decline in gag abundance should be much less pronounced than observed from sampling sites of *lower* intrinsic habitat quality;
   c. In a recovering stock, the initial rate of increase in gag abundance should be greater than observed from sampling sites of *lower* intrinsic habitat quality.
2. For reef habitat patches of ***lower***, i.e. intermediate**,** intrinsic habitat quality:
   a. Gag abundance at sampling sites should be proportional to the overall stock level;
   b. In a declining stock, the rate of decline in gag abundance should be more pronounced than observed from sampling sites of *higher* intrinsic habitat quality;
   c. In a recovering stock, the increase in gag abundance should be slower and lag behind any increase observed from sites of *higher* intrinsic habitat quality.
3. By contrast, flat hard-ground habitat of the ***lowest*** intrinsic habitat quality should be sparsely occupied by gag, except at near-virgin stock levels or as part of gag home ranges adjacent to higher-quality reef habitat patches (see Biesinger et al. *in press* and 2011).

Given prior experiments (Lindberg et al. 2006) and our sampling of natural hard-bottom habitats of the region (Lindberg 2008), we consider the standardized habitat units (SHUs) used in this study to be replicate sampling sites with habitat quality corresponding to predictions 1a-c and 2a-c. For example, widely dispersed 16-cube SHUs were more preferred by gag than widely dispersed 4-cube SHUs (see Lindberg et al. 2006, figure 5, page 739). All SHU configurations in the present study were comparable to either high- or intermediate-quality natural habitat.

Two standardized reef systems were sampled annually (Figure 1). In the Suwannee Regional Reef System (SRRS) only widely dispersed reef arrays were sampled, with equal numbers of both 16-cube SHUs and 4-cube SHUs (hereafter SRRS-high and SRRS-low, respectively, referring to their relative intrinsic habitat quality). Our analyses include a 12-year dataset from the SRRS. Further offshore, forty 4-cube SHUs (hereafter SFMA-low) bracket the Florida Big

Bend, as part of an evaluation plan for the Steinhatchee Fisheries Management Area (SFMA). The SFMA-low reefs are the same design as the SRRS-low and therefore represent the same intrinsic habitat quality. The SFMA-low reefs were built in 2005 and sampled annually since 2007. The SRRS reefs were built in 1991-1993 and were fully colonized well before the present study began. Our analyses compare gag abundances from SRRS-high, SRRS-low and SFMA-low during a period when the Gulf of Mexico gag stock declined and presumably began to recover.

Methods

Data Collection

An underwater visual census (UVC) procedure identical to that employed by Lindberg et al. (2006) has been conducted annually from 2001 for the SRRS reefs and since 2007 for the SFMA reefs. The UVC counted gag in 10 cm size classes ranging from <20 cm TL to >89cm TL. All UVCs prior to 2007 were done by divers on open-circuit SCUBA. However, from 2007 and beyond, censuses were conducted by divers using closed-circuit rebreathers (Dive Rite, O_2ptima). Experimental comparison of UVCs on open-circuit SCUBA versus closed-circuit rebreathers showed no significant difference between gag counts (Lindberg and Marcinek 2007). Figure 1 shows the general locations of the reefs of interest.

Statistical Analyses

Mean Gag Abundance

Total gag counts for the SRRS and SFMA reefs were recorded for each SHU. However, total gag were reported for the array of SHUs for SRRS reefs, not individual SHUs. The effects of system (SRRS, SFMA), habitat quality (low, high), and year were assessed using a general linear mixed model with year*system*habitat combinations as levels of a single fixed effect, with array nested within system as a random factor to capture nesting of multiple SHUs/array for the SRRS reefs, and using compound symmetry to account for the repeated observations of array within a system across years. In addition we found that the high quality reefs in the SRRS system had different variance than the low quality arrays in either system, so we included unequal variances to account for that effect. The response variable was $Y = log(counts + 1)$ and it was assumed to be normally distributed. The assumptions of normality and homogeneous variance of the Pearson residuals were found to be reasonable (See Appendix 1). Because of the variance-covariance structure, denominator degrees of freedom were adjusted according to the Kenward-Roger method (1997); experiment-wise error rates for pairwise comparisons were controlled using the Tukey-Kramer approach. All analyses were done in SAS v9.2 (SAS Institute, Cary, NC).

We also considered and rejected several alternative distributions, including Delta-Lognormal, Poisson, overdispersed Poisson, and Negative Binomial. We also considered a square root transformation for approximate normality. In all cases, either the residuals were poorly behaved or the model did not converge or the resulting back-transformed predicted values were biased very low with high variance.

Comment: We do not recommend back-transformation of the predicted values for $\hat{Y} = log(\widehat{counts} + 1)$ using either $\exp(\hat{Y}) - 1$ or $\exp(\hat{Y}_i + 0.5\hat{\sigma}^2_{\hat{Y}_i}) - 1$. Both are biased for the true mean; the first because it is an approximate estimator of the median of the total gag distribution and the second because it is not the best linear unbiased estimator of the mean of total gag and has been shown to be biased (Christman, 2013). The correct estimator, the BLUE, replaces the approximation $\exp(0.5\hat{\sigma}_{Y_i}^2)$ with the minimum variance unbiased estimator of $\exp(0.5\sigma_{Y_i}^2)$ derived by Goldberger (1968).

Size Frequency Analyses

The distribution of gag among different size classes was analyzed to determine if there were differences due to year, system or habitat quality. Data were counts by size classes ranging from 20 cm to 80 cm in bins of 10 cm widths. In the first analysis, counts were analyzed using a generalized linear mixed model and a multinomial distribution with a cumulative logit link with a random effect for array within system. This allowed us to test for differences among year*system*habitat combinations but does not allow any testing of vectors of probabilities by size directly. Hence, we also ran a number of contingency table analyses to test for differences in size frequency distributions by year or system or both. The first contingency table analysis used the Cochran-Mantel-Haenszel (CMH) approach to testing for differences in distributions among years using system and habitat as strata. This test was confined to the years 2007 – 2012 where we had data to test all three system/habitat combinations (SRRS-low, SRRS-high, and SFMA-low). The second test was to test differences in systems within years for all years of data – this is the equivalent of testing pairwise differences within a generalized linear model if the response had been scalar rather than a vector. For each year, we tested if the system/habitat combinations had different size frequency distributions using Monte Carlo approximations to the exact test of differences with a simulation of 10,000 samples for each test. We included the 80-89 cm bin in these analyses as we were doing exact tests.

Results

Changes in Mean Abundance

Overall there was a significant difference among year*system*habitat type combinations ($F_{29,76.11} = 5.88, p < 0.0001$; Figure 2). We tested differences among system*habitat quality combinations for each year (Table 1). The mean counts for SRRS-low reefs were statistically significantly lower than the SRRS-high reefs in 2004 and from 2009 onward (Table 2). The means for the SFMA-low reefs were statistically significantly lower than the means for the SRRS-high reefs in all years in which both were measured (Table 2). Finally, there were no statistically significant differences between annual means for the SFMA-low and SRRS-low reefs (Table 2).

Changes in Size Frequency Distributions

The generalized linear mixed model indicated that the size frequency distribution varied among years and systems for at least 1 year-system combination ($F_{30,12259} = 34.80, p < 0.0001$). Modeling includes all years (2001 – 2012) and systems (SRRS-low, SRRS-high, SFMA-low). The subsequent CMH tests (Table 3) rejected the null hypotheses of independence between year and size frequency distribution. The distributions appear to shift to larger sizes through time (Figure 3) in all three systems but the SRRS reefs also appear to have one influx of smaller fish occurring in 2008. The tests within years of whether the three systems had similar size frequency distributions were also rejected (Table 4). The distributions are shown in Figure 4.

Discussion

Our predictions in the Introduction were clearly supported by results from fishery-independent sampling of standardized reef units that controlled and contrasted intrinsic habitat quality. As such, MacCall's (1990) Basin Model was corroborated as consequential to fishery-independent indices of abundance for reef fish like gag, which exhibit DDHS and for which intrinsic habitat quality can be assessed.

The higher quality reef habitat (i.e., SRRS-high) showed no significant trend in gag abundance over a 12-year time period that included: (1) a substantial stock decline after 2005 (i.e. the "red tide model" of the 2009 gag update assessment), (2) subsequent strong year classes, and (3) severe limitations on fishing mortality in recent years. The lack of trend could be interpreted as wholly consistent with predictions 1a-c, if strong year classes and tight fishing regulations initiated a stock recovery for Gulf of Mexico gag. However, taken alone, results from the SRRS-high reefs would be inconclusive and subject to alternative explanations.

By contrast, the intermediate quality reef habitat (i.e., SRRS-low) showed a significant declining trend in gag abundance, especially following 2005, with no evidence yet of recovery. Taken together the SRRS-high and SRRS-low results indicate that stock status for gag has not changed much since the 2009 (actually 2010) update assessment, though there is reason for cautious optimism.

One criticism of the 12-year SRRS data set is that its geographic range is too small relative to the range of the GOM gag stock. Two arguments effectively counter that criticism. First, empirically, the results from the regional SFMA-low reefs perfectly track results from the SRRS-low after 2009, consistent with the regional distribution of gag among reef habitats being in equilibrium. Second, logically and supported by the empirical evidence, stock assessment models implicitly assume that the geographic distribution of gag among habitat patches conforms to an ideal free distribution (IDF). It would be logically inconsistent to accept that IDF assumption while rejecting the SRRS data as not representative of the regional stock.

Interestingly, the SFMA-low reefs, built in September 2005 took 4 years to reach a saturated, equilibrium abundance of gag. By comparison, the widely spaced SRRS-low reefs built in the early 1990's took 4-5 years to reach equilibrium at a higher abundance of gag per patch reef (Lindberg et al. 2006). In context of the Basin Model, this comparison is consistent with recent gag stock levels being lower than during the early 1990's.

Differences in gag size-frequency distributions among the three reef types (i.e., SRRS-high, SRRS-low and SFMA-low) are consistent with what is known about gag habitat selection and ontogenetic shifts by juvenile gag across the shallow continental shelf. Furthermore, some differences among years indicate that strong year classes might be detectable, though binning gag in 10-cm size classes during the underwater visual census likely obscures the tracking of year classes over years in the resultant data.

Two benefits accrue from our approach to fishery-independent indices of abundance for gag. First, the standardization of intrinsic habitat quality controls one important source of variation in census data and offers the potential for cost-effective monitoring. Second, the experimental results inherent in our study should help to inform the refinement of other FIM sampling designs.

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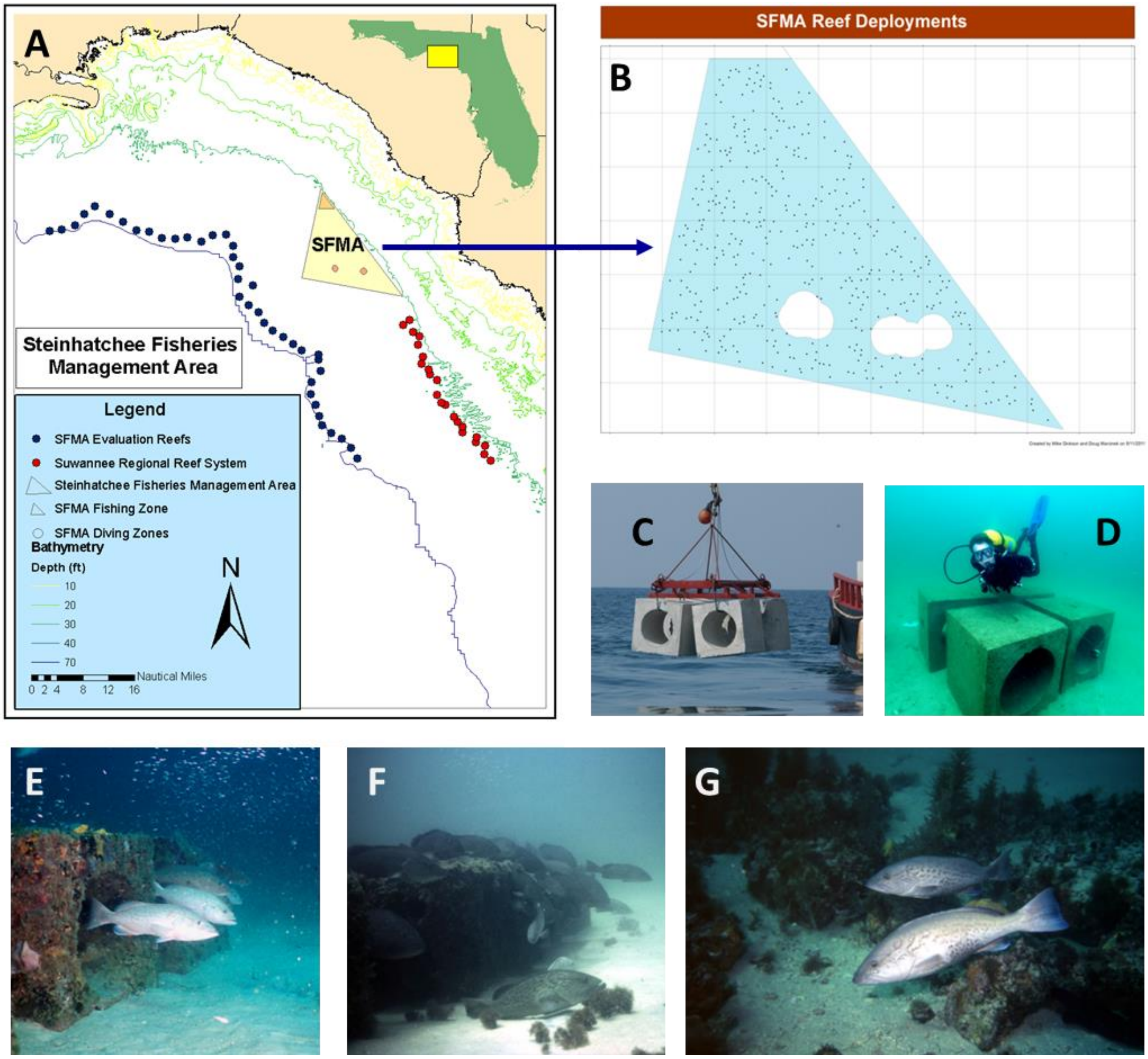


Figure 1: Reef systems in the NE Gulf of Mexico that are sampling sites and habitat manipulations for this program: (A) Location map showing the Suwannee Regional Reef System (SRRS, red dots), the Steinhatchee Fisheries Management Area (SFMA, yellow triangle), and the SFMA-low reefs (blue dots); (B) Chart showing randomly selected sites of 500 conservation reefs deployed within the SFMA (black dots, white areas are excluded zones); (C & D) photos of a 4-cube SHU being deployed and on the seafloor; (E & F) gag on SRRS patch reefs of relatively lower and higher intrinsic habitat quality, i.e. 4-cube and 16-cube SHUs, respectively; (G) gag on natural hard-bottom habitat of an intermediate habitat quality in the NE Gulf of Mexico.

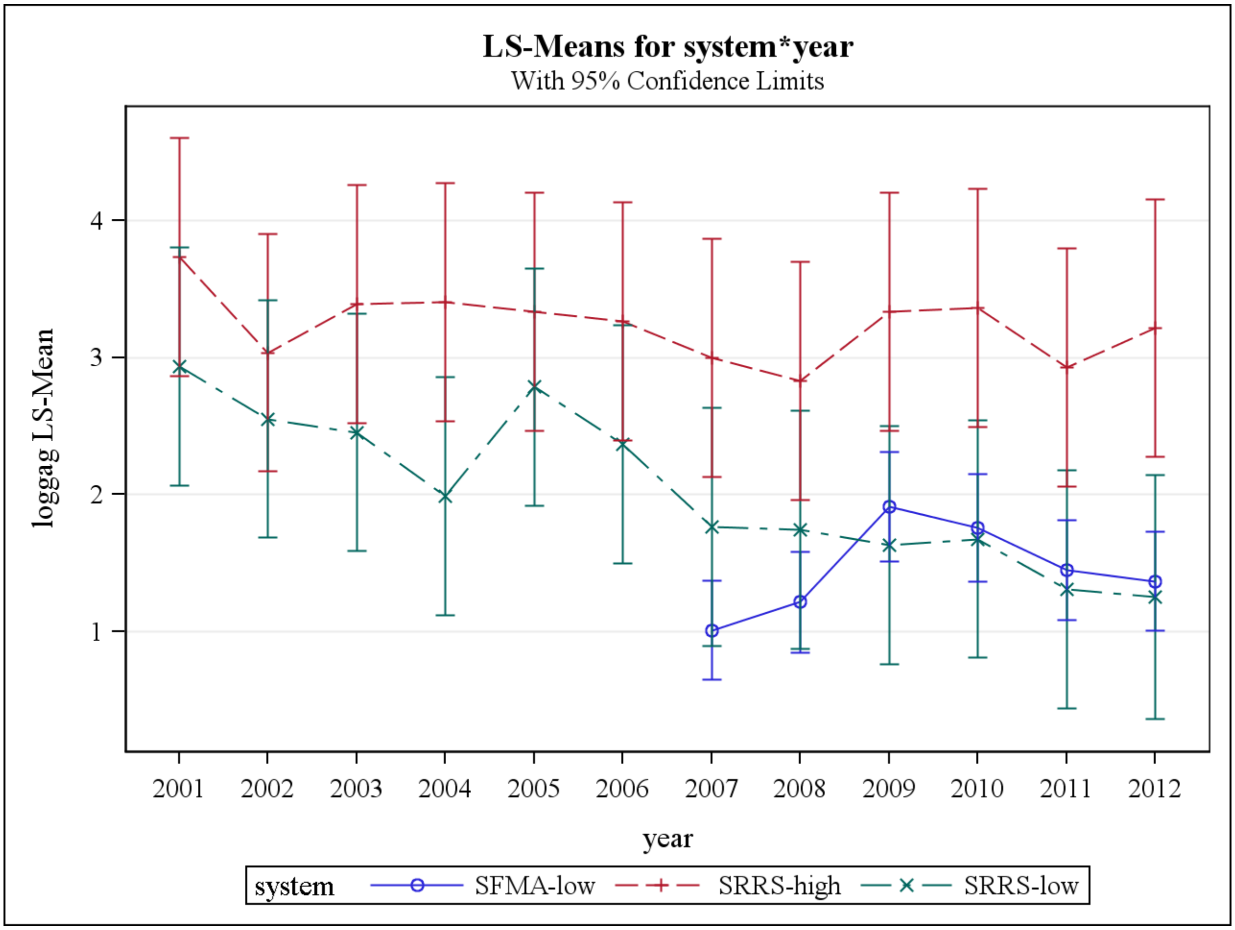


Figure 2: Predicted values and 95% confidence intervals for mean $Y = log(counts + 1)$ by year, reef system, and habitat quality.

Table 1: Tests of differences among means for system*habitat-quality combinations within each year. 2007 is the first year that the SFMA reef system was measured.

Tests of Effect Slices for system*year Sliced By year				
year	**Num DF**	**Den DF**	**F Value**	**Pr > F**
2001	1	43.48	1.72	0.1962
2002	1	43.48	0.63	0.4313
2003	1	43.48	2.35	0.1329
2004	1	43.48	5.39	0.0250
2005	1	43.48	0.81	0.3740
2006	1	43.48	2.19	0.1465
2007	2	48.74	9.49	0.0003
2008	2	49.11	6.09	0.0043
2009	2	51.04	5.13	0.0094
2010	2	50.75	6.03	0.0045
2011	2	48.92	5.30	0.0082
2012	2	56.61	7.02	0.0019

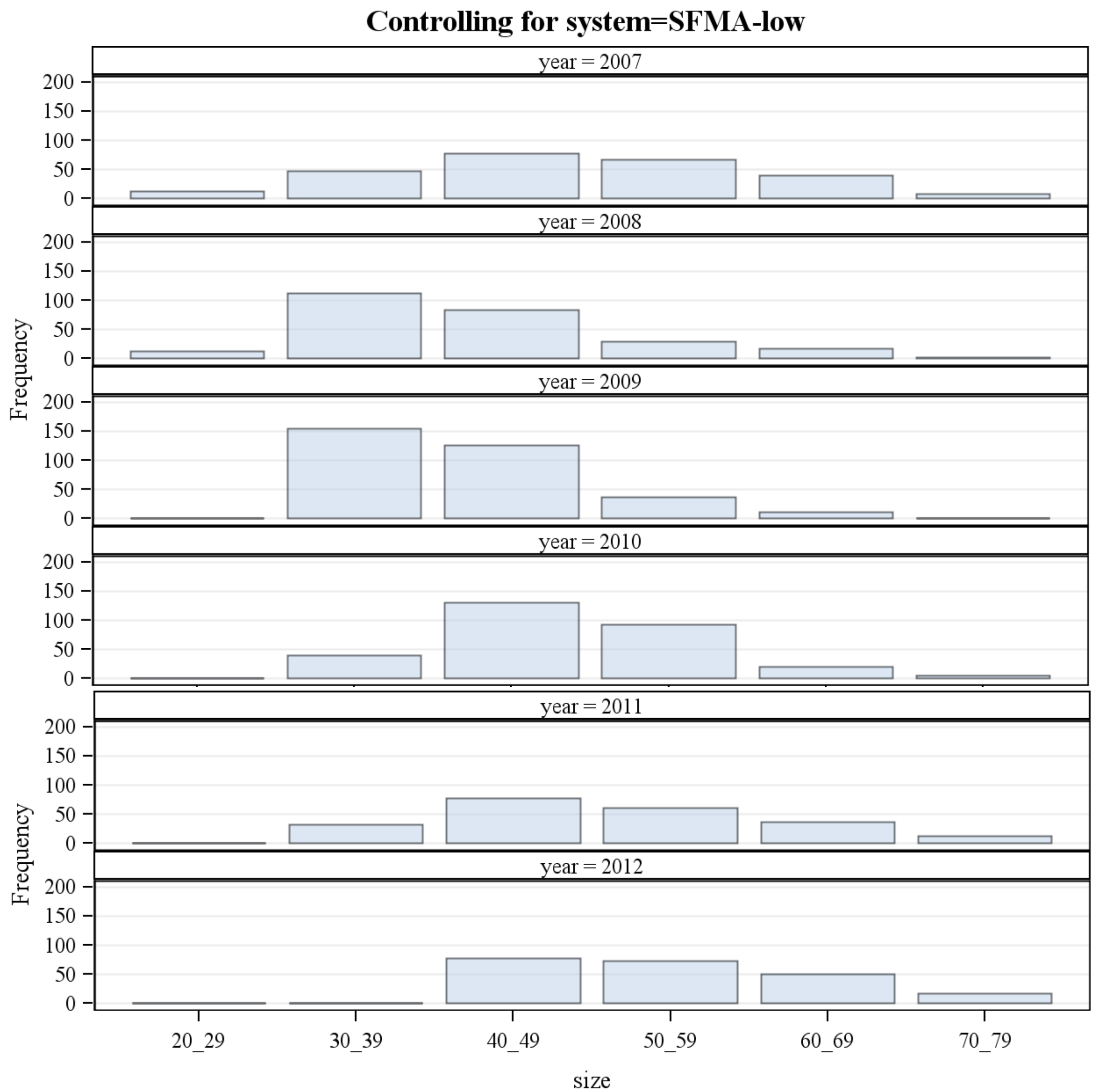
Table 2: Pairwise comparisons of means for all levels of system*habitat quality combinations within each year.

Simple Effect Comparisons of system*year Least Squares Means By year								
Year	**System 1 – System 2**		**Estimated Difference**	**Standard Error of Difference**	**DF**	**t Value**	**Pr > |t|**	**Adj P**
2001	SRRS-high	SRRS-low	0.7998	0.6093	43.48	1.31	0.1962	0.1932
2002	SRRS-high	SRRS-low	0.4840	0.6093	43.48	0.79	0.4313	0.4295
2003	SRRS-high	SRRS-low	0.9331	0.6093	43.48	1.53	0.1329	0.1298
2004	SRRS-high	SRRS-low	1.4142	0.6093	43.48	2.32	0.0250	0.0230
2005	SRRS-high	SRRS-low	0.5473	0.6093	43.48	0.90	0.3740	0.3719
2006	SRRS-high	SRRS-low	0.9007	0.6093	43.48	1.48	0.1465	0.1434
2007	SFMA-low	SRRS-high	-1.9875	0.4682	49.34	-4.25	<.0001	0.0002
2007	SFMA-low	SRRS-low	-0.7585	0.4680	49.58	-1.62	0.1114	0.2432
2007	SRRS-high	SRRS-low	1.2290	0.6093	43.48	2.02	0.0499	0.1150
2008	SFMA-low	SRRS-high	-1.6147	0.4694	49.83	-3.44	0.0012	0.0027
2008	SFMA-low	SRRS-low	-0.5281	0.4693	50.07	-1.13	0.2658	0.5015
2008	SRRS-high	SRRS-low	1.0866	0.6093	43.48	1.78	0.0815	0.1820
2009	SFMA-low	SRRS-high	-1.4239	0.4758	52.5	-2.99	0.0042	0.0103
2009	SFMA-low	SRRS-low	0.2783	0.4757	52.68	0.59	0.5610	0.8285
2009	SRRS-high	SRRS-low	1.7023	0.6093	43.48	2.79	0.0077	0.0179
2010	SFMA-low	SRRS-high	-1.6082	0.4749	52.09	-3.39	0.0014	0.0032
2010	SFMA-low	SRRS-low	0.07955	0.4747	52.28	0.17	0.8676	0.9846
2010	SRRS-high	SRRS-low	1.6878	0.6093	43.48	2.77	0.0082	0.0191
2011	SFMA-low	SRRS-high	-1.4804	0.4688	49.58	-3.16	0.0027	0.0064
2011	SFMA-low	SRRS-low	0.1392	0.4686	49.82	0.30	0.7677	0.9526
2011	SRRS-high	SRRS-low	1.6196	0.6093	43.48	2.66	0.0110	0.0256
2012	SFMA-low	SRRS-high	-1.8473	0.5032	59.37	-3.67	0.0005	0.0013
2012	SFMA-low	SRRS-low	0.1141	0.4799	53.48	0.24	0.8130	0.9693
2012	SRRS-high	SRRS-low	1.9614	0.6455	52.62	3.04	0.0037	0.0090

Table 3: Cochran-Mantel-Haenszel tests for association of year and size frequency distribution.

Summary Statistics for year by size Controlling for system				
Cochran-Mantel-Haenszel Statistics (Based on Table Scores)				
Statistic	**Alternative Hypothesis**	**DF**	**Value**	**Prob**
1	**Nonzero Correlation**	1	273.7871	<.0001
2	**Row Mean Scores Differ**	5	506.0032	<.0001
3	**General Association**	25	975.0015	<.0001

Figure 3: Size frequency distributions of gag by system and year.



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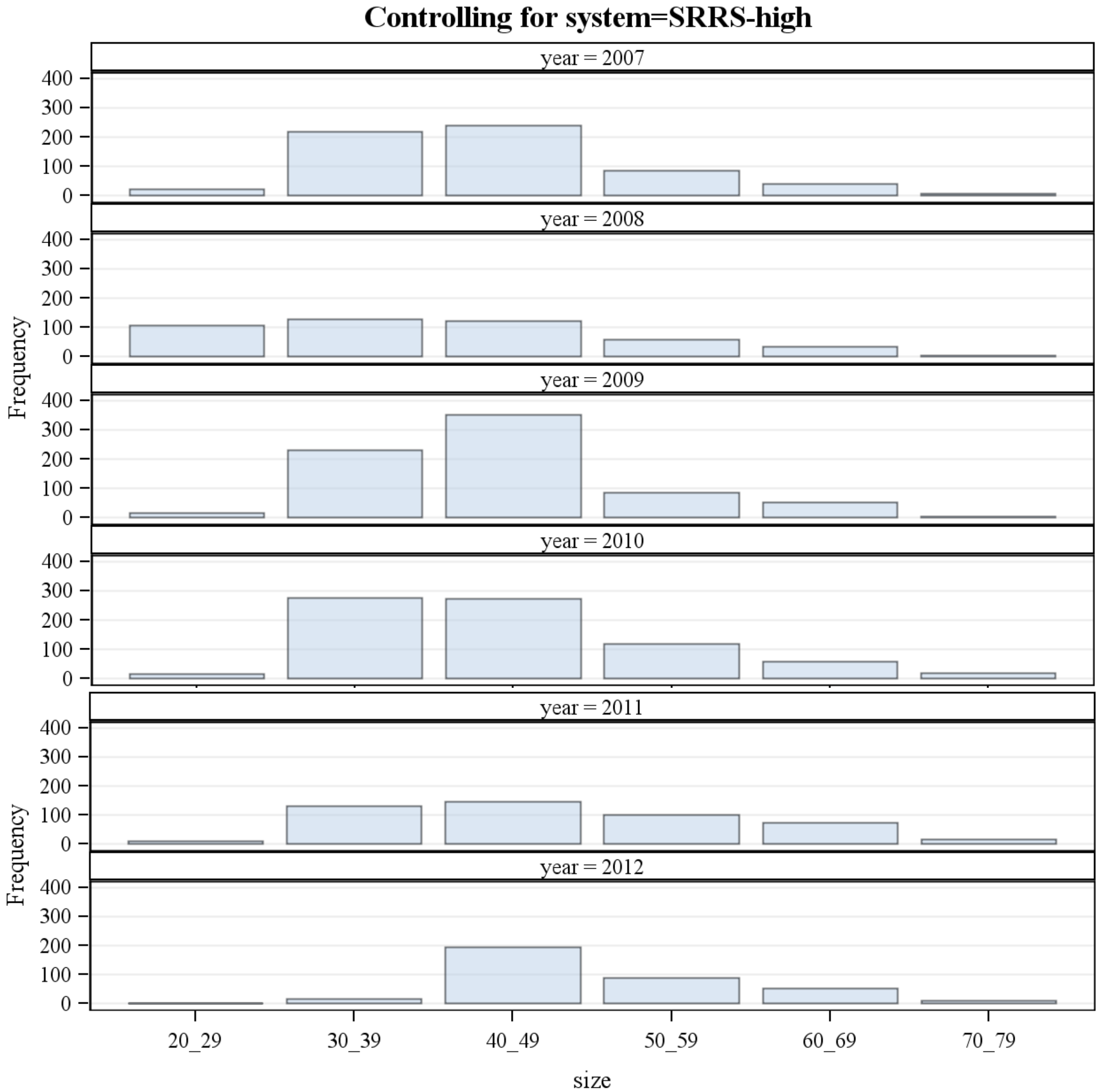

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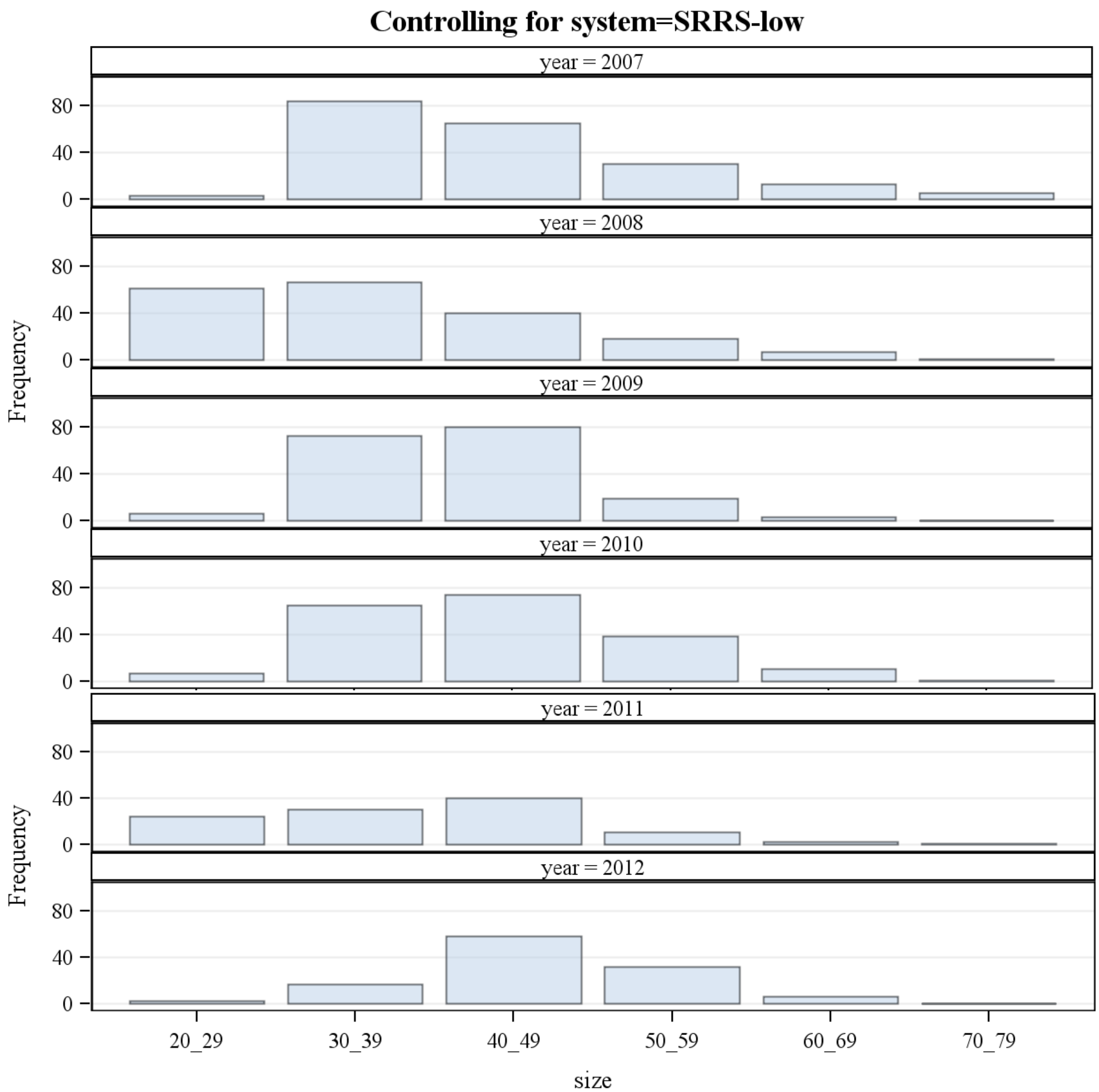
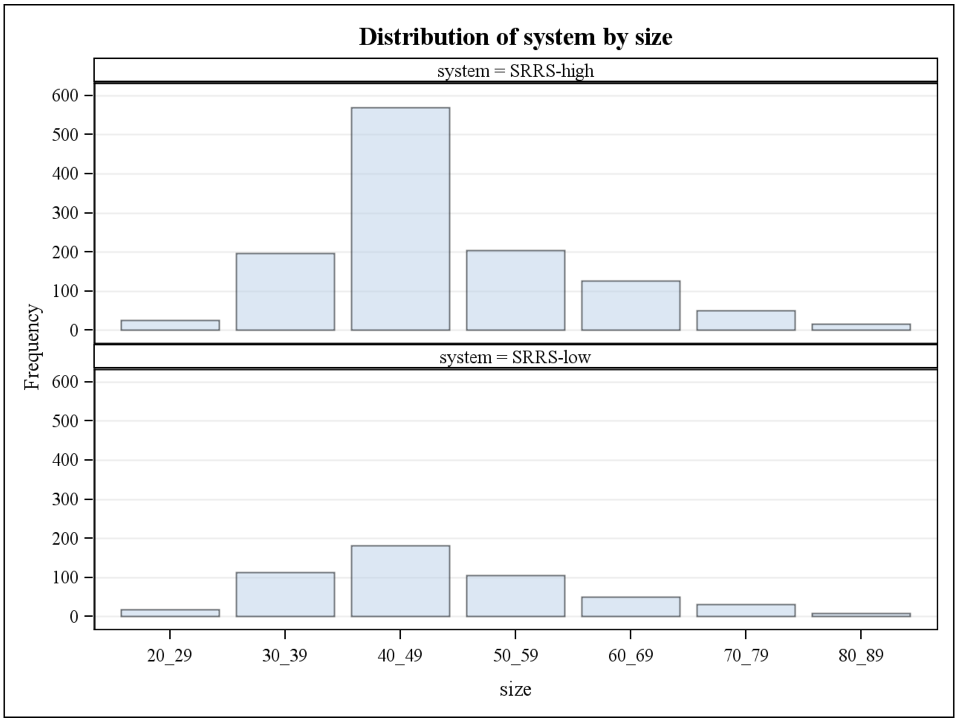


Table 4: Monte Carlo approximate p-values for the exact tests of differences among systems in size frequency distribution.

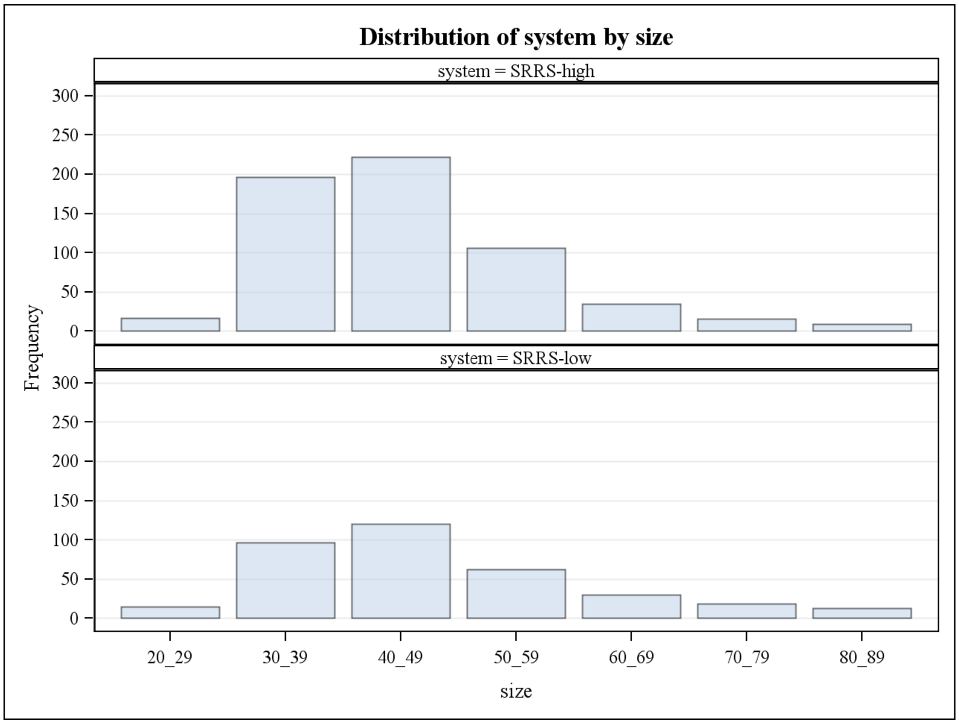
Monte Carlo Estimate for the Exact Test	
Year	**Pr >= ChiSq**
2001	5.000E-04
2002	0.0280
2003	0.0000
2004	0.1567
2005	0.0000
2006	0.3641
2007	0.0000
2008	0.0000
2009	0.0000
2010	0.0000
2011	0.0000
2012	0.0000

Figure 4: Size frequency distributions of gag by system and year.

2001



2002



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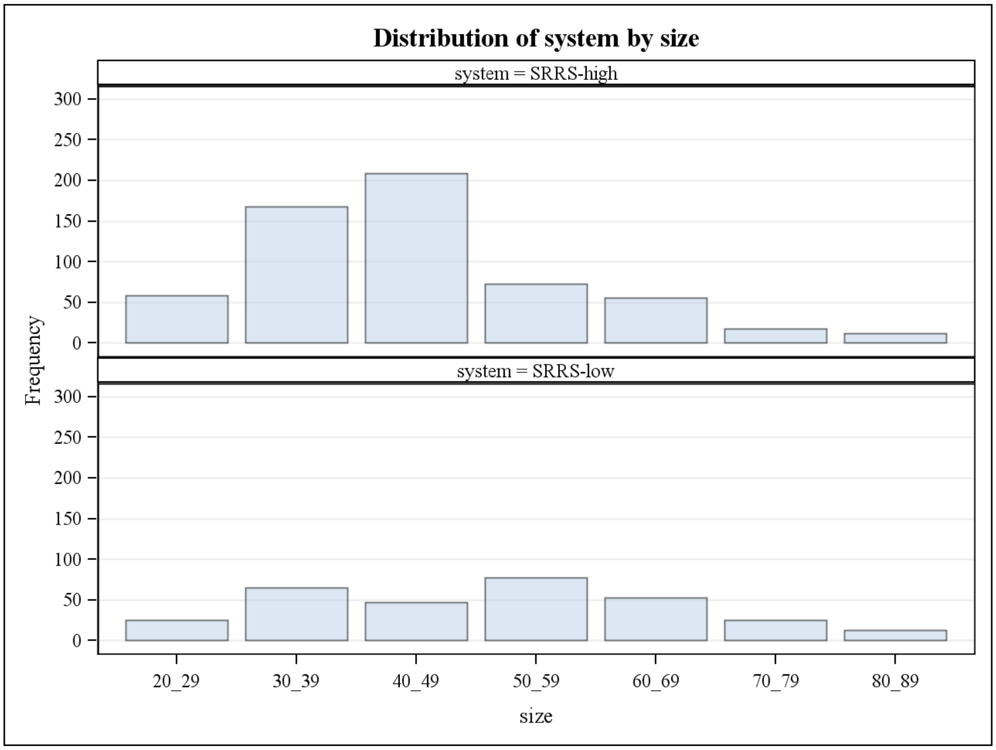
Distribution of system by size
system = SRRS-high
system = SRRS-low
Frequency
300
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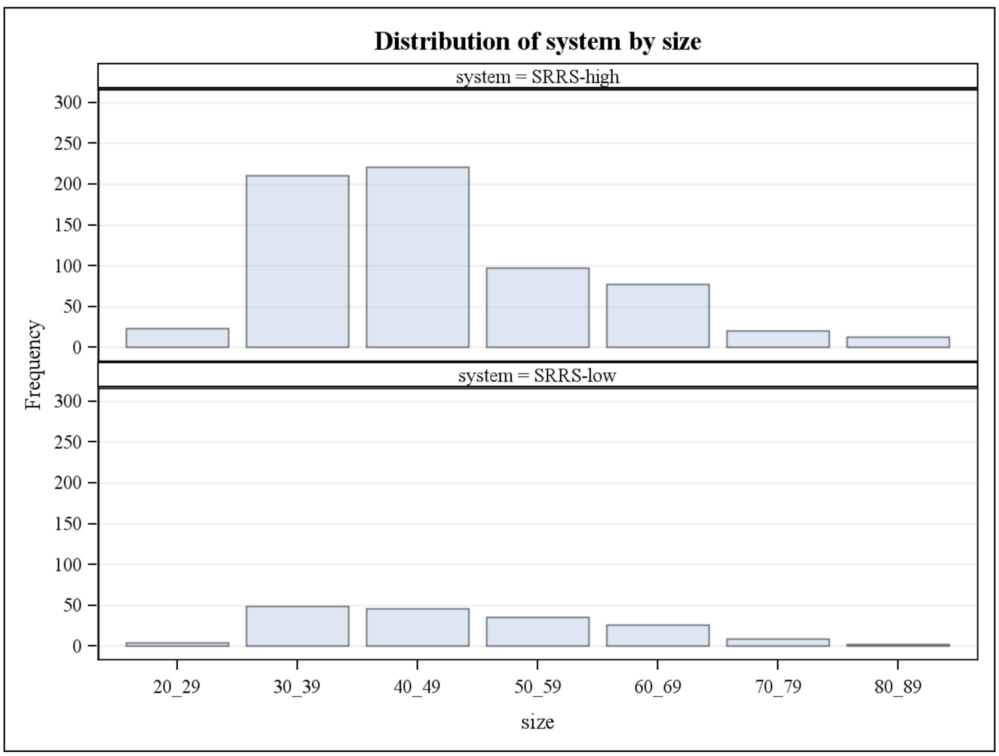
70_79
80_89
size

2004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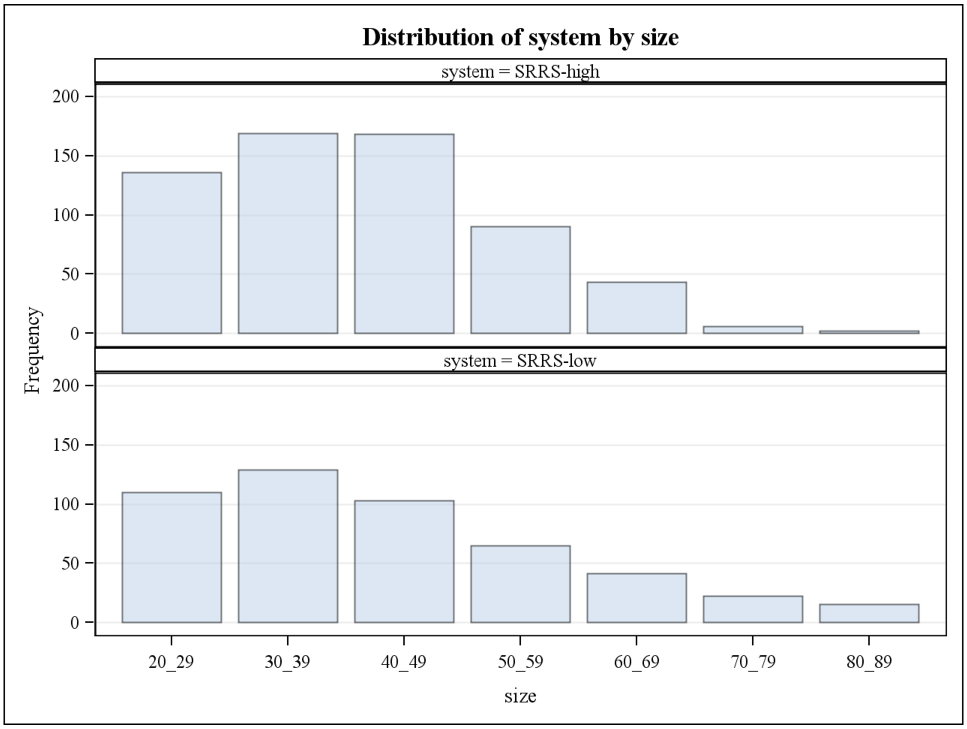
size

2005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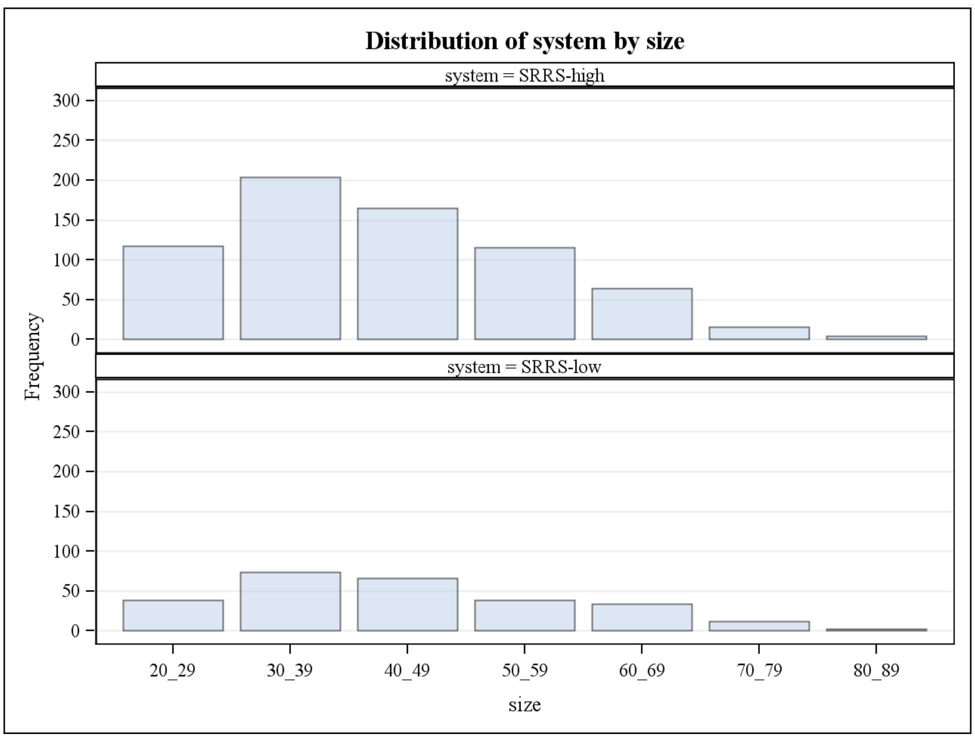
size

2006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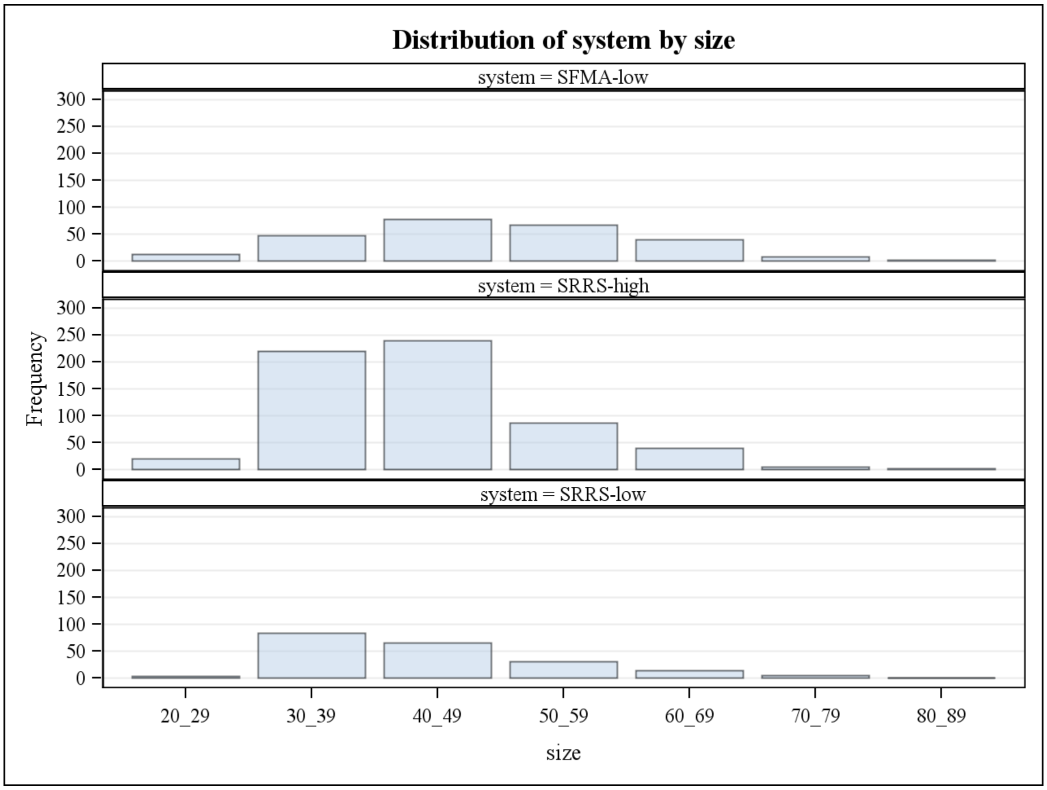
2007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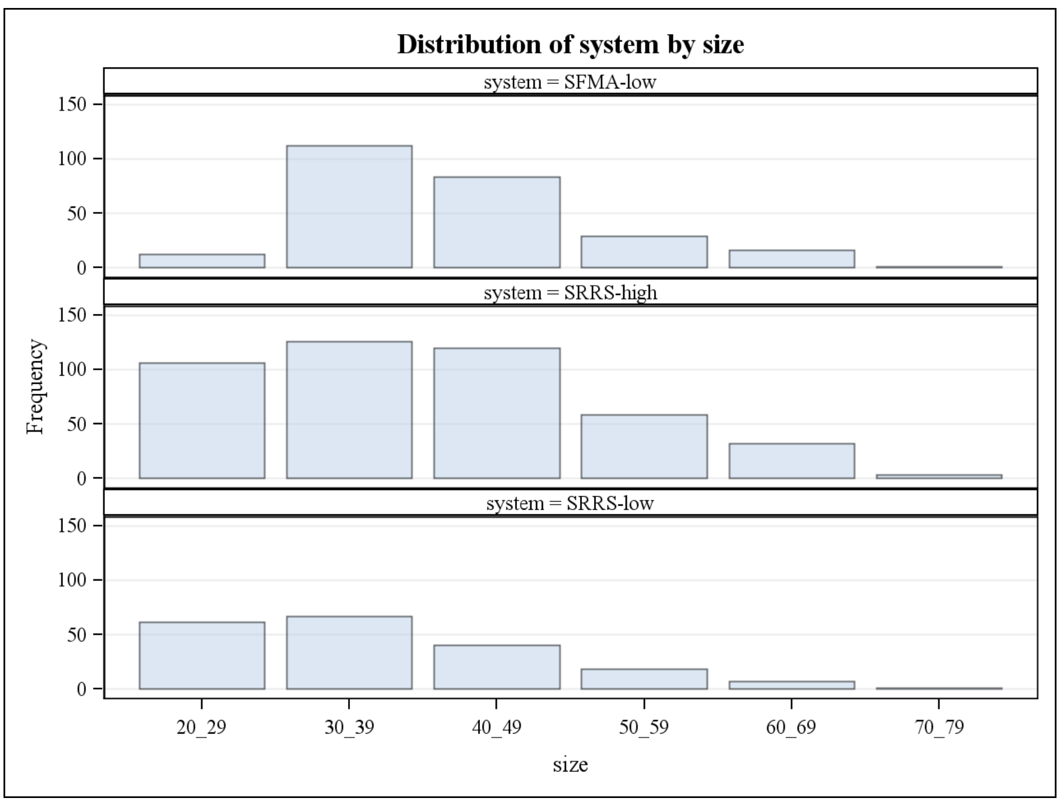
2008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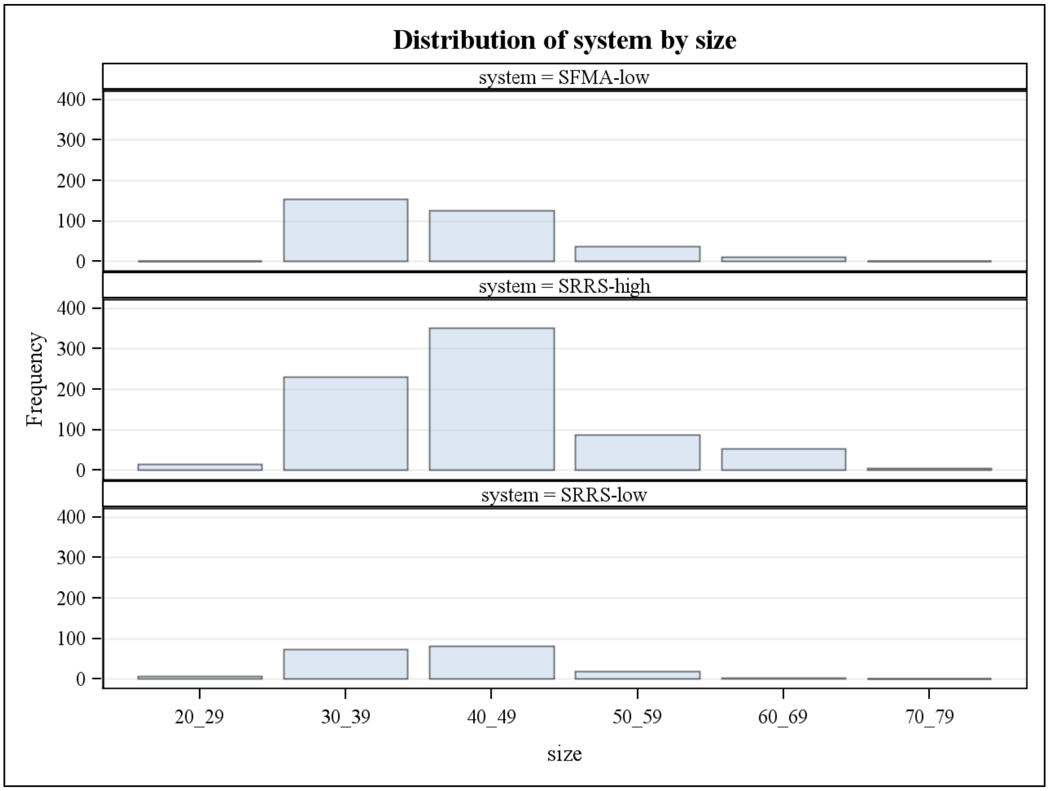
2009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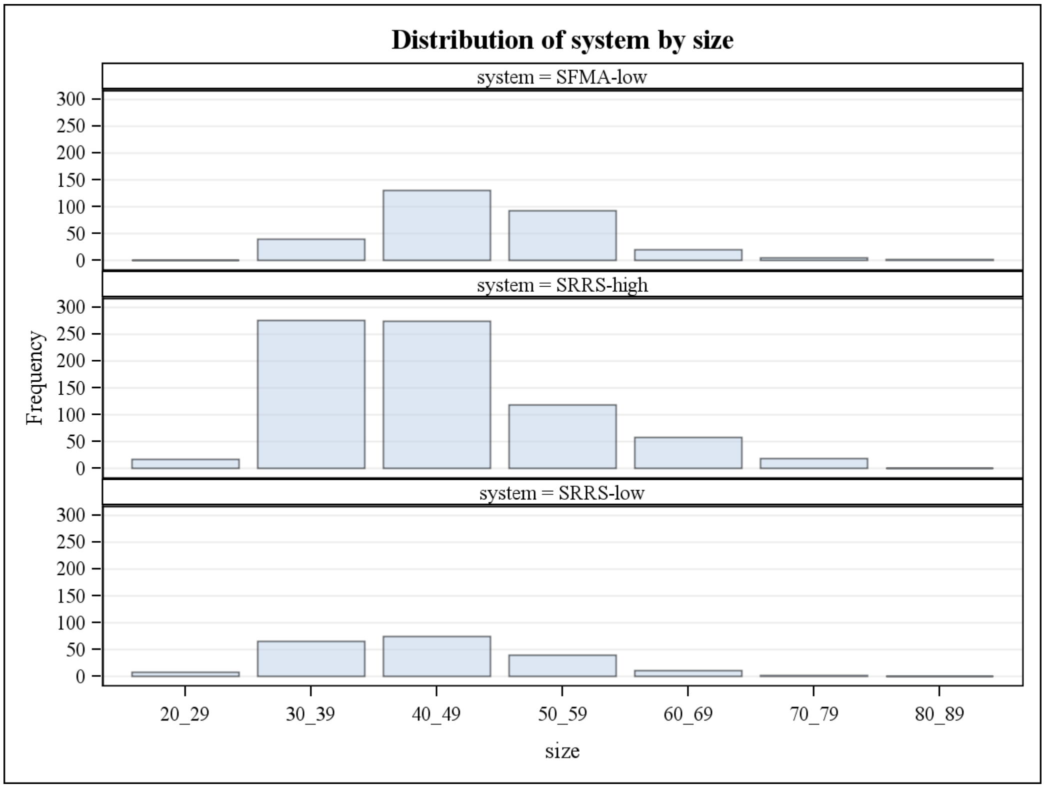
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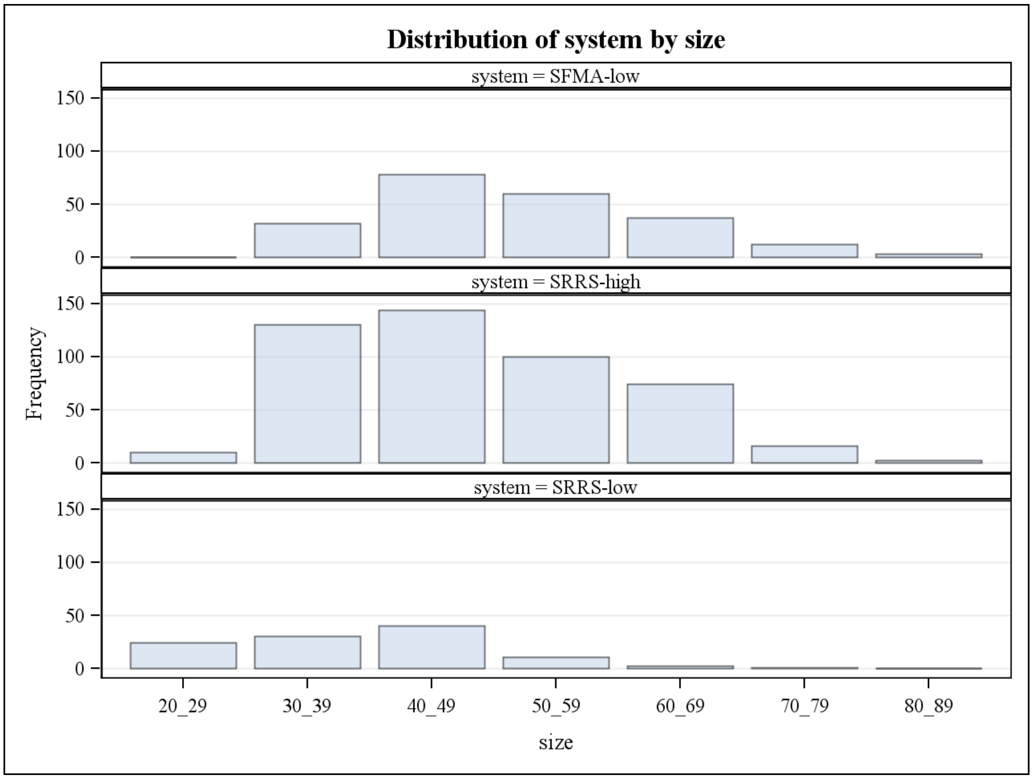
2011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system = SRRS-high
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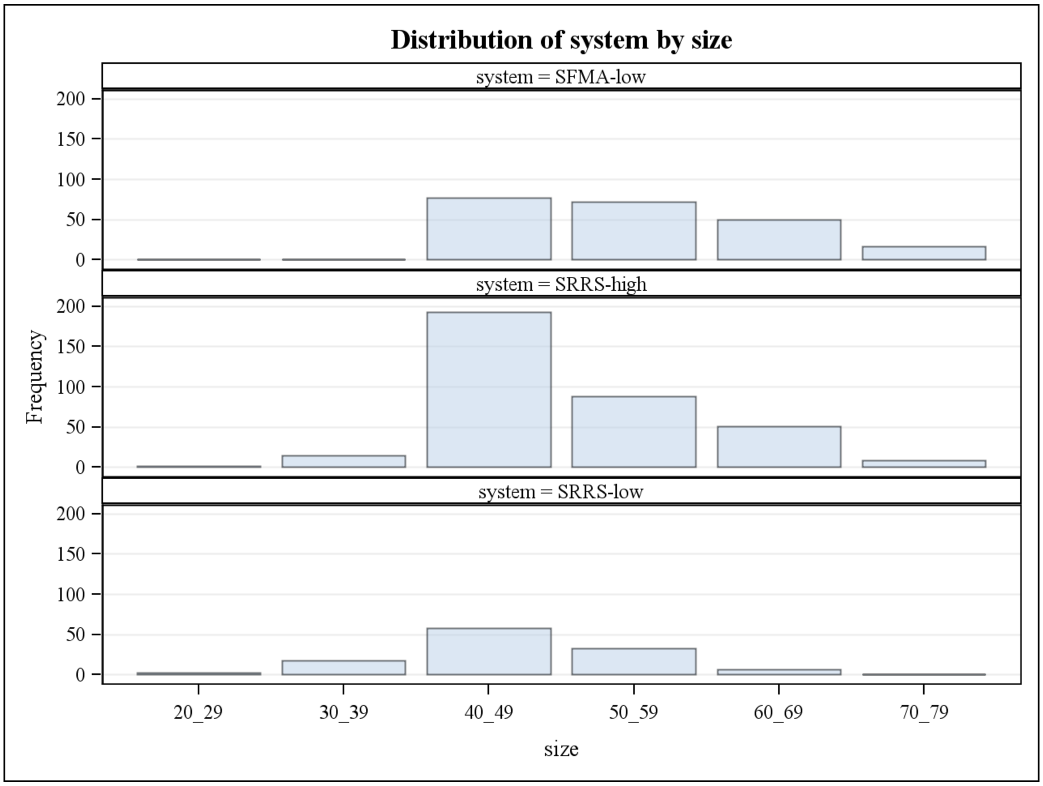
2012


Distribution of system by size
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system = SRRS-high
system = SRRS-low
Frequency
200
150
100
50
0
20_29
30_39
40_49
50_59
60_69
70_79
size

Appendix 1

Output for Analyses of Change in Mean Gag Abundance in Time and System

What follows are the SAS code used and additional relevant output from the general linear mixed modeling of log-transformed total gag.

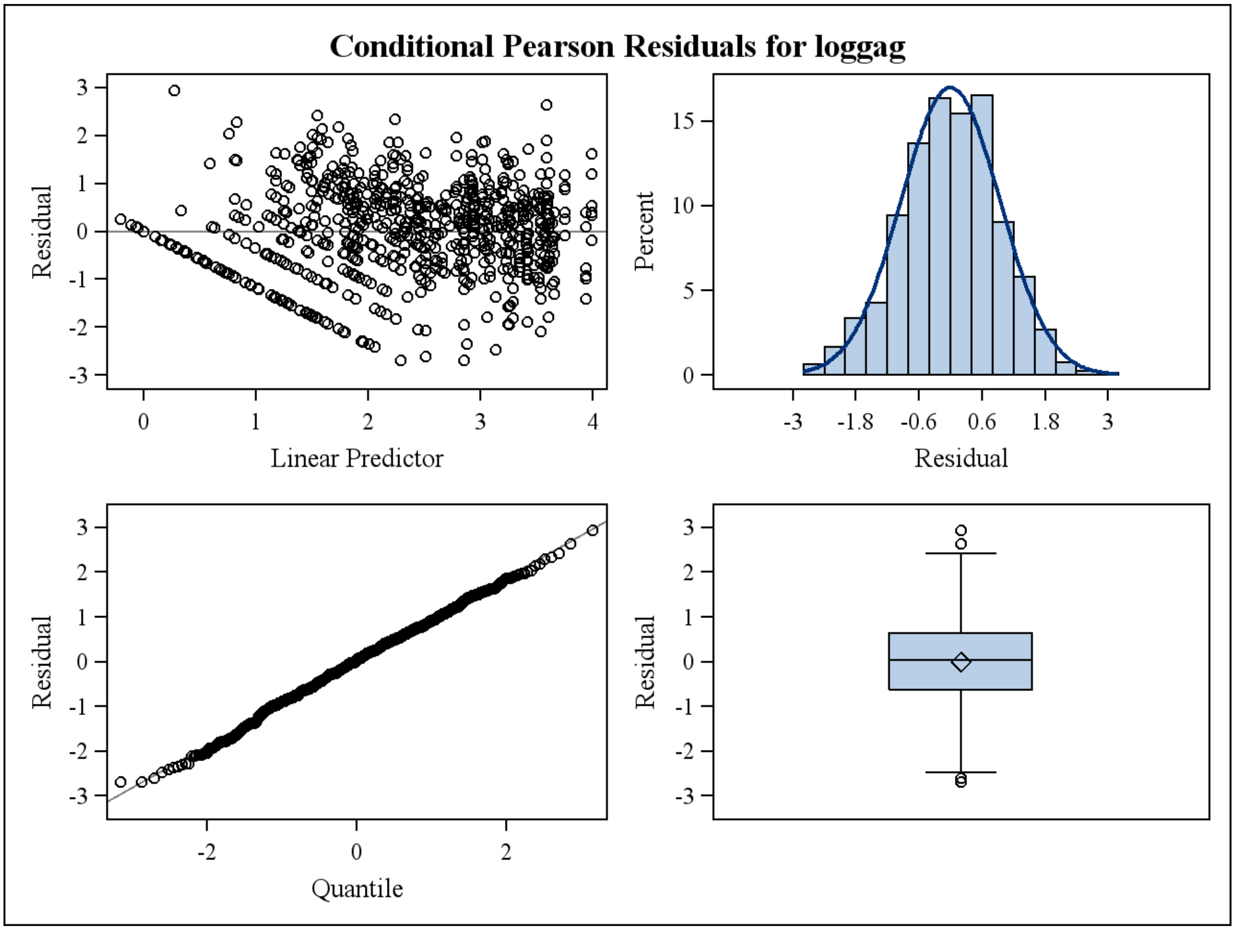
```
Data gag.sfma;
 set gag.sfma;
 system = 'SFMA-low ';
run;

data gag.srrs;
 set gag.srrs;
 if gag_1_20 = -99 then gag_1_20 = .;
 if gag_89 = -99 then gag_89 = .;
 drop system;
run;

data gag.srrs225;
 set gag.srrs;
 if array = 21 or array = 16 or array = 7 or array = 4 or array = 0 or array
= 11 or array = 13 or array = 20;
 system = 'SRRS-high';
 if array = 21 or array = 16 or array = 7 or array = 4 then system = 'SRRS-
low';
run;

data gag.both;
 set gag.srrs225 gag.sfma;
 vargrp = 1;
 if system = "SRRS-high" then vargrp = 2;
run;
/* NOTE: There were 576 observations read from the data set GAG.SRRS.
   NOTE: There were 223 observations read from the data set GAG.SFMA.
   NOTE: The data set WORK.BOTH has 799 observations and 16 variables. */

ods graphics;
title Total Gag Counts by System and Year;
title2 Log(Gag+1) ~ Normal;
proc glimmix data=gag.both ABSPCONV=0.000001 plots=pearsonpanel;
 where year > 2000;
 nloptions maxiter=100;
 class system year array vargrp;
 model loggag = system*year / ddfm=kr;
 random array(system);
 random residual / subject=array(system*year) group=vargrp type=cs;
 lsmeans system*year /plot=meanplot(sliceby = system CL join)
                      slice=(year) slicediff=(year) adjust=tukey;
 output out=logpreds pred=logpred stderr= logSEM UCL=Upper LCL=Lower;
quit;
```

Model Information	
Data Set	GAG.BOTH
Response Variable	loggag
Response Distribution	Gaussian
Link Function	Identity
Variance Function	Default
Variance Matrix	Not blocked
Estimation Technique	Restricted Maximum Likelihood
Degrees of Freedom Method	Kenward-Roger
Fixed Effects SE Adjustment	Kenward-Roger

Fit Statistics	
-2 Res Log Likelihood	1772.28
AIC (smaller is better)	1782.28
AICC (smaller is better)	1782.36
BIC (smaller is better)	1791.63
CAIC (smaller is better)	1796.63
HQIC (smaller is better)	1785.81
Generalized Chi-Square	746.00
Gener. Chi-Square / DF	1.00

Covariance Parameter Estimates				
Cov Parm	**Subject**	**Group**	**Estimate**	**Standard Error**
array(system)			0.6176	0.1580
Variance	array(system*year)	vargrp 1	0.7172	0.05603
CS	array(system*year)	vargrp 1	0.004974	0.03458
Variance	array(system*year)	vargrp 2	0.2037	0.01900
CS	array(system*year)	vargrp 2	0.09114	0.03189

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
system*year	29	76.11	5.88	<.0001


Conditional Pearson Residuals for loggag
Residual
Linear Predictor
Percent
Residual
Residual
Quantile
Residual
-3
-1.8
-0.6
0.6
1.8
3