Eastern Bering Sea bottom temperature and growth of Yellowfin Sole

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Background

Year-class strength of flatfishes is thought to be determined during the first few years of life between the pelagic egg and benthic settlement (van der Veer et al., 2015). Temperature in the early life stages can affect egg size, larval duration, size at settlement, as well as the size of suitable nursery habitat (Yeung and Cooper 2019). It has been hypothesized that colder bottom temperatures delay migration and spawning in Yellowfin Sole. As a result, mature individuals may reside in nearshore nursery grounds during months in which the NMFS survey occurs, which likely decreases survey biomass estimates during cold years (Nichol et al., 2019; Yeung and Cooper 2019). Survey timing may therefore also affect the size of the fish that are observed.

YFS may be less sensitive to temperature than Northern Rock Sole due to their settlement timing, relative to Northern Rock Sole. YFS settle later in summer, when the influence of the cold pool is weaker and nearshore bottom temperature is relatively stable and high (Yeung and Yang, 2018). In contrast, YFS migrate across the shelf to spawn near their nursery habitat, rather than relying on currents for larval transport to nursery habitat (Nichol and Acuna, 2001); therefore, their larvae may be less susceptible to variable currents (Yeung and Cooper 2019).

Yellowfin Sole otolith growth increment chronologies have been shown to be strongly related to summertime eastern Bering Sea bottom temperatures (Matta et al. 2010). The R2 values of yellowfin sole, Alaska plaice, and northern rock sole wiht the EBS bottom temperatures were 0.81, 0.61, and 0.34, respectively (Matta et al. 2010). Thus, an analysis of Yellowfin Sole growth with respect to Bering Sea bottom temperatures was merited.

There is some evidence of temperature-dependent growth by Yellowfin sole (Yeung et al. 2021). It appears that YFS remain in the shallow nearshore nursery areas through at least their first 2 years post-settlement. They begin to disperse offshore age 3-5 and by 5-8 years they follow adult migratory patterns. There is also evidence that Yellowfin Sole may be growing larger over the past 5 decades (Figure 1, Figure 2). There is no strong evidence thus far that Yellowfin sole have shifted distribution in response to climate change. Research on this topic includes beam trawl studies to better sample YFS throughout their distribution. Some tolerance to temperatures may be explained by observations that Yellowfin sole settle later in summer, when the influence of the cold pool is weaker and nearshore bottom temperature is relatively stable and high (Yeung and Cooper 2019). Therefore, an investigation of temperature-mediated growth is warranted as a covariate in the model. Currently, weight at age is incorporated in the model based on survey weight at age data.

Mean survey weight at age shown in Figure 3 seems to correlate closely with temperature anomalies at some ages (4, 5) but not other ages (8 and others not shown). This is likely due to the fact that size is cumulative over several years in which conditions may differ.

Figures

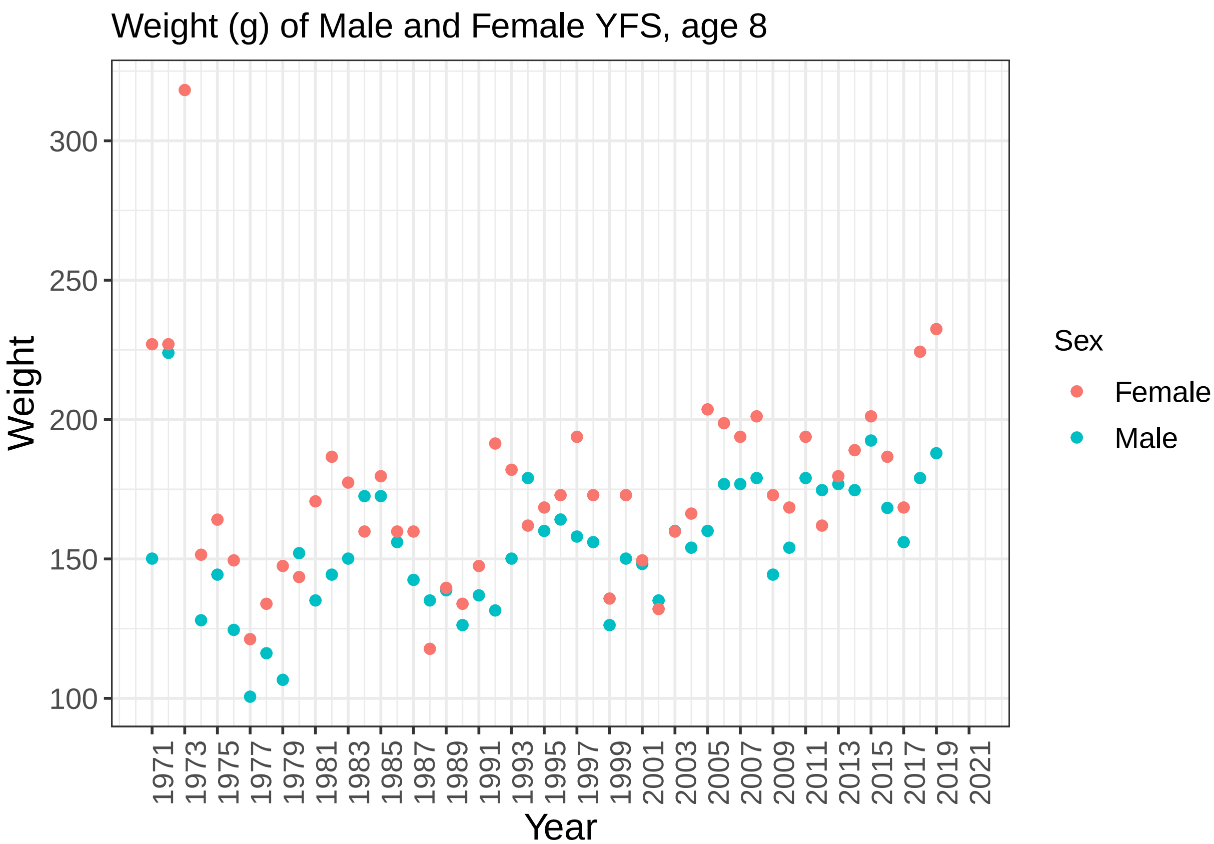


Figure 1: Mean weight at age (g) for Yellowfin Sole Age 8 females and males from the Eastern Bering Sea survey, 1971-2019. High values early in the time series are likely outliers.

Does weight go up over time since 1971? Yes it is significant for males,

```
##
## Call:
## lm(formula = LW2MF8$Weight[1:50] ~ seq(1, 50, 1))
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -39.138 -12.227  -0.325   9.503  88.173
##
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept)   134.1762     6.2622  21.426  < 2e-16 ***
## seq(1, 50, 1)   0.7931     0.2158   3.675  0.00062 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 20.82 on 46 degrees of freedom
##   (2 observations deleted due to missingness)
## Multiple R-squared:  0.2269, Adjusted R-squared:  0.2101
## F-statistic:  13.5 on 1 and 46 DF,  p-value: 0.0006198
```

and significant for females

```
##
## Call:
## lm(formula = LW2MF8$Weight[51:100] ~ seq(1, 50, 1))
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -54.572 -17.907  -4.146  15.513 150.589
##
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept)   166.6828     9.9691  16.720   <2e-16 ***
## seq(1, 50, 1)   0.3139     0.3471   0.904     0.37
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 34.36 on 47 degrees of freedom
##   (1 observation deleted due to missingness)
## Multiple R-squared:  0.01711,	Adjusted R-squared:  -0.003805
## F-statistic: 0.8181 on 1 and 47 DF,  p-value: 0.3704
```

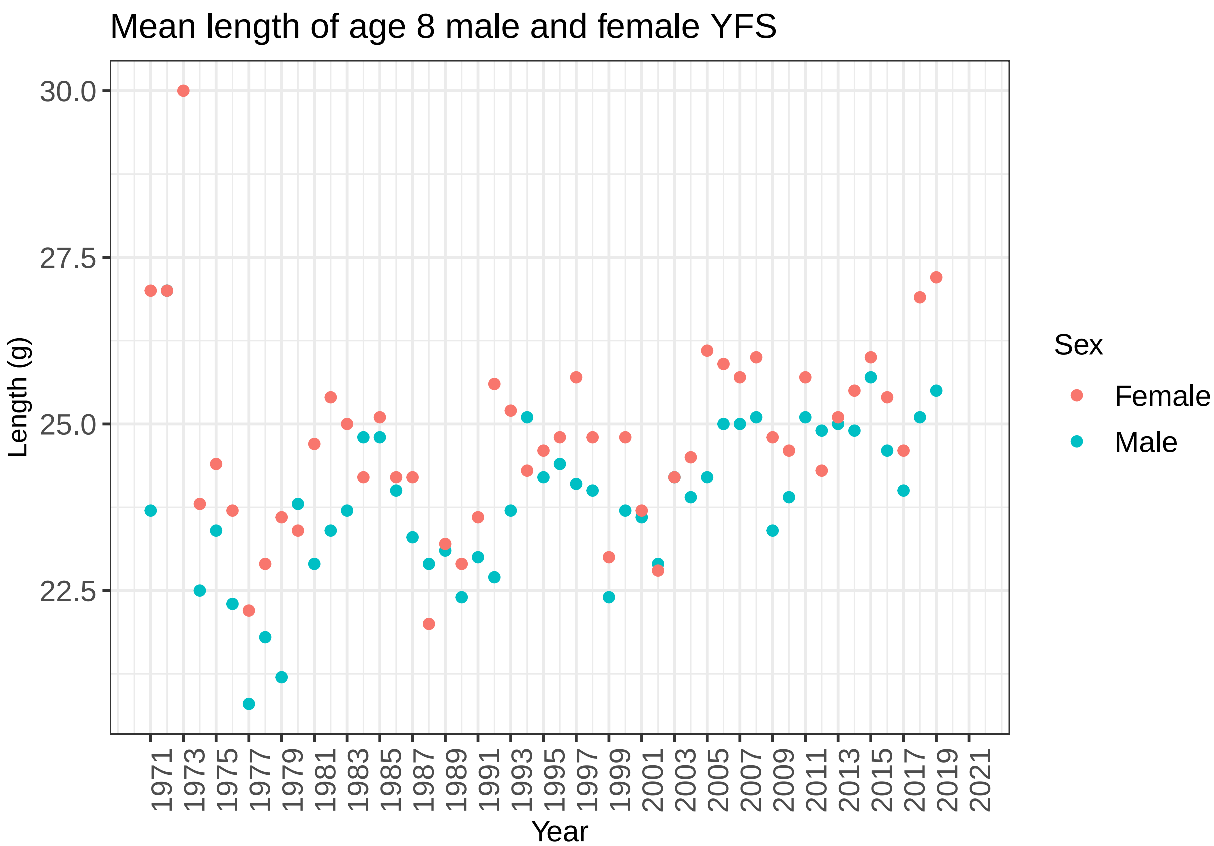
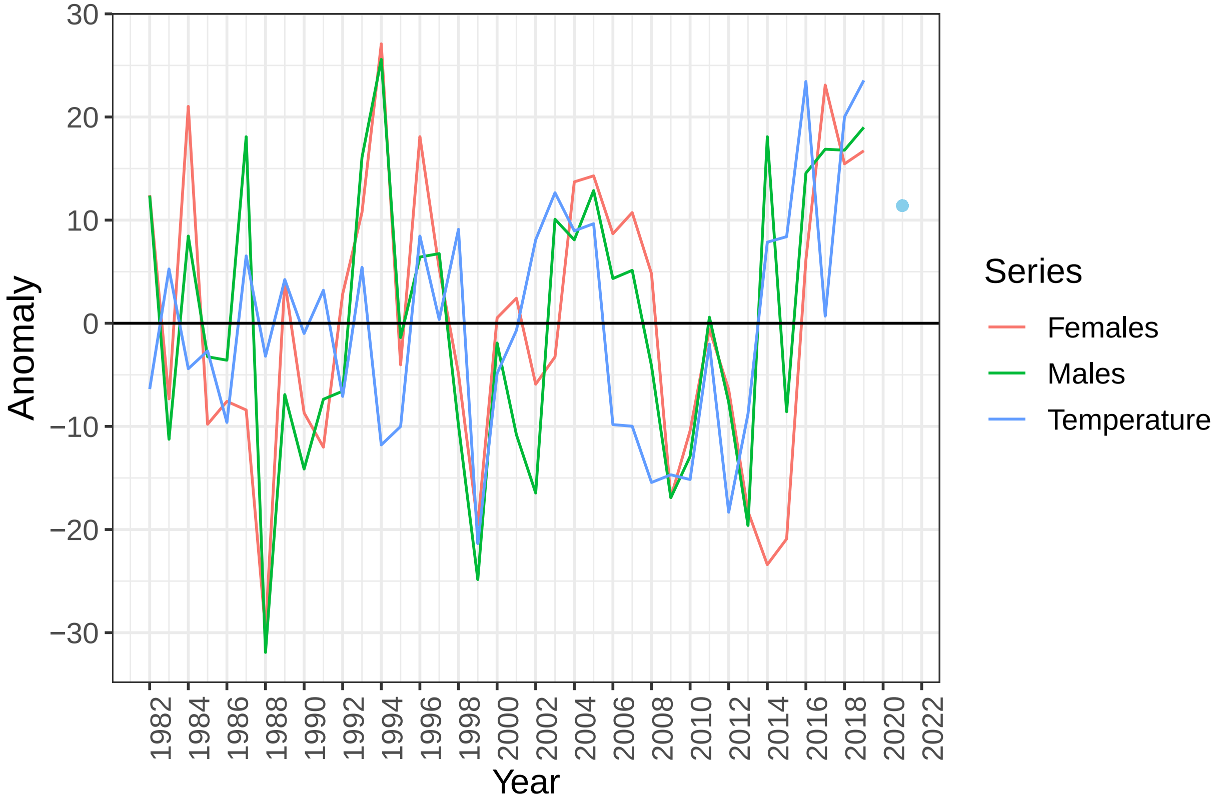
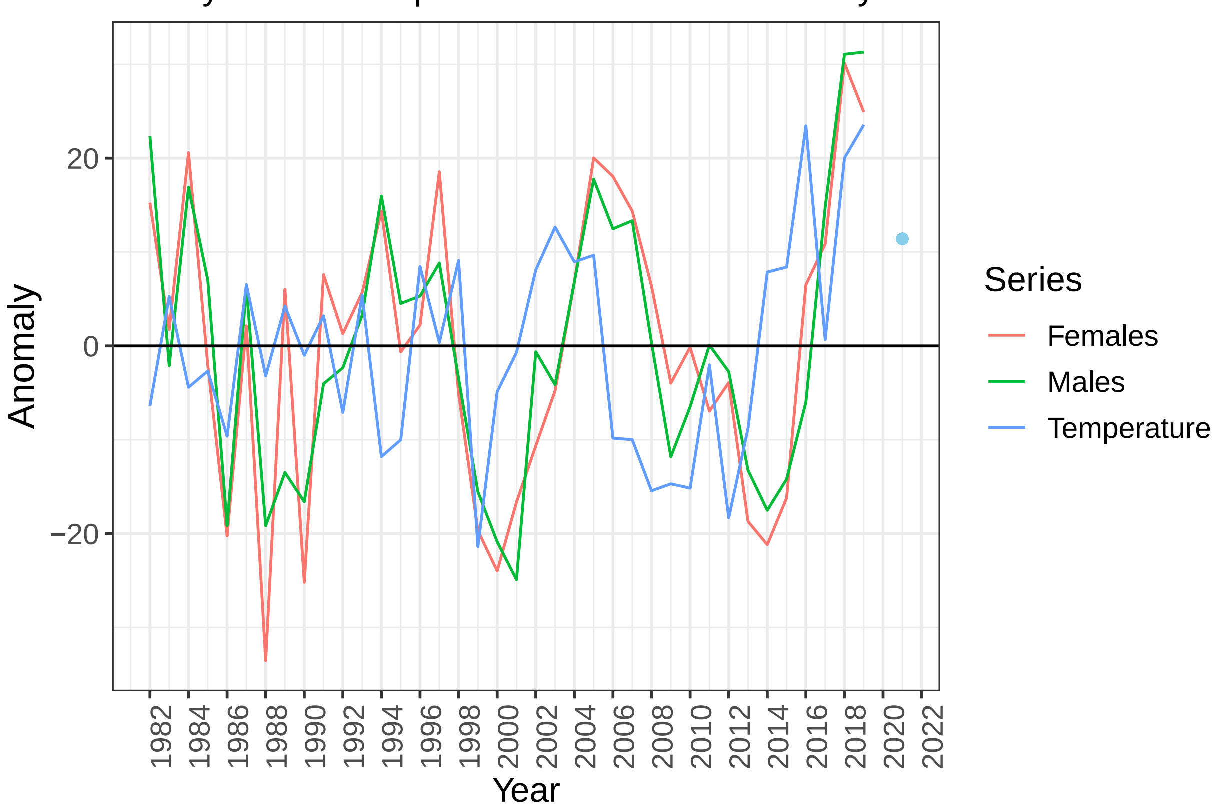


Figure 2: Mean length at age (cm) for Yellowfin Sole Age 8 females and males from the Eastern Bering Sea survey, 1971-2019.

Survey Bottom Temp and 4 Year old size anomaly



Survey Bottom Temp and 5 Year old size anomaly



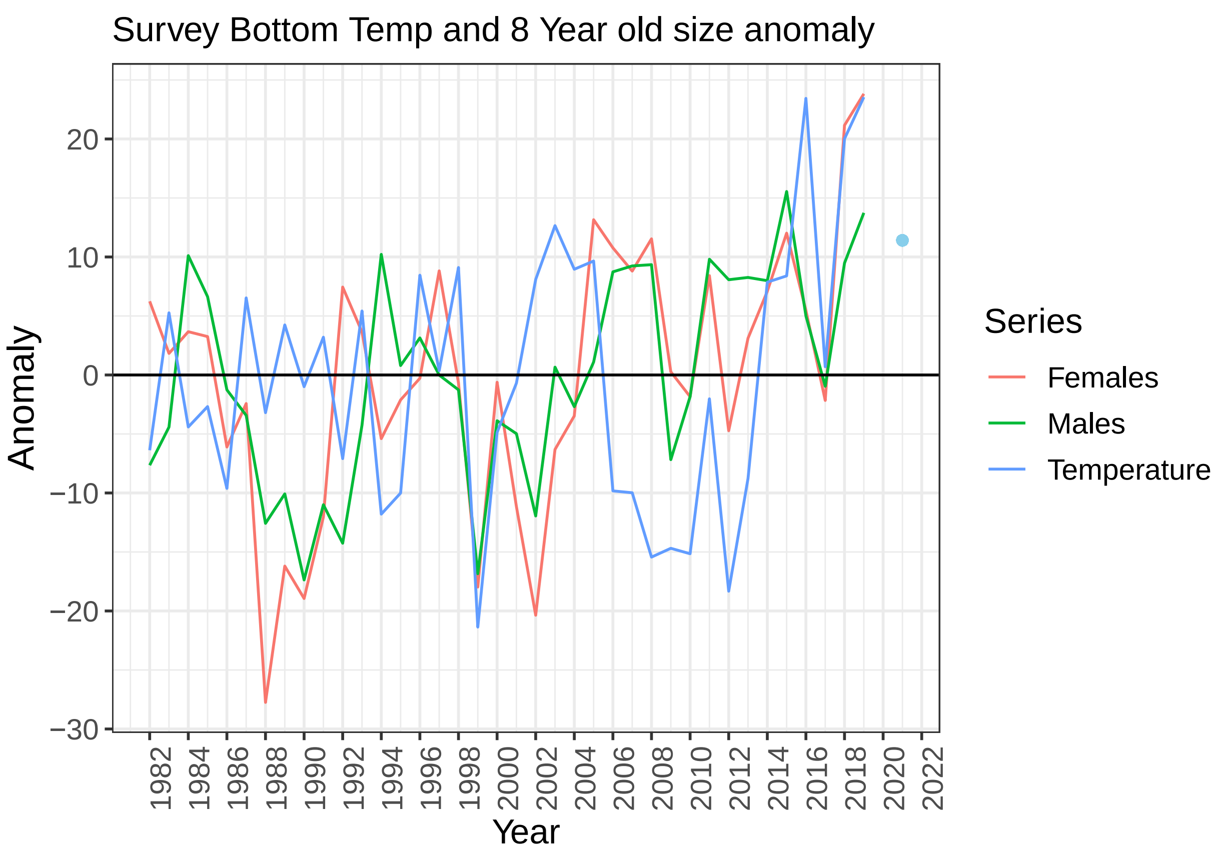
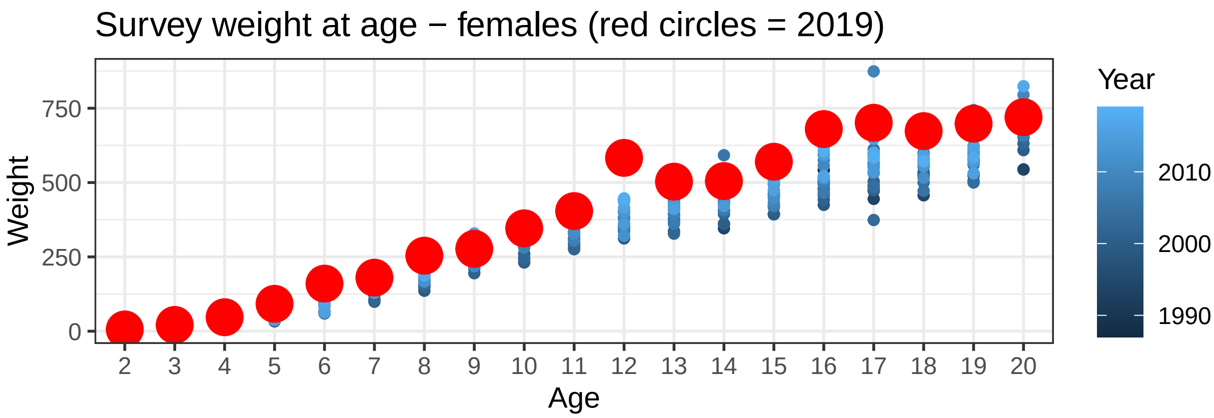
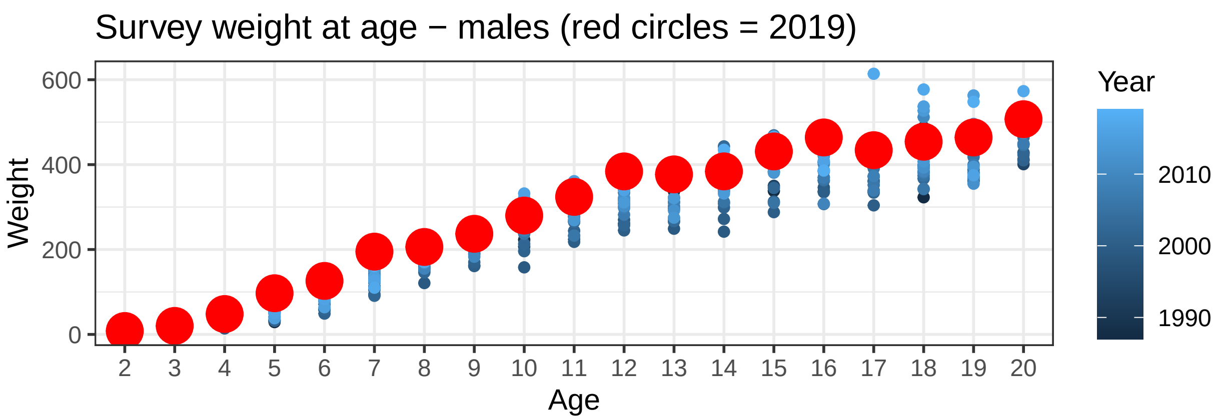


Figure 3: Raw survey weight at age anomalies and temperature anomalies, for ages 4, 5, and 8.

We used two sources to look at growth. The first was using years in which fish weight was recorded at the time of otolith collection. Age data was available for years 1999-2019 that included weights for aged fish. This is a new approach in which we are looking at incremental growth from one age tothe next and looking for trends based on the summer water temperature. The "Year" here is the year class of the fish Figure 4 .

```
#now plot survey
srvF=read.csv("/Users/ingridspies/Documents/WorkDellStuff/Assessments/YFS/2021/survey_wtage/mat_wtage_s
colnames(srvF)=c("Year",seq(2,20,1))
srvF2=reshape2::melt(srvF,id=c("Year"))
colnames(srvF2)=c("Year","Age","Weight")
sF=ggplot(data=srvF2)+geom_point(aes(x=Age,y=Weight,color=Year))+geom_point(data=srvF2[which(srvF2$Year

srvM=read.csv("/Users/ingridspies/Documents/WorkDellStuff/Assessments/YFS/2021/survey_wtage/mat_wtage_s
colnames(srvM)=c("Year",seq(2,20,1))
srvM2=reshape2::melt(srvM,id=c("Year"))
colnames(srvM2)=c("Year","Age","Weight")
sM=ggplot(data=srvM2)+geom_point(aes(x=Age,y=Weight,color=Year))+geom_point(data=srvM2[which(srvM2$Year

grid.arrange(sF,sM)
```





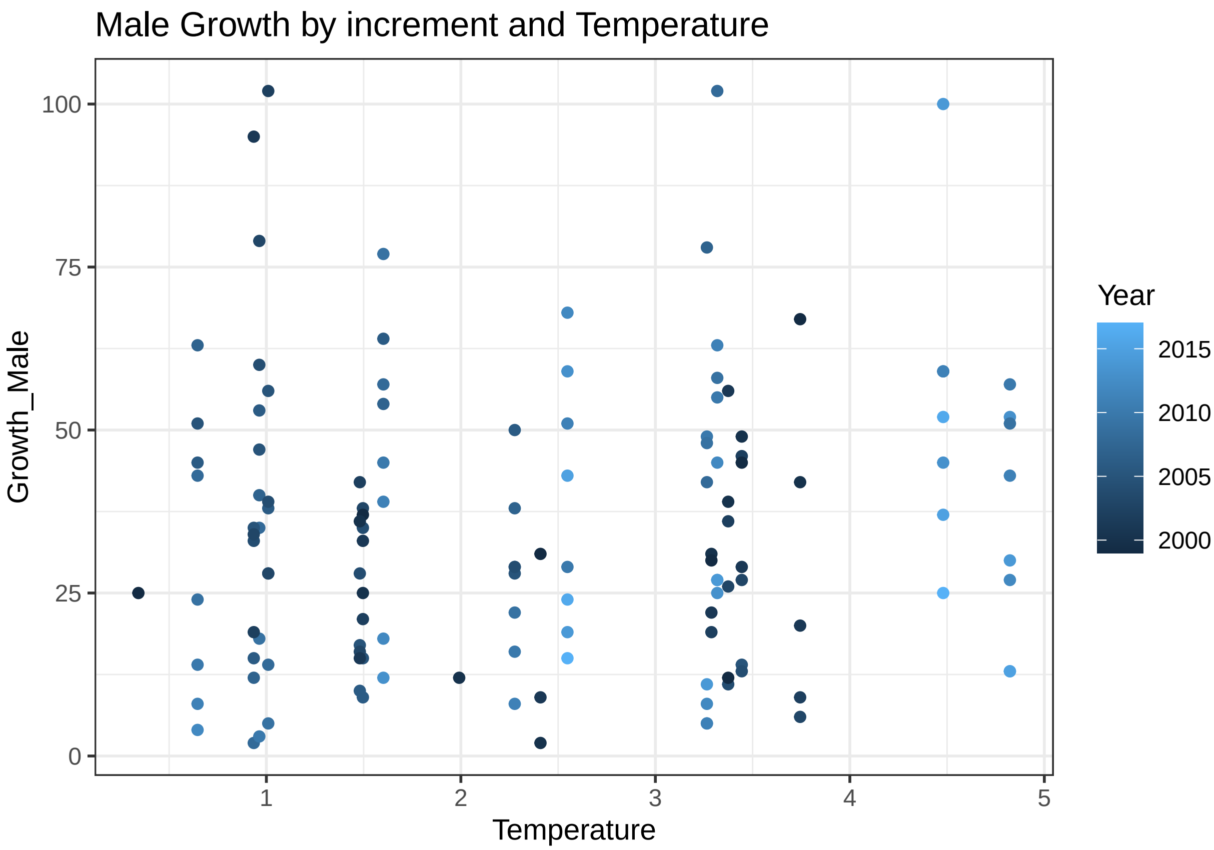

```
#JUst plot wt_pop_M for comparison - this is legacy weight at age
wtM=read.csv("/Users/ingridspies/Downloads/YFS_wtpopM.csv",header=TRUE)
colnames(wtM)=c("Year",seq(1,20,1))
wtM2=reshape2::melt(wtM,id=c("Year"))
colnames(wtM2)=c("Year","Age","Weight")
wtM2$Weight=as.integer(wtM2$Weight)


#ggplot(data=wtM2)+geom_point(aes(x=Age,y=Weight,color=Year))+geom_point(data=wtM2[which(wtM2$Year==202
```

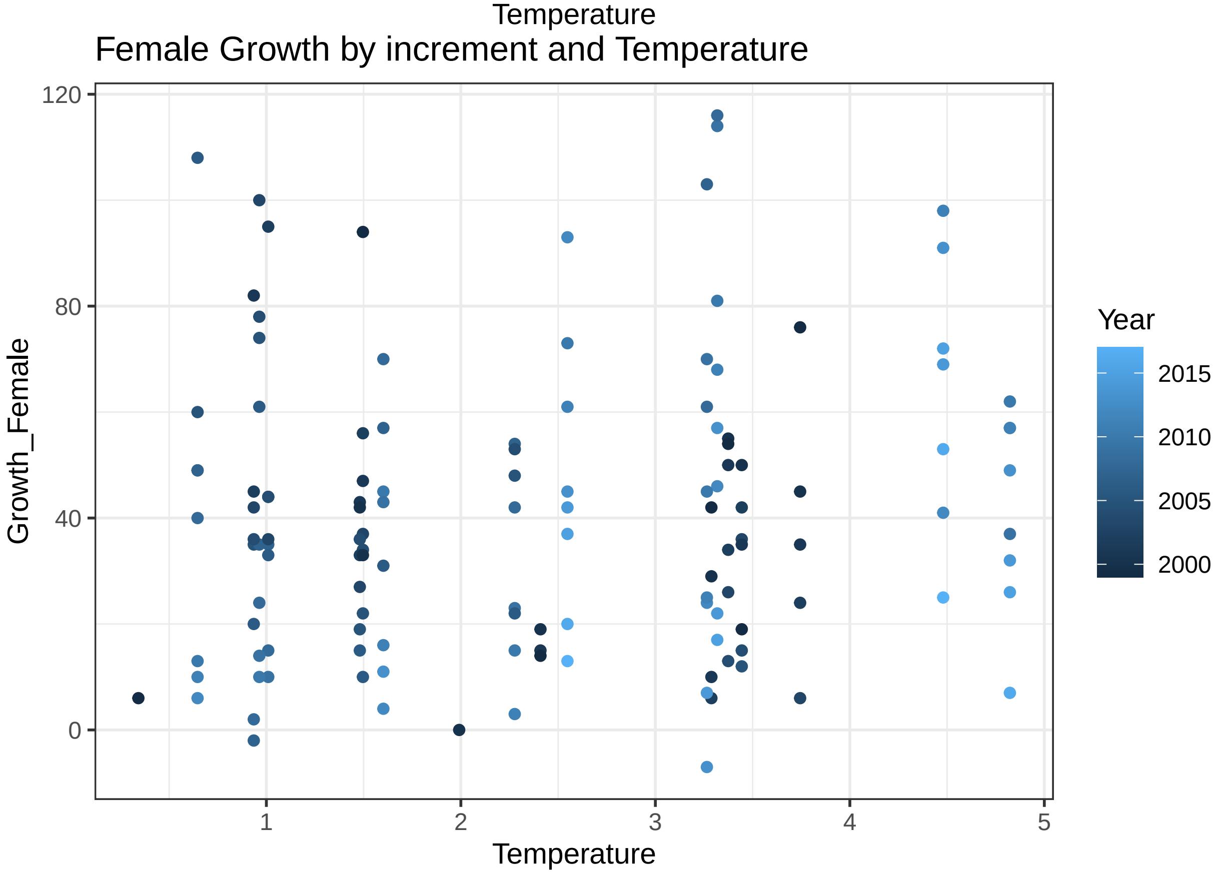
```
##       Year
##  [1,] 1999 0.3419065 1.9914129 2.4093430 3.2881762 3.7443768 3.3745162
##  [2,] 2000 1.9914129 2.4093430 3.2881762 3.7443768 3.3745162 3.4442771
##  [3,] 2001 2.4093430 3.2881762 3.7443768 3.3745162 3.4442771 1.4962738
##  [4,] 2002 3.2881762 3.7443768 3.3745162 3.4442771 1.4962738 1.4804767
##  [5,] 2003 3.7443768 3.3745162 3.4442771 1.4962738 1.4804767 0.9351870
##  [6,] 2004 3.3745162 3.4442771 1.4962738 1.4804767 0.9351870 1.0096464
##  [7,] 2005 3.4442771 1.4962738 1.4804767 0.9351870 1.0096464 0.9635137
##  [8,] 2006 1.4962738 1.4804767 0.9351870 1.0096464 0.9635137 2.2769129
##  [9,] 2007 1.4804767 0.9351870 1.0096464 0.9635137 2.2769129 0.6461782
## [10,] 2008 0.9351870 1.0096464 0.9635137 2.2769129 0.6461782 1.6015940
## [11,] 2009 1.0096464 0.9635137 2.2769129 0.6461782 1.6015940 3.2650201
## [12,] 2010 0.9635137 2.2769129 0.6461782 1.6015940 3.2650201 3.3182785
## [13,] 2011 2.2769129 0.6461782 1.6015940 3.2650201 3.3182785 4.8229035
## [14,] 2012 0.6461782 1.6015940 3.2650201 3.3182785 4.8229035 2.5479303
## [15,] 2013 1.6015940 3.2650201 3.3182785 4.8229035 2.5479303 4.4799719
## [16,] 2014 3.2650201 3.3182785 4.8229035 2.5479303 4.4799719 0.0000000
```

```
## [17,] 2015 3.3182785 4.8229035 2.5479303 4.4799719 0.0000000 0.0000000
## [18,] 2016 4.8229035 2.5479303 4.4799719 0.0000000 0.0000000 0.0000000
## [19,] 2017 2.5479303 4.4799719 0.0000000 0.0000000 0.0000000 0.0000000
##
##  [1,] 3.4442771 1.4962738 1.4804767 0.9351870 1.0096464 0.9635137 2.2769129
##  [2,] 1.4962738 1.4804767 0.9351870 1.0096464 0.9635137 2.2769129 0.6461782
##  [3,] 1.4804767 0.9351870 1.0096464 0.9635137 2.2769129 0.6461782 1.6015940
##  [4,] 0.9351870 1.0096464 0.9635137 2.2769129 0.6461782 1.6015940 3.2650201
##  [5,] 1.0096464 0.9635137 2.2769129 0.6461782 1.6015940 3.2650201 3.3182785
##  [6,] 0.9635137 2.2769129 0.6461782 1.6015940 3.2650201 3.3182785 4.8229035
##  [7,] 2.2769129 0.6461782 1.6015940 3.2650201 3.3182785 4.8229035 2.5479303
##  [8,] 0.6461782 1.6015940 3.2650201 3.3182785 4.8229035 2.5479303 4.4799719
##  [9,] 1.6015940 3.2650201 3.3182785 4.8229035 2.5479303 4.4799719 0.0000000
## [10,] 3.2650201 3.3182785 4.8229035 2.5479303 4.4799719 0.0000000 0.0000000
## [11,] 3.3182785 4.8229035 2.5479303 4.4799719 0.0000000 0.0000000 0.0000000
## [12,] 4.8229035 2.5479303 4.4799719 0.0000000 0.0000000 0.0000000 0.0000000
## [13,] 2.5479303 4.4799719 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
## [14,] 4.4799719 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
## [15,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
## [16,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
## [17,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
## [18,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
## [19,] 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
##
##  [1,] 0.6461782 1.601594 3.265020 3.318279 4.822903
##  [2,] 1.6015940 3.265020 3.318279 4.822903 2.547930
##  [3,] 3.2650201 3.318279 4.822903 2.547930 4.479972
##  [4,] 3.3182785 4.822903 2.547930 4.479972 0.000000
##  [5,] 4.8229035 2.547930 4.479972 0.000000 0.000000
##  [6,] 2.5479303 4.479972 0.000000 0.000000 0.000000
##  [7,] 4.4799719 0.000000 0.000000 0.000000 0.000000
##  [8,] 0.0000000 0.000000 0.000000 0.000000 0.000000
##  [9,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [10,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [11,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [12,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [13,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [14,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [15,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [16,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [17,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [18,] 0.0000000 0.000000 0.000000 0.000000 0.000000
## [19,] 0.0000000 0.000000 0.000000 0.000000 0.000000
```

```
##       Year
##  [1,] 1999 25 -11 31 30  67 12 45  37 26  46  40 -18  82.0   0.0   9  108 -162
##  [2,] 2000 12   2 31 42  39 49 25  36 32  46  76  24 -39.0  83.0 -21   29   22
##  [3,] 2001  9  22 20 56  29 33 15  95 28 -13 -10  79  53.0   8.0  11  134  -29
##  [4,] 2002 19   9 36 46  21 42 19 102 39 -21 -45  57  67.5   9.5 205 -183   33
##  [5,] 2003  6  26 27 38  16 34 28  79 21  63 -25  46  49.0  67.0 -59   30    0
##  [6,] 2004 11  13 35 28  33 39 60  29 13  42  57  26  72.0 -80.0  48    0    0
##  [7,] 2005 14  15 17 35  56 47 28  51 46  73  20 -26  41.0  43.0   0    0    0
##  [8,] 2006  9  10 15 38  53 50 45  64 69 -21  64  31  -4.0   0.0   0    0    0
##  [9,] 2007  0  12 28 40  38 63 54  78  6  40  17   0   0.0   0.0   0    0    0
```

```
## [10,] 2008  2  14 35 29  43 57 42 102 15  56 -26   0   0.0   0.0   0    0    0
## [11,] 2009  5  18 22 24  77 48 58  51  5  68   0   0   0.0   0.0   0    0    0
## [12,] 2010  3  16 14 45  49 55 57  29 48   0   0   0   0.0   0.0   0    0    0
## [13,] 2011  8   8 39  5  63 43 51  59  0   0   0   0   0.0   0.0   0    0    0
## [14,] 2012  4  18  8 45  27 68 59   0  0   0   0   0   0.0   0.0   0    0    0
## [15,] 2013 12   5 25 52  59 45  0   0  0   0   0   0   0.0   0.0   0    0    0
## [16,] 2014 11  27 30 19 100  0  0   0  0   0   0   0   0.0   0.0   0    0    0
## [17,] 2015 27  13 43 37   0  0  0   0  0   0   0   0   0.0   0.0   0    0    0
## [18,] 2016 13  24 52  0   0  0  0   0  0   0   0   0   0.0   0.0   0    0    0
## [19,] 2017 15  25  0  0   0  0  0   0  0   0   0   0   0.0   0.0   0    0    0
##
##  [1,] 198
##  [2,] -12
##  [3,] -41
##  [4,]   0
##  [5,]   0
##  [6,]   0
##  [7,]   0
##  [8,]   0
##  [9,]   0
## [10,]   0
## [11,]   0
## [12,]   0
## [13,]   0
## [14,]   0
## [15,]   0
## [16,]   0
## [17,]   0
## [18,]   0
## [19,]   0
##       Year
##  [1,] 1999  6 17 14 42 76 54  19  94 -21  68  69  -5  61  16  18  57  25 206
##  [2,] 2000  0 19 29 45 55 50  33  42  53  69  16 110 -56 119  55 -67   5  92
##  [3,] 2001 15 10 35 50 35 47  43  82  16  68  47  22  21 101 -15 120  16   3
##  [4,] 2002  6 24 34 42 56 33  45  95 -14  -8  94   6  53  48  79 -30 127   0
##  [5,] 2003  6 26 36 37 27 42  36 100  49  32  29  56  25 138 -61  87   0   0
##  [6,] 2004 13 15 34 36 36 44  78  53  49  -6  51  54  88  53  95   0   0   0
##  [7,] 2005 12 22 19 35 44 74  48  60  50  69  80 -14  39 138   0   0   0   0
##  [8,] 2006 10 15 20 33 61 22 108  31 112  -3 121 -58  92   0   0   0   0   0
##  [9,] 2007 16 -2 35 35 54 49  57 103  62  19  68   1   0   0   0   0   0   0
## [10,] 2008  2 15 24 42 40 70  61 116   4  65  56   0   0   0   0   0   0   0
## [11,] 2009 10 14 23 49 43 70 114  37  55 162   0   0   0   0   0   0   0   0
## [12,] 2010 10 15 13 45 45 81  62  73  58   0   0   0   0   0   0   0   0   0
## [13,] 2011  3 10 16 25 68 57  61  98   0   0   0   0   0   0   0   0   0   0
## [14,] 2012  6  4 24 46 57 93  41   0   0   0   0   0   0   0   0   0   0   0
## [15,] 2013 11 -7 57 49 45 91   0   0   0   0   0   0   0   0   0   0   0   0
## [16,] 2014  7 22 32 42 69  0   0   0   0   0   0   0   0   0   0   0   0   0
## [17,] 2015 17 26 37 72  0  0   0   0   0   0   0   0   0   0   0   0   0   0
## [18,] 2016  7 20 53  0  0  0   0   0   0   0   0   0   0   0   0   0   0   0
## [19,] 2017 13 25  0  0  0  0   0   0   0   0   0   0   0   0   0   0   0   0
```


Male Growth by increment and Temperature
Growth_Male
100
75
50
25
0
1
2
3
4
5
Temperature
Year
2015
2010
2005
2000


Female Growth by increment and Temperature
Growth_Female
120
80
40
0
1
2
3
4
5
Temperature
Year
2015
2010
2005
2000