

1 Evidence for a growing population of eastern migratory monarch butterflies is currently
2 insufficient
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10 Abstract: The eastern migratory population of monarch butterflies has experienced a multi-
11 decadal decline, but a recent increase in abundance (to 6.05 ha in winter 2018) has led some
12 observers to question whether the population has reversed its long-standing decline and
13 embarked on a trajectory of increasing abundance. We examined this possibility through
14 changepoint analyses, first assessing whether a change in trajectory existed and whether that
15 change was sufficient to alter our estimated risk for the population. We found evidence of a
16 change in trajectory in 2014, but insufficient statistical support for a significantly increasing
17 population since that time ($\beta = 0.285$, 95% CI = -0.127, 0.697). If the population estimate for
18 winter 2019 is ≥ 4.0 ha, we will then be able to credibly assert the population has been increasing
19 since 2014. However, given estimated levels of time series variability, presumed habitat capacity
20 and no recent change in status or trend, there was a 13.5% probability of observing a population
21 estimate as large or larger than was reported for winter 2018. Despite insufficient evidence for an
22 increasing population, near-term risk of quasi-extinction by 2023 has declined (mean risk

23 declining from 43% to 20%) because of higher abundance estimates since 2014. Our analyses
24 highlight the incredible difficulty in drawing robust conclusions from annual changes in
25 abundance over a short time series, especially for an insect that commonly exhibits considerable
26 year-to-year variation. Thus, we urge caution when drawing conclusions regarding species status
27 and trends for any species for which limited data are available.

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29 Key Words: changepoint, *Danaus plexippus*, extinction risk, small data

30

31 “Short-term fluctuations may or may not contain messages about longer-term trends” – Art
32 Shapiro

33 Populations vary over time in their abundance, and this variability can impart uncertainty to the
34 status and trend of a species. As population dynamics approach extinction, dynamics become
35 more variable (Holmes and Fagan 2006), which means short-term highs might become higher,
36 even while abundance is declining on average. In addition to the stochastic variation in
37 abundance imposed by the environment, uncertainty in species status and trend arises from
38 population sizes most often being estimated rather than counted; trends being inferred from
39 limited duration time series; and latent characteristics of a population, such as its relation to
40 carrying capacity or quasi-extinction thresholds, generally being inferred properties rather than
41 an observable quantity. Thus, given these various sources of uncertainty, it is difficult enough to
42 determine the trajectory for a population, let alone any change that may occur in that trajectory,
43 especially one that may occur near the terminus of a time series based on limited data.

44 Estimates of the population size of the eastern North American migratory population of
45 monarch butterflies (*Danaus plexippus*, hereafter monarchs) in their overwintering locations in
46 high-elevation oyamel fir (*Abies religiosa*) forests of central Mexico suggest a long-term decline
47 in abundance. Using a model allowing separation of observation-induced error from natural
48 process variability, Semmens et al. (2016) estimated monarchs declined by 84% between the
49 winters beginning in 1996 (18.19 ha) and 2014 (0.67 ha), with an estimated annual population
50 rate of change of 0.94. This rapid decline in monarch abundance led to widespread concern
51 regarding the imperilment of the species (Brower et al. 2011), including a petitioning of the U.S.
52 Fish and Wildlife Service (USFWS) to consider listing the species under the U.S. Endangered
53 Species Act (ESA) of 1973 (Center for Biological Diversity et al. 2014).

54 The estimated rate of decline ($\lambda = 0.94$) in monarchs was, however, considerably
55 uncertain, with credible intervals spanning from as low as 0.69 to as high as 1.30. This
56 uncertainty, in turn, led to considerable uncertainty in the estimates of risk faced by the
57 population; for instance, depending on the quasi-extinction threshold chosen, the range of
58 uncertainty in the risk was as much as one or two orders of magnitude wide (i.e., 0-34% at a 0.01
59 ha quasi-extinction threshold and 7-88% at 0.25 ha). The principal reasons for this large
60 uncertainty in the trajectory of monarchs and their subsequent risk of further decline are the
61 environmental and biological variability this insect faces over its annual cycle and our ability to
62 intuit the species response to this variability with the limited data available from monitoring
63 programs. Density-independent mortality, caused by a wide array of annually variable
64 environmental stressors, is offset against density-dependent reproduction (Yakuba et al. 2004,
65 Drury and Dwyer 2006, Flockhart et al. 2012, Marini and Zalucki 2017), and this tension
66 between birth and death processes plays out over multiple generations and across the vastness of

67 eastern North America (Flockhart et al. 2015, Oberhauser et al.2017). In some years, these
68 processes complement one another, leading to booms or busts in the population (Himes Boor et
69 al. 2018). In other years, increases in one are offset by the other, mitigating any sizeable year-to-
70 year change in population size.

71 In winter 2018, estimates of monarch abundance in their overwintering areas indicated
72 monarchs increased by 144% over their previous year's abundance, to an index of population
73 size of 6.05 ha (Conanp and WWF-Mexico 2019). This estimate has led some observers to
74 question whether the population has grown in recent years to the point at which it is no longer at
75 risk. This seemingly simple question is manifold in nature. The question suggests that there may
76 have been a change in the trajectory of the species in recent years, from a population in decline
77 to one of increase, that in turn begs whether the evidence of this change in trajectory supports a
78 reduced risk of quasi-extinction. An alternative possibility could be that the underlying status and
79 trajectory of the population had not changed but instead the species demonstrated the extreme
80 variability in year-to-year abundance that is not uncommon for insects.

81 To address this question, we conducted a time-series analysis examining whether the
82 observed series of population sizes experienced changes in mean or trajectory anywhere over the
83 25-year period of record. We also refit the model of Semmens et al. (2016) with subsequent
84 years of data reflecting the most recent observations of population size. In these ways, we can
85 test whether the population has reversed its long-term decline and the risk it faces has
86 appreciably declined as a result. The population as measured in Mexico reached its nadir in
87 abundance in winter 2013 (WWF 2016); we hypothesized that any change in status and any
88 reversal of trend should occur at this point in the time series.

89

90 Methods

91 The overwinter index of population size (in hectares) we used in our models was that used by the
92 USFWS in its Species Status Assessment for informing considerations of whether listing under
93 the ESA is warranted. With these data, we evaluated two models, a step arrangement (\bar{y}_t)
94 evaluating whether there was a demonstrable change in status (i.e., mean abundance) during the
95 time period and a segmented model (\hat{y}_t) examining whether there was a change in the trend; we
96 specifically tested for a reversal of trend from a period of decline to one of growth. We fit these
97 models in R (R Core Team 2018) with the *changePoint* (Killick et al. 2016) and *chngpt* (Fong
98 and Gilbert 2017) packages. Assumptions of independent, normally distributed data (on a log_e
99 scale) with constant variance pre- and post-change were evaluated with Shapiro and
100 Kolmogorov-Smirnov tests and inspection of quantile-quantile and autocorrelation plots.

101 Pleasants (2017) suggested there was sufficient milkweed in the upper midwestern U.S.
102 to support a mean population size overwintering in Mexico of 3.2 ha. He also asserted that in
103 some years, the reported abundance is likely to be lower because of the accumulation of poor
104 conditions faced by the population during its annual cycle, whereas in some years favorable
105 conditions will lead to a population increase higher than 3.2 ha. We calculated the probability
106 from a log-normal distribution of observing a 6.05-ha population relative to the 3.2-ha expected
107 population size. We calculated the variance for this log-normal distribution from the variance of
108 the post-2013 period.

109 Given that a changepoint was identified and the post-changepoint period was
110 nonsignificantly increasing (95% confidence interval of the slope parameter overlapping 0) (see
111 Results), we asked the question: How many more years of positive increase would be necessary

112 to provide statistically robust evidence that the population was growing? To evaluate this
113 question, we extrapolated the post-change point period abundance given the estimated post-
114 change point slope and refit the segmented change point model with additional years of
115 extrapolated abundance.

116 To examine potential change in risk of quasi-extinction given the recent population size
117 estimates for monarchs, we re-fit the Bayesian state-space model of Semmens et al. (2016),
118 calculating a new measure of risk with the additional years of estimated abundance since winter
119 beginning in 2014 (the last winter included in Semmens et al. 2016) (Figure 1). We set the quasi-
120 extinction threshold to 0.25 ha. We calculated this risk to winter 2023 (+5 years) and compared it
121 to the risk estimate for 2023 from the original Semmens et al. (2016) calculation. An important
122 aspect of the Semmens et al. model is that it used the conjoint patterns in overwinter abundance
123 and egg production in the breeding grounds to disentangle observation error from process error.
124 This egg production information is derived from an extrapolation of egg density data applied to
125 year-specific estimates of monarch-appropriate land cover. Unfortunately, annual land cover
126 information is insufficiently compiled for the most recent years at this time to reconstitute a
127 longer time series of egg production; nevertheless, the egg density time series used in Semmens
128 et al. is sufficient for the purposes of separating the two principal sources of error. An important
129 assumption we made in re-estimating risk was that there was no change in the trajectory of the
130 population over the full time series.

131 The time series after the estimated change point (described below) is too short to allow
132 proper estimation using the methods of Semmens et al. for only that post-change point period.
133 Thus, we used a simpler population-projection population viability analysis (Morris and Doak
134 2002) to estimate risk for the post-change point period in year 2023. As before, we set the quasi-

135 extinction threshold to 0.25 ha, counting the number of 1,000 simulations of population size
136 dropping below that threshold, and then compared that proportion to the quasi-extinction risk
137 estimated by Semmens et al. (2016). Calculation of this population-projection population
138 viability analysis, with 95% bootstrapped confidence intervals, was conducted following Morris
139 and Doak (2002, box 7.3) with the *popbio* package using the `countCDFxt` function (Stubben et
140 al. 2018) in R.

141

142 Results

143 When examining the time series of overwinter abundance of the eastern migratory population of
144 monarch butterflies for a change in mean abundance (i.e., step change), we identified a single
145 credible changepoint in winter 2009. For the period preceding this year, mean abundance was
146 6.69 ha (95% CI = 4.43, 8.94). For the period after winter 2009, mean abundance was 1.52 ha
147 (95% CI = >0.001, 4.68). The population variance was 15% higher in this latter period (
148 $\sigma_{\leq 2009}^2 = 1.32$ vs $\sigma_{> 2009}^2 = 1.52$), exhibiting greater variability at lower population sizes. If the
149 underlying milkweed is currently sufficient to support a winter population of 3.2 ha (Pleasants
150 2017), then a population as large or larger than 6.05 ha is expected to occur 13.5% of the time.

151 Fitting a segmented changepoint model, rather than a step function, suggested the best-
152 supported year for the changepoint threshold was 2014 (likelihood ratio $\lambda = 8.167$, $p = 0.0221$;
153 bootstrapped 95% CI = 2002, 2026), with 2013 close behind (Figure 2). The slope describing the
154 decline of monarchs in the period before winter 2014 was -0.103 (Table 1), whereas after this
155 winter the population exhibited a non-significant increase, though with confidence intervals >5:1
156 in favor of an increase ($\beta = 0.285$, 95% CI = -0.127, 0.697) (Figure 1).

157 Residuals from these step and segmented models before and after their changepoints were
158 independent, normally distributed about their respective mean, and had constant variance.
159 Comparing the segmented model (AIC = 45.3) with the step model (AIC = 49.5) suggested an
160 88% probability (odds 7.2:1) that the segmented model served as a better description of the data.
161 Both models were appreciably better than a null model comprising only an intercept (AIC =
162 62.8) and a linear model regressing the $\log_e(\text{overwinter estimate})$ against year (AIC = 51.5).

163 If the winter 2019 population continues the mean rate of increase observed since 2014,
164 then with this single additional year of data, we would have sufficient information statistically to
165 conclude the population was growing ($\beta = 0.399$, 95% CI = 0.072, 0.727). Further, if the index of
166 abundance was any value ≥ 4.00 ha, this amount too would be statistically sufficient ($p < 0.05$) to
167 support a conclusion that the population was growing. Any value < 4.00 ha, however, would cast
168 doubt on a growing population.

169 Refitting the model of Semmens et al. (2016) to assess whether the population's risk of
170 quasi-extinction had appreciably changed, as measured over the entire 25-year period of record,
171 indicated declining risk with improving abundance assuming no change in trajectory (Table 2).
172 If, however, the post-2014 winter trajectory continues, the risk of quasi-extinction by 2023 could
173 drop to negligible levels.

174

175 Discussion

176 At this time, there is insufficient statistical evidence to confidently assert that the eastern
177 migratory monarch population has significantly grown since winter 2014. If the dynamic of
178 population growth for the few years post-winter 2014 holds, then winter 2019-2020's population

179 size estimate should provide evidence as to whether the trend has credibly changed from one of
180 decline to one of increase.

181 In a noisy time series, stochastic fluctuations may lead to observed increases over
182 relatively long periods, even when populations have an average negative growth rate. Similarly,
183 stochastic fluctuations may cause a population to decrease, even when the long-term average
184 growth rate is positive. Our analysis and the uncertainty it reveals highlights the difficulty in
185 assessing species status and trend with even a 25-year dataset, especially when interannual
186 variation is high. Semmens et al. (2016) reported a mean declining dynamic, but one with a non-
187 negligible probability of a possible underlying growth rate that was positive. Their findings
188 showed that two-thirds of the credible interval distribution about their estimate of the population
189 growth rate was <1 , indicating that the odds were 2:1 in favor of a declining population.
190 Nevertheless, one-third of the distribution suggested a stable or growing population. Conversely,
191 based on the interval width we calculated for the post-2014 trajectory, the odds are roughly 5:1
192 in favor of an increasing population. Unfortunately, the post-2014 period is too short to
193 confidently conclude, at this time, a reversal in trajectory.

194 Despite a lack of statistical support for a positive trend since 2014, the near-term risk of
195 quasi-extinction appears to have declined by at least half. Nevertheless, there remains a 1 in 5
196 chance of quasi-extinction within 5 years if the population has not truly changed trajectory. If it
197 has changed trajectory, then the near-term risk is further ameliorated to near zero by 2023 (also
198 see table 2, Semmens et al. 2016).

199 In any time series, the sample size is the number of years, and 10-30 years are often
200 necessary to detect a significant trend even for species with average interannual variation
201 (Urquhart, 2012; White, 2018). Despite the challenge of high interannual variation, the monarch

202 butterfly is an iconic and highly visible species that benefits from strong public interest
203 (Diffendorfer et al., 2014) and a corresponding availability of data (Ries and Oberhauser, 2015).
204 For many species considered for listing under the ESA, even less information is available for
205 evaluating the statistical support for any apparent decline. Thus, the challenge of assessing trend
206 becomes even greater as one examines short-term time series or smaller periods of time within
207 long-running time series; what may initially appear to be a short-term trend may have no
208 statistical support in the context of the population's history. While assessing subsets of a time
209 series could be a useful way to evaluate whether a species is moving toward recovery, caution is
210 warranted when making conclusions based on limited data. Aside from the estimate of trend,
211 other metrics can be useful in such cases, such as whether mean abundance falls below the
212 estimated threshold for a secure population. In the case of the monarch butterfly, the recent mean
213 of 1.52 ha falls well below the threshold of 6.0 ha estimated by Semmens et al. (2016) and
214 established by the three nations of Canada, U.S. and Mexico as the near-term population goal for
215 the eastern population of migratory monarch butterflies. If we take this 6.0 ha threshold as a
216 recovery criterion and assume a $\sigma_{>2009}^2 = 1.52$, then the population is likely to need to reach a
217 mean of 6.85 ha for 3 years to confidently assert the population has crossed this threshold
218 (analysis not shown). Thus, this mean population size warrants continuing concern given the
219 uncertain growth in recent years and the high year-to-year variability exhibited by this insect
220 species.

221

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223 Any use of trade, firm, or product names is for descriptive purposes and does not imply
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227

228 Author Contributions

229 WT and JS conceived the study, WT conducted the analyses, and WT, JS, and EW wrote the
230 manuscript.

231

232 Conflict of Interest Statement

233 The work was not carried out in the presence of any personal, professional, or financial
234 relationships that could be construed as a conflict of interest.

235

236 Figure Legend

237 Figure 1. Time series segmented into original series analyzed by Semmens et al. (2016)(1994-
238 2014), the full set (1994-2018), and the post-change period (2013-2018). Risk of quasi-extinction
239 was calculated for each of these three periods.

240

241 Figure 2. Segmented time series of the index of overwinter abundance (ha) of eastern migratory
242 monarch butterflies. The bootstrapped frequency of the changepoint estimate from 10^3 replicates
243 is provided (inverted, in gray); the gray line represents the lower 2.5% symmetric bootstrap
244 confidence limit.

245

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305

306 Table 1. Parameter estimates for the best-supported linear segmented changepoint model for
307 1994-2018 estimates of overwinter abundance of the eastern migratory monarch butterfly
308 population.

	Estimate	SE	2.5% Confidence Limit	97.5% Confidence Limit	p-value
Intercept	207.540	102.49	-7.685	422.766	0.0588
Year	-0.103	0.051	-0.210	0.005	0.0612
Year – changepoint (2014)	0.388	0.170	-0.154	0.930	0.1608

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310

311

312 Table 2. Median risk of quasi-extinction by 2023 (quasi-extinction threshold = 0.25 ha) from the
313 original Semmens et al. (2016) model (with overwinter abundances from 1994-2014), for the full
314 time series of overwinter abundances (1994-2018, again using the methods of Semmens et al.),
315 and for the post-change period (2013-2018), using a count-based population viability model.

Time Period	Method	Median (50%) Risk	Lower Limit (2.5%)	Upper Limit (97.5%)
1994-2014	State-space model (Semmens et al. 2016)	0.387	0.064	0.855
1994-2018	State-space model (Semmens et al. 2016)	0.166	0.024	0.507
2013-2018	Count-based PVA, no K	<0.001	<0.001	0.148

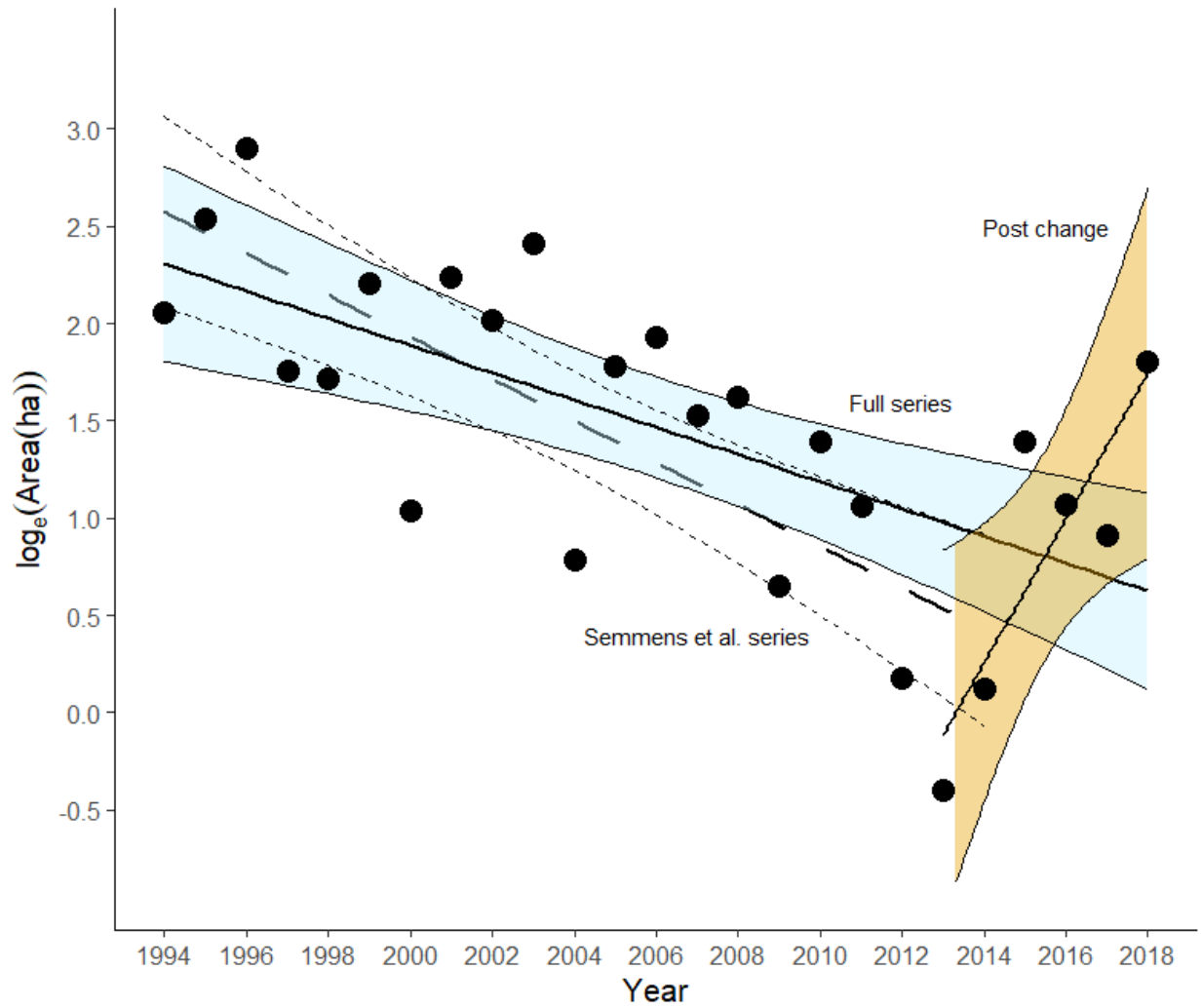
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320 Figure 1.

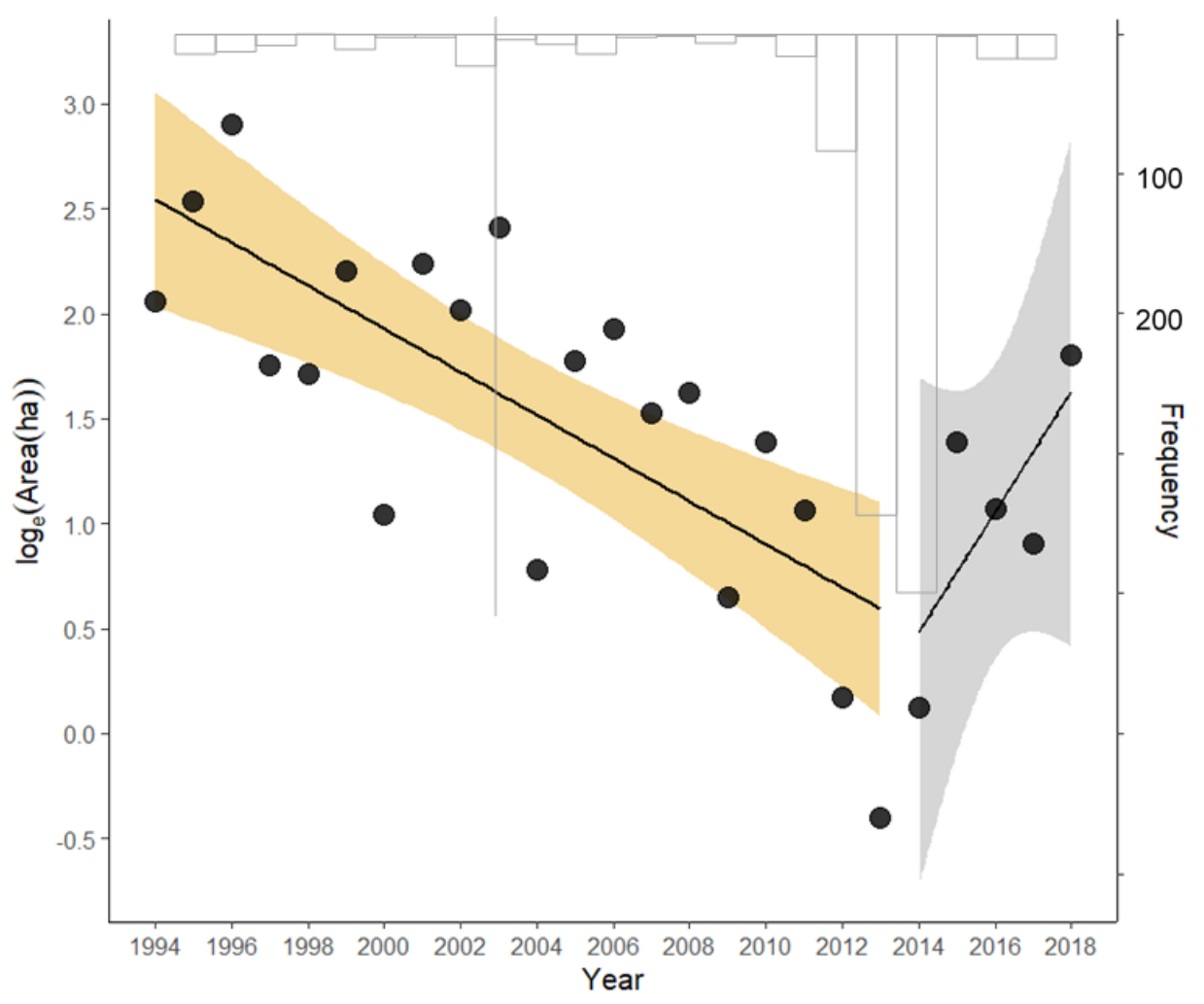


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322

323 Figure 2.

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