Demographic, ecological and physiological responses of ringed seals to an abrupt decline in sea ice availability

Steven H Ferguson [Corresp., 1, 2, 3] , Brent G Young [1, 2] , David J Yurkowski [1, 2] , Randi Anderson [2] , Cornelia Willing [2, 3] , Ole Nielsen [1]

[1] Fisheries and Oceans Canada, Winnipeg, Manitoba, Canada

[2] Department of Biological Sciences, University of Manitoba, Winnipeg, Manitoba, Canada

[3] Centre for Earth Observation Science, University of Manitoba, Winnipeg, Manitoba, Canada

Corresponding Author: Steven H Ferguson
Email address: steve.ferguson@dfo-mpo.gc.ca

To assess whether demographic declines of Arctic species at the southern limit of their range will be gradual or punctuated, we compared large-scale environmental patterns including sea ice dynamics to ringed seal (*Pusa hispida*) reproduction, body condition, recruitment, and stress in Hudson Bay from 2003-2013. Aerial surveys suggested a gradual decline in seal density from 1995-2013, with the lowest density occurring in 2013. Body condition decreased and stress (cortisol) increased over time in relation to longer open water periods. The 2010 open water period in Hudson Bay coincided with extremes in large-scale atmospheric patterns (NAO, AO, ENSO) resulting in the earliest spring breakup and the latest ice formation on record. The warming event was coincident with high stress level, low ovulation rate, low pregnancy rate, few pups in the Inuit harvest, and observations of sick seals. Results provide evidence of changes in the condition of Arctic marine mammals in relation to climate mediated sea ice dynamics. We conclude that although negative demographic responses of Hudson Bay seals are occurring gradually with diminishing sea ice, a recent episodic environmental event played a significant role in a punctuated population decline.

1   **Demographic, ecological and physiological responses of ringed seals to an abrupt**

2   **decline in sea ice availability**

3   Steven H. Ferguson*[1,2,3], Brent G. Young[1,2], David J. Yurkowski[1,2], Randi Anderson[2], Cornelia

4   Willing[2,3], Ole Nielsen[1]

5   [1]Fisheries and Oceans Canada, 501 University Crescent, Winnipeg, MB, Canada

6   [2]Department of Biological Science, University of Manitoba, Winnipeg, MB, Canada

7   [3]Centre for Earth Observation Science, University of Manitoba, Winnipeg, MB, Canada

9   Corresponding Author:

10   Steven H. Ferguson

11   Fisheries and Oceans Canada, 501 University Crescent, Winnipeg, MB, Canada

12   e-mail: steve.ferguson@dfo-mpo.gc.ca

14 ABSTRACT

15 To assess whether demographic declines of Arctic species at the southern limit of their

16 range will be gradual or punctuated, we compared large-scale environmental patterns

17 including sea ice dynamics to ringed seal (*Pusa hispida*) reproduction, body condition,

18 recruitment, and stress in Hudson Bay from 2003-2013. Aerial surveys suggested a gradual

19 decline in seal density from 1995-2013, with the lowest density occurring in 2013. Body

20 condition decreased and stress (cortisol) increased over time in relation to longer open

21 water periods. The 2010 open water period in Hudson Bay coincided with extremes in

22 large-scale atmospheric patterns (NAO, AO, ENSO) resulting in the earliest spring breakup

23 and the latest ice formation on record. The warming event was coincident with high stress

24 level, low ovulation rate, low pregnancy rate, few pups in the Inuit harvest, and

25 observations of sick seals. Results provide evidence of changes in the condition of Arctic

26 marine mammals in relation to climate mediated sea ice dynamics. We conclude that

27 although negative demographic responses of Hudson Bay seals are occurring gradually

28 with diminishing sea ice, a recent episodic environmental event played a significant role in

29 a punctuated population decline.

31   BACKGROUND

32   Organisms evolve specific adaptations to their habitats through natural selection (Mayr

33   1963) and when their habitats change gradually, organisms can adjust phenotypically

34   within an evolved range of flexibility (Levins 1962). However, this evolved adaptation has

35   limitations and in extreme situations, organisms may not be able to adapt to particular

36   habitats and environmental conditions above an evolved threshold (Southwood 1977).

37   Under these circumstances, populations suffer mortality of individuals, declines in

38   reproduction, and/or immigrate to new habitats that may allow increased demographic

39   success (MacArthur and Wilson 1966). The result is a shift in species distribution (Guisan

40   and Thuiller 2005) and understanding this process by identifying thresholds to

41   adaptability and the mechanism of population decline are both critical to species

42   conservation.

43   Predicting how climate warming will result in retraction of an Arctic species range

44   northward requires knowledge of demographic changes and their ecological plasticity in

45   response to environmental change. Few studies have linked marine mammal demographic

46   responses to climate change (Poloczanaska et al. 2007) with the notable exception of polar

47   bears (*Ursus maritimus*) (Regehr et al. 2007; Hunter et al. 2010; Lunn et al. 2016), where

48   the majority of research relates to loss of space and time opportunities for feeding on a

49   lipid-rich diet (Thiemann et al. 2008; Rode et al. 2016). Ringed seals (*Pusa hispida*) have a

50   circumpolar distribution and show high variability in the relative importance of predation

51   from polar bears (Thiemann et al. 2008) and to varying food habits (Yurkowski et al.

52   2016a). However, key habitat attributes are linked to survival and successful reproduction.

53   In particular, ringed seals require sea ice during the critical spring period when

54   reproduction and molting occurs (Smith & Stirling 1975) and a seasonal pulse in food

55   availability in the summer ice-free season (Young & Ferguson 2013). Evolved life history

56   characteristics that match these high-latitude environmental features include relative small

57   body size for a pinniped and a life history characterized by early age of maturation, annual

58   birthing, short lactation duration, widely varying but high pup mortality, relatively low

59   adult mortality, and greater fitness investment in long life (Ferguson & Higdon 2006).

60   High latitude species are characterized by a strong seasonal cycle of feast and fast

61   with both periods critical to reproduction and survival (Boyce 1979). Ringed seals are

62   adapted to cycle annually from intensive foraging during the open water season to

63   accumulate fat reserves to sustain them over winter and during the birthing, nursing, and

64   mating periods when adults are restricted to small home ranges with depleted food

65   resources (Luque et al. 2014; Young and Ferguson 2014). In spring, pups are independent

66   and adults undergo molting with little feeding opportunities and increased risk of

67   predation (Stirling and Archibald 1977; Young and Ferguson 2015). During periods of

68   deteriorating environmental conditions, the phenology of ringed seals can be interrupted

69   leading to inadequate energy reserves prior to the next year's reproduction (Harwood et al.

70   2012). Ringed seal populations can also be negatively affected by infrequent, annual,

71   extreme climatic conditions that exert pressure on their demographics (Stirling and Smith

72   2004).

73   Endemic Arctic species are challenged by the rapid pace of sea ice declines and

74   resulting changes in ecological dynamics of the marine ecosystem (Post et al. 2013).

75   Hudson Bay represents one of the most southerly distributions of ringed seals and

76   therefore, as an ice-obligate marine mammal, the prediction is for a retraction northward

77   in range (Kovacs & Lydersen 2008). The Hudson Bay ecosystem is at the southern edge of

78   maximum sea ice extent and goes through a seasonal cycle of complete ice formation and

79   loss (Saucier et al. 2004). The initial characteristics of population and demographic changes

80   may already be occurring with a decrease in ringed seal density observed in western

81   Hudson Bay between the two recent aerial surveys in spring 2010 and 2013 (0.78 to

82    $0.20^/km^2$) (Young et al. 2015).

83   Here, we compare indices in the productivity and health of the Hudson Bay ringed

84   seal population with environmental covariates over time. Our data sets were annual trends

85   in sea ice breakup and formation, major climatic indices, and biological data from seal

86   collections, 2003-13: (1) body condition (% fat) from seals harvested by Inuit, (2)

87   reproduction from examination of reproductive tracts, (3) recruitment from hunter harvest

88   statistics, and (4) stress from blubber cortisol levels. We hypothesize that gradual

89   deteriorating change in sea ice characteristics will correlate with a gradual decrease in

90   ringed seal body condition, ovulation rate and pup recruitment (Stirling 2005), whereas an

91   abrupt decline in sea ice availability in 2010 will result in dramatic negative demographic,

92   ecological and physiological responses by ringed seals.

93   METHODS

94   Sea ice breakup and freeze-up dates were determined from weekly data obtained from the

95   Canadian Ice Service using Icegraph 2.0 (http://iceweb1.cis.ec.gc.ca/IceGraph/), for

96   eastern Hudson Bay, 1979-2014. The majority of biological data for ringed seals was

97   derived from the Sanikiluaq (southeast Hudson Bay) seal collection whereas Arviat

98   (southwest Hudson Bay) only provided the time-series of cortisol measures. Therefore, we

99   only present annual changes in sea ice coverage (Fig, 1b) for this eastern region

100   (Sanikiluaq) although we found strong correlations with other Hudson Bay regions

101   identified by the Canadian Ice Service. We were unable to assess the effect of east-west

102   differences (Young and Ferguson 2014) and how they may influence our results because

103   our datasets were not balanced (i.e., biological measures from Sanikiluaq were not

104   available from Arviat). Ice breakup date was defined as the date on which the sea ice

105   concentration decreased and remained below 50% (Stirling et al. 1999). Conversely,

106   freeze-up date was defined as the date on which sea ice concentration increased and

107   remained above 50%. Open-water duration was calculated by subtracting the breakup and

108   freeze-up dates. Major climatic indices were obtained from the Climate Prediction Center

109   (http://www.cpc.ncep.noaa.gov/), including the Arctic Oscillation (AO), the North Atlantic

110   Oscillation (NAO), and El Nino-Southern Oscillation (ENSO) for the December to February

111   monthly mean estimates from 1971-2014. We included ENSO due to its significant climatic

112   influence in North America and due to its effect on ecological relationships in several

113   ecosystems across the globe (Wang et al. 2010; Nye et al. 2014; Rustic et al. 2015). NAO

114   and AO were included since previous research found that they were related to ringed seal

115   recruitment and timing of spring ice breakup (Ferguson et al. 2005). The longer time frame

116   available for environmental data provided a background to the 2003-2013 period with

117   available ringed seal biological data.

118   Morphological measurements and tissue samples were collected from 1425 Hudson Bay

119   ringed seals harvested during the Inuit subsistence hunt from Sanikiluaq (n=917), NU,

120   Canada (56°32′34″ N, 79° 13′ 30″ W) and Arviat (n=508), NU (61° 6′ 29″ N, 94° 3′ 25″ W)

121   from 2003-2013. Permits to collect samples as part of the Inuit subsistence hunts were

122   acquired from Fisheries and Oceans Canada. All biological data with the exception of

123   cortisol was derived from seals collected by Sanikiluaq hunters in the eastern region of

124   Hudson Bay. Samples were collected in autumn (Oct. to Dec.) in Arviat. In Sanikiluaq some

125   samples were collected throughout the year but we used only autumn collections for

126   age/sex composition as the late open-water season provides a representative sample of the

127   population (see Holst et al. 1999; Ferguson et al. 2005). Permits to collect samples as part

128   of the Inuit subsistence hunts were acquired from Fisheries and Oceans Canada. Canine

129   teeth were extracted from the lower jaw for age determination using annual growth layer

130   groups in the cementum (Chambellant and Ferguson 2009). Pup survival was defined as

131   the percentage of pups (i.e., <1 year) in the autumn subsistence hunt and is considered a

132   good measure of 0-6 month survival (Chambellant et al. 2012). Total body weight and sculp

133   weight (weight of blubber layer, skin and fur) were recorded by the hunters at the time of

134   sample collection. Body condition was calculated as percent blubber (sculp weight*100 /

135   total bodyweight). Reproductive tracts were stored frozen before being examined. After

136   gross examination of reproductive tracts, ovaries were excised, formalin-fixed and

137   sectioned at 2-mm intervals, and examined macroscopically for the presence of a corpus

138   luteum (ovulation in the year of collection) and corpora albicantia (previous pregnancies)

139   (Laws 1956). Estimation of ovulation was only calculated if sample size for a particular

140   year exceeded 5 mature adult females which excluded 2003-6. An extraction method for

141   ringed seal blubber samples was used in conjunction with radioimmunoassay to measure

142   cortisol levels representing stress (Trana et al. 2014). Cortisol measures from Arviat seals

143   were not available in 2013.

144   Four separate general linear models were used to investigate relationships between

145   environmental (i.e. duration of the open water period, ENSO, NAO and AO indices) and

146   biological variables (i.e. percentage of ovulating females, percentage of pups in the harvest,

147   body condition and cortisol levels) over time using R v 3.2.3 (R Core Team 2015).

148   Continuous predictor variables were screened for collinearity and removed when a

149   Pearson's correlation coefficient was ≥ 0.6 and a variance inflation factor (VIF) was > 3.0.

150   NAO and AO were highly correlated (0.8). We retained NAO for all analyses due to its

151   stronger association with sea ice (Nakamura et al. 2015). Prior to analysis, percentage of

152   ovulating females, percentage of pups in harvest, and body condition were normally

153   distributed upon visual examination of histograms and quantile-quantile plots. Cortisol

154   levels were log-transformed before analysis to improve normality.

155   RESULTS

156   Results support a gradual pattern of earlier spring ice breakup and later autumn freeze-up

157   in Hudson Bay; where from 2003-2013, sea ice breakup has varied more widely than

158   freeze-up. No relationship occurred with any climate variability index over 1979-2014, but

159   the NAO and AO have been more positive from 1999-2015 (Fig. 1). The longest ice-free

160   season on record for eastern Hudson Bay occurred in 2010, with the earliest spring

161   breakup (May) and latest freeze-up (January 2011) and an anomalous negative NAO and

162   AO, and a high ENSO index (Fig. 1).

163

164   Figure 1. Top: Annual winter (December to February) North Atlantic Oscillation index

165   (NAO), Arctic Oscillation (AO), and El Nino-Southern Oscillation (ENSO), 1971-2014. Note

166   red arrows indicate possible regime shifts (1977, 1989, 1989/99, 2010) and black arrows

167   possible years with poor ringed seal condition: 1973/74, 1983, 1992, 1998, 2010 (Smith

168   and Stirling 1978; Hare and Mantua 2000; Smith and Harwood 2001; Benson and Trites

169   2002; Ferguson et al. 2005; Litzow 2006). Bottom: Sea ice patterns over the day of the year

170   showing inter-annual variation in timing of spring breakup, duration of open water season,

171   and time of freeze-up, 2003-2013. Note that autumn 2010 freeze-up did not occur until

172   January 2011.

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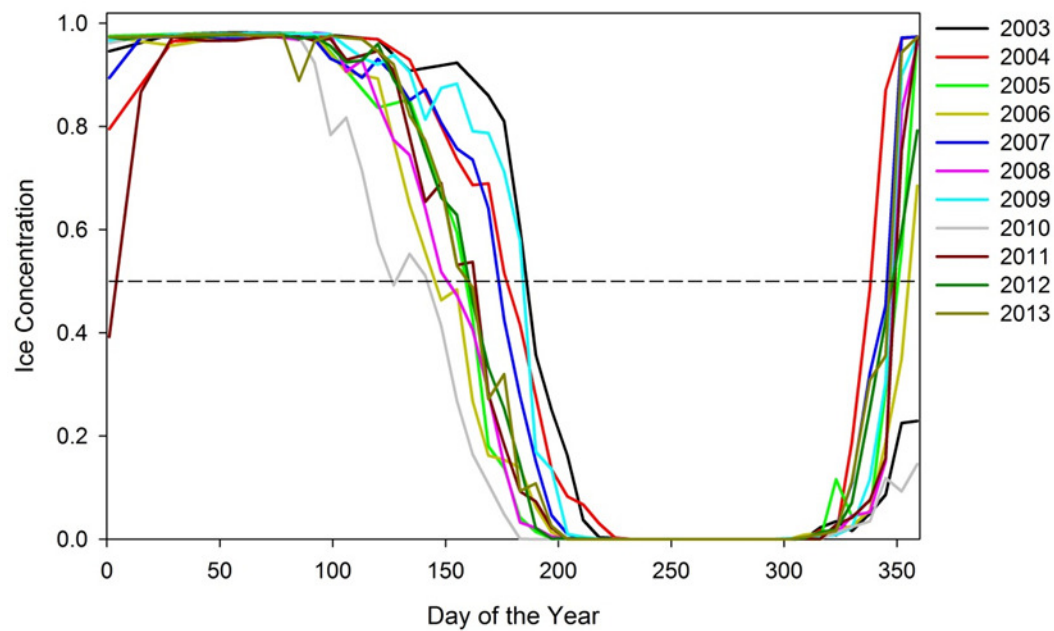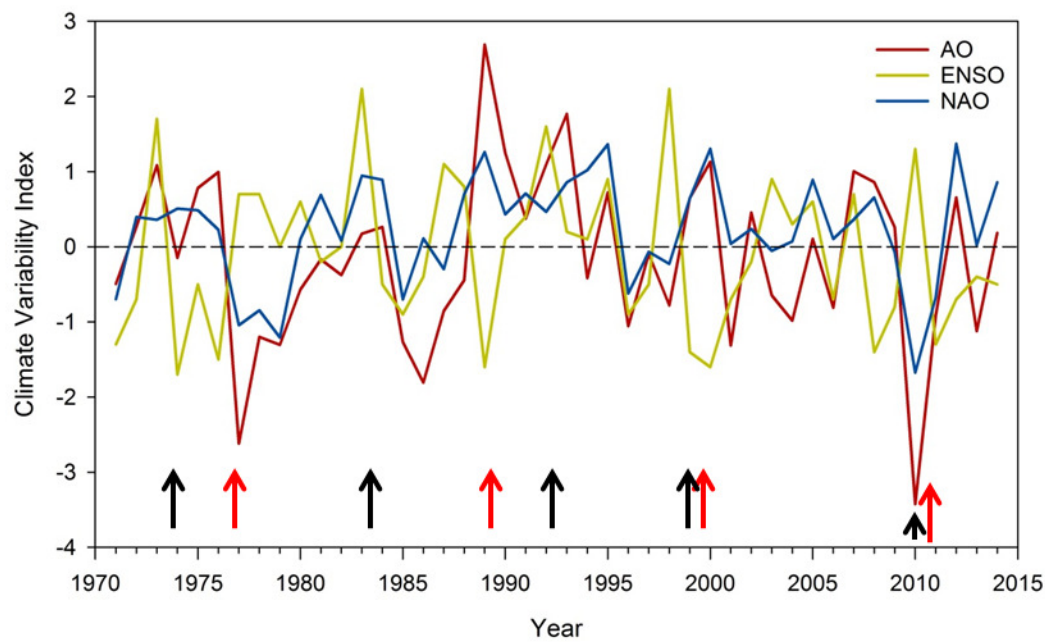
177   Body condition significantly decreased over time (t = -8.2, p < 0.001), from 55.4%

178   blubber mass in 2004 to 40.3% in 2012 before increasing to 48.1% in 2013 (Table 1; Fig.

179   2). In addition, body condition significantly decreased with increasing open water period (t

180   = -2.0, p < 0.05), ENSO index (t = -2.3, p = 0.02) and NAO index (t = -2.0, p < 0.05; Table 2;

181   Fig. 3). Ovulation rate varied considerably among years from 100% in 2008 to 56% in

182   2011, albeit with no relationship with year, open water duration, or climatic indices.

183   Percentage of pups in the harvest, as an estimate of pup survival, exhibited a marginal

184   decline from 2003-2013 (t = -2.09, p = 0.08) from about 40% of the harvest to about 20%

185   (Table 2; Fig 2). Stress, as measured by cortisol concentration (ng/g), significantly

186   increased over time (t = 8.0, p < 0.001) from about 0.1 to 0.6ng/g over the 2003-12 period

187   (Table 2; Fig. 2). A significant decrease in cortisol level occurred with NAO index (t = -2.6, p

188   = 0.01; Fig. 3). In 2010, cortisol levels in ringed seals had the highest amount of variability

189   (standard deviation = 1.84) compared to other years (Fig. 2). High stress levels occurred in

190   2010 and low ovulation rates occurred in 2011 which supports the pattern of a decrease in

191   ovulation rate after the high stress levels.

192   Table 1. Biological data from harvested ringed seals collected in Hudson Bay, Canada. Mean ±
193   standard error (sample size).

194

Year	Body condition (% fat)	Percent Ovulation	Percent Young of Year	RIA Cortisol (ng/g)
2003			39.1 (115)	0.07 ± 0.01 (72)
2004	55.4 ± 1.0 (45)		30.4 (56)	0.10 ± 0.02 (32)
2005	52.8 ± 0.9 (71)		40.9 (88)	0.10 ± 0.01 (120)

2006	49.7 ± 0.7 (80)		42.7 (82)	0.14 ± 0.05 (40)
2007	46.9 ± 0.6 (123)	85.7 (7)	52.4 (126)	0.32 ± 0.10 (27)
2008	47.5 ± 0.8 (102)	100.0 (5)	48.6 (105)	0.24 ± 0.04 (56)
2009	45.2 ± 1.2 (41)	88.9 (9)	38.1 (42)	0.28 ± 0.04 (51)
2010	43.9 ± 0.9 (90)	66.7 (18)	28.1 (96)	0.86 ± 0.27 (46)
2011	46.4 ± 0.8 (97)	56.3 (16)	20.6 (97)	0.51 ± 0.12 (30)
2012	40.3 ± 1.2 (65)	83.3 (12)	10.8 (65)	0.43 ± 0.07 (34)
2013	48.1 ± 1.4 (42)	100.0 (6)	20.0 (45)	

195

196   Table 2. Relationships between Hudson Bay ringed seal biological parameters and

197   environmental correlates assessed using general linear models, 2003-2013.

Covariates	Ovulation rate (%)	Pup recruitment (%)	Seal condition (blubber %)	Cortisol (ng/g)
Intercept	-48.00 ± 69.51	41.96 ± 39.1	**25.20 ± 2.58*****	**-34.90 ± 43.48*****
Year	0.02 ± 0.03	-0.021 ± 0.020	**-0.012 ± 0.001*****	**0.002 ± 0.0002*****
Ice-free period (days)	0.0003 ± 0.006	-0.00036 ± 0.0033	-0.0003 ± 0.0002[a]	0.00003 ± 0.0005
El-Niño Southern Oscillation	0.004 ± 0.01	0.0175 ± 0.072	**-0.008 ± 0.004***	0.001 ± 0.006[b]
North Atlantic Oscillation	0.011 ± 0.012	0.00719 ± 0.072	**-0.009 ± 0.004***	**-0.02 ± 0.007 ***

[a] = 0.08; [b] = 0.055; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

R^2 was 0.40 for ovulation rate model, 0.19 for pup recruitment model, 0.12 for body condition model, and 0.21 for cortisol level model.

198

199   Figure 2. Barplots (A and B) of annual ovulation rates (%) from adult female ringed seals

200   and annual percentage of pups in the harvest (Table 1). Linear regressions between seal

201   body condition and harvest year (C; slope = -0.01, t = -8.2, p <0.001), and cortisol level and

202   harvest year (D; slope = 0.02, t = 8.0, p < 0.001).

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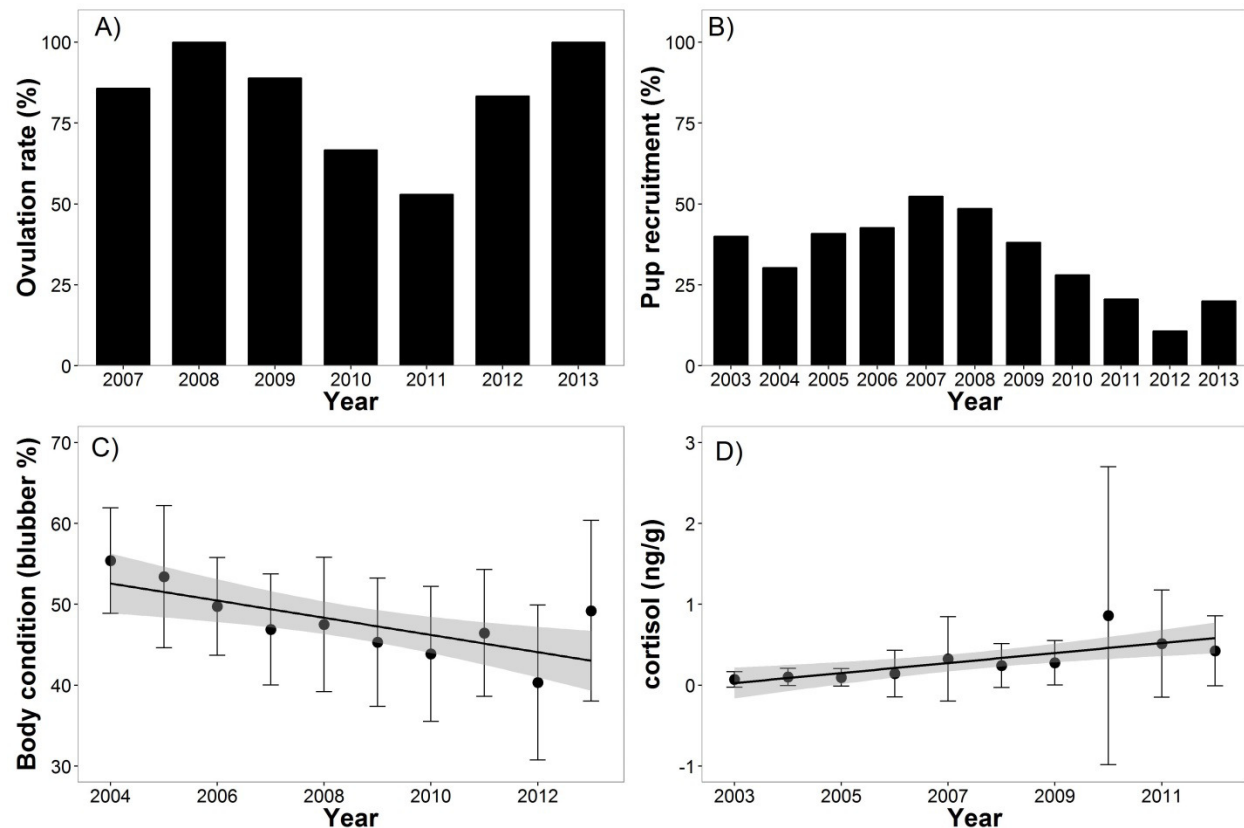
205   Figure 3. Linear regressions between ringed seal body condition and ice-free duration (A;

206   slope = -0.0004, t = -2.0, p < 0.05), body condition and El-Nino Southern Oscillation (ENSO)

207   index (B; slope = -0.009, t = -2.32, p = 0.02), body condition and North Atlantic Oscillation

208   (NAO) index (C; slope = -0.009, t = 2.0 , p < 0.05), and cortisol and NAO index (D; slope = -

209   0.02, t = 2.6, p = 0.01).

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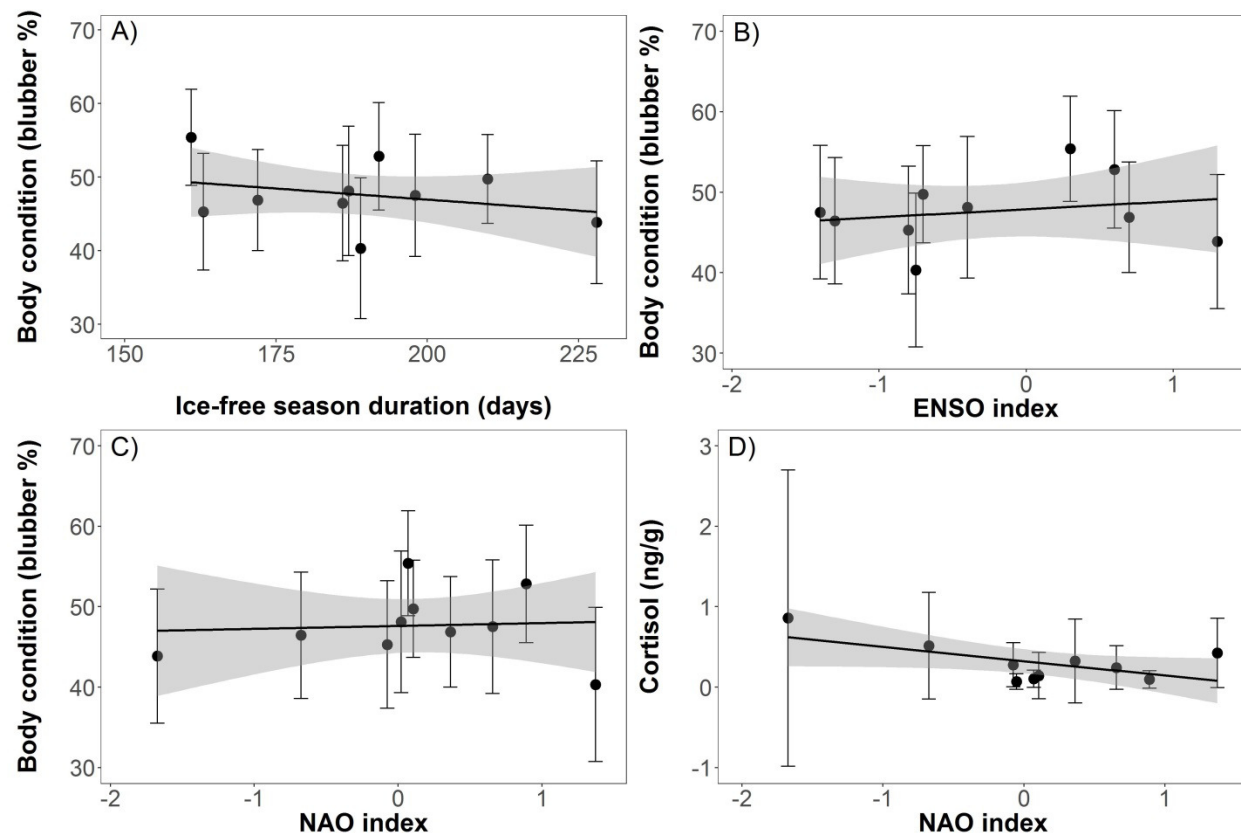
211   DISCUSSION

212   We predicted demographic change occurring at the southern limit of the ringed seal

213   distribution with both gradual changes in environmental variables and episodic events

214   associated with extreme lows in sea ice concentration. Our results suggest both patterns

215   have occurred in southern Hudson Bay over the past decade. Previous research has

216   indicated that Hudson Bay ringed seals (Chambellant et al. 2012) and polar bears (Regehr

217   et al. 2007; Lunn et al. 2016; Obbard et al. 2016) have shown gradual reductions in body

218   condition and survival over the past decades which are concurrent with negative

219   consequences of continued environmental change (Holst et al. 1999; Ferguson et al. 2005).

220   We provide additional evidence for a continuation of these progressive patterns for ringed

221   seals with decreasing body condition and increasing stress over 2003-2013. However, no

222   research results have suggested short-temporal pulses in condition and abundance (i.e.,

223   Young et al. 2015) for either seals or polar bears in the Hudson Bay ecosystem, although a

224   regime shift likely occurred in late 1990s (Gaston et al. 2012). Here, we document for the

225   first time, a relationship with ringed seal demographics and the 2010 climatic event that

226   resulted in a punctuated decrease in ovulation, reduced body condition, and increased

227   cortisol levels. Reduced seal pups in the following autumn harvest would likely follow with

228   a lag effect (Ferguson et al. 2005; Iacozza and Ferguson 2014). Ringed seals display a

229   remarkable ability to adjust their body condition and reproduction with different

230   environmental conditions as exemplified by the return to high ovulation levels and body

231   condition (% fat) in the years following the 2010 extreme event. However, age structure

232   would likely maintain a record of a cohort effect with a reduced number of seals moving

233   through the population over time.

234   Gradual reduction in body condition could be associated with the recent changes in

235   Hudson Bay prey resource abundance and availability. The prevalence of capelin (*Mallotus*

236   *villosus*) and sand lance (*Ammodytes spp.*) and decrease in Arctic cod (*Boreogadus saida*)

237   abundance in Hudson Bay since 2000 has caused dietary shifts from endemic Arctic cod to

238   sub-Arctic capelin and sand lance in Arctic marine megafauna including sea birds (Gaston

239   et al. 2003), beluga whales (*Delphinapterus leucus*; Kelley et al. 2010), and ringed seals

240   (Chambellant et al. 2012). In addition, the isotopic niche size of Hudson Bay ringed seals is

241   significantly larger than individuals from higher latitudes which principally consume Arctic

242   cod, indicating a more diverse and omnivorous diet (Young and Ferguson 2013; Yurkowski

243   et al. 2016a, b). Among ringed seal prey items, Arctic cod represent the highest energy

244   content compared to other fish and invertebrate species (Weslawski et al. 1994; Hedeholm

245   et al. 2011; Harwood et al. 2015). Thus, a recent change in Hudson Bay ringed seal diet due

246   to shifts in forage fish availability and abundance may have negatively impacted ringed seal

247   body condition.

248   Assessing the causes of an episodic event is more difficult to establish. The

249   extremely low extent and duration of the 2010 ice-covered period in Hudson Bay may have

250   adversely affected the abundance, availability and distribution of prey resources but it is

251   unlikely to have triggered a punctuated decrease in their physiological and energetic

252   demands. We summarized anecdotal evidence for an episodic event affecting the

253   abundance and body condition of ringed seals in Hudson Bay related in 2010-11 (see

254   supplementary material). Anecdotal observations in 2010 are suggestive of a hitherto

255   never before seen event causing impaired biological responses in ringed seal behaviour

256   including unusual approachability, lethargy, and increased tendency for hauling out on

257   land, possibly due to associated respiratory problems that were first seen during that

258   autumn season. Polar bears are thought to have benefited from this behavior since affected

259   seals were easily captured but no estimate of predation over and above normal could be

260   calculated. Evidence for a biological response to an episodic environmental event comes

261   from the low ringed seal density observed between spring 2010 and 2013 surveys and the

262   unusual environmental patterns that suggest a possible shift in seal condition after 2010.

263   Evidence for a dramatic decline in ringed seal abundance associated with the 2010

264   climatic event in Hudson Bay is both anecdotal (Supplementary Table) and circumstantial

265   (aerial survey abundance estimates; Young et al. 2015). The mechanism of such a decline is

266   not well understood but we postulate that it may be linked to the inability of the seals to

267   properly moult in spring due to a lack of a resting platform with the early loss of sea ice

268   which sets up a physiological predisposition for disease. In addition, hyperthermia in

269   autumn when seals are at their maximum blubber fatness (Young and Ferguson 2013) may

270   be a potential mechanism for the observations of lethargy and use of tidal flats resulting in

271   greater polar bear predation (Supplementary Table). The evidence for a decline in Hudson

272   Bay ringed seal body condition from 2003 to 2013 has statistical support and continues a

273   pattern previously reported (Stirling 2005). Periods of declines in ringed seal body

274   condition have been documented in the western Canadian Arctic (Harwood et al. 2012) and

275   Svalbard (Hamilton et al. 2015) as well as periods of improving body condition in western

276   Hudson Bay (Chambellant et al. 2012). In all cases, top down predation is not considered

277   the agent of change but rather bottom up changes in food supply.

278   Longer periods of open-water have been linked to access to more food for ringed

279   seals allowing for a longer period of fattening (Young and Ferguson 2013). Possible

280 explanations for this novel pattern of decreased ringed seal condition with a warming

281 ocean include (1) a shift in the types of forage fish available that result in lower lipid intake

282 – a requirement for ringed seals with their large blubber biomass (Gaden et al. 2009;

283 McKinney et al. 2013; Yurkowski et al. 2016a, b); (2) greater competition from temperate

284 species making forays into the subarctic (Finley et al. 1990; Berg et al. 2010); (3) greater

285 predation effect from new predators moving into areas from which they were previously

286 excluded by sea ice forcing ringed seals to compromise foraging activities in favor of

287 predator avoidance (Laidre et al. 2008; Higdon and Ferguson 2009); and (4) new or

288 increased disease arising from physiological stress associated with warmer temperatures

289 (Pounds et al. 2006; Burek et al. 2008). For Hudson Bay we found ringed seal condition

290 problems linked to large scale climatic patterns that likely cycle over multiple years and

291 possibly explain the periods of good (Chambellant et al. 2012) and bad (this study) in

292 Hudson Bay. However, the mechanistic link between early spring breakup and late ice

293 formation and poor seal condition is not well understood possibly because it has been

294 rarely observed (Ferguson et al. 2005).

295 An Unusual Mortality Event was declared in 2011 by the US government due to a

296 'new' ulcerative-dermatitis-disease-syndrome of unknown etiology observed in Alaskan ice

297 seals and Pacific walrus (Atwood et al. 2015) that resulted in significant pathology of the

298 lung, liver, immune system, and skin of the seals (Barbosa et al. 2015; Bowen et al. 2015).

299 As observed in Hudson Bay, the affected ice seals displayed uncommon behaviours such as

300 unusual approachability, lethargy, and increased tendency for hauling out on land, as well

301 as respiratory problems. There was some mortality associated with the disease syndrome;

302   however reliable baseline abundance estimates were not available to assess its

303   significance.

304   Potential repercussions of a gradual sea ice decline and punctuated decreases in

305   some years include a continual reduction in ringed seal body condition and greater stress

306   leading to implications on their demographics. The years marked by extremes in climatic

307   indices (Fig. 1) are associated at higher latitudes with excessive sea ice extremes; whereas

308   our results at the southern range of ringed seals indicate a lack of sea ice may have

309   attributed to decreased body condition, increased stress, and low ovulation rates and pup

310   recruitment. Spring 2010 recorded an unusually early ice breakup that may have

311   predisposed seals to a delayed molt. In the fall of 2010, numerous (100's) moribund seals

312   were found in distress along the shore of western and eastern Hudson Bay suggesting that

313   both regions were affected.

314   Numerous examples of episodic events causing major ecological shifts include

315   regime shifts (Hughes et al. 2013), continental growth (Santosh 2013), drought (Ireland et

316   al. 2012), disease (Pickles et al. 2013), and range shifts due to climate (Baker et al. 2008;

317   Seppä et al. 2009; Chen et al. 2011). For ringed seals, the literature suggests periods of

318   ringed seal crashes in abundance associated with poor reproduction during significant

319   heavy ice years. Variation in ringed seal density associated with ENSO events include 1973

320   (Smith and Stirling 1978), 1992 (Ferguson et al. 2005), 1998 (Smith and Harwood 2001),

321   and in 2010 (Fig. 1). Evidence of high latitude regime shifts include 1977 and 1989 (Hare

322   and Mantua 2000), 1998-99 (Litzow 2006; Benson and Trites 2002). Also, the Greenland

323   Blocking Index for 2010 was the highest year in the annual, spring, winter and December

324   series, 1851-2015 (Hanna et al., 2016). Synchronous fluctuations of seabird species across

325   the entire Arctic and sub-Arctic regions were associated with changes in sea surface

326   temperatures that were linked to two climate shifts, in 1977 and again in 1989 (Irons et al.

327   2008), and 1998 (Flint 2013), including Hudson Bay in 1998 (Gaston et al. 2003). Major

328   atmospheric patterns suggest that we can expect episodic events occurring once every 10-

329   15 years and that they are largely unpredictable in timing but have major consequences on

330   ecosystem structure and function (Ottersen et al. 2004).

331   CONCLUSIONS

332   Considerable uncertainties exist with deciphering past patterns to determine possible

333   cause and effect relationships among environmental variation, body condition, and their

334   demographic responses. However, mounting evidence indicates endemic Arctic species,

335   such as ringed seals, are under immense pressure from climate change and complex spatio-

336   temporal shifts in ecology have subsequently resulted in decreased abundance as a

337   harbinger of range shift. Managers need to be wary of climate change culminating in both a

338   gradual decline in condition and unpredictable episodic events that when combined can

339   have major abundance and distribution consequences.

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344

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560

561 Supplementary Table1. 1971-2014 NAO, AO, ENSO, and eastern Hudson Bay breakup and
562 freeze-up from 1979 to 2014.

Year	AO	ENSO	NAO	Breakup	Freeze-up
1971	-0.49459	-1.3	-0.69667		
1972	0.264983	-0.7	0.396667		
1973	1.08517	1.7	0.36		
1974	-0.1462	-1.7	0.506667		
1975	0.781803	-0.5	0.486667		
1976	0.993478	-1.5	0.226667		
1977	-2.6173	0.7	-1.04333		
1978	-1.20007	0.7	-0.84667		
1979	-1.30322	0	-1.20667	166	340
1980	-0.56821	0.6	0.1	163	335
1981	-0.16841	-0.2	0.69	191	337
1982	-0.37507	0	0.08	164	334
1983	0.17346	2.1	0.946667	171	339
1984	0.262857	-0.5	0.89	156	328
1985	-1.2665	-0.9	-0.7	151	333
1986	-1.80645	-0.4	0.11	185	326
1987	-0.85368	1.1	-0.29667	180	345
1988	-0.44515	0.8	0.7	154	342
1989	2.688033	-1.6	1.26	180	334
1990	1.252883	0.1	0.433333	180	335
1991	0.374647	0.4	0.706667	174	336
1992	1.094977	1.6	0.466667	181	329

1993	1.768833	0.2	0.856667	169	328
1994	-0.41784	0.1	1.02	180	348
1995	0.722987	0.9	1.363333	173	334
1996	-1.05476	-0.9	-0.62	184	357
1997	-0.09629	-0.5	-0.06667	164	330
1998	-0.7783	2.1	-0.22667	159	352
1999	0.648627	-1.4	0.643333	146	350
2000	1.1297	-1.6	1.303333	157	351
2001	-1.31188	-0.7	0.04	150	361
2002	0.454133	-0.2	0.236667	171	338
2003	-0.64532	0.9	-0.05333	185	362
2004	-0.98303	0.3	0.07	177	338
2005	0.105223	0.6	0.89	158	350
2006	-0.81005	-0.7	0.104837	145	355
2007	1.002867	0.7	0.36307	173	345
2008	0.859387	-1.4	0.6561	150	348
2009	0.25841	-0.8	-0.07584	184	347
2010	-3.42177	1.3	-1.67293	141	369
2011	-0.9129	-1.3	-0.67427	163	349
2012	0.654935	-0.7	1.371767	159	348
2013	-1.12184	-0.4	0.02096	159	346
2014	0.183305	-0.5	0.85704	168	341

563

564   Supplementary Table2. Chronology of unusual ringed seal and polar bear observations

565   gathered from Hudson Bay communities related to a warming event in 2010.

Date	Comment	Reporter
4 Nov. 2010	I've only seen about 3 kills in the 11 years I've worked for you guys and now 7 in a month?	Marc Hebert, Manitoba Conservation Officer
14 Nov. 2010	He has also seen quite a few seals and seal kills by Polar Bears. He also flew over Button Bay and saw a number of seal kills that hadn't been consumed.	Mike Macri (Sea North Tours, Churchill)
16 Nov. 2010	He states that seals are venturing inland than normal. Bears are eating seals. The only physical problems or abnormalities he notes he has seen is one seal that appeared to be bleeding from the anus. Sick seals -- showing evidence of hair loss.	Amanda Currie (DFO) conversation with Donnie (Great White Bear tours).
16 Nov. 2010	Recently found a seal that was still alive but crawling over land near the Rx road just out of the Town of Churchill.	LeeAnn Fishback (CNSC) with Manitoba Conservation
17 Nov. 2010	First Vince had heard of dead seals. But noted Darryl Hedman flew coast and saw over 300 bears - saw 18 dead seals that had been killed so he says by bears - when I	Ole Nielson (DFO Science) with Vince Crichton (Manitoba

asked him how the bears were catching seals he said they are likely getting caught on the flats when tide goes out and bears just taking advantage of easy meal - maybe something wrong with seals that they are getting caught like this.

Conservation Manager, Game Fur & Problem Wildlife)

18 Nov. 2010

They both confirm they're have been no reports of any killer whale sightings in the area, as its too late in the seasons for Killer Whales. Also the local polar bears are also very fat, and several appear to be 'stock piling' the seals they catch (i.e. some people have witness and photographed the bears stock piling or buried seals inland instead of eating them). Mike was on a flight a week ago and saw a fat polar bear kill a seal, walk away and kill another seal on the shore, drag it back to the first, and then walk away without eating either. And another sow with cubs had a dead seal and was not eating it. Another seal was seen moving along RX road about 1-2 km from shore. Received two pictures of this from Mike Macri.

Tara Bortoluzzi (DFO Science) spoke with Mike Macri and Bob Windsor (Conservation Officer in Churchill)

24 Nov. 2010

I met two hunters from Chesterfield Inlet and Whale Cove in the Iqaluit airport on Monday that were also very concerned with the 'behavior' of ringed seals near their

Ole Nielsen (DFO)

communities this fall. I'm following up with them and several other HTOs. They reported that they are catching more adult seals this year which are really large, and very few pups. The seals are also very easy to catch, in many cases they said 'too easy'. One hunter caught 30 seals in one day trip. The seals are also coming inland and hanging around the shoreline for extended periods of time. Of course, it's great for hunting, but they were really concerned as this is very unusual.

26 Nov. 2010	Some of the Hunters and Trappers Organizations in the Kivalliq region have recently reported concerns with 'odd behaviour' of ringed seals near the communities (i.e. seals coming close to shore and hanging around, and hauling out on shore), as well as some seals that appears to be sick (i.e. molting and loss of hair, seal pocks, low fat content, etc.).	Tara Bortoluzzi (DFO) summarizing response from Kivalliq Region communities
26 Nov. 2010	She has heard the same concerns from hunters: "After discussion with my board of directors, they have reported some hunters catching seals on shore, and far away from shore with loss of hair (like bald patches) but nobody took pictures and the seals were used as dog food."	Leah Muckpah (Arviat HTO Manager)

27 Nov. 2010	He hasn't seen any more seals on shore, neither have the helicopters or tundra buggy camps. Also notes another odd thing, the zodiacs, for the first time ever, are covered with scratches from bearded seals who were hauling up into them in September.	email from Mike Macri (Sea North Tours)
17 Dec. 2010	"A couple weeks ago while he was out of town, Lucasssie Takatak, found 6 dead seals on the beach, their heads seem to be craving for air like their heads up back."	Lucassie Arragutainaq (Secretary Manager Sanikiluaq HTO)
06 Jan. 2011	They observed a very few number of seals were shedding and that even a few number of them were sinking after being shot. The seal harvest in Arviat is usually done when the first ice forms in the salt water, usually late October to Late November. During that time, it is unheard of that seals would be shedding fur and that they would sink after being shot.	reports from local hunters of Arviat
26 Jan. 2011	Ringed seals usually molt in the spring but locals noted seals molting in the fall. The local Conservation Officer sent seal parts to DFO showing the unusual molt. During fall large numbers (100s) of seals were observed along shorelines. Other communities including Repulse Bay also noted the same unusual conditions. Coral Harbour	Ferguson phone conversation with Noah Nakoolak of Coral Harbour HTO

seldom sees seals near town but this past fall large numbers were in the Harbour and some went on land in the harbour (very unusual).

His own personal experience - he was traveling along shoreline in August and found a seal on the beach. The ringed seal kept traveling up the shore – unusual behaviour. Three weeks later he was in a different area and saw a harp seal on land – about ¼ mile inland. It was a late freeze up this autumn and a very warm fall. The ice formed along the shoreline twice in mid-November but drifted off with winds both times before it finally formed fast in December. In December rain fell.

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