Working Paper 2

Development of ecosystem indicators for Northwest Atlantic Cod

Working paper for the 2023 Research Track Stock Assessment

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Indicator identification

Ecosystem influences on Atlantic cod were identified in the Ecosystem Profile (ToR 1 Chapter). The Term of Reference 1 (TOR1) working group discussed these ecosystem linkages and identified several potential indicators that could be developed to monitor relevant ecosystem information.

Indicator selection

The TOR1 working group discussed the indicators on the basis of theoretical merit (the ability of the indicator to inform knowledge of a key process) and operational merit (the ability of the indicator to be created and analyzed in a timely manner). These discussions helped the TOR1 working group reduce the number of indicators under consideration by eliminating redundant indicators (indicators that addressed the same linkage or process) as well as indicators that would not be feasible to create and/or analyze under the constraints of the working group's timeline. Additionally, written comments on this narrowed down list were collected from the TOR1 working group using a Google Forms survey. The TOR1 working group presented this reduced group of indicators to the full working group and discussed the reasoning behind each indicator. Following this presentation, the full working group and interested collaborators were sent a Google Forms survey to document their written comments on the proposed indicators. Based on the survey feedback, six final indicator groups were identified. Each of these indicator groups consists of data from a single source, but in several cases, the data was aggregated over multiple geographic and monthly and/or seasonal periods, such that the total number of indicator time series presented is greater than the six nominal indicators.

Selected indicators

1. Sea surface temperature (proxy for spawning, egg development, recruitment)
    a. **Linkage to cod:** Cod spawning and early life history are associated with optimal temperatures. Warmer temperatures will likely decrease cod spawning and egg survival (Klein et al. 2017) and therefore would ultimately decrease recruitment.
    b. **Relevance to management:** Decreased recruitment potential associated with changes to sea surface temperature could be incorporated into the assessment model and would improve the determination of stock status and projections.
    c. **Summary of comments from the working group:** Commenters agreed that temperature was an important environmental influence on cod spawning and early life history. Data quality and availability were also viewed positively. Some

comments raised concerns that it may be difficult to identify the proper spawning timing and locations over which to assess temperature. Additionally, commenters identified potential issues with assessing the relationship between temperature and a modeled recruitment index. Some commenters suggested that bottom temperature could also inform cod spawning and early life history.

2. Bottom temperature (proxy for growth)
    a. **Linkage to cod:** Cod growth peaks between temperatures of 10-15C (Drinkwater 2005). Temperatures within this range would optimize cod growth, while temperatures outside this range would be detrimental for cod growth.
    b. **Relevance to management:** Changes with growth associated with changes to bottom temperature could be used to inform expectations for weights at age.
    c. **Summary of comments from the working group:** Commenters noted that temperature may have a nonlinear effect on cod, as there would be an optimal temperature and performance would be reduced at higher and lower temperatures. It was also suggested that temperature could have an indirect linkage through affecting cod prey. Commenters agreed that bottom temperature was a useful indicator.
3. Gulf Stream Index
    a. **Linkage to cod:** The north wall of the Gulf Stream impacts the gyres on Georges Bank and the retention of larvae; therefore the position of the north wall may affect cod recruitment success. Larval retention is expected to be higher in years with a more northward north wall of the Gulf Stream (CAUSES 2018).
    b. **Relevance to management:** Changes to recruitment potential associated with the position of the Gulf Stream could be incorporated into the assessment model and would improve the determination of stock status and projections.
    c. **Summary of comments from the working group:** Commenters agreed that the Gulf Stream Index could affect cod, especially the more southern stocks in recent years. It was suggested that there could be a lag between GSI and recruitment. Commenters supported testing this indicator with the Georges Bank cod stock.
4. Marine heatwaves
    a. **Linkage to cod:** Temperatures above optimal could increase mortality of cod.
    b. **Relevance to management:** Changes to natural mortality associated with more frequent marine heatwave events could be incorporated into the assessment model and would improve the determination of stock status and projections.
    c. **Summary of comments from the working group:** Commenters supported using this indicator. It was suggested that heatwaves may affect recruitment as well as natural mortality.
5. Zooplankton
    a. **Linkage to cod:** Zooplankton are an important prey item for larval and juvenile cod. Higher zooplankton density would improve the fitness and survival of the early life stages of cod.
    b. **Relevance to management:** Changes to recruitment potential associated with the density of important zooplankton prey could be incorporated into the assessment model and would improve the determination of stock status,

however, it would not be possible to incorporate zooplankton information into projections because zooplankton density cannot be accurately forecasted.

   c. **Summary of comments from the working group:** Commenters suggested that the zooplankton indicator should be developed to cover the most important cod prey with appropriate spatiotemporal coverage. Commenters agreed that the ecological linkage to cod was clear.

6. Cod condition
   a. **Linkage to cod:** Poor condition may reflect higher susceptibility to natural mortality.
   b. **Relevance to management:** Changes to natural mortality associated with cod condition could be incorporated into the assessment model and would improve the determination of stock status and projections.
   c. **Summary of comments from the working group:** Commenters agreed that cod condition is important, but questioned how it could be quantitatively linked to natural mortality. Some concerns about the data were raised, including possible spurious effects of reproductive phenology, whether the data would be able to be parsed along stock boundaries, and whether spring data would be available.

Indicators proposed to the full working group, not selected

1. Herring abundance
   a. **Linkage to cod:** Herring are a predator of larval cod. Better understanding of predation mortality on early life history stages of cod could improve recruitment estimates.
   b. **Relevance to management:** Changes to recruitment associated with herring predation on larval cod could be incorporated into the assessment model and would improve the determination of stock status, however, it would be difficult to incorporate herring information into projections.
   c. **Summary of comments from the working group:** While commenters agreed that herring is an important predator of larval cod, there were questions about whether the spatial overlap between larval cod and herring could adequately be determined with the resources available.
2. Primary production
   a. **Linkage to cod:** The timing and magnitude of the phytoplankton bloom could affect cod production and recruitment (CAUSES 2018).
   b. **Relevance to management:** Changes to recruitment associated with primary production could be incorporated into the assessment model and would improve the determination of stock status, however, it would not be possible to incorporate primary production into projections because primary production cannot be accurately forecasted.
   c. **Summary of comments from the working group:** Although commenters agreed that primary production would have ecosystem impacts that would affect cod, many comments highlighted the complexities of selecting the spatiotemporal

bounds for this indicator and connecting indicator measurements to cod outcomes. Zooplankton were viewed as a more direct indicator.

3. Downwelling winds
    a. **Linkage to cod:** Downwelling winds have been correlated with higher cod recruitment (Siceloff and Howell 2013; Hare et al. 2015).
    b. **Relevance to management:** Changes to recruitment associated with downwelling winds could be incorporated into the assessment model and would improve the determination of stock status, however, it would not be possible to incorporate downwelling winds into projections due to uncertainty around future values.
    c. **Summary of comments from the working group:** Although commenters agreed with the connection to cod, commenters suggested that this indicator could be redundant with the Gulf Stream Index. Additionally, they suggested that the calculations could be challenging and effort would be better spent elsewhere.
4. Prey condition
    a. **Linkage to cod:** The energy content of prey may be changing due to increasing temperature, which could affect the status of cod (CAUSES 2018).
    b. **Relevance to management:** Changes to size-at-age associated with prey condition could be incorporated into the assessment model and would improve the determination of stock status, however, it would be difficult to incorporate this information into projections.
    c. **Summary of comments from the working group:** Commenters highlighted the difficulties of determining the appropriate prey species, locations, and times of year to assess. It was suggested that prey abundance could be a more manageable indicator to pursue.
5. Surface temperature (proxy for prey availability)
    a. **Linkage to cod:** Cod prey have preferred temperatures; therefore, sea surface temperature could be a proxy for prey availability.
    b. **Relevance to management:** Changes to size-at-age or recruitment associated with prey availability could be incorporated into the assessment model and would improve the determination of stock status and projections.
    c. **Summary of comments from the working group:** Commenters suggested that this indicator could be too indirect of a linkage to cod and that direct prey information would be more appropriate.
6. Temperature proxy for migrations
    a. **Linkage to cod:** Increases in temperature may result in earlier spring migrations and delayed fall returns (Drinkwater 2005).
    b. **Relevance to management:** Changes to cod distribution associated with changes in migration timing could be incorporated into the calculation of survey indices.
    c. **Summary of comments from the working group:** Commenters agreed that temperature effects on cod migration are important, but questioned whether there is enough data to determine migration dates and suggested that other temperature indicators would be more important to pursue.

Indicators discussed among the TOR1 working group, not selected

1. Size at age 1
    a. **Linkage to cod:** Size at age 1 was proposed as a proxy for cod growth.
    b. **Relevance to management:** Changes in size at age 1 could inform growth and natural mortality estimates.
    c. **Summary of comments from the working group:** The TOR1 working group felt that size at age 1 is already sufficiently incorporated into the assessment modeling process.
2. Age at maturity
    a. **Linkage to cod:** Warmer bottom temperatures may reduce age at maturity (Drinkwater 2005), and younger age at maturity may increase natural mortality (Swain 2010).
    b. **Relevance to management:** Changes in maturity would be important to incorporate into the assessment model. Changes to natural mortality associated with age at maturity could be incorporated into the assessment model and would improve the determination of stock status and projections.
    c. **Summary of comments from the working group:** The TOR1 working group felt that age at maturity is already sufficiently incorporated into the assessment modeling process.
3. Size at maturity
    a. **Linkage to cod:** Size at maturity was proposed as a proxy for growth and natural mortality.
    b. **Relevance to management:** Changes in maturity would be important to incorporate into the assessment model. Changes to natural mortality associated with size at maturity could be incorporated into the assessment model and would improve the determination of stock status and projections.
    c. **Summary of comments from the working group:** The TOR1 working group felt that size at maturity is already sufficiently incorporated into the assessment modeling process.
4. Age 0 index
    a. **Linkage to cod:** The age 0 index was proposed as a proxy for natural mortality.
    b. **Relevance to management:** Changes to natural mortality could be incorporated into the assessment model and would improve the determination of stock status and projections.
    c. **Summary of comments from the working group:** The TOR1 working group felt that other indicators of natural mortality would be more appropriate.
5. Bottom temperature (proxy for maturity)
    a. **Linkage to cod:** Warmer bottom temperatures may reduce age at maturity (Drinkwater 2005).
    b. **Relevance to management:** Changes in maturity would be important to incorporate into the assessment model.

c. **Summary of comments from the working group:** The TOR1 working group felt that age at maturity is already sufficiently incorporated into the assessment modeling process.

Data

Geography

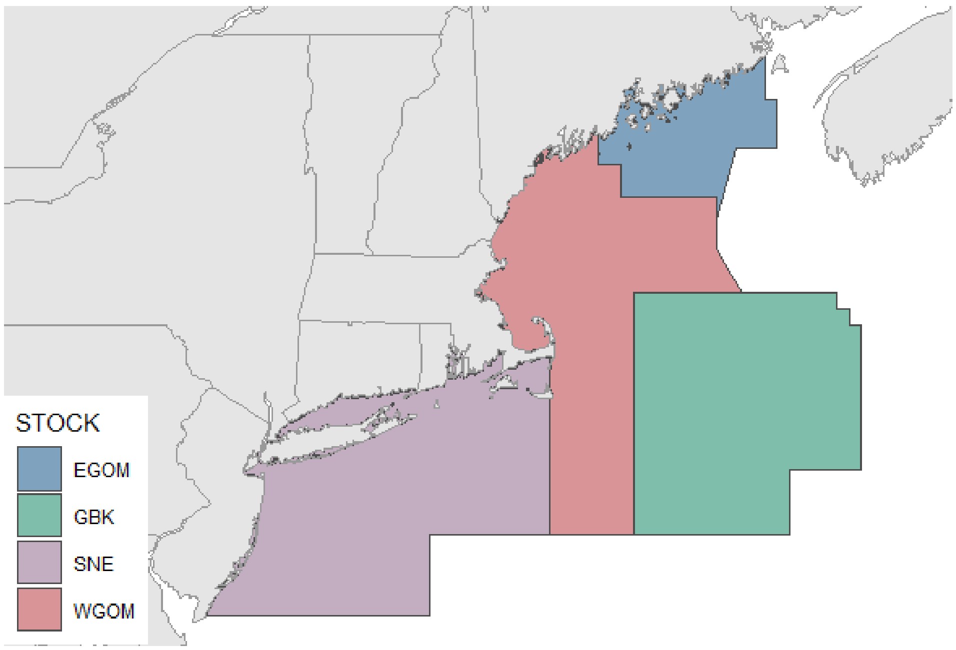

Figure 1. Geographic boundaries of the four Northwest Atlantic cod management units.

Northwest Atlantic cod stock structure was reevaluated in 2022. Five biological stocks were identified, which were condensed into four assessment units for management (Fig 1). Spatial indicator data was aggregated and analyzed according to the four management units.

Indicator data

Optimal Interpolation Sea Surface Temperature (OISST) data were queried from the Physical Sciences Laboratory. Data were masked to cod stock regions and a spatial average was calculated for each month in each year. Optimal area for spawning was defined as the area with temperatures under 11°C.

Gridded monthly mean bottom temperature data were provided by Hubert du Pontavice (du Pontavice et al. 2023). Data were masked to each of the four stock regions and the average regional bottom temperature was calculated for each month in each year.

Monthly GSI data were obtained from the {ecodata} R package. The annual GSI was calculated as the annual mean of the monthly data.

Annual cumulative heatwaves and maximum heatwave intensity by stock region were provided by Kim Bastille. Heatwaves were calculated according to the definition in Hobday et al. (2016). Heatwaves are defined as temperatures that exceed the 90th percentile for at least 5 consecutive days for surface heatwaves and at least 30 consecutive days for bottom heatwaves.

Relative cod condition data were provided by Charles Perretti. Relative condition was calculated as the difference between the actual weight of a given individual and the predicted weight, given the individual's length. Values under one represent a fish that is "skinnier" than expected, while values over one represent a fish that is "fatter" than expected.

Zooplankton data were provided by Ryan Morse. Zooplankton anomalies, aggregated to cod region and season, were calculated by subtracting the measured value at the given day of year from the expected value at the given day of year based on interpolated splines from all samples in the region (1977-2021), similar to Kane et al. 2009.

Analytical methods

Linear regressions between year and indicator values were assessed in order to determine trends over time.

Cumulative sum analysis (Regier et al. 2019) was used to identify breakpoints in the indicator time series. Briefly, indicators were standardized and the cumulative sum was calculated for each year. Periods when the cumulative sum is decreasing indicate periods when the indicator values were consistently below the mean, while periods when the cumulative sum increases indicate that indicator values were consistently above the mean; inflection points indicate a breakpoint.

Results

+ = Positive Trend

- = Negative Trend

= No Trend

Figure 2. Color legend for time trend tables.

Sea surface temperature

Sea surface temperature had an increasing trend over time in nearly all months in nearly all regions. Correspondingly, the amount of area within the optimal cod temperature range had a decreasing trend in five or more months in all regions.

Sea surface temperatures were cooler than the time series average from 1982 until approximately 2000. Between 2000 and 2010, temperatures were either cooler than average or near average. Since 2010, sea surface temperatures have been warmer than average.

The area with optimal temperature showed an inverse pattern to surface temperatures. Areas were larger than the time series average from 1982 until approximately 2000. Between 2000 and 2010, areas were either larger than average or near average. Since 2010, areas with optimal temperatures have been smaller than average.

Month												Indicator	Stock Area
J	F	M	A	M	J	J	A	S	O	N	D		
+	+	+	+	+	+	+	+	+	+	+	+	SST	EGOM
					-	-		-	-	-		Optimal area	EGOM
+	+	+			+	+	+	+	+	+	+	SST	GBK
-	-	-			-		x	x		-	-	Optimal area	GBK
+				+	+	+	+	+	+	+	+	SST	SNE
-	-	-	-			x	x	x		-		Optimal area	SNE
+	+	+	+	+	+	+	+	+	+	+	+	SST	WGOM
-	-	-		-	-	-	x		-	-	-	Optimal area	WGOM

Table 1. Time trends in sea surface temperature and optimal area in the four cod regions. Optimal area for spawning was defined as the area with temperatures under 11°C.

x = No optimal area over the entire time series.

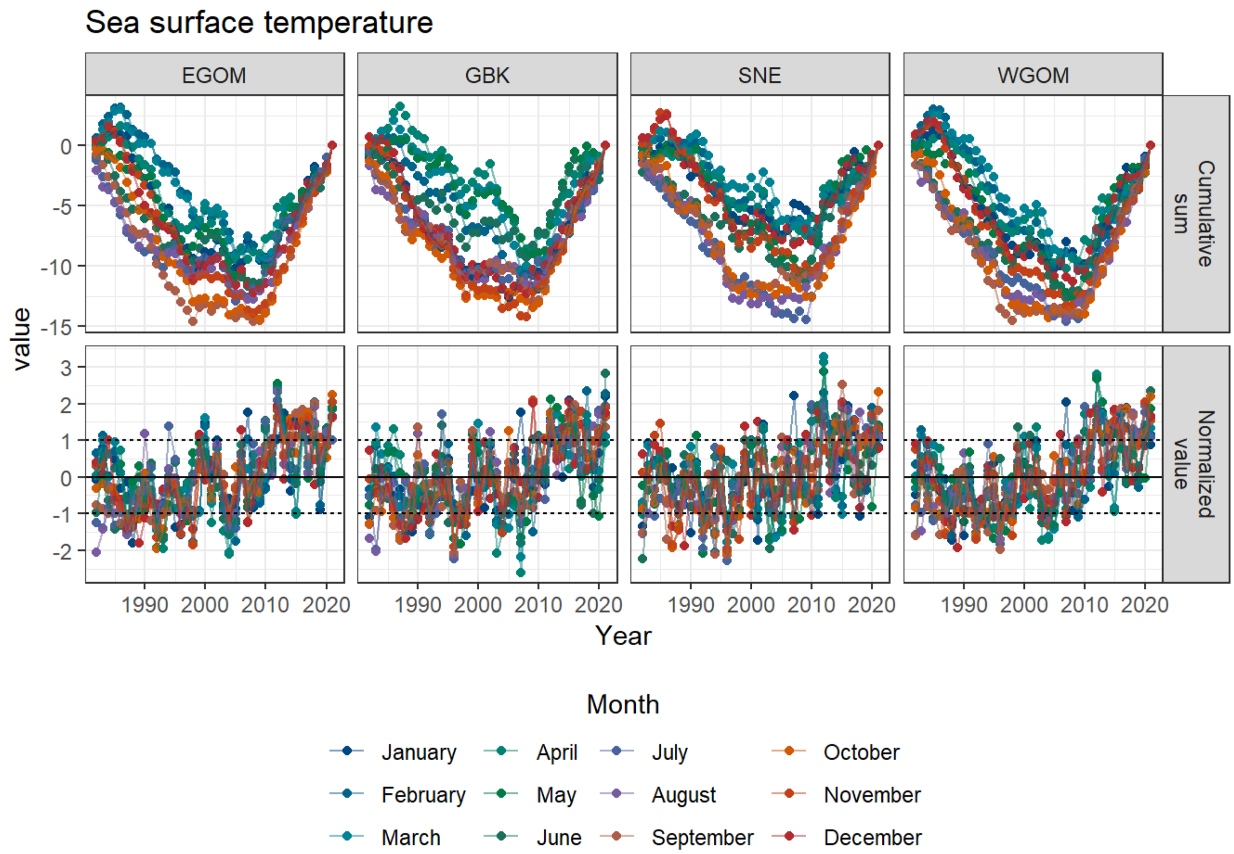

Figure 3. Normalized sea surface temperature and cumulative sum over time.

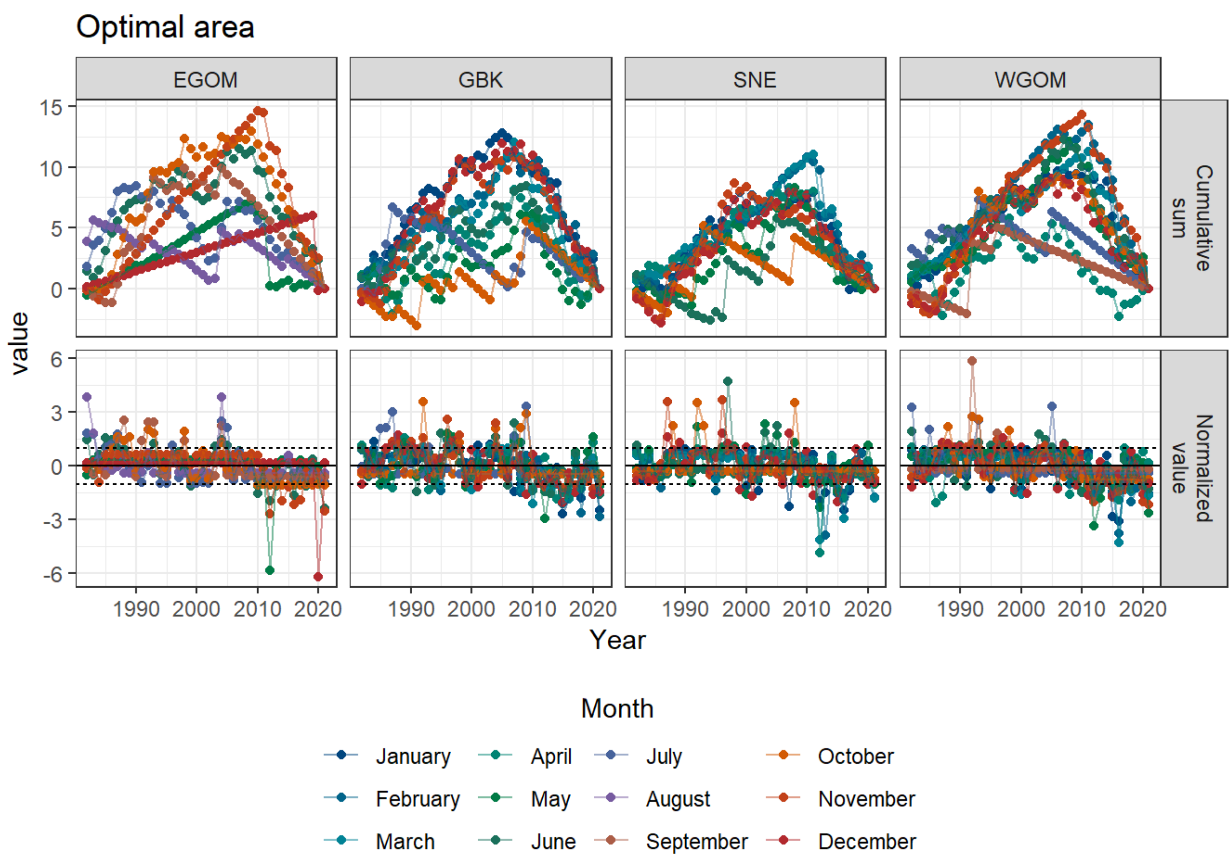

Figure 4. Normalized optimal area (area under 11C) and cumulative sum over time.

Bottom temperature

Bottom temperature is increasing in all months of the year in all regions. Bottom temperatures were cooler than the time series average from 1963 until approximately 1980. Between 1980 and 2010, temperatures were near average. Since 2010, bottom temperatures have been warmer than average.

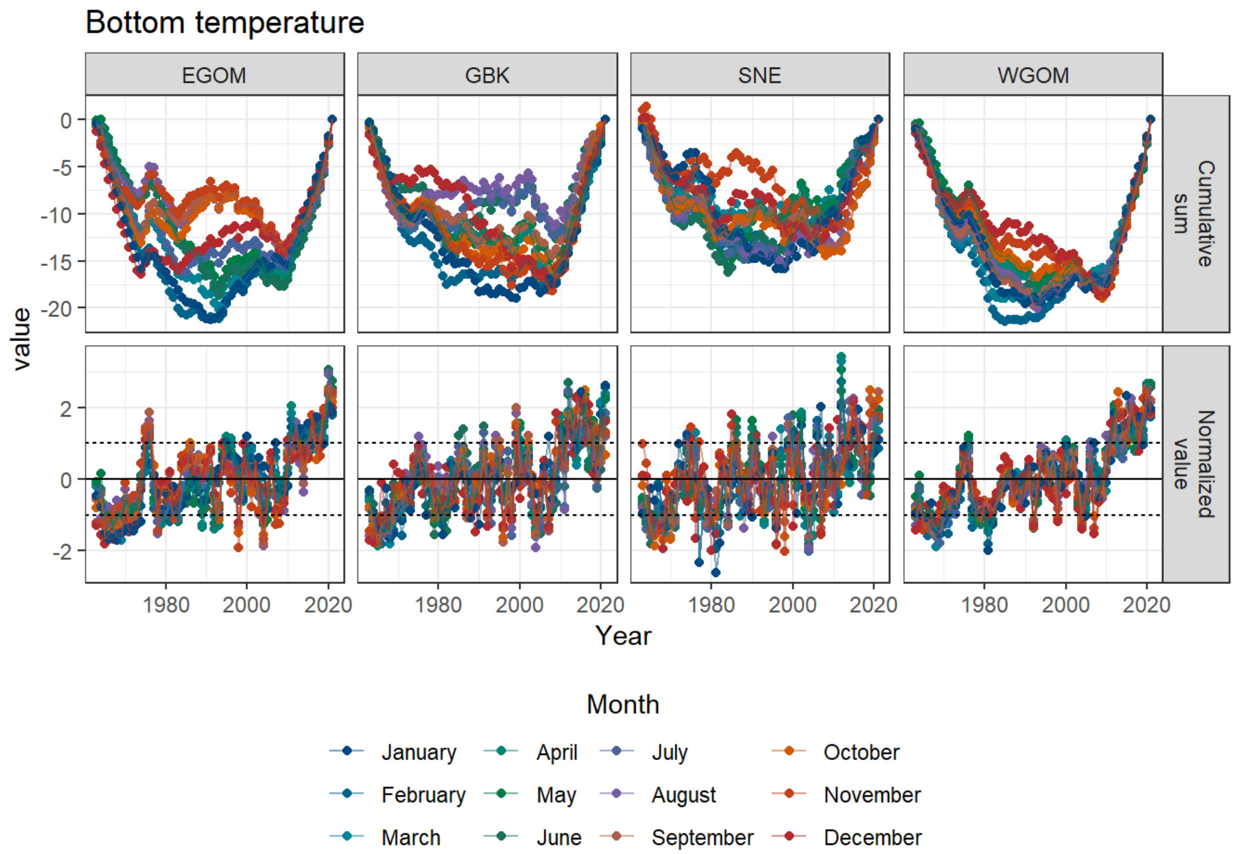

Figure 5. Normalized sea surface temperature and cumulative sum over time.

Gulf Stream Index

The Gulf Stream Index is increasing annually in all months and all regions. The Gulf Stream Index was more south than the time series average from 1954 until approximately 1970. Between 1970 and 1990, the Gulf Stream Index was near average. Since approximately 1990, the Gulf Stream Index has been more north than average.

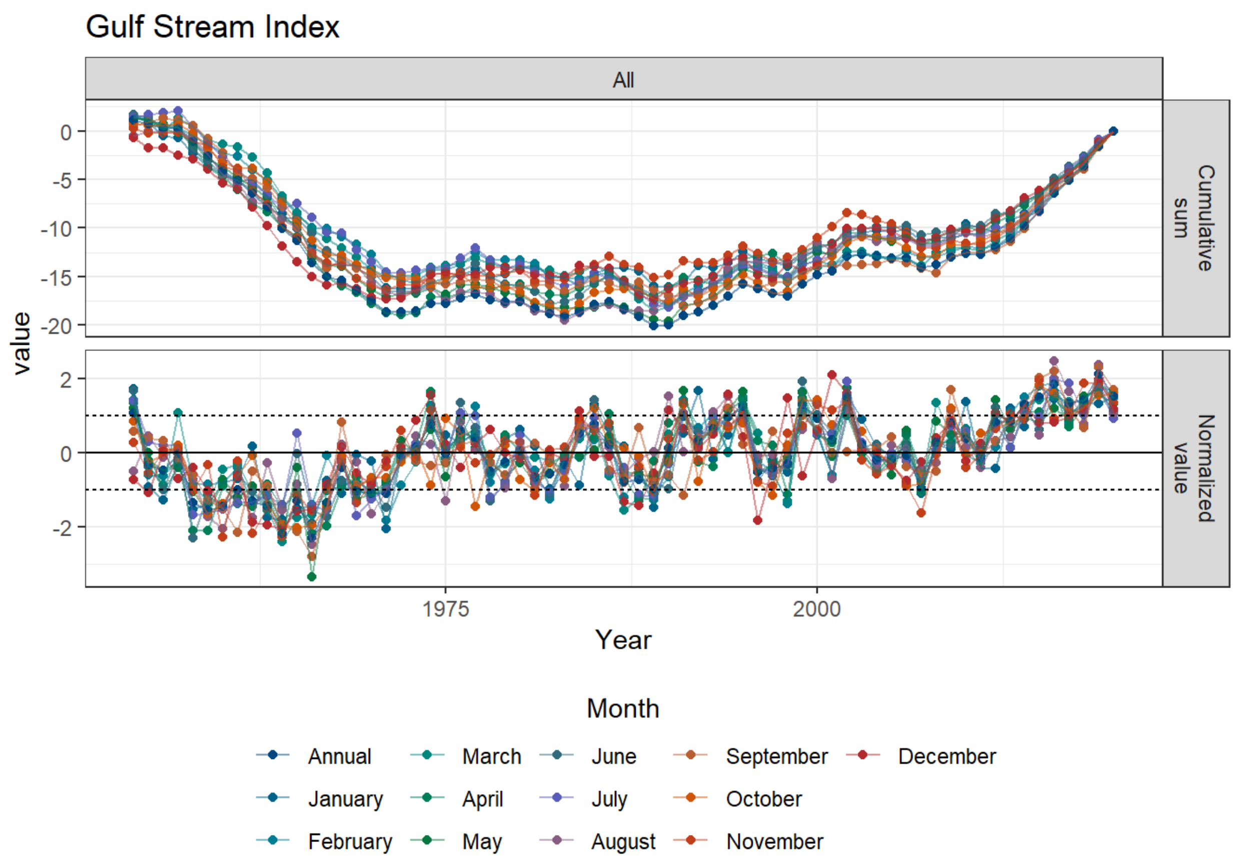

Figure 6. Normalized Gulf Stream Index and cumulative sum over time.

Marine heatwaves

Marine heatwave cumulative intensity and maximum intensity have a positive trend over time in all regions. Maine heatwave cumulative and maximum intensities were below average until approximately 2010; heatwave intensities have been above average since 2010.

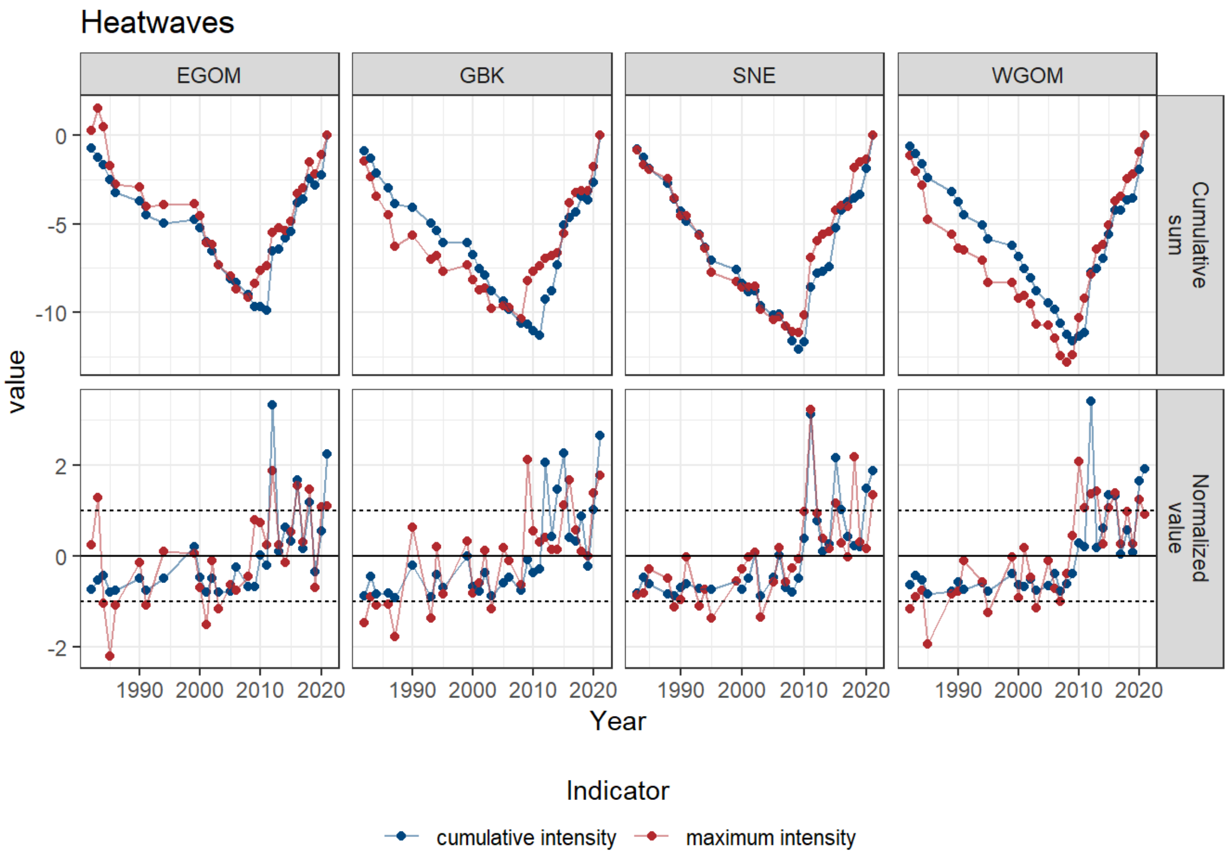

Figure 7. Normalized heatwave indices and cumulative sum over time.

Cod condition

Most condition data did not show a trend over time. Condition was fairly stable in the Eastern Gulf of Maine and Southern New England. Georges Bank and the Western Gulf of Maine both showed some fluctuations over time. In these regions, conditions were near or above average until approximately 2000, after which conditions were below average until approximately 2012. Conditions have been near average since 2012.

Season		Indicator	Stock Area
Spring	Fall		
		Condition (NMFS)	EGOM
		Condition (NMFS)	GBK
–		Condition (NMFS)	SNE

		Condition (NMFS)	WGOM
		Condition (MADMF)	WGOM

Table 2. Time trends in cod condition in the four cod regions.

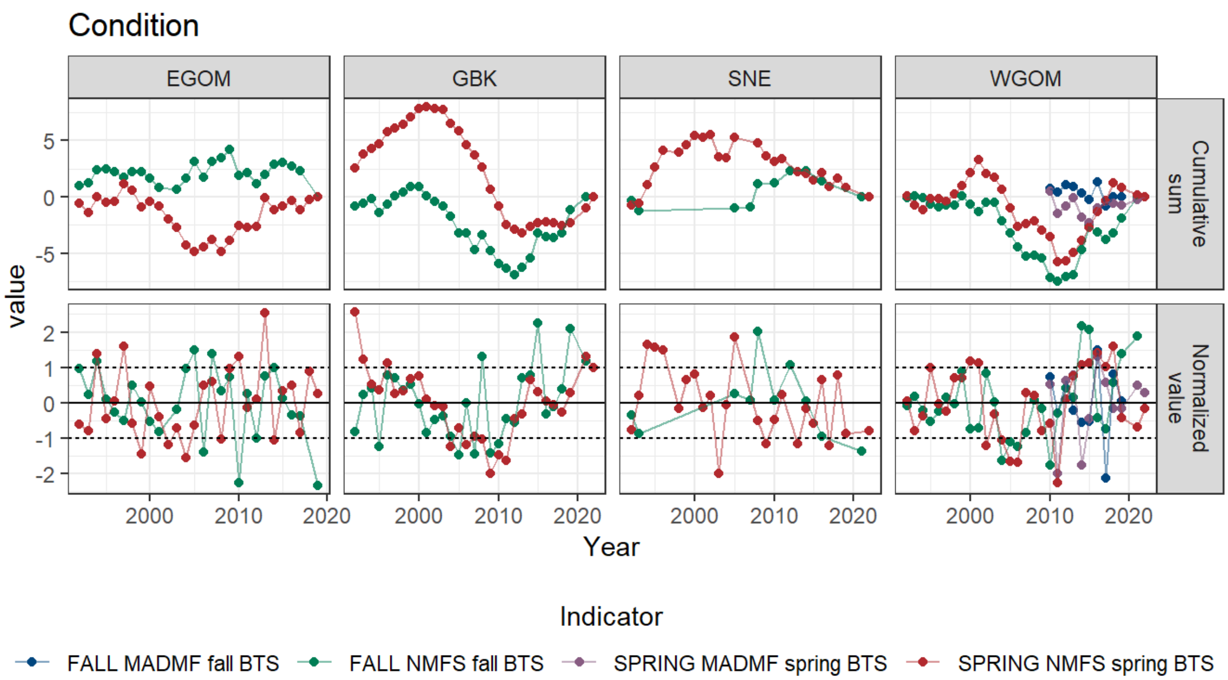

Figure 8. Normalized cod condition and cumulative sum over time.

Zooplankton

Species patterns

Zooplankton trends were mixed (Figs. 9-12). *Temora longicornis* increased in every region in the spring, and also increased in several regions in the winter and summer (Figs. 9-12). Many regions also showed decreases in zooplankton in the fall.

Centropages typicus showed a similar cyclic pattern in all regions. Values were near average from 1978 to approximately 1990, at which point values were above average until approximately 2000. Values were below average from approximately 2000 to 2010, and values have been near average since 2010.

Pseudocalanus sp. also showed a similar cyclic pattern in all regions. Values were above average from 1978 to approximately 2000, and values have been below average since 2000. Spring showed a slightly different pattern than the other seasons, with values being below average until 1990, above average from 1990-2000, below average from 2000-2010, and above average until present.

Calanus finmarchicus patterns differed by region. There was little variation in the Eastern Gulf of Maine; values were slightly below average until approximately 2000, and near or above average since then.

Regional patterns

In Georges Bank, summer and fall zooplankton densities were near or slightly above average until approximately 2005 and have been below average since then; spring showed an opposite pattern with densities below average until approximately 2000 and above average since then. Winter on Georges Bank had little or no pattern.

In Southern New England, winter zooplankton densities increased until 1990, decreased between 1990-2000, and have been near average since then. Fall densities were near average until 2000, and then increased until approximately 2010, and have decreased since then. Spring and summer densities have stayed closer to average over the time series.

All seasons followed a similar pattern in the Western Gulf of Maine, with an approximately 2 year lag between spring/summer and fall/winter. Zooplankton densities were near average and then decreased until approximately 1990, and then increased until approximately 2005. Densities have been near average since 2005, with some decreases in fall and increases in spring.

Synthesis

In the spring, the zooplankton in all regions showed a "W" pattern of decrease-increase-decrease-increase with a periodicity of approximately 20 years (lows occurring in c. 1990 and 2010 and highs occurring in c. 1980, 2000, and 2020; Figs. 9-10). Other seasons had more mixed patterns (Figs. 9-10). *Calanus finmarchicus* sometimes showed complementary patterns to the other zooplankton species, for example in winter in all regions except Georges Bank *C. finmarchicus* had the opposite trend from all other species. In fall, *C. finmarchicus* had an opposite trend compared to *Pseudocalanus* sp. until approximately 2010, when their trend became synchronous. *Centropages typicus* and *Temora longicornis* always had similar patterns.

Most zooplankton species had similar trends across all four seasons (Figs. 11-12). One exception was *Temora longicornis* in Southern New England in the spring, which showed an approximately opposite trend to winter and fall (summer had almost no trend).

Season				Indicator	Stock Area
Winter	Spring	Summer	Fall		
	+	+		Temora longicornis	EGOM
			-	Pseudocalanus typicus	EGOM
				Calanus finmarchicus	EGOM
				Centropages typicus	EGOM
+	+	+		Temora longicornis	GBK
			-	Pseudocalanus typicus	GBK
		-	-	Calanus finmarchicus	GBK
				Centropages typicus	GBK
-	+		-	Temora longicornis	SNE
-	-		-	Pseudocalanus typicus	SNE
				Calanus finmarchicus	SNE
	+		-	Centropages typicus	SNE
+	+	+		Temora longicornis	WGOM
			-	Pseudocalanus typicus	WGOM
	+			Calanus finmarchicus	WGOM
				Centropages typicus	WGOM

Table 3. Time trends in zooplankton density in the four cod regions.

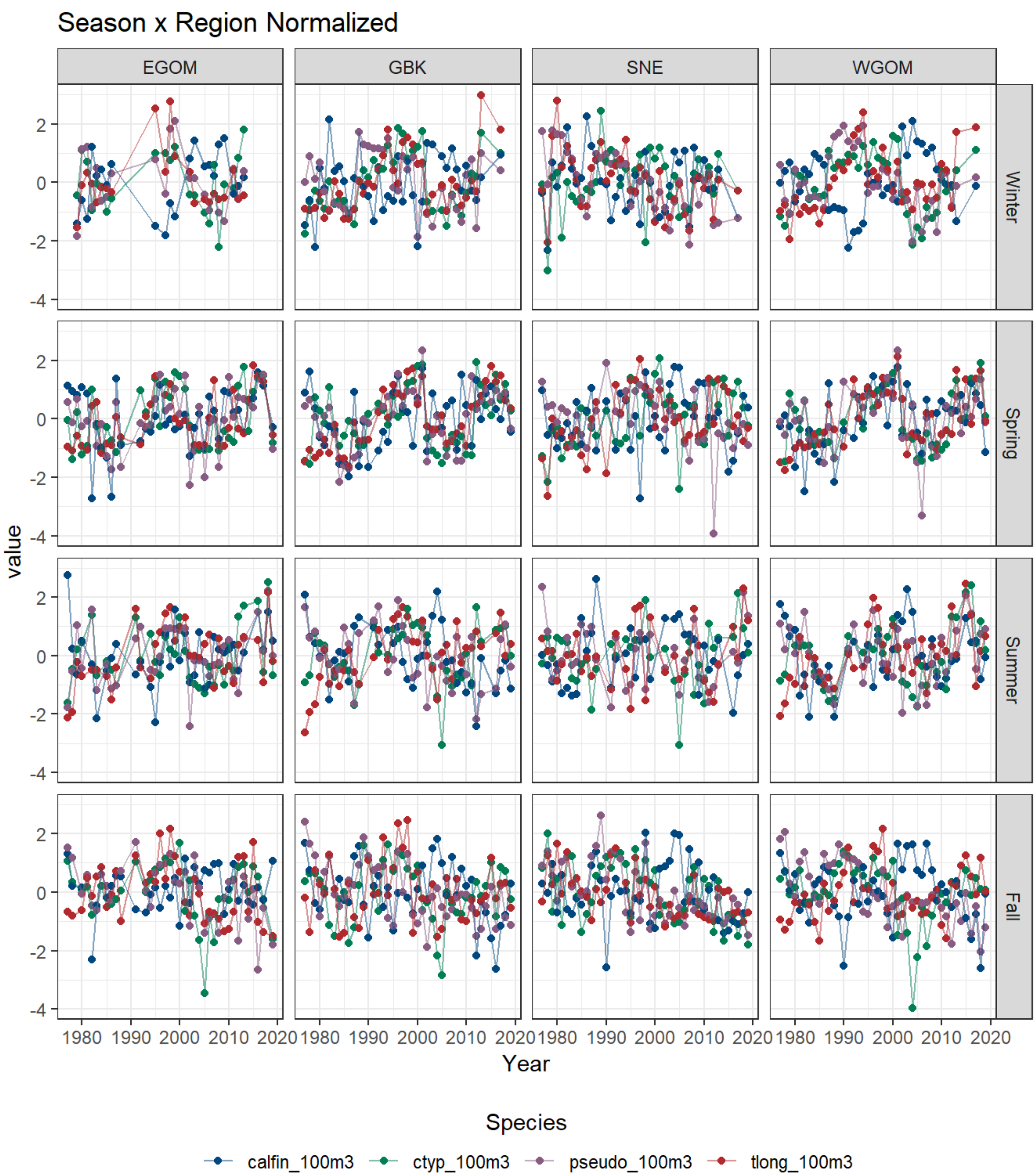

Figure 9. Normalized zooplankton density by region and season over time.

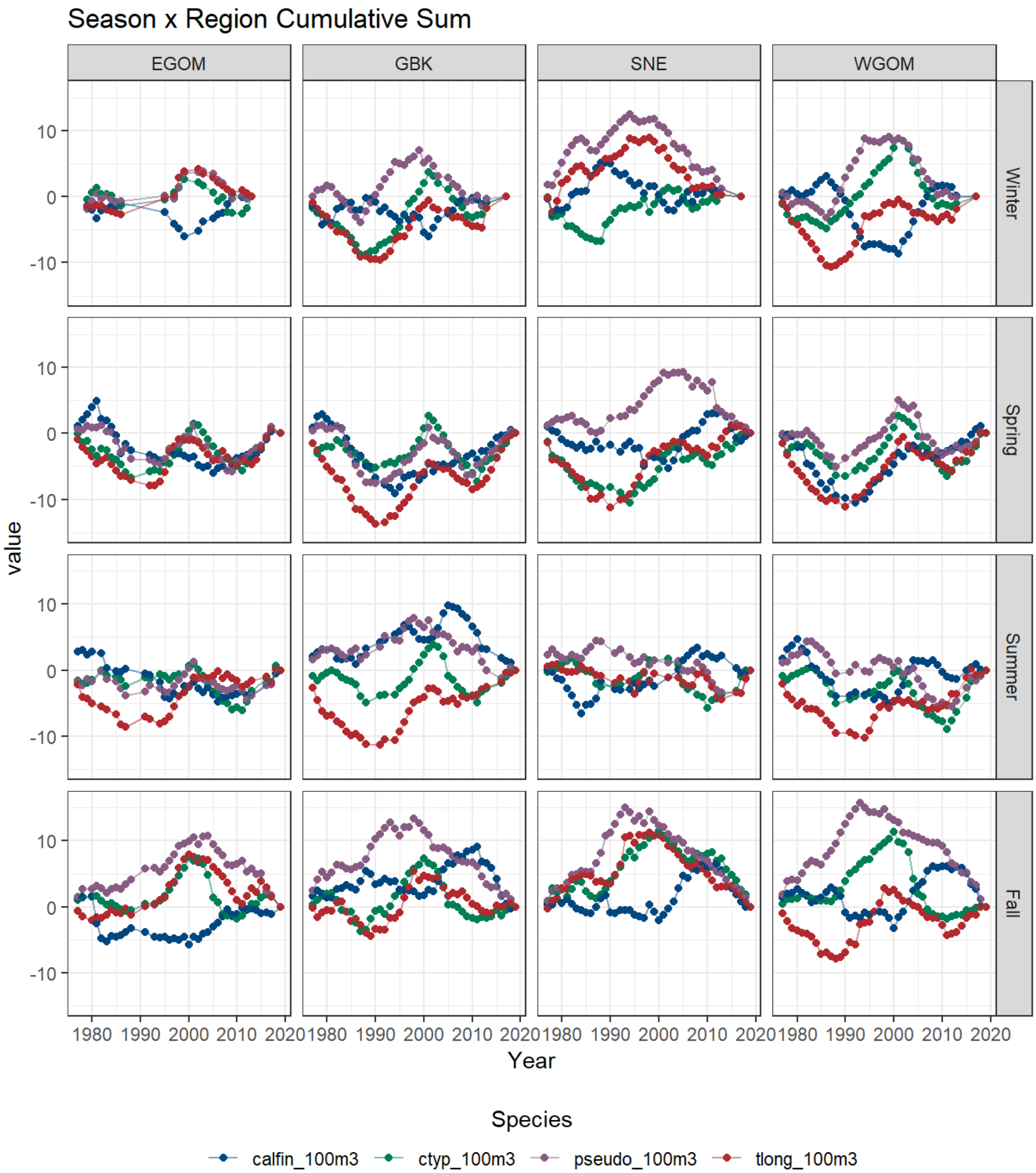

Figure 10. Cumulative sum of zooplankton density by region and season over time.

Figure 11. Normalized zooplankton density by region and species over time.

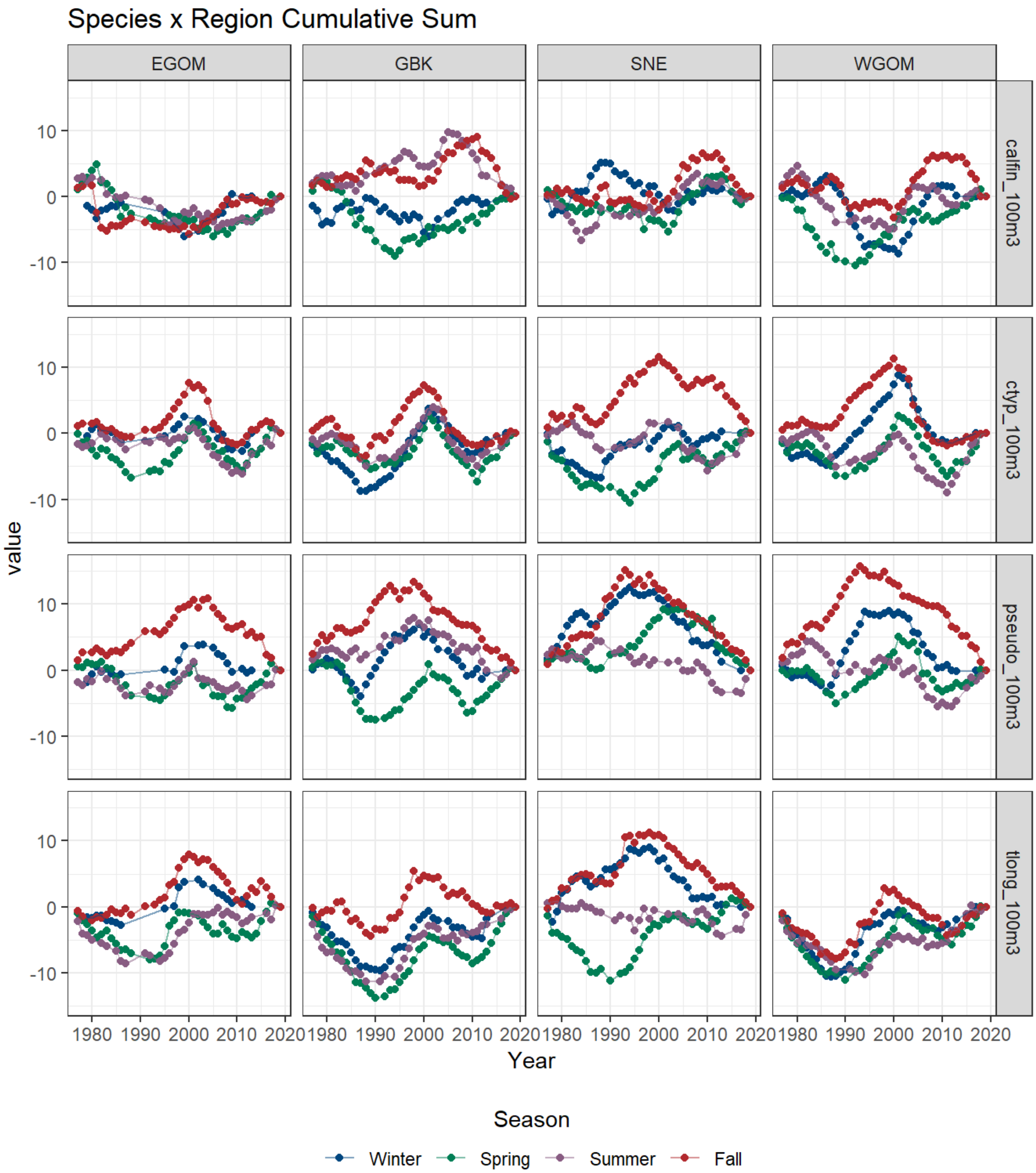

Figure 12. Cumulative sum of zooplankton density by region and species over time.

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