Long-term diet analyses of broad whitefish sampled in the Anguniaqvia Niqiqyuam Marine Protected Area reveals trophic level consistency amidst variability in habitat use

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Abstract

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Climate change is rapidly altering Arctic food webs by reshaping habitat connectivity and the availability of aquatic resources across freshwater and marine systems. Understanding of how these changes impact trophic pathways remains limited, particularly for anadromous species that utilize prey associated with freshwater and marine habitats in coastal zones. To address this gap, we examined the diet of broad whitefish *Coregonus nasus* using stomach content and stable isotopes ($\delta^{13}C$, $\delta^{15}N$) analyses collected from 2014 and 2016-2024 in the Anguniaqvia Niqiqyuam Marine Protected Area (ANMPA), Northwest Territories. The use of these complementary approaches in recent years of sampling allowed for the assessment of both short-term diet composition and longer-term integration of resource use over a long time period. Stomach content analyses revealed consistent reliance on invertebrate prey, such as chironomids and copepods, from both freshwater and marine environments, along with variability in $\delta^{13}C$ from stable isotope data, indicating use of both freshwater and marine carbon sources across years. In contrast, $\delta^{15}N$ values remained relatively stable, suggesting a consistent trophic position despite flexible habitat use. Together, these findings support a generalist foraging strategy, with individuals exploiting a mosaic of habitats and prey resources characteristic of Arctic coastal systems. Overall, broad whitefish represent a valuable indicator species for monitoring the MPA as their diet and isotopic signatures indicate trophic stability and habitat connectivity. Continued monitoring for shifts in these parameters can therefore provide insight into the broader impacts of environmental change on Arctic food webs.

RÉSUMÉ

Loewen, S.T., McNicholl, D.G., Christie, L.R., Koopman, N.C., Paulatuk Hunters and Trappers Committee, Dunmall, K.M. 2026. Long-term diet analyses of broad whitefish sampled in the Anguniaqvia Niqiqyuam Marine Protected Area reveals trophic level consistency amidst variability in habitat use. Can. Tech. Rep. Fish. Aquat. Sci. 3791: vii + 27 p. https://doi.org/10.60825/g5bb-1469

Les changements climatiques modifient rapidement les réseaux trophiques de l'Arctique en altérant la connectivité des habitats et la disponibilité des ressources aquatiques dans les systèmes d'eau douce et d'eau marine. La compréhension des répercussions de ces changements sur les relations trophiques demeure limitée, notamment pour les espèces anadromes qui se nourrissent de proies associées à des habitats d'eau douce et d'eau marine dans les zones côtières. Pour combler cette lacune, nous avons examiné le régime alimentaire du corégone tschir (*Coregonus nasus*) à l'aide d'analyses de contenus stomacaux et d'isotopes stables ($\delta^{13}C$ et $\delta^{15}N$) prélevés en 2014 et de 2016 à 2024 dans la zone de protection marine d'Anguniaqvia niqiqyuam, dans les Territoires du Nord-Ouest. L'utilisation de ces approches d'échantillonnage complémentaires au cours des dernières années a permis d'évaluer à la fois la composition du régime alimentaire à court terme et l'évolution de l'utilisation des ressources sur une longue période. Les analyses des contenus stomacaux ont révélé une dépendance constante à l'égard de proies invertébrées, comme des chironomes et des copépodes, provenant de milieux d'eau douce et de milieux d'eau marine, ainsi qu'une variabilité de $\delta^{13}C$ d'après les données sur les isotopes stables, ce qui indique l'utilisation de sources de carbone provenant de milieux d'eau douce et de milieux d'eau marine au fil des années. En revanche, les valeurs de $\delta^{15}N$ sont demeurées relativement stables, ce qui indique une position trophique constante malgré une utilisation variable de l'habitat. Ensemble, ces résultats révèlent que les individus appliquent une stratégie d'alimentation généraliste et exploitent une mosaïque d'habitats et de proies caractéristique des systèmes côtiers de l'Arctique. Dans l'ensemble, le corégone tschir est une espèce indicatrice utile pour le suivi de la zone de protection marine, car son régime alimentaire et ses signatures isotopiques indiquent une stabilité trophique et une connectivité de l'habitat. Un suivi continu des changements dans ces paramètres pourrait donc permettre de mieux comprendre les répercussions générales des changements environnementaux sur les réseaux trophiques de l'Arctique.

1.0 Introduction

Arctic coastal ecosystems are undergoing rapid environmental changes that are driven by climate warming, altered sea-ice dynamics, and increasing anthropogenic disturbance (Huntington et al. 2020). Variability in sea ice break-up and freeze-up timing, coastal erosion, and riverine inputs have cascading effects on food web structure and function (Niemi et al. 2024). Anadromous fish may serve as an important indicator of these environmental changes as their diet may inform trophic and habitat connectivity, and the use of diverse freshwater, estuarine, and marine habitats (Laske et al. 2018; Leppi et al. 2022).

Broad whitefish *Coregonus nasus*, a commonly found anadromous species, holds cultural, socioeconomical, and ecological significance for Inuvialuit communities within the Anguniaqvia Niqiqyuam Marine Protected Area (ANMPA). These fish tolerate a wide range of temperature and salinity conditions, and occupy freshwater, estuarine, and marine habitats (McNicholl et al. 2020; Leppi et al. 2022). Their anadromous life-history strategy facilitates access to seasonally abundant prey in marine environments during the summer and freshwater habitats for spawning and overwintering (Figure 1), thereby maximizing energetic returns in a highly seasonal Arctic ecosystem (Chapman et al. 2012; Leppi et al. 2022). Broad whitefish in the Beaufort Sea region have been known to consume a diverse selection of prey items, feeding on both pelagic and benthic, marine and freshwater sources, including copepods, nematodes, and insect larvae (Laske et al. 2018; Wight et al. 2023). They also exhibit diverse life history strategies, including anadromous and semi-anadromous forms (Harris et al. 2012). Their high mobility and generalist feeding strategy likely reflect adaption to the seasonally constrained productivity and patchy habitat mosaic characteristic of the Arctic (Leppi et al. 2022). This enables the use of a wide range of habitats they can access to adjust for factors such as the productivity of the area and the presence of predators.

Historically, broad whitefish have not been studied in detail in ANMPA (Ehrman et al. 2022). Some stomach content, morphometric, and stable isotope data are available for broad whitefish through community-based monitoring programs such as DFO-led Arctic Coast (McNicholl et al. 2020; McNicholl et al. 2024; Christie et al. 2025) or through by-catch in DFO-led Arctic char stock assessment programs (Harwood and Babaluk 2014; Gallagher et al. 2017; Ehrman et al. 2022). These surveys provide useful baseline data; however, the diet and habitat use of broad whitefish over time in the ANMPA and more broadly in Darnley Bay remain relatively unknown.

Stomach content and stable isotope analysis provide insight into the trophic position and sources of prey consumed by a species (Fry 2006; Post 2002; Vander Zanden & Rasmussen 1999). These are useful tools in ecological studies to examine species niches and breadth of prey sources consumed. $\delta^{13}C$ values indicate the use of basal carbon sources, wherein more negative values suggest terrestrial or freshwater sources and less negative values suggest marine sources (Fry, 2006). Higher $\delta^{15}N$ values correspond to higher trophic positions within the food web, reflecting greater nitrogen isotope enrichment with each trophic transfer, while relatively lower $\delta^{15}N$ values correspond to lower trophic positions (Fry 2006). Past research in the Beaufort Sea region suggests broad whitefish maintain similar trophic roles across life stages, evidenced by relatively constrained $\delta^{15}N$ muscle values from 6 to 13.1 ‰ (Leppi et al. 2022). While these stable isotopes integrate assimilated diet over longer periods (approximately 4-6 months according to Weidel et al. 2011), stomach contents represent short-term dietary snapshots (Vander Zanden and Rasmussen 1996). Together, these tools enable a more complete assessment of realized trophic niches and food web linkages than abundance or biomass metrics alone (Layman et al. 2005).

Here, our goal is to evaluate broad whitefish diet in the coastal ecosystem of ANMPA over a 10-year timeframe. To do this, our objective is to characterize habitat use and assess variability in diet for broad whitefish from 2014 to 2024 using stomach content and stable isotope analyses. Prey taxa biomass and counts are summarized for all fish analyzed between 2016 and 2026, with taxonomic data provided to the lowest possible level. Dietary data are also presented using carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotopes to examine trophic position and prey sources used by broad whitefish within and across sampling years, and between summer and fall seasons. This information will help to assess fluctuations in prey availability and changes in feeding strategies, contributing to the potential for broad whitefish to be an indicator of ecosystem change in ANMPA.

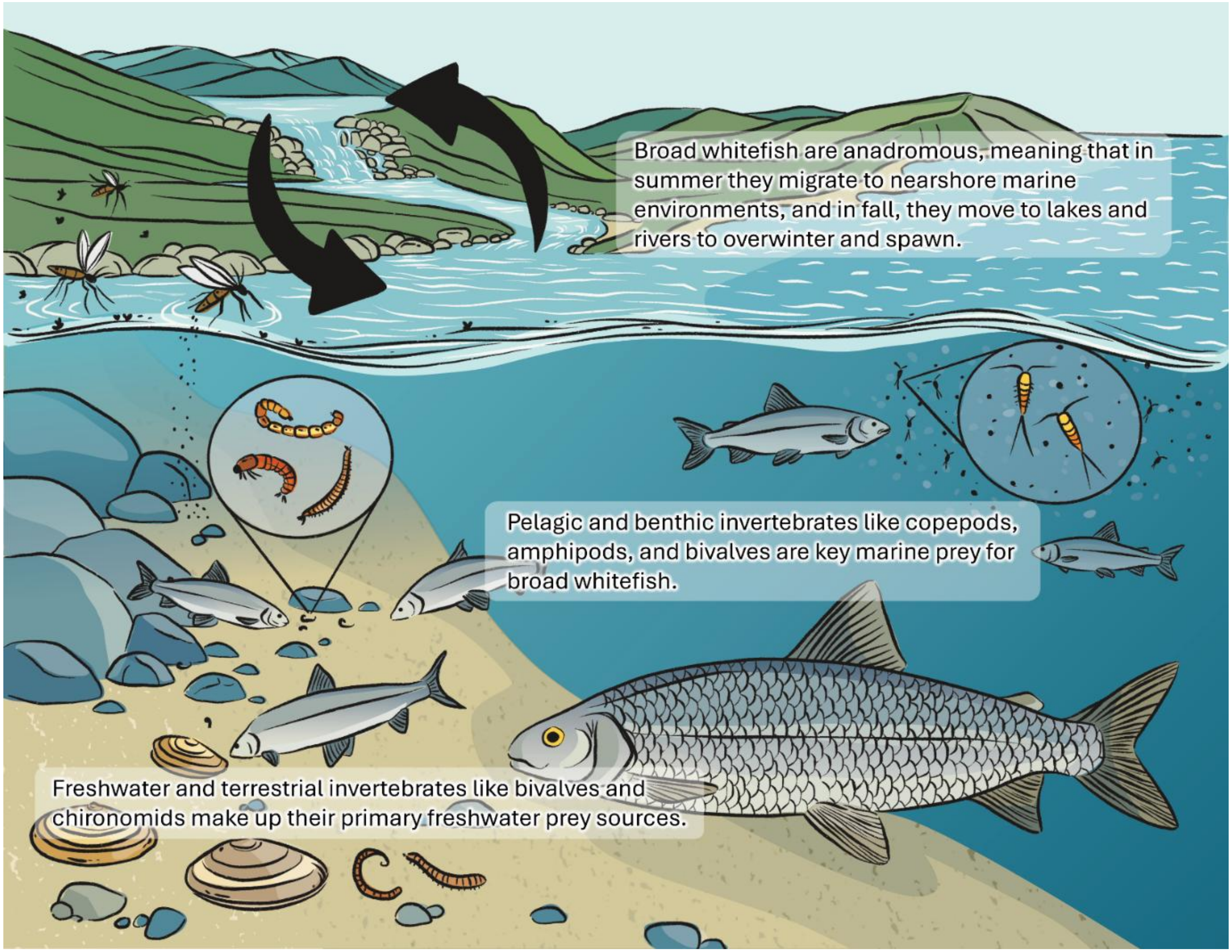

Figure 1. Overview of the anadromous life-history strategy and associated diet of broad whitefish across freshwater and marine habitats. Illustration credit: Viventem.

2.0 Methods

2.1 Study Area

The ANMPA, in the Inuvialuit Settlement Region, Northwest Territories (NT), is located on the western side of Darnley Bay, which is in the southern region of Amundsen Gulf (Figure 2). In 2016, it became the second Marine Protected Area (MPA) designated in the Canadian Arctic and the first MPA to have a conservation objective established based solely on Indigenous knowledge (DFO 2015). The nearby Inuvialuit community of Paulatuk holds the ANMPA in cultural, ecological, and socioeconomic significance, as it depends on the area for subsistence, including marine mammals and anadromous fishes that use the region as a migratory corridor (Paulic et al. 2012). In a partnership between Fisheries and Oceans Canada (DFO) and the PHTC, the Arctic Coast community-led monitoring program has operated among three sites in the ANMPA: Argo Bay, Bennett Point, and Brown's Harbour (Figure 2; McNicholl et al. 2024; Christie et al. 2025) since 2012.

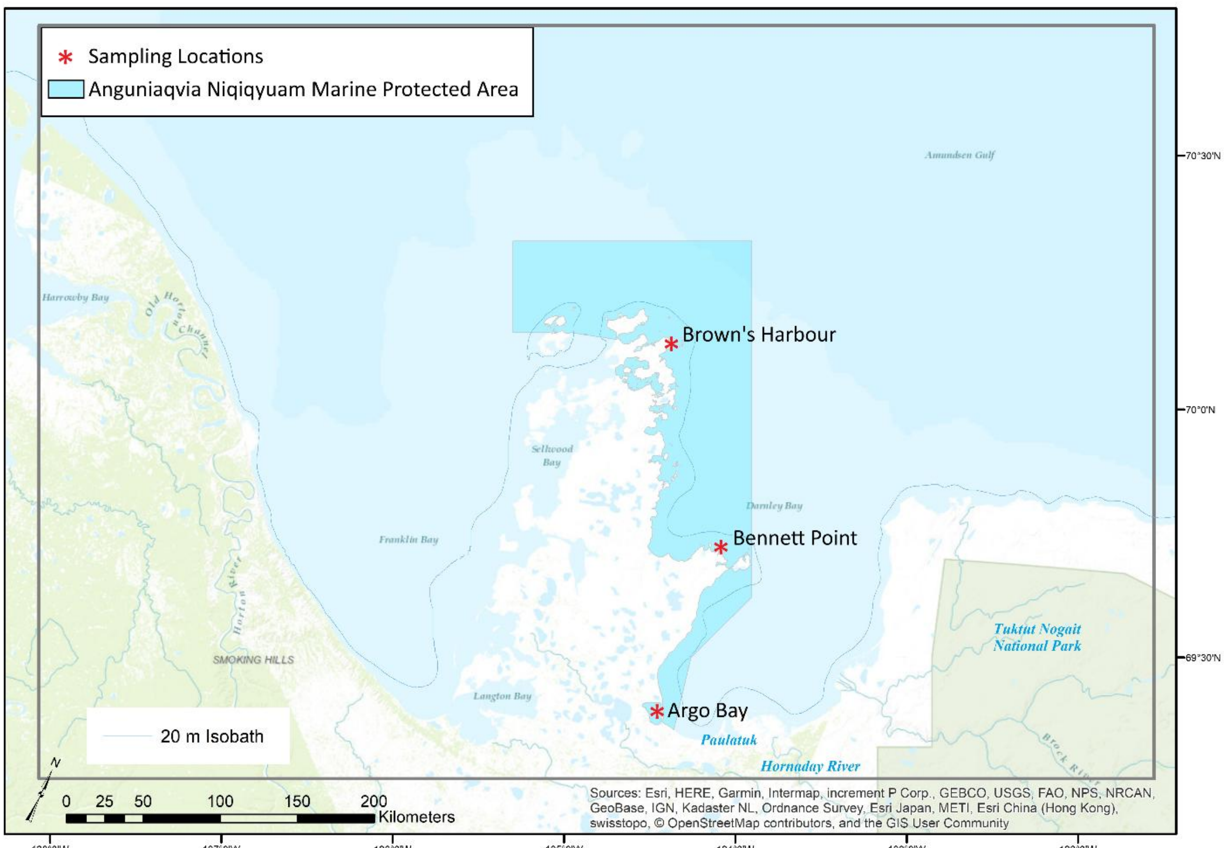

Figure 2. The Anguniaqvia Niqiqyuam Marine Protected Area (ANMPA, shaded in blue) and surrounding areas, showing the community of Paulatuk, Northwest Territories and the three sampling areas (Argo Bay, Bennett Point, and Brown's Harbour) for Arctic Coast. No broad whitefish samples were collected in Brown's Harbour, although it is a sampling site for Arctic Coast.

2.2 Collection of Fish

Adult broad whitefish, collected as a component of the Arctic Coast program from 2014–2024, were used for an assessment of diet. Fish were captured and processed for biological data (length, sex, species; Table 1) using methods outlined in Arctic Coast protocols (McNicholl et al. 2017; McNicholl et al. 2024; Christie et al. 2025). While juvenile broad whitefish as well as those of unknown maturity were collected via Arctic Coast, only adult individuals were used for this study. Up to 30 broad whitefish during each field season and site were dissected to obtain anterior dorsal muscle tissue and stomachs for diet analysis. After these 30 were dissected, the subsequent catches of broad whitefish were measured for total length and were then live-released. Tissues collected from each dissected fish were frozen in the field, and shipped to DFO in Winnipeg, MB for stomach content and stable isotopes analyses. Broad whitefish with full stomachs were prioritized for analysis, relative to those that appeared empty at the time of dissection. We assume that the individuals with contents reflect the overall feeding behaviour, though it is possible this biases our results at the time of capture to individuals actively feeding that may have different behaviour or metabolic demands.

2.3 Sample Processing and Analyses

Stomach content processing methods changed over time, but the resulting data were analyzed using biomass and prey counts to enable consistent dietary comparisons across years. In 2016 and 2017, stomach content processing was completed using dissection under a microscope and provided wet weights of prey items and stomachs, counts of prey items, and prey item identification. From 2018 onwards, stomachs were rinsed, dissected, and processed through a 250 µm sieve to obtain stomach content wet weight and prey item wet weight, biomass, and identification. Stomach content analyses were performed in Excel (Microsoft Corporation 2026) and used recorded biomass percentages of the total biomass of each year or season. Pie charts were created to represent the prey taxa in each available year. For years with a large variety of prey items, taxa representing < 2% of total contribution to diet were not shown graphically and were instead listed in Appendix A. Similar to other studies (e.g., Faulkner et al. 2025), stomachs containing only non-prey items, such as highly digested material that could not be reliably assigned taxonomically, plant material, and synthetic fibres, were excluded to avoid overestimating their dietary importance due to accumulation (Battaglia et al. 2013).

To analyze fish muscle samples for stable isotopes, approximately 10 g of frozen dorsal muscle were freeze-dried for 48 h (LAB-CONCO-FreeZone 4.5), homogenized using a ceramic mortar and pestle, and weighed into aluminum capsules (400 ± 10 µg of tissue in each capsule) in preparation for analysis in the mass spectrometer. Stable carbon ($\delta^{13}C$) and stable nitrogen ($\delta^{15}N$) isotope ratios were measured using a continuous-flow isotope ratio mass spectrometer (Thermo-Delta 5 Plus) coupled with a Costech elemental analyser at the University of Waterloo Environmental Isotope Lab.

Isotopic ratios were expressed as deviations from international standards (carbon: Vienna Pee Dee Belemnite; nitrogen: atmospheric N_2) in parts per thousand (‰). δ values were calculated following Peterson and Fry (1987) as:

$$\delta X = [(R_{sample} / R_{standard}) - 1] \times 1000$$

where X represents ^{13}C or ^{15}N, R_{sample} is the isotope ratio ($^{13}C/^{13}C$ or $^{15}N/^{15}N$) in the sample, and $R_{standard}$ is the corresponding ratio in the reference material. Standard deviations of repeated measurements of certified reference materials (USGS 40 and 41a) were < 0.1‰ for $\delta^{13}C$ and < 0.16‰ for $\delta^{15}N$. In-house standards showed mean deviations of < 0.08‰ for $\delta^{13}C$ and < 0.11 for $\delta^{15}N$, while duplicate samples yielded standard deviations of < 0.07‰ for $\delta^{13}C$ and < 0.05‰ for $\delta^{15}N$ across species. These values fall within acceptable ranges for direct comparison (Hobson and Schell, 1998). R (Version 4.5.2) was used for statistical analyses (i.e., means and counts) and to produce all bar charts, biplots, and box plots.

3.0 Results

3.1 Diet Analysis

Among whitefish collected by the Arctic Coast program, *n* = 76 were processed for stomach contents and *n* = 203 were processed for stable isotopes, which are summarized in this report (Table 1). All individuals that were processed for stomach content analyses were also used in stable isotope analyses (i.e., total individuals examined is equivalent to *n* = 203 analyzed for SIA). In 2014, fieldwork was only conducted at Bennett Point and Brown's Harbour, with few (*n* = 9) broad whitefish analyzed during this pilot year and all were from Bennett Point. In subsequent years of sampling (2016-2024) most broad whitefish were from Argo Bay relative to other monitoring sites. No broad whitefish were caught in 2015 given that sampling was focused at Brown's Harbour (Figure 2), where no broad whitefish have been observed or collected. In 2016, broad whitefish were collected for the first time in Argo Bay (primarily in August). From 2017 to 2020, fish were collected from Argo Bay in July, but from 2021 to 2024, sampling in Argo Bay occurred from July through September, as the field objectives expanded to include a fall sampling program.

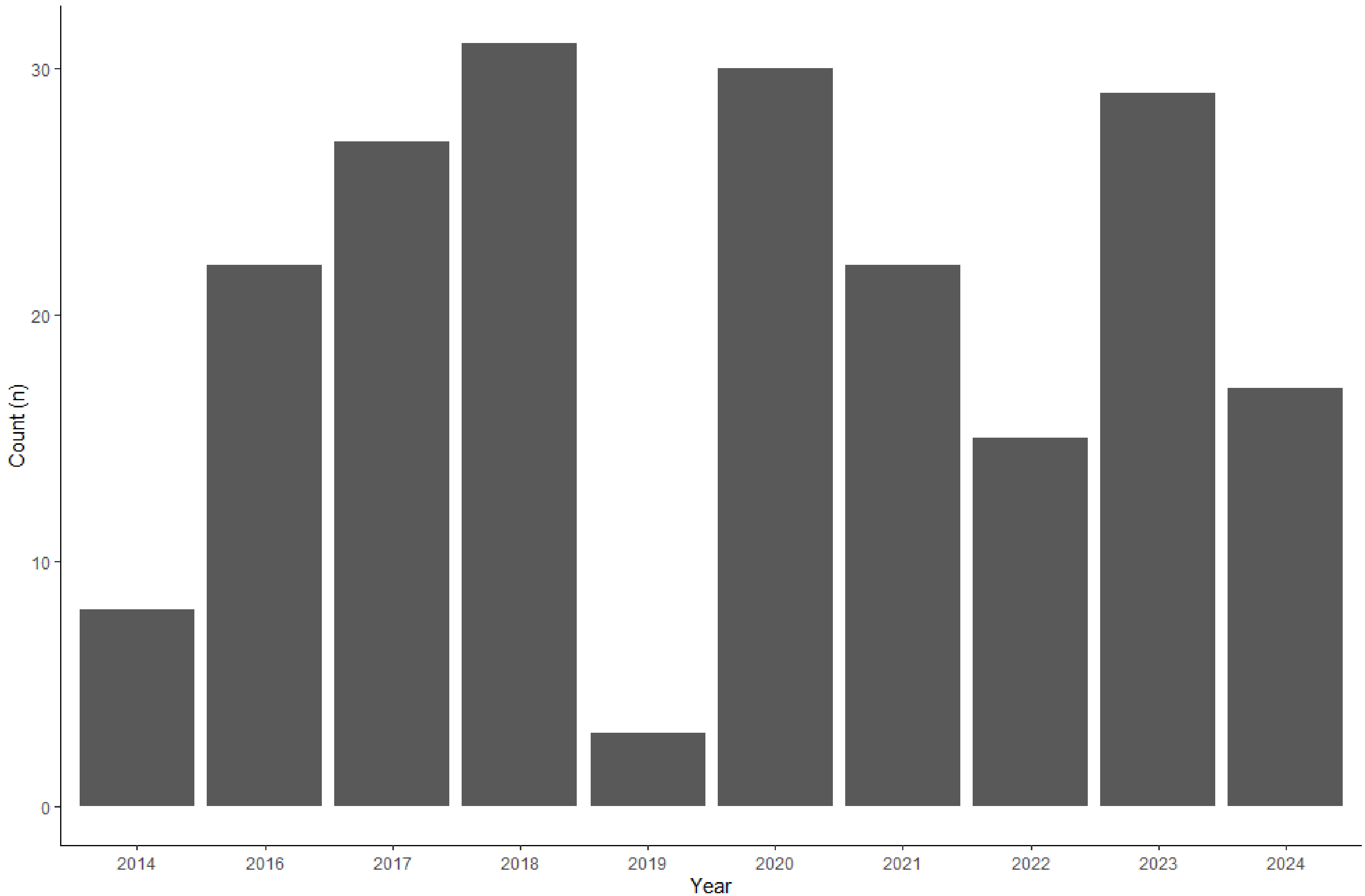

Figure 3. Number of adult broad whitefish analyzed for diet analysis (*n* = 203) between July-Sept from 2014 and 2016-2024 in the ANMPA (Argo Bay and Bennett Point).

3.2 Biological Characteristics

Biological data of individuals used in this study for stomach content and stable isotope analysis of adult broad whitefish are summarized in Table 1. The number of stomachs collected from these individuals and those processed for subsequent dietary analysis are also summarized in Table 1.

3.3 Stomach Content Analysis

A total of 76 adult broad whitefish stomachs collected between 2016 and 2024 were analyzed (no stomachs were collected in previous years; Table 1). All analyzed stomachs were collected from Argo Bay and 56.6% of the samples were obtained in July, 18.4% in August, and 25% in September.

Stomach contents were broadly consistent among years, with diets repeatedly featuring freshwater insects, while other freshwater and marine invertebrates contributed in varying proportions over time (Figures 4 and 5). Freshwater flies (Diptera *spp*, most commonly chironomids) made up a substantial portion of the total wet weight of stomach content analyzed, with insects making up 57.5% in total for all years. Marine invertebrates, including amphipods, copepods, and bivalves, comprised 5.5%, 12.0%, and 22.2%, respectively, of combined years. A complete table of all taxa found, including those representing < 2% of total contribution to diet in years with a large variety of prey items, are in Appendix A.

Broad whitefish stomach contents were also examined by the month when the stomachs were sampled (Figure 6). In July, insects, primarily Diptera *spp*, made up the majority of contributions (71.6%), copepods comprised 18.2% (4.5% from order Calanoida), amphipods comprised 7.9% (7.0% from *Gammarus wilkitzkii*), and molluscs made up 2.3% (bivalves 1.7%, gastropods 0.6%). Stomachs from August were only collected in 2016 and contained 81.0% chironomids and 19.0% unidentified fish remains. Bivalves made up most of the September stomach contents, at 87.8%, though 7.6% were separated further into Autobranchia (6.5% *Macoma spp*, 1.0% Sphaeriida). Gammaridae contributed 1.2% (*Gammarus wilkitzkii* 1%, *Gammarus oceanicus* 0.3%) to contents, while unidentified fish remains and Priapulidae accounted for 1.9% and 1.0%, respectively.

Table 1. Number of samples and biological data of adult broad whitefish that were used in diet analyses and were captured among sites in the ANMPA, 2014-2024.

Year	Site	Date range of catch	Analyzed for stable isotopes (n)	Analyzed n for stomach contents (n)	Total length range (mm)	Mass range (g)	Ratio of female to male
2014	Bennett Point	July 14-18	8	0	396 -528	528 - 1048	3:6
2016	Argo Bay	July 29 – Aug 9	22	14	360 - 577	330 - 1638	5:17
2017	Argo Bay	July 5-13	27	7	330 - 598	390 - 2163	10:16
2018	Argo Bay	July 10-16	31	8	416 – 646	480 - 3040	18:14
2019	Argo Bay	July 19	3	1	510 -525	1180 - 1550	0:3
2020	Argo Bay	July 15-17	30	12	430 - 570	380 - 1910	9:21
2021	Argo Bay	August 7-September 5	22	2	443 - 540	690 - 1620	4:18
2022	Argo Bay	July 15-September 19	15	8	440 - 554	760 - 1760	6:9
2023	Argo Bay	July 11-September 8	29	16	250 - 1810	220 - 1943	11:19
2024	Argo Bay	July 11-September 15	18	8	270 - 590	192 - 2213	7:7

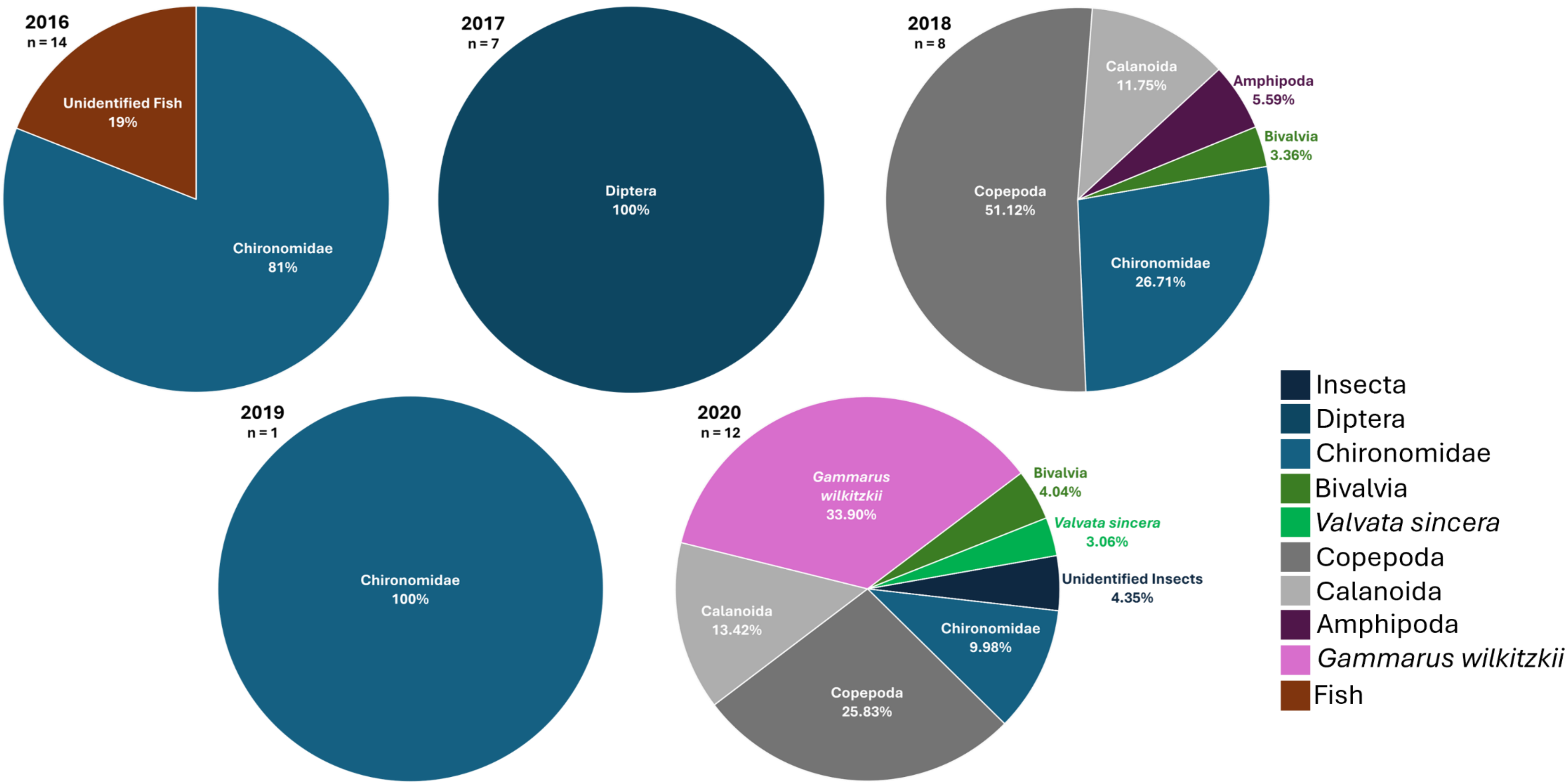

Figure 4. Percent contribution of prey items (based on wet weight) to stomach contents of adult broad whitefish collected in ANMPA, 2016-2020 (n = 42).

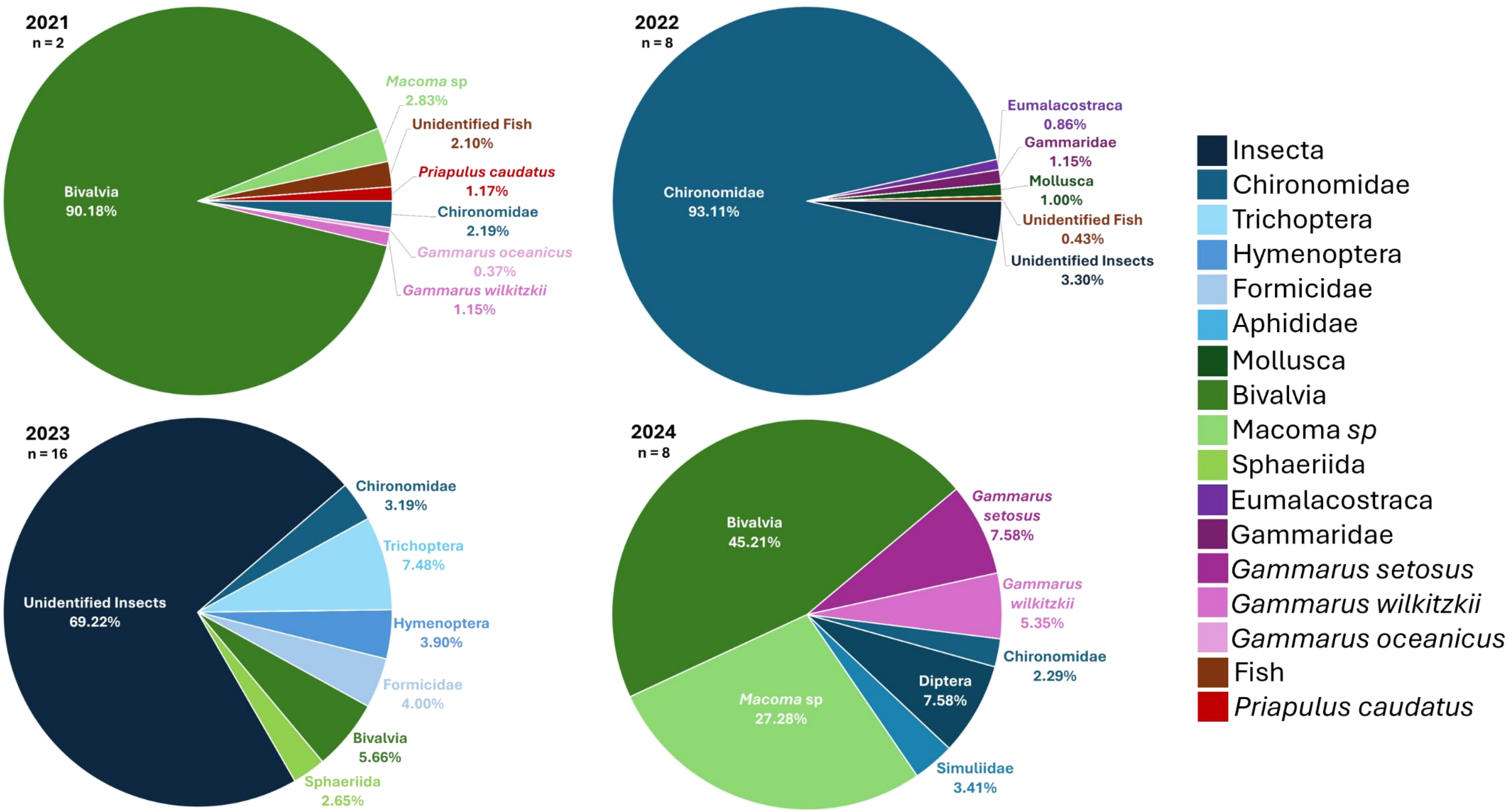

Figure 5. Percent contribution of prey items (based on wet weight) to stomach contents of broad whitefish collected in ANMPA, 2021-2024 (n = 34).

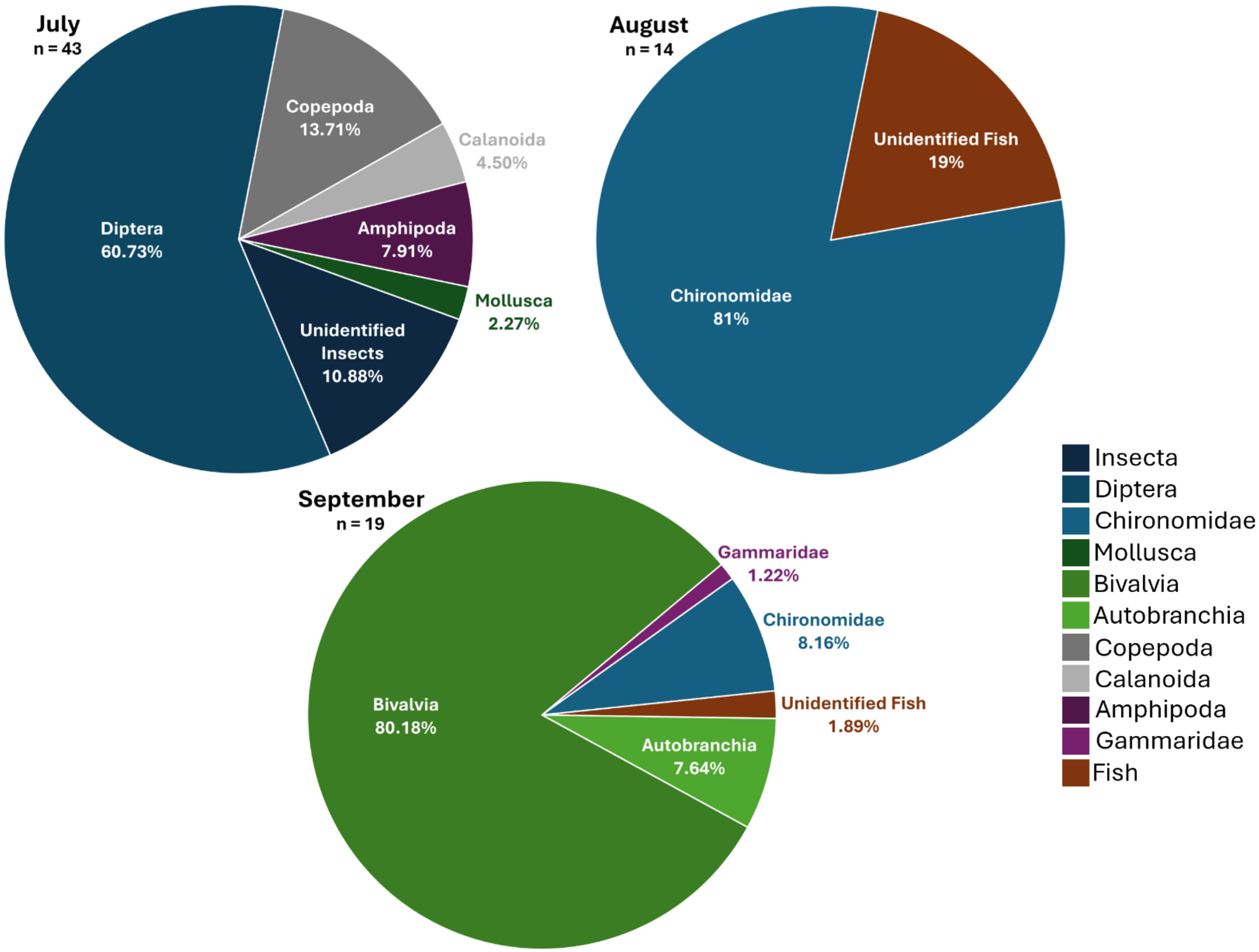

Figure 6. Percent contribution of prey items (based on taxa frequency) in stomach contents of broad whitefish in the ANMPA for July, August and September 2016-2024 (*n* = 76).

3.4 Stable Isotope Analysis

Stable isotope data collected from broad whitefish are summarized in Table 2, with 64.9% of the samples obtained in July, 9.8% in August, and 25.3% in September. Additionally, 95.5% (n = 195) were from Argo Bay and 4.5% (n = 8) were from Bennett Point.

Broad whitefish muscle $\delta^{13}C$ values varied across years from 2014-2024 (Figure 7), although were more consistent when compared monthly (Figure 8), while $\delta^{15}N$ showed stability across years (Figure 9). The earlier years (e.g., 2014) $\delta^{13}C$ values appeared more enriched (less negative) and mid-sampling years (e.g., 2018) more depleted, before shifting back toward enrichment in recent years (e.g., 2023–2024). It is important to note, however, that 2014 samples were obtained from Bennett Point, whereas the rest of the samples were obtained from Argo Bay. The lowest mean $\delta^{13}C$ value, -25.06 ± 1.93 ‰, occurred in 2018, and the highest mean, -19.63 ± 1.57 ‰, in 2014. Mean $\delta^{13}C$ values among months (July, August, September; Figure 8) appeared consistent. July had the lowest mean (-22.85 ± 2.67 ‰) while August had the highest (-21.40 ± 1.93 ‰). The mean $\delta^{15}N$ values were very consistent among years, with the lowest mean observed in 2022 (7.52 ± 0.27 ‰) and the highest mean in 2019 (9.06 ± 0.48 ‰) (Figure 9). $\delta^{15}N$ values among months maintained similar consistency, with the lowest mean, 8.26 ± 0.89 ‰, in July, and the highest mean, 8.55 ± 0.52 ‰, in August (Figure 10). Among sampling years, there was no discernible trend in broad whitefish trophic position based on their $\delta^{15}N$ values.

Table 2. Collection information and stable isotopes data of adult broad whitefish captured among sites in the ANMPA, 2014-2024.

Year	Site	Month	Total n analyzed for stable isotopes	Mean $\delta^{13}C \pm SD$ (‰)	Mean $\delta^{15}N \pm SD$ (‰)
2014	Bennett Point	July	8	-19.66 ± 1.67	8.31 ± 0.58
2016	Argo Bay	July	1	-23.05	8.81
		August	21	-21.27 ± 1.97	8.61 ± 0.44
2017	Argo Bay	July	27	-23.19 ± 2.64	8.48 ± 0.60
2018	Argo Bay	July	31	-25.21 ± 1.76	8.78 ± 0.57
2019	Argo Bay	July	3	-24.66 ± 1.27	9.06 ± 0.48
2020	Argo Bay	July	30	-23.81 ± 1.92	8.77 ± 0.42
2021	Argo Bay	August	2	-23.13 ± 1.01	8.68 ± 0.16
		September	20	-23.60 ± 1.54	8.47 ± 0.28
2022	Argo Bay	July	2	-24.05 ± 2.93	8.52 ± 1.05
		September	13	-23.14 ± 1.23	8.25 ± 0.15
2023	Argo Bay	July	11	-21.46 ± 3.17	8.28 ± 1.11
		September	18	-23.30 ± 1.32	8.32 ± 0.37
2024	Argo Bay	July	10	-22.17 ± 2.13	8.09 ± 0.69
		September	8	-20.25 ± 1.59	8.33 ± 0.88

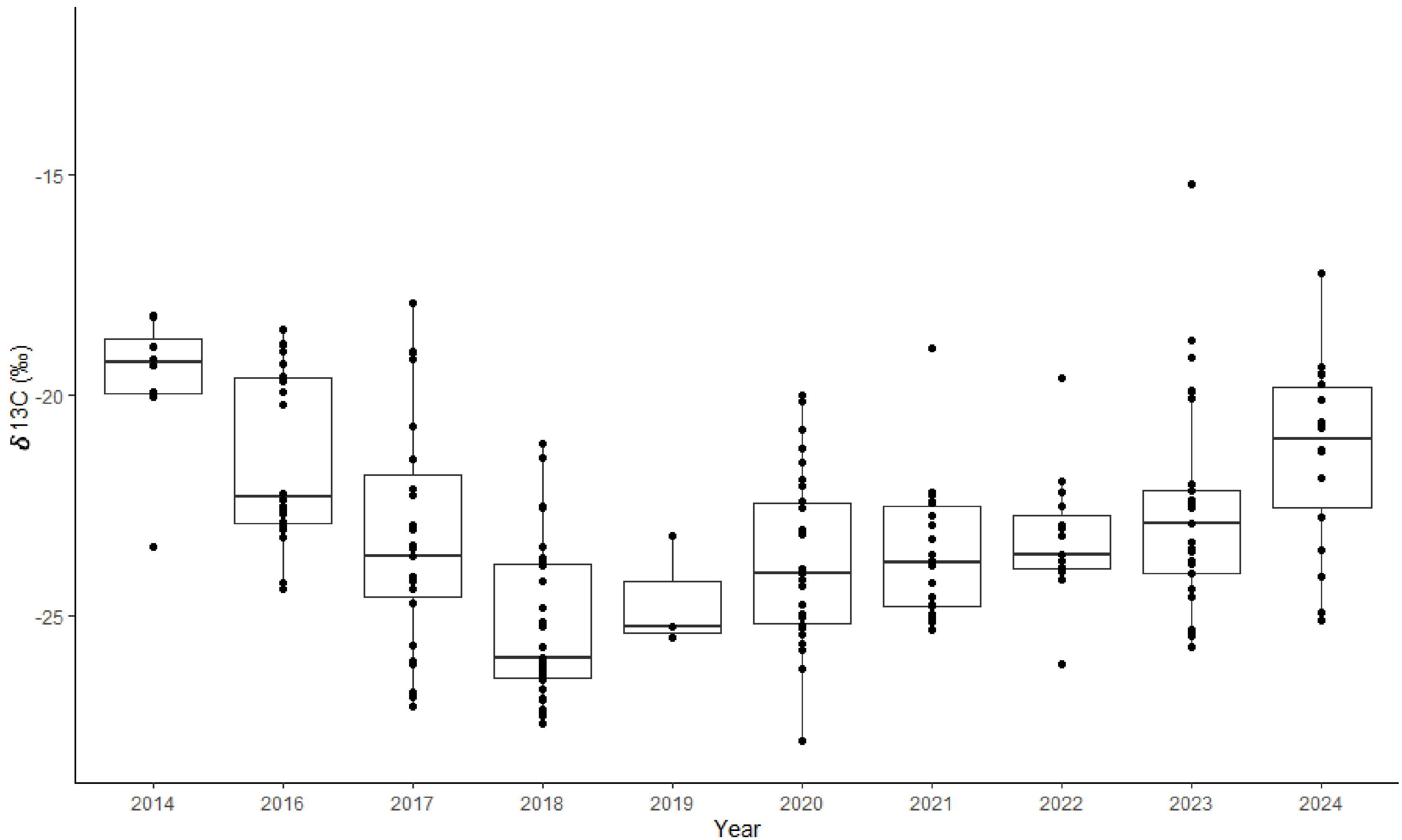

Figure 7. Boxplot of $\delta^{13}C$ from adult broad whitefish muscle, 2014 and 2016-2024 in Bennett Point and Argo Bay.

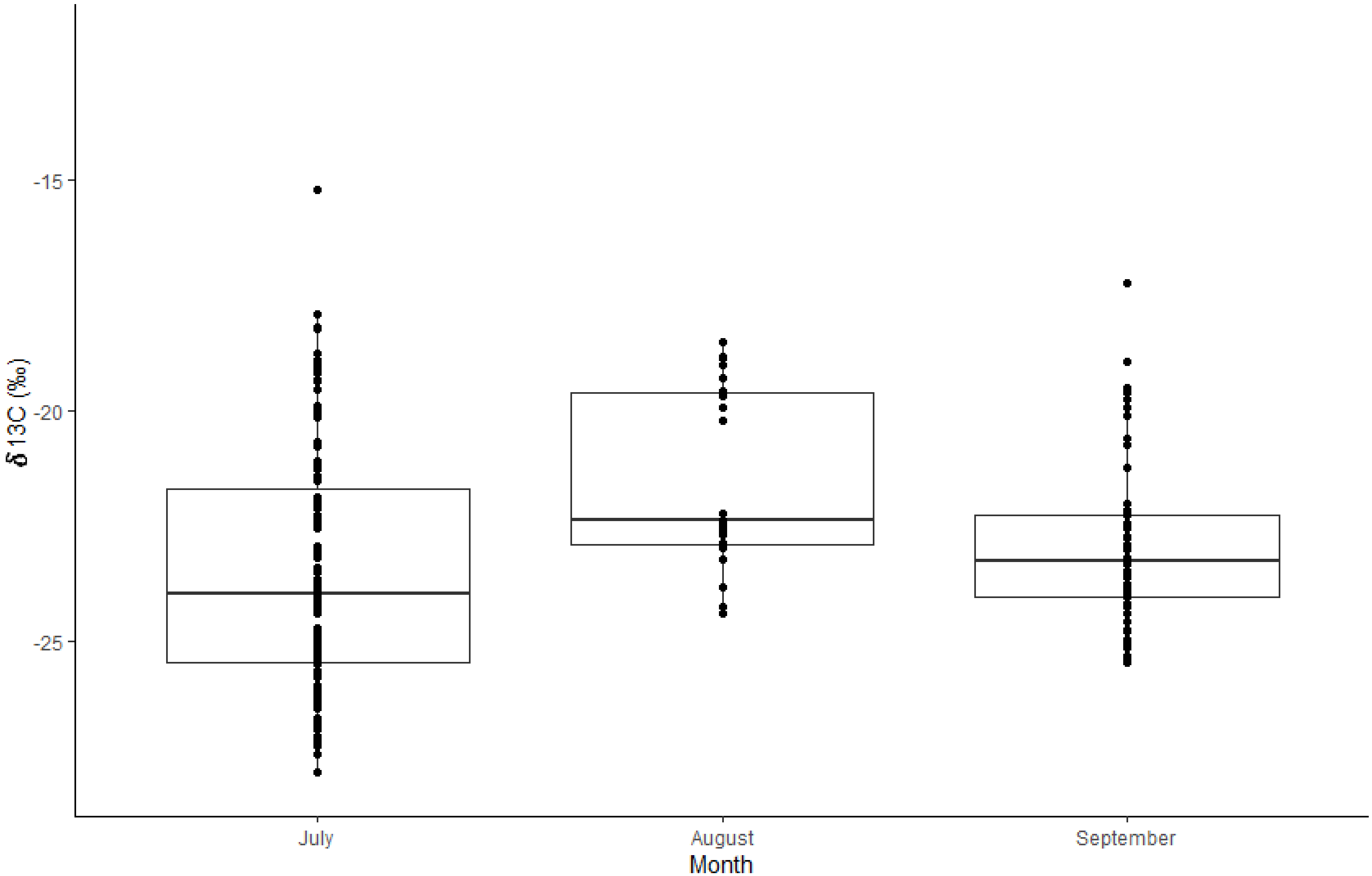

Figure 8. Boxplot of $\delta^{13}C$ from adult broad whitefish muscle in July (*n* = 123), August (*n* = 23), and September (*n* = 59) among combined years, 2014 and 2016-2024.

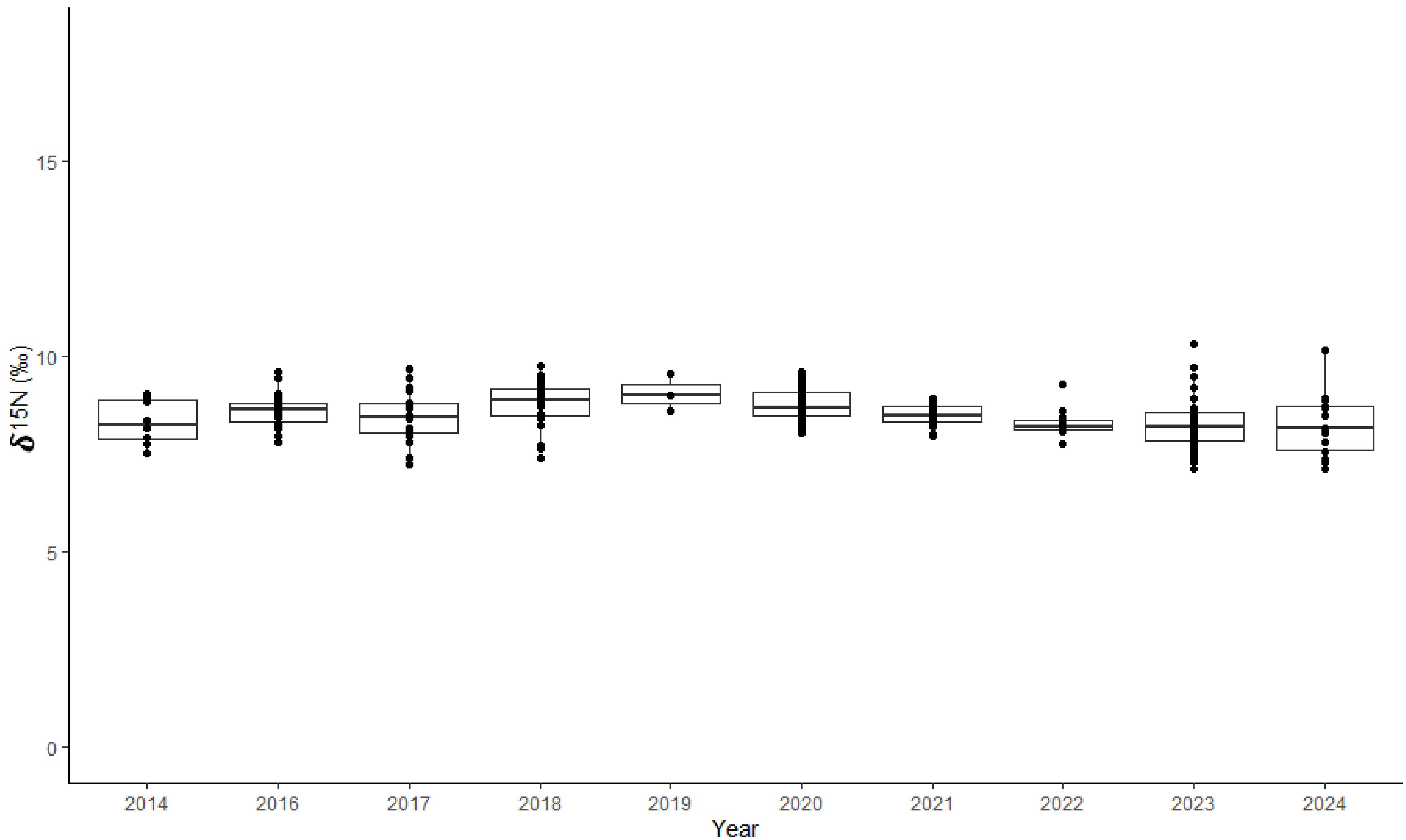

Figure 9. Boxplot of $\delta^{15}N$ from adult broad whitefish muscle, 2014 and 2016-2024.

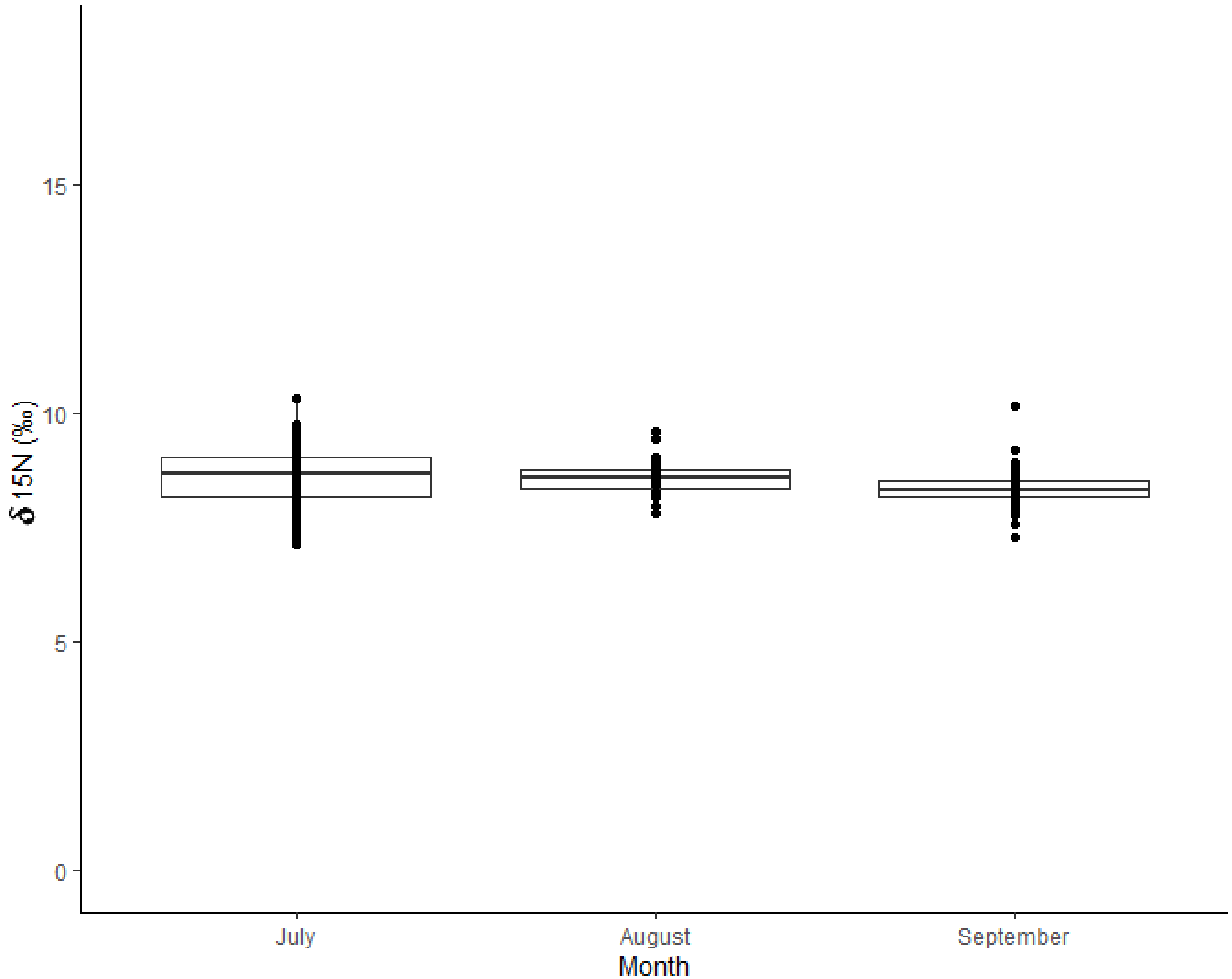

Figure 10. Boxplot of $\delta^{15}N$ from adult broad whitefish muscle tissue collected in July, August, and September 2014 and 2016-2024.

4.0 Discussion

This study investigated annual and seasonal variation in the diet of broad whitefish within ANMPA, in the western Canadian Arctic. Although broad whitefish are recognized as flexible consumers that integrate resources across freshwater and marine habitats, their long-term diet dynamics in ANMPA are understudied. Broad whitefish were collected in the coastal environment of the ANMPA during the summer and fall months, which was consistent with other regions of the Beaufort Sea. The individuals caught in this study are assumed to be foraging in the marine environment, before traveling back into the fresh water to overwinter (Harris et al. 2012). By combining stomach content and stable isotope analyses across a decade of sampling, we help to addressed key knowledge gaps related to trophic stability and resource use in an ecologically and culturally important anadromous fish species. Improving understanding of these patterns is critical, as shifts in broad whitefish feeding ecology may reflect broader ecosystem changes, which may impact the subsistence resources relied upon by northern communities.

Stomach content analyses revealed that broad whitefish in the coastal areas of ANMPA consistently relied on invertebrate prey, with substantial contributions from both freshwater and marine taxa. Key prey items include freshwater invertebrates, such as insects (Diptera *spp*., particularly chironomids), and pelagic zooplankton (amphipods, copepods). Similar seasonal shifts in habitat use and feeding are well documented in other Arctic anadromous fish, such as Arctic char, which overwinter in freshwater or estuarine habitats and migrate to coastal marine environments during the short summer to exploit prey resources there (Harwood and Babaluk, 2014). These summer foraging periods are important, as individuals obtain the majority of their annual energy intake during a brief open-water window before returning to overwinter and spawn (Fechhelm et al. 1992). Diversity in prey taxa supports a migratory feeding strategy whereby mobile individuals access both freshwater and coastal resources across connected habitats. The diverse prey base of broad whitefish aligns with their habitat use, including lakes, rivers, streams, estuaries, and nearshore marine zones, enabling exploitation of spatially and temporally patchy resource distributions (Gross et al. 1988; Brewster et al. 2016; McNicholl et al. 2017). Flexible foraging behaviour is particularly advantageous in northern systems, where brief open-water periods and spatially variable productivity require fishes to adapt to resources that are available (Gross et al. 1988; Leppi et al. 2022).

The observed temporal variability in mean $\delta^{13}C$ values is also consistent with flexible foraging behaviour in broad whitefish sampled within the ANMPA. The decline in $\delta^{13}C$ values from 2014 and 2016-2019 reflect an increasing dependence on freshwater-derived carbon, similar to what was observed in the stomachs with generally greater contributions of freshwater prey (e.g., Diptera including chironomids) during these years (but no stomach contents are available from 2014). Differences in sampling location, however, may also contribute to the higher $\delta^{13}C$ value in 2014, when samples were collected from Bennett Point, compared to other years, when samples were obtained from Argo Bay. As the salinity of Bennett Point is generally higher than that of Argo Bay due to the greater connectivity of Argo Bay to freshwater sources such as lakes and lagoons (McNicholl et al. 2025), the enriched $\delta^{13}C$ values in 2014 relative to other years may reflect this salinity gradient and therefore greater exposure to marine foraging opportunities than broad whitefish in Argo Bay. In contrast, the depleted $\delta^{13}C$ values observed in 2019 may reflect environmental conditions as break up occurred in early June that year, which was the earliest break up on record since the 1980s (Gully et al. 2023). It is also possible that the depleted values in 2019 are a reflection of sample size, given the limited number of samples that year. Differences in the timing of sampling may also contribute to the observed differences in $\delta^{13}C$ values observed across years. Given the values reflect carbon accumulated several months prior, the depleted values observed among the individuals captured in July (2014, 2017-2020) may indicate potential foraging in the freshwater environment (Weidel et al. 2011; Leppi et al. 2022). Conversely, the slightly elevated $\delta^{13}C$ values from individuals captured in August and September (2016, 2021-2024), suggest a greater reliance on marine carbon sources, potentially indicating increased marine foraging as the summer progresses. However, monthly differences in $\delta^{13}C$ are minor, with July samples only slightly more depleted and August samples slightly more enriched. Overall, the interannual variability in $\delta^{13}C$ reflects a generalist foraging strategy by broad whitefish during the months leading up to sampling in ANMPA, with some individuals relying more on freshwater sources and others using marine-derived prey taxa, including potentially foraging outside the MPA within Darnley Bay and also accessing adjacent estuarine habitats (lagoons) connected to Darnley Bay (Chapman et al. 2012; Leppi et al. 2022).

In contrast to $\delta^{13}C$, $\delta^{15}N$ values remained relatively stable among years, indicating little to no change in the trophic position of broad whitefish sampled in the ANMPA within or among years. The narrow range observed here suggests broad whitefish are a mid-level consumer, feeding on invertebrate prey and despite potential shifts in prey composition or habitat use, broad whitefish are not moving substantially higher or lower in the food web (Laske et al. 2018; St. George et al. 2023). As such, broad whitefish appear to maintain a steady position within the food web over time (Leppi et al. 2022; St. George et al. 2023).

5.0 Conclusion

The feeding ecology of broad whitefish sampled in the ANMPA underscores the importance of habitat connectivity across freshwater, estuarine, and marine systems. Overall, the combined stomach contents and stable isotope results indicate broad whitefish exhibit a flexible, invertebrate-based foraging strategy supported by both freshwater and marine habitats. This is consistent with other studies that indicate their seasonal migration between marine and freshwater environments. These traits highlight the ecological flexibility of broad whitefish and their value as an indicator species for monitoring ecosystem changes in rapidly shifting Arctic coastal environments.

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Appendix A: Prey Items

Table A1. Summary of taxa found in broad whitefish stomachs sampled in the ANMPA, identified to the lowest possible taxonomic level.

Year	Prey Items						Item Count	Wet Weight (Gg	% Stomach Contents
2016	Chordata	Teleosti		Unidentified Fish Remains			-	0.915	19.35%
	Hexapoda	Insecta	Pterygota	Diptera	Chironomidae		-	3.814	80.65%
2017	Crustacea	Malacostraca	Eumalacostraca	Amphipoda			2	0	0.00%
	Hexapoda	Insecta	Pterygota	Coleoptera			-	0.005	0.03%
				Diptera	Chironomidae		2	0.004	0.02%
					Diptera		3	18.984	99.95%
2018	Crustacea	Malacostraca	Eumalacostraca	Amphipoda	Gammaridae	*Gammarus wilkitzkii*	6	0.245	3.85%
					Uristidae	*Onisimus nanseni*	7	0.102	1.60%
					Amphipoda		1	0.009	0.14%
				Isopoda	Chaetiliidae	*Saduria sibirica*	11	0.044	0.69%
				Mysida	Mysidae	*Mysis* sp	1	0.000	0.00%
		Copepoda		Calanoida	Calanidae	*Calanus hyperboreus*	246	0.714	0.22%
						Calanus sp	3	0.014	0.31%
					Temoridae	*Eurytemora herdmani*	14	0.020	0.00%
					Calanoida		1	0.000	11.22%
				Copepoda			-	3.253	51.12%
		Crustacea					-	0.029	0.46%
	Hexapoda	Insecta	Pterygota	Diptera	Chironomidae		1074	1.7	26.71%
			Insecta				2	0.006	0.09%
	Mollusca	Bivalvia					9	0.214	3.36%
		Gastropoda					1	0.014	0.22%
2019	Hexapoda	Insecta	Pterygota	Diptera	Chironomidae		16	0.072	100.00%
2020	Crustacea	Copepoda		Calanoida	Calanidae	*Calanus hyperboreus*	4	0.032	0.50%
					Calanoida		2	0.831	12.92%
				Cyclopoida			1	0.001	0.02%

				Copepoda			2	1.661	25.83%
		Malacostraca	Eumalacostraca	Amphipoda	Gammaridae	*Gammarus wilkitzkii*	31	2.180	33.90%
					Ischyroceridae	*Ischyrocerus* sp	1	0.005	0.08%
					Oedicerotidae		1	0.022	0.34%
					Pontoporeiidae		1	0.001	0.02%
	Hexapoda	Insecta	Pterygota	Coleoptera			-	0.002	0.03%
				Diptera	Chironomidae		327	0.642	9.98%
					Culicidae		-	0.001	0.02%
					Simuliidae		23	0.036	0.56%
					Tipulidae		2	0.015	0.23%
					Diptera		2	0.069	1.07%
				Trichoptera			2	0.049	0.76%
			Insecta				2	0.28	4.35%
	Mollusca	Bivalvia	Autobranchia	Mytilida	Mytilidae	*Mytilus edulis*	2	0.126	1.96%
				Sphaeriida			6	0.020	0.31%
			Bivalvia				59	0.26	4.04%
		Gastropoda	Heterobranchia	Heterostropha	Valvatidae	*Valvata sincera*	17	0.197	3.06%
2021	Chordata	Teleosti		Unidentified Fish Remains			-	0.22	2.10%
	Crustacea	Malacostraca	Eumalacostraca	Amphipoda	Gammaridae	*Gammarus oceanicus*	3	0.039	0.37%
						Gammarus wilkitzkii	1	0.12	1.15%
	Hexapoda	Insecta	Pterygota	Diptera	Chironomidae		60	0.23	2.19%
	Mollusca	Bivalvia	Autobranchia	Cardiida	Tellinidae	*Macoma* sp	12	0.297	2.83%
			Bivalvia				-	9.451	90.18%
	Priapulida			Priapulomorpha	Priapulidae	*Priapulus caudatus*	3	0.123	1.17%
2022	Chordata	Teleosti		Unidentified Fish Remains			-	0.003	0.43%
	Crustacea	Malacostraca	Eumalacostraca	Amphipoda	Gammaridae	*Gammarus* sp	1	0.008	1.15%
				Eumalacostraca			1	0.006	0.86%
		Copepoda		Harpacticoida	Laophontidae		1	0.001	0.14%
	Hexapoda	Insecta	Pterygota	Diptera	Chironomidae		394	0.649	93.11%
			Insecta				2	0.023	3.30%
	Mollusca						-	0.007	1.00%

2023	Annelida	Polychaeta	Sedentaria	Terebellida	Pectinariidae	*Cistenides* sp	-	0.001	0.02%
	Chelicerata	Arachnida	Acari				2	0.002	0.04%
	Chordata	Teleosti		Unidentified Fish Remains			-	0.023	0.44%
	Crustacea	Copepoda		Cyclopoida	Cyclopidae		1	0	0.00%
		Malacostraca	Eumalacostraca	Amphipoda	Gammaridae	*Gammarus wilkitzkii*	1	0.008	0.15%
						Gammarus sp	1	0.034	0.66%
				Mysida	Mysidae	*Mysis* sp	1	0.001	0.02%
				Eumalacostraca			-	0.001	0.02%
	Hexapoda	Insecta	Pterygota	Diptera	Chironomidae		197	0.165	3.19%
					Culicidae		2	0.020	0.39%
					Diptera		4	0.018	0.35%
				Hymenoptera	Formicidae		101	0.207	4.00%
					Hymenoptera		26	0.202	3.90%
				Trichoptera			15	0.387	7.48%
			Insecta				2	3.581	69.22%
	Mollusca	Bivalvia	Autobranchia	Cardiida	Tellinidae	*Macoma balthica*	1	0.009	0.17%
						Macoma sp	5	0.084	1.62%
				Sphaeriida			6	0.137	2.65%
			Bivalvia				-	0.293	5.66%
2024	Crustacea	Malacostraca	Eumalacostraca	Amphipoda	Gammaridae	*Gammarus setosus*	2	0.129	7.58%
						Gammarus wilkitzkii	1	0.091	5.35%
	Hexapoda	Insecta	Pterygota	Diptera	Chironomidae		43	0.039	2.29%
					Simuliidae		7	0.058	3.41%
					Diptera		7	0.129	7.58%
				Hemiptera	Aphididae		1	0.002	0.12%
			Insecta				1	0.009	0.53%
	Mollusca	Bivalvia	Autobranchia	Mytilida	Mytilidae	*Mytilus edulis*	3	0.011	0.65%
				Cardiida	Tellinidae	*Macoma* sp	143	0.464	27.28%
			Bivalvia				15	0.769	45.21%