

**Oceanographic assessment of the planktonic communities in
the northeastern Chukchi Sea**

Report for Survey year 2011

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EXECUTIVE SUMMARY

Surveys of the planktonic communities over the Klondike, Burger and Statoil survey areas were completed during August 2011 and again as part of a broad scale effort in September/October of 2011. Chlorophyll and nutrient concentrations suggest that August sampling occurred post-phytoplankton bloom in all study areas, with some elevated concentrations maintained in the winter-water cold pools over Burger and Statoil. In total, 77 taxonomic categories of zooplankton, including 10 meroplanktonic larval categories, were observed during the 2011 field year. The greatest taxonomic diversity was observed within the copepods (25 species, plus juvenile categories), followed by the cnidarians (13 species), with most species typical for the region and are seeded from the Bering Sea. A notable exception to previous years occurred in 2011 with the transport of the Arctic basin copepod species *Calanus hyperboreus* into the study area during a period of sustained upwelling in Barrow Canyon. An average abundance of ~4500 individuals m^{-3} and 37.7 mg DW m^{-3} was captured by the 150- μm net and an average of 134 individuals m^{-3} and 26.3 mg DW m^{-3} captured by the 505- μm net. The contribution by meroplankton to both abundance and biomass was substantial, especially for larval decapods that dominated biomass at some stations. Holozooplankton and meroplankton total abundance and biomass were generally within the range observed in previous years. In 2011, Klondike zooplankton could generally be separated from Burger and Statoil based on community structure, with a temporal evolution of the community structure apparent at each location. Differences in community structure between each study year were also identified. Differences in ice-melt timing, water temperatures, transport of water masses, nutrients and chlorophyll-*a* are believed to influence the large inter-annual difference observed in the planktonic communities over the past 4 years.

INTRODUCTION

Purpose of Study and Rationale

Chukchi Lease Sale 193 occurred in February 2008, followed by the completion of the first year of a 5-year multidisciplinary environmental studies program initiated by ConocoPhillips in cooperation with Shell Exploration & Production Company, and Statoil USA Exploration & Production Inc. The 2011 field effort represents a fourth year of data collection that will aid in the preparation of a defensible NEPA document in support of exploratory drilling. Pelagic biological oceanography forms one aspect of the baseline studies program, because the productivity of the water column determines the flux of energy to the seafloor, as well as productivity transferred through zooplankton to higher trophic levels such as fish, seabirds and marine mammals. Alterations to water column productivity as a result of inter-annual variability, long-term climate change or human activity, could have direct impact on the ecosystem, including the more visible vertebrates. The data collected through this program, combined with historical and region-wide data, will provide us with direct observations of community composition and biomass, which is the only means to compare temporal and spatial variation in biological communities to environmental change.

Objectives of Study

The major objective of this study is to describe the spatial and seasonal characteristics of the plankton (phytoplankton and meta-zooplankton) communities, with specific detail in the three study areas. Planktonic communities are strongly coupled to the underlying physical oceanography, with major differences in water-masses generally reflected in the plankton. The study areas are near the historical transition between Alaska Coastal waters and Bering Shelf waters, both of which have unique assemblages of zooplankton. Simultaneous measurement of the physical, chemical, and biological oceanographic setting is therefore essential to forming an understanding of the patterns and the range of seasonal and inter-annual variability characteristic of the region.

Brief History of Planktonic Biological Oceanography in Chukchi Sea

The Chukchi Sea represents a complex ecosystem at the Pacific Ocean's gateway into the Arctic where water masses of Pacific origin interact with those of the central Arctic Ocean and its continental-shelf seas. Large quantities of Pacific nutrients, phytoplankton and zooplankton enter the region through the Bering Strait, in a complicated mixture of water masses (i.e. Alaska Coastal, Bering Shelf, and Anadyr Water), each with unique assemblages and quantities of zooplankton (Springer *et al.*, 1989; Coyle *et al.*, 1996; Hopcroft *et al.*, 2010). It has been estimated that 1.8 million metric tons of Bering Sea zooplankton are carried into the Chukchi Sea annually (Springer *et al.*, 1989) and that this, along with the entrained phytoplankton communities, are responsible for the high productivity of the Chukchi Sea in comparison to adjoining regions of the Arctic Ocean (e.g. Plourde *et al.*, 2005).

During the ice-free season, the southern Chukchi zooplankton fauna is primarily Pacific in character. During summer, the Pacific inflow is diluted by Coastal Arctic waters carried along by the East Siberian Current and water carried in from the deeper waters of the Canada Basin or Chukchi Plateau (Grebmeier *et al.*, 1995). Nonetheless, Pacific species are carried northward as

far as the eastern side of Wrangel Island (Hopcroft *et al.*, 2010), as well as to the shelf break in the northeastern Chukchi Sea (Lane *et al.*, 2008, Nelson *et al.* 2009). The influx of these “rich” Pacific waters determines the reproductive success of both the imported and resident zooplankton communities (Plourde *et al.*, 2005; Hopcroft and Kosobokova, 2010). Both inter-annual and long-term variations in climate affect the relative transport of these various water masses and hence the composition, distribution, standing stock, and production of zooplankton and their predators within the Chukchi Sea.

A regional and basin-wide review of Arctic zooplankton, their composition, seasonal life cycles, and trophic interactions was completed nearly two decades ago (Smith and Schnack-Schiel, 1990). A more recent effort emphasizing the Russian literature for the Bering Sea and parts of the southern Chukchi has also been completed (Coyle *et al.*, 1996), as well as a review of zooplankton in Arctic polynyas (Deibel and Daly, 2007). The most current review is specific to the Chukchi and Beaufort Seas and has an extensive review of the literature for zooplankton as well as other groups (Hopcroft *et al.*, 2008). Comparison of studies prior to the 1990s is hampered by lack of standardized sampling techniques, many of which used only a single net of 303 to ~600 μm mesh that missed the majority of the zooplankton community numerically, and a substantial proportion of the community biomass and diversity. Pacific-Arctic studies have now standardized on 150- μm mesh nets (e.g. Kosobokova and Hirche, 2000; Ashjian *et al.*, 2003; Lane *et al.*, 2008; Kosobokova and Hopcroft, 2010) that result in more complete sampling of the numerically dominant copepods in the genera *Oithona*, *Oncaea*, *Microcalanus* and *Pseudocalanus* (*ibid*; Conover and Huntley, 1991; Auel and Hagen, 2002; Hopcroft *et al.*, 2010), although passage of the early developmental stages of these small species still occurs (Hopcroft *et al.*, 2005).

Over the past decade, biological oceanographers have assembled a relatively complete list of zooplankton species inhabiting the Chukchi Sea, with species diversity dominated by copepods (e.g. Sirenko, 2001; <http://www.marinespecies.org/arms/index.php>). Nonetheless, prior to the lease sale, we lacked comprehensive estimates of the abundance, biomass and relative composition of the zooplankton throughout the Chukchi Sea, and in particular their seasonal and inter-annual variability. In this regard, recent publications by RUSALCA (Russian American Long-term Census of the Arctic), SBI (Shelf-Basin Interactions) and Arctic Ocean Biodiversity (ArcOD) programs provide excellent regional context with which to compare the result of this program (Questel *et al.*, *in press*).

It is now clear that the spatial distribution of zooplankton communities in the Chukchi Sea is largely tied to the different water masses present in this region (Hopcroft *et al.*, 2010, Questel *et al.* *in press*). While copepod crustaceans generally dominate zooplankton communities in most ocean regions, both larvaceans and meroplankton contribute significantly to community abundance and biomass (Lane *et al.*, 2008; Hopcroft *et al.*, 2009, 2010a,b). Similarly, a relatively diverse group of jellyfish, and a single species of chaetognaths remain important predatory components of the zooplankton community (Ashjian *et al.*, 2003; Lane *et al.*, 2008; Hopcroft *et al.*, 2005, 2009, 2010a,b). Arguably the greatest strength of this study has been the observation of the seasonal progression of the planktonic communities, and a consistent sampling framework to highlight the extent of spatial and inter-annual variability within these communities.

METHODS

Survey Design

The 2011 schedule consisted of a 20 day cruise in August followed by a 40 day cruise from early September into early October; the survey area on the later cruise being greatly expanded from previous years (Fig. 1). The core sampling areas occurred within of a 30 x 30 nautical mile (NM) box at the Klondike and Burger surveys, with a grid of 5x5 stations, at ~7.5 NM spacing, plus a somewhat irregular rectangle of 22 stations at similar spacing within the Statoil survey. The expanded sampling domain was approximately 120 NM across. Bottom depth over the core survey areas was similar and relatively constant, varying between approximately 35 and 45 m, and slightly deeper in parts of the expanded grid. Inorganic macronutrients, phytoplankton (as chlorophyll) and metazoan zooplankton were sampled on each cruise, concurrent with collection of CTD measurements.

Collection Procedures

Phytoplankton were assessed as chlorophyll *a* concentration from samples collected with 4-L Niskin bottles on a Seabird SBE19/SBE55 CTD rosette (Weingartner and Danielson, 2010) during upcasts at 6 depths per station: 0, 5, 10, 20, and 30 m, plus 3m above the sea floor. Samples were filtered under low pressure onto 47-mm Whatman GF/F filters and frozen at -20 °C for post-cruise analysis (Parsons *et al.*, 1984). Nutrient samples were taken from the same Niskin bottles as chlorophyll, frozen immediately and analyzed post-cruise for nitrate, phosphate and silicate concentrations (Whitledge *et al.*, 1981; Gordon *et al.*, 1993).

Smaller metazooplankton were collected at each station by paired 150- μ m-mesh ring nets of 60-cm diameter hauled vertically from within 3 m of the bottom to the surface at 0.5 m s⁻¹. The volume of water filtered was measured by Sea-Gear flowmeters in each vertical net. To target larger, more mobile zooplankton, a set of 60-cm diameter 505- μ m Bongo nets were deployed in a double oblique tow with the ship moving at an average speed of 2 kts. General Oceanic flowmeters installed in each Bongo net were used to estimate the volume of water filtered. Upon retrieval, at primary stations, both samples were preserved in 10% buffered formalin, while at secondary stations one sample of each mesh size was preserved in 10% formalin, and the other in 95% ethanol (required for molecular identification). When present, large cnidarians and ctenophores were removed, measured, photographed, identified and then discarded prior to sample preservation.

Sample Processing

Frozen filters were extracted for chlorophyll *a* in 95% acetone and concentrations determined fluorometrically post-cruise (Parsons *et al.*, 1984) using a Turner Fluorometer. Measurements can be used to calibrate *in vivo* fluorescence profiles measured at stations. Integral chlorophyll concentration was calculated by assuming each depth represented the concentration to the midpoint depth between each sampling interval. Frozen nutrient samples were measured post-cruise using an Alpkem Rapid Flow Analyzer (Whitledge *et al.*, 1981) and conformed to WOCE standards (Gordon *et al.*, 1993).

Formalin-preserved samples were processed for quantitative determination of species composition, and prediction of biomass, at 13 stations for Klondike and Burger and at 11 stations

for Statoil. Alternating samples were analyzed within the expanded grid yielding and additional 46 samples outside the primary surveys. During taxonomic processing, all larger organisms (primarily shrimp and jellyfish) were removed, enumerated, and measured, then the sample was divided with a Folsom splitter until the smallest subsample contained about 100 specimens of the more abundant taxa. Specimens were identified to the lowest taxonomic category possible, staged where appropriate, enumerated, and measured (Roff and Hopcroft, 1986). Increasingly larger fractions were examined to identify, measure, enumerate and weigh the larger, less abundant taxa, particularly in the 505- μm net which typically captures the largest taxonomic diversity. A minimum of 300 individual organisms were identified from each sample. Larval fish were excluded from the analysis, and passed to the fisheries ecology team for detailed identification.

If earlier copepodites could not be distinguished, they were grouped with the sibling species. Adults were identified to the species level. In the case of *Calanus*, where distinguishing *C. marshallae* from *C. glacialis* has proven problematic, we assumed they were represented primarily by the latter species (Nelson et al. 2009). The larger *C. hyperboreus* was distinguished by size (e.g. Unstad and Tande, 1991; Hirche *et al.*, 1994). The weight of each specimen was predicted from species-specific relationships, or from those of a morphologically similar species of holozooplankton (Table 1). For the 2011 season, considerable effort was taken to refine these relationships for meroplankton, decapods, and ice-associated amphipods. The impact of these changes was greatest for the decapod larvae, where weights have been under predicted in previous years by 10-20 fold. No published length-weight has been discovered for echinoderm larvae, which still remain crude approximations. Where necessary, ash-free dry weight (AFDW) was converted to dry weight (DW) assuming 10% ash (Båmstedt, 1986), and dry weight was assumed to be 18% of wet-weight (Davis and Weibe, 1985). We assumed carbon to be 40% of DW for *Oikopleura vanhoeffeni*, as is typical of many copepods (Båmstedt, 1986).

Data Analysis

In addition to a descriptive summary, community patterns were explored using the Primer (V6) software package which has been shown to reveal patterns in zooplankton communities (e.g. Clarke and Warwick 2001; Wishner *et al.*, 2008). Data sets were power transformed (4th root), and the Bray-Curtis similarity index between stations was calculated employing all taxonomic categories that contributed at least 3% to any sample in that dataset. Significant groups within the hierarchical clustering were established with the SIMPROF routine, and these clusters were superimposed on the 2D and 3D plots of the multi-dimensional scaled (MDS) datasets, as well as spatial plots of the data. Relationships linking zooplankton community patterns with normalized physical data (above and below the thermocline) and integral chlorophyll were explored with Primer's BEST routine.

Quality Control Procedures

In the field, samples were collected in duplicate, so discrepancies in the flowmeter readings were readily apparent. The SeaGear meters used on the vertical nets are rigged not to spin during descent, but can be problematic - when measured values were unreasonably large they were constrained to station depth. During the first cruise we ran one-way General Oceanic and SeaGear flowmeters in tandem, and confirmed the former to be more reliable. When values from both brands of flowmeters were taken concurrently, the GO flowmeter values were employed.

Table 1. Relationships employed to predict weight from length for the holozooplankton encountered in the study region. Where species-specific relations were not employed we used relationships from: * *T. japonica*, ** *Oithona nana*, + *F. pellucida*, ++ *Pseudocalanus*. DW- dry weight, AFDW- ash-free dry weight, CW- carbon weight, BL-total body length, TL-trunk length, PL- prosome length, CL- carapace length, SD- shell diameter

Species	Regression	Units	Source
<i>Acartia longiremis</i>	$CW=1.023 \cdot 10^{-8} \cdot PL^{2.906}$	μm, μg	Hansen <i>et al.</i> , 1999
<i>Calanus glacialis/marshallae</i>	$\log DW=4.034 \cdot \log PL-11.561$	μm, μg	Liu & Hopcroft, 2007
<i>Calanus hyperboreus</i>	$DW = 0.0027 \cdot PL^{3.718}$	mm, mg	Ashjian <i>et al.</i> , 2003
<i>Centropages abdominalis</i>	$\log DW = 3.00 \cdot \log PL-7.89$	μm, μg	Uye, 1982
<i>Eucalanus bungii</i>	$\log DW=3.091 \cdot \log PL-0.0026$	mm, μg	Hopcroft <i>et al.</i> , 2002
<i>Eurytemora herdmani</i>	$\log DW = 2.96 \cdot \log PL-7.60$	μm, μg	Middlebrook & Roff, 1986
<i>Metridia longa</i>	$DW = 0.0101 \cdot PL^{3.100}$	mm, mg	Mumm, 1991
<i>Metridia pacifica</i>	$\log DW = 3.29 \cdot \log PL-8.75$	μm, μg	Liu & Hopcroft, 2006b
<i>Neocalanus plumchrus/flemingerii</i>	$\log DW=3.56 \cdot \log PL-2.32$	mm, mg	Liu & Hopcroft, 2006a
<i>Neocalanus cristatus</i>	$\log DW=4.001 \cdot \log PL-11.776$	μm, μg	Kobari <i>et al.</i> , 2003
<i>Paraeuchaeta</i> spp.	$AFDW=0.0075 \cdot PL^{3.274}$	mm, mg	Mumm, 1991
<i>Pseudocalanus</i> spp.	$\log DW=-2.85 \cdot \log PL-7.62$	μm, μg	Liu & Hopcroft, 2008
<i>Oithona similis</i> **	$\log AFDW=3.16 \cdot \log PL-8.18$	μm, μg	Hopcroft <i>et al.</i> , 1998
<i>Oncaea</i> spp.**	$\ln DW=2.90 \cdot \ln PL-16.81$	μm, μg	Satapoomin, 1999
<i>Oikopleura vanhoeffeni</i>	$\log C=3.20 \cdot \log TL-8.93$	μm, μg	Deibel, 1986
<i>Fritillaria borealis</i> ⁺	$\log DW=3.21 \cdot \log TL-9.11$	μm, μg	Fenaux, 1976
Other calanoids ⁺⁺	$\log DW=-2.85 \cdot \log PL-7.62$	μm, μg	Liu & Hopcroft, 2008
<i>Microsetella norvegica</i>	$CW=2.65 \cdot 10^{-6} \cdot BL^{1.95}$	μm, μg	Uye <i>et al.</i> , 2002
Other harpacticoids	$DW=8.148 \cdot 10^{-8} \cdot BL^{2.736}$	μm, μg	Ara, 2001
<i>Themisto abyssorum/pacifica</i> *	$DW=0.0049 \cdot BL^{2.957}$	mm, μg	Ikeda & Shiga, 1999
<i>Themisto libellula</i>	$DW=0.006 \cdot BL^{2.821}$	mm, μg	Auel & Werner, 2003
<i>Apherusa glacialis</i>	$DW=2.556 \cdot BL^{3.0960}$	mm, μg	Werner & Auel, 2005
<i>Gammarus</i> spp.	$DW=0.824 \cdot BL^{3.378}$	mm, μg	Werner & Auel, 2005
<i>Onisimus</i> spp.	$DW=8.558 \cdot BL^{2.890}$	mm, μg	Werner & Auel, 2005
Ostracods	$AFDW=0.0228 \cdot BL^{2.3698}$	mm, mg	Mumm, 1991
<i>Thysanoessa inermis/raschii</i>	$\log DW=2.50 \cdot \log CL-1.162$	mm, mg	Pinchuk & Hopcroft, 2007
<i>Eualus gaimardi</i> , other decapods	$WW=8.56 \cdot BL^{2.995}$	mm, μg	Weslawski, 1987
Mysids	$WW=0.20 \cdot BL^{3.678}$	mm, μg	Chippis & Bennett, 2000
<i>Evadne</i> & <i>Podon</i>	$\log DW=4.0 \cdot \log BL-10.5$	μm, μg	Uye, 1982
<i>Tomopteris</i>	$DW=0.005 \cdot BL^{2.25}$	mm, mg	Matthews & Hestad, 1977
<i>Clione limacina</i>	$\ln WW=2.53 \cdot \log BL-6.89$	mm, mg	Davis & Wiebe, 1985
<i>Limacina helicina</i>	$AFDW=0.0390 \cdot SD^{3.5032}$	mm, mg	Mumm 1991
<i>Eukrohnia hamata</i>	$DW=0.00032 \cdot BL^{3.00}$	mm, mg	Matthews & Hestad, 1977
<i>Parasagitta elegans</i>	$DW=0.000064 \cdot BL^{3.30}$	mm, mg	Matthews & Hestad, 1977
<i>Aglantha digitale</i> & other jellies	$DW=0.00194 \cdot PL^{3.05}$	mm, mg	Matthews & Hestad, 1977
Decapod zoea	$\log DW=2.35 \cdot \log CL+1.74$	mm, μg	Lindley, 1998
Decapod megalopa	$\log DW=2.58 \cdot \log CL+2.04$	mm, μg	Lindley, 1998
Barnacle nauplii	$\log DW=3.356 \cdot \log BL-9.060$	μm, μg	Muxagata <i>et al.</i> 2004
Barnacle cyprids	$\log DW=2.763 \cdot \log BL-6.985$	μm, μg	Muxagata <i>et al.</i> 2004
Bivalve larvae	$DW=0.000000306 \cdot BL^{2.88}$	μm, μg	Fotel <i>et al.</i> 1999
Polychaete larvae	$\log DW=2.06 \cdot \log BL-5.372$	μm, μg	Hansen, 1999

In the lab, replicate samples are not routinely analyzed, but serve as insurance in the event one sample is compromised. Data files were inspected for valid taxa and taxa-specific length measurements. Where necessary, specimens were compared to the voucher set housed at UAF, and periodic cross-comparison occurred between the co-authors processing samples.

RESULTS

Nutrients and chlorophyll

Nitrate, silicate and phosphate were virtually absent from surface waters even during the first cruise, generally increased toward the seafloor, and were somewhat irregular in their profiles within each grid (Fig. 2-15). Chlorophyll concentrations were consistent with the patterns of these nutrients that fuel phytoplankton production, being extremely low in the upper 10m, but frequently increased below this, typically with increased concentrations below 20 m (Fig. 2, 4, 6, 8, 10, 11, 14). All nutrients were low over Klondike on the first cruise (Fig. 2, 3), and virtually disappeared on the second cruise (Fig. 8, 9). On the first cruise, notable deep nutrient concentrations occurred at depth within Burger and Statoil, with some deep pools still remaining at Burger and Statoil on the second cruise (Fig. 4-7, 10-15). Chlorophyll declined concurrently between cruises (Fig. 16). Looking across the extended study area (Fig. 14-15, 17-19), there is a clear increase in deep nutrient pools moving from south to north for nitrate, a less strong pattern for phosphate and little pattern for silicate.

Chlorophyll concentrations were notably variable within each survey, with some moderate peaks observed at a few stations during each cruise (Fig. 16). As in previous years, mean concentrations at Klondike were lower than at Burger or Statoil, with concentrations declining on the second cruise, especially at Klondike (Table 2). Over the expanded study area, chlorophyll averaged 28.6 mg m^{-2} , with lowest values in the south. The surface nutrient depletion accompanied by low chlorophyll suggests that sampling had occurred post-spring phytoplankton bloom. While spatially consistent near-bottom and mid-water increases are confirmed by *in situ* fluorescence profiles (not shown), it is possible that some of the spottier deep-water increases are a consequence of the CTD having hit bottom and contaminated the rosette with chlorophyll-rich sediments.

Table 2. Average integral chlorophyll concentration (mg m^{-2}) at the Klondike, Burger and Statoil survey grids during 2011.

Cruise	Klondike	Burger	Statoil
August	32.1	43.5	49.6
September	15.5	29.3	43.8

Zooplankton

In total, 83 taxonomic categories of zooplankton, including 12 meroplanktonic larval categories, were observed during the 2011 field year. An average abundance of $4505 \text{ individuals m}^{-3}$ and $37.7 \text{ mg DW m}^{-3}$ was captured by the $150\text{-}\mu\text{m}$ net and an average of 134 m^{-3} and $26.3 \text{ mg DW m}^{-3}$ captured by the $505\text{-}\mu\text{m}$ net over the Klondike, Burger and Statoil survey grids (Table 3). The equivalent numbers including the expanded survey grid were very similar: 4408 m^{-3} and

Table 3. Zooplankton species observed during 2011, in the Klondike, Burger and Statoil surveys, along with their average abundance and biomass across all samples examined. Data is presented for both vertical 150- μm collections and the 505- μm oblique tows. ‘Trace’ refers to taxa observed only once or twice during analysis and of insignificant biomass.

	150- μm net		505- μm net	
	Abundance (Ind. m^{-3})	Biomass (mg DW m^{-3})	Abundance (Ind. m^{-3})	Biomass (mg DW m^{-3})
Copepoda				
<i>Acartia</i> spp.	29.86	0.033	0.06	0.000
<i>Acartia longiremis</i>	16.48	0.076	1.18	0.006
<i>Acartia hudsonica</i>	0.50	0.003	0.00	0.000
<i>Eurytemora pacifica</i>	0.37	0.002	0.00	0.000
<i>Calanus hyperboreus</i>	0.31	0.201	0.26	0.154
<i>Calanus glacialis/marshallae</i>	72.68	13.930	58.04	13.133
<i>Centropages abdominalis</i>	5.34	0.031	0.10	0.001
<i>Epilabidocera amphitrites</i>	0.09	0.001	0.00	0.000
<i>Eucalanus bungii</i>	0.78	0.089	0.27	0.041
<i>Gaetanus tenuispinus</i>	Trace	Trace	0.00	0.000
<i>Metridia longa</i>	0.03	0.001	0.11	0.005
<i>Metridia pacifica</i>	29.57	0.437	1.32	0.073
<i>Microcalanus pygmaeus</i>	0.25	0.000	0.00	0.000
<i>Neocalanus flemingerii</i>	1.40	0.507	0.58	0.314
<i>Neocalanus plumchrus</i>	0.21	0.096	0.01	0.009
<i>Neocalanus cristatus</i>	0.15	0.855	0.27	1.378
<i>Paraeuchaeta glacialis</i>	0.00	0.000	0.01	0.004
<i>Pseudocalanus</i> spp. (juvenile)	18.59	0.099	0.34	0.002
<i>Pseudocalanus</i> spp. (male)	920.11	2.852	3.79	0.032
<i>Pseudocalanus minutus</i>	13.41	0.215	3.15	0.067
<i>Pseudocalanus acuspes</i>	31.92	0.345	1.71	0.028
<i>Pseudocalanus newmanii</i>	33.91	0.194	0.44	0.003
<i>Pseudocalanus mimus</i>	11.09	0.206	0.06	0.001
<i>Tortanus discaudatus</i>	Trace	Trace	0.00	0.000
<i>Oithona similis</i>	931.86	1.125		
<i>Triconia (Oncaea) borealis</i>	7.13	0.019		
Harpacticoida	1.30	0.007		
<i>Microsetella norvegica</i>	1.59	0.002		
Calanoida nauplii	375.20	0.208		
Cyclopoida nauplii	57.88	0.014		
Larvaceans				
<i>Oikopleura vanhoeffeni</i>	407.96	1.121	30.71	0.169
<i>Fritillaria borealis</i>	989.89	0.028	0.84	0.000
Pteropods				
<i>Limacina helicina</i>	30.37	4.121	0.52	0.667
<i>Clione limacina</i>	0.05	0.140	0.07	0.337
Cladocerans				
<i>Podon leuckartii</i>	0.06	0.000	0.00	0.000
Ostracods				
<i>Boroecia maxima</i>			trace	

Table 3 continued

	150- μ m net		505- μ m net	
	Abundance	Biomass	Abundance	Biomass
Euphausiids				
<i>Euphausiid nauplii</i>	1.75	0.006	0.00	0.000
<i>Euphausiid calyptopis</i>	0.36	0.000	0.09	0.001
<i>Euphausiid furcillia</i>	3.40	0.141	3.36	0.227
<i>Euphausiid juvenile</i>	0.33	0.105	0.58	0.147
<i>Thysanoessa inermis</i>	0.00	0.004	0.00	0.000
<i>Thysanoessa longipes</i>	0.00	0.000	0.63	0.370
<i>Thysanoessa raschii</i>	0.01	0.007	0.31	0.163
<i>Thysanoessa spinifera</i>	Trace	0.000	Trace	0.000
Shrimps and Mysids				
Hippolytidae (juvenile)	0.04	0.049	0.12	0.100
Pandalidae (juvenile)	0.01	0.028	0.02	0.163
<i>Eualus gaimardii</i>	0.00	0.005	0.00	0.144
<i>Mysis oculata</i>	Trace		0.01	0.392
<i>Mysis/Neomysis spp.</i>	0.00	0.000	0.00	0.000
Amphipods				
<i>Apherusa glacialis</i>	0.00	0.000	0.00	0.011
<i>Hyperia galba/medusarum</i>	0.05	0.003	0.02	0.009
<i>Hyperoche medusarum</i>	0.09	0.152	0.03	0.036
<i>Themisto libellula</i>	0.00	0.026	0.01	0.222
<i>Themisto abyssorum/pacifica</i>	0.01	0.025	0.05	0.037
Gammaridae	0.07	0.016	0.07	0.018
Ctenophores				
<i>Ctenophora</i>	0.05	0.058	0.00	0.015
<i>Mertensia ovum</i>	0.47	0.971	0.36	0.861
Cnidarians				
<i>Aeginopsis laurentii</i>	0.21	0.000	0.01	0.006
<i>Aglantha digitale</i>	67.08	2.195	8.96	2.966
<i>Bougainvillia superciliaris</i>	Trace		Trace	
<i>Catablema vesicarium</i>	0.06	0.952	0.01	0.080
<i>Halitholus cirratus</i>	0.00	0.023	0.00	0.000
<i>Melicertum octopunctata</i>	0.06	0.045	0.02	0.048
<i>Obelia longissima</i>	0.00	0.000	0.00	0.000
<i>Rathkea octopunctata</i>	0.23	0.003	0.03	0.000
<i>Sarsia tubulosa</i>	0.00	0.002	0.00	0.000
<i>Tiariopsis multicirrata</i>	0.00	0.032	0.00	0.000
Miscellaneous cnidaria	1.81	0.001	0.01	0.148
<i>Aurelia aurita</i>	0.00	0.000	0.00	0.084
<i>Cyanea capillata</i>	0.00	0.000	0.00	0.033
<i>Chrysaora melanaster</i>			observed	
Chaetognaths				
<i>Eukrohnia hamata</i>	0.00	0.000	0.01	0.003
<i>Parasagitta elegans</i>	30.88	8.351	6.70	6.133
Polychaetes				
<i>Tomopteris sp.</i>	0.31	0.006	0.00	0.000
TOTAL Holozooplankton	4037	31.8	118	22.7

Table 3 continued	150- μm net		505- μm net	
	Abundance	Biomass	Abundance	Biomass
Bivalvia larvae	110.17	0.029		
Gastropod larvae	0.66	0.000		
Barnacle cyprid	244.04	4.306	6.95	0.132
Barnacle nauplii	21.31	0.042	5.28	0.023
Decapoda zoea	0.36	0.104	0.62	2.103
Paguriidae zoea	0.15	0.119	0.39	0.336
Crangonidae zoea	0.00	0.00	0.01	0.00
Decapoda megalopa	0.31	0.448	0.87	1.031
Polychaeta larvae	181.24	0.906	1.27	0.014
Ophiuroid larvae	0.43	0.001		
Asteroid bipinnaria	20.50	0.011		
Echinoid larvae	9.48	0.001		
Total Meroplankton	468	5.9	15.4	3.6
TOTAL Zooplankton	4505	37.7	134	26.3

31.3 mg DW m⁻³ captured by the 150- μm net, and 104 m⁻³ and 21.2 mg DW m⁻³ captured by the 505- μm . The greatest diversity was observed within the copepods (25 species, plus juvenile categories), followed by the cnidarians (13 species). The relative importance of taxa varied depending on the net considered, and whether abundance or biomass was used for such assessment. For the 150- μm nets, abundance was dominated by the cyclopoid copepod *Oithona similis*, the small larvacean *Fritillaria borealis*, and the *Pseudocalanus* copepod species complex all in nearly equal numbers, followed by copepod nauplii, the larvacean *Oikopleura vanhoeffeni*, barnacle larvae (nauplii and cyprids), polychaete larvae, and bivalve larvae, all averaging more than 100 m⁻³. These were followed by the copepod *Calanus glacialis*, and the hydromedusae *Aglantha digitale* that exceeded 50 m⁻³. Biomass in the 150- μm nets was dominated by several of these taxa: the copepod *Calanus glacialis* contributed the greatest to biomass, followed by the chaetognath *Parasagitta elegans*, barnacle larvae, the *Pseudocalanus* copepods, and the medusae *Aglantha digitale*.

In contrast, the top 10 abundance ranking for the 505- μm nets was led by the copepod *Calanus glacialis* (nearly half of the holozooplankton), the larvacean *Oikopleura vanhoeffeni*, the medusae *Aglantha digitale*, the barnacle larvae (cyprids plus nauplii), the chaetognath *Parasagitta elegans*, the *Pseudocalanus* species complex, larval euphausiids, the copepod *Metridia pacifica*, and larval decapods, and the larvacean *Fritillaria borealis*. Biomass in the 505- μm nets was dominated by the copepod *Calanus glacialis*, and the chaetognath *Parasagitta elegans*, with only the medusae *Aglantha digitale*, the copepod *Neocalanus cristatus*, crab larvae, and the ctenophore *Mertensia ovum* contributing more than 0.5 mg DW m⁻³. The top ten ranked biomass was rounded out with the euphausiid *Thysanoessa inermis*, euphausiid larvae, the amphipod *Themisto libellula*, and the copepod *Neocalanus flemingerii*. Collections in 2011 are notable in that the Arctic basin copepods *Calanus hyperboreus* and *Metridia longa* were observed in the 505- μm nets at multiple stations, often in non-trivial abundances.

Summarizing the averages for each cruise by major taxonomic groups, in terms of abundance copepods and larvaceans, followed by meroplankton, appear to dominate numerically across all cruises for both nets (Fig. 21). Based on the 505- μm net, large-bodied copepod numbers were relatively more abundant on the first compared to the second cruise. Predatory groups remained

low in numbers across all cruises, and there is a suggestion that zooplankton numbers declined from south to north on the second cruise. In terms of biomass, copepods again dominated both nets, with limited contribution by larvaceans, while meroplankton, chaetognaths and hydrozoan medusae became visible predatory components (Fig. 22).

Changes in the relative contributions of the different groups are more striking when viewed at the station level (Fig. 23-26). For the 150- μm nets, in August each survey area appears distinct: Klondike was dominated numerically by copepods and their nauplii, followed by larvaceans; meroplankton became more prominent in Burger; and moving across Statoil copepods declined as larvaceans became more important (Fig. 23). In September/October copepods were more important in the southwest and declined in relative importance in the northeast except along the northern-most boundary. In terms of biomass, copepods often dominated, with obvious contributions from chaetognaths, medusae, and meroplankton, with increased importance of others (mostly amphipods in the Northern Hanna Shoals on the later cruise (Fig. 24). In terms of numerical contribution for the 505- μm nets, in August Klondike appeared dominated by numerous small larvaceans over-retained by the net (Fig. 25), while Burger and Statoil showed dominance by copepods with greater numbers of meroplankton. In September/October copepods dominated in many areas while medusae dominated in other patches. In terms of biomass, while copepods remained important at many stations, they were often displaced in importance by meroplankton (predominately decapod larvae), chaetognaths and medusae (Fig. 26).

Looking more closely at the species and genus level, faunal differences become apparent between the cruises and survey areas. For the 150- μm nets, the strongest signals were in the copepods, *Calanus glacialis*, *Neocalanus* spp., *Metridia pacifica*, barnacle larvae and polychaete larvae which declined between cruises, while echinoderm larvae and bivalve larvae may have increased (Fig 27-30). For the 505- μm nets, somewhat similar patterns are observed for these same species, with both the medusae *Aglantha digitale* and the chaetognath *Parasagitta elegans* also increasing (Fig. 30-33).

Broad-scale patterns

The greater Hanna Shoal survey conducted in 2011 provides a unique opportunity to examine zooplankton community patterns over an extended scale. Beginning with the 150- μm nets, it appears copepods are more abundant in the southern part of the survey (Fig. 34), although increased numbers along the deeper northern edge of the sampling area suggest the pattern may be partly related to depth. This pattern of zooplankton holds for the abundant neritic genera *Pseudocalanus*, *Oithona*, and particularly *Acartia* (Fig. 35), but *Calanus glacialis* shows a different pattern where it is most abundant in the deepest waters (Central Channel, shelf break, Burger) with the suggestion of an incursion of more oceanic water from the Barrow Canyon counter flow. Larvaceans are more evenly distributed, although abundances declined somewhat in the middle of the survey region, the pteropod *Limacina* appeared more prominent in the northeastern sampling region, and meroplankton was distributed throughout the region (Fig. 36). The predatory groups, chaetognath and medusae, appeared somewhat more concentrated in the middle of the sampling region, while euphausiids were concentrated in the southern region with two pronounced patches encountered (Fig 37).

The 505- μm nets show an accentuation of some patterns suggested by the 150- μm nets. Large copepods are most abundant at deeper stations (Fig. 38), with patterns most pronounced

for the polar *Calanus glacialis*, and a strong incursion signal observed for the Arctic endemic species *Calanus hyperboreus*. In contrast, the two large Pacific copepod groups, *Eucalanus bungii* and the 3 species of *Neocalanus* are only prominent in the southern parts of the study area, while later stages of *Metridia* are only abundant in waters deeper than 50 m (Fig. 39). Euphausiids remain more abundant in the southern parts of the study area, while medusae and chaetognaths are more spread-out, although the latter seems to avoid the shallowest parts of Hanna Shoal (Fig 40).

Community patterns

Cluster analysis of samples using Bray-Curtis similarity on the 150- μ m abundances, suggested ~12 distinct clusters (and several strays) within the samples, with ~5 major clusters emerging at the ~75% similarity level (Fig. 41). The first Klondike cruise tends to distinctly cluster from the other survey grids, then groups most closely the more southern stations in the expanded Hanna Shoals domain, and then groups with the second Klondike survey. Most of Burger and Statoil tended to be intertwined on the first survey (although several stations remained outcasts), and this cluster was very distinct from both Klondike's first cruise and all stations sampled during the second cruise. Most of Burger and Statoil remained intertwined on the second cruise, and interestingly were distinct from the extended Hanna Shoal survey areas. In general, these grouping are also supported by the multidimensional scaling (MDS) of the data (Fig. 42). MDS plots also suggest collections are moving along a temporal trajectory between the first and second cruise, with the Statoil stations becoming somewhat intermediary between the Klondike and Burger stations, and the Northern Hanna shoal stations being more distant in similarity. Not surprisingly, the transitional stations fell between and/or overlap the 3 primary survey grids.

Cluster analysis of the 505- μ m zooplankton abundances again showed Klondike being divergent on the first cruise, with Burger and Statoil intertwined, and some mingling of all 3 areas, but the 3 surveys became more separated on the second cruise (Fig. 43). Klondike remained relatively distinct on the second cruise although it clustered with some of the south Hanna Shoal region, and it was also more similar to the first cruise than the majority of the second survey. Burger mostly clustered together on the second cruise, while Statoil was dispersed within the extended Hanna Shoal survey areas. The MDS analysis was consistent with this interpretation and also consistent in overall structure with the patterns observed in the 150- μ m nets (Fig. 44), but suggests greater dispersion of the communities within a survey grid during the September period then observed during August. As in previous years, Primer's BEST routine indicated that temperature, as well as consecutive days of sampling, salinity, fluorescence and station depth explains a moderate level of the observed patterns.

Inter-annual comparisons

A comparison across the four years by sampling month does not show large differences between abundances in August (Fig. 45), although it appears that 2011 began as a year favorable to copepods. In terms of biomass, August 2011 was somewhat higher for both large- and small-bodied copepods compared to prior years (Fig. 46). In contrast, September 2011 was relatively unremarkable in terms of copepods numbers compared to the prior year (Figure 47), but was more comparable to 2010 in terms of biomass for many zooplankton categories (Figure 48).

Looking at the species-level details, in the 150- μm nets abundances of the major zooplankton copepod genera saw declines in copepod abundances compared to the peak year of 2010, with the exception of *Calanus* and *Metridia* during August, and for the larvacean *Oikopleura* (Fig. 49), with even the meroplankton declining (Fig. 50). In the 505- μm nets, the large copepod *Calanus glacialis* was also more abundant in August 2011 than observed in 2010, although other large-bodied Pacific copepods (i.e. *Eucalanus* and *Neocalanus*) tended to decline (Fig. 51). As also indicated in the 150- μm nets, abundance of the filter-feeding larvacean *Oikopleura* and euphausiids (mostly larval and juvenile stages) were higher in 2011 than previous years (Fig. 52). Among the larger predators, the cnidarian *Aglantha digitale* and the chaetognath *Parasagitta elegans* remained abundant in 2011 (although lower than in 2010), while the ctenophore *Mertensia ovum* increased slightly in abundance (Fig. 53).

DISCUSSION

Chlorophyll and Nutrients

Phytoplankton pigments and their spatial or temporal variations during the spring and summer are related to water-column irradiance and nutrient concentration (Hill et al., 2005; Lee et al., 2007). High concentrations of nutrients in the surface waters during spring are typically depleted rapidly during bloom conditions along the ice edge, or in open water where stratification limits replenishment of nutrients from below the mixed layer to the surface. Thus, observations north of our study area near the shelf break (Hill et al., 2005) show low chlorophyll concentrations and moderate nutrients during the ice-covered period. This gives way to depleted surface nutrients and subsurface chlorophyll peaks of 2-12 mg m^{-3} during the spring bloom, consistent with our observations. Further removed from our study area, concentration peaks in excess of 200 mg m^{-2} have been observed, although values below 50 mg m^{-2} are also common (Lee et al., 2007).

During all the 2011 surveys, low nutrient and chlorophyll concentrations were persistent in surface waters, with even subsurface nutrients and most chlorophyll notably depleted at all depths for Klondike on both surveys. In contrast, Burger and Statoil showed some subsurface nutrients and chlorophyll in August, which declined further for Burger in September. In aggregate these observations indicate all sampling occurred post-bloom in August, but that some elevated chlorophyll was maintained by the higher nutrients persisting in the winter-water deep cold-pools that remained at Burger and Statoil (Weingartner et al., 2013). Differing transport rates and water masses between the survey areas thus contribute to some of the observed differences. A compilation of chlorophyll values from the 1974-1995 period (Dunton et al., 2005) suggest large spatial gradients of chlorophyll occur throughout the Chukchi Sea, with their value in our study area approximately 80-200 mg m^{-2} . Our 2011 observations generally fall below these estimates.

Zooplankton composition

The Chukchi Sea displays a similar level of species diversity, but high summer biomass compared to the adjoining East Siberian (Jaschnov, 1940; Pavshstiks, 1994) and Beaufort (e.g. Horner, 1981) seas. In contrast, the Chukchi Sea has lower diversity than is present in the adjoining vertically-structured central Arctic basins where depths can exceed 3000 m (e.g. Kosobokova and Hirche, 2000; Kosobokova and Hopcroft, 2010). As was observed for the past

3 years (Questel et al, *in press*), most copepod species observed in this study were common to the subarctic Pacific Ocean and/or the Bering Sea rather than specific to the Arctic (Brodsky, 1950, 1957) due to the generally northward advection of waters through the Bering Strait (e.g. Weingartner *et al.*, 2005). The genus *Calanus* provides a notable exception this habitat affinity, with a Pacific genotype of the Arctic endemic *Calanus glacialis* now believed to be maintained in the Bering Sea (Nelson et al. 2009). Furthermore, in this study year an incursion of offshore Arctic water appears to have occurred over Burger bringing in the Arctic endemic *Calanus hyperboreus* (see below). In contrast to most other planktonic groups, the hydrozoan medusae assemblage is more arctic in character, presumably because they are released to the water column by their benthic life-stage further south within the Chukchi. Nonetheless, the zooplankton community composition is generally similar to that observed by other studies during the summer ice-free period in this region when similar-sized finer collecting meshes are employed (e.g. Springer *et al.*, 1989; Kulikov, 1992; Hopcroft *et al.*, 2010), or similar coarser nets are compared (e.g. Wing, 1974; English and Horner, 1977).

In contrast, our estimates of ~ 4500 individuals m^{-3} and ~ 38 mg DW m^{-3} (~ 1.6 g DW m^{-2}) captured by the 150- μm net, and the average of 135 individuals m^{-3} and 26.3 mg DW m^{-3} (~ 0.75 g DW m^{-2}) captured by the 505- μm net are comparable to previous studies from the Chukchi Sea. In waters to the south and west of the Klondike and Burger survey areas an average of 5760 individuals m^{-3} and 42 mg DW m^{-3} were recently determined using identical techniques with a 150- μm vertical net (Hopcroft *et al.*, 2010). There is also a broad range of older biomass estimates for the region, ~ 2 g DW m^{-2} for herbivorous zooplankton in summer north and south of the Bering Strait (Springer *et al.*, 1989), 2.5-5.5 g DW m^{-2} on the US side of the Chukchi Sea or 1.3 g DW m^{-2} spanning both sides of the Chukchi (Turco, 1992a, b). Furthermore, 14.8 g WW m^{-2} (Kulikov, 1992) and 356 mg WW m^{-3} (14.2 g WW m^{-2} - Pavshchikov, 1984) for all mesozooplankton spanning the Chukchi Sea are also somewhat lower, if we assume DW is 10-15% of WW (Wiebe *et al.*, 1975). Our 2011 observations overlap the range of recent observations (3-58 mg DW m^{-3}) to the north of the study area near the shelf break (Lane *et al.* 2008; Llinás *et al.*, 2009), as well as values for the upper 50 m (42 mg DW m^{-3}) further into the adjoining basin (Kosobokova and Hopcroft, 2010).

In terms of composition, the species observed in this study have all been reported previously for this region, but not consistently within a single publication. Our 505- μm data is directly comparable to data from the ISHTAR (Inner Shelf Transfer and Recycling) program (Springer *et al.*, 1989; Turco, 1992a,b), who noted the predominance of *Calanus marshallae/glacialis*, *Pseudocalanus* spp., *Acartia longiremis* and *Oikopleura* among the herbivorous grazers. In addition to awareness of differences between collecting mesh size, detailed comparison to previous studies also requires an awareness of changes in taxonomic resolution, and taxonomy itself (e.g. *Pseudocalanus* - Frost, 1989; *Neocalanus* - Miller, 1988; *Calanus* - Frost, 1974). Even today, routine morphological separation of several of these species is difficult (Llinás, 2007; Lane *et al.*, 2008). Other holoplanktonic crustacean groups, such as euphausiids and cladocerans, present less of a taxonomic challenge, although they are not always reported to the species level. Non-crustacean groups have been recorded with variable resolution and proficiency in previous studies. This study is consistent with an emerging realization that considerable populations of larvaceans, specifically the large arctic *Oikopleura vanhoeffeni* and the much smaller *Fritillaria borealis*, are present in the northern Bering and Chukchi Sea (e.g. Kulikov, 1992; Lane *et al.*, 2008; Hopcroft *et al.*, 2010) at times reaching high biomass (Springer *et al.*, 1989; Shiga *et al.*, 1998, Hopcroft *et al.*, 2010).

The dominant predators in terms of abundance and biomass were the chaetognaths, almost exclusively *Parasagitta elegans*, consistent with other studies from the region (e.g. Cooney, 1977; Neimark, 1979; Springer *et al.*, 1989; Kulikov 1992; Lane *et al.*, 2008; Hopcroft *et al.*, 2010). Consistent with these studies there was considerable biomass in both small and large gelatinous organisms: *Aglantha digitale* and *Rathkea octopunctata* being most common, but with larger species periodically captured but poorly quantified. Finally, suspension-feeding meroplanktonic larvae of benthic organisms were extremely common throughout the sampling region. High abundance of meroplankton is typical of summer-time data in this region (e.g. Cooney, 1977; Neimark, 1979; Springer *et al.*, 1989; Kulikov, 1992; Hopcroft *et al.*, 2010), and knowledge of their abundance and distribution is relevant to understanding recruitment to the rich benthic communities in this region (Bluhm *et al.*, 2009), and relationships to the work by Blanchard *et al.*

Community patterns

The spatial distribution of the zooplankton communities in the Chukchi Sea has been frequently tied to the different water masses in this region. Such patterns were first recognized by Russian researchers as early as the 1930s (Stepanova, 1937a,b), and are to a large extent a continuation of patterns observed in the northern Bering Sea (see review by Coyle *et al.*, 1996). These patterns were reiterated by later Russian studies (e.g. Pavshchikov, 1984) that identified at least three water types in the region. Although the first few years of the ISHTAR program were restricted to sampling in US waters, the oceanic Anadyr waters, continental shelf and low-saline near-shore waters were also recognized (Springer *et al.*, 1989). Cross-basin studies by the international BERPAC (Bering-Pacific) program also identified three zooplankton clusters within the Chukchi Sea, but failed to articulate their species assemblages or associate them with specific water masses (Kulikov, 1992). Recent sampling in the Chukchi to the south and west by the RUSALCA program also confirms strong ties to water masses (Hopcroft *et al.*, 2010).

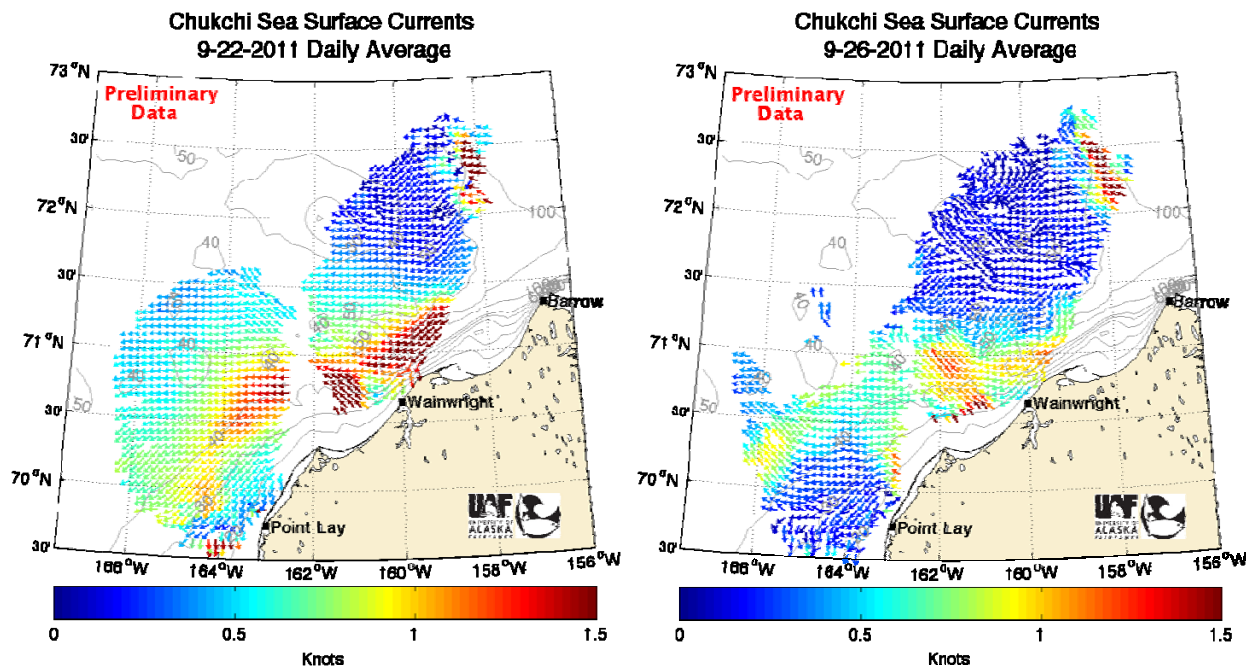
The distribution maps of the more dominant species show that small neritic copepod genera (e.g. *Acartia*, *Pseudocalanus*, *Oithona*) are generally more abundant in the southern part of the expanded study area where waters were warmer. Similarly species of strong subarctic Pacific affinity (e.g. *Eucalanus*, *Neocalanus*, and euphausiids) may be abundant in the southwestern parts of the study area, but decline rapidly as we move across Burger and Statoil. The pteropod *Limacina* shows the opposite pattern during 2011, while several more predatory groups remained broadly distributed. While we had anticipated the occurrence of more species of Arctic Basin affinity to the north of Hanna Shoal where shelf-basin exchanges are relatively common (Lane *et al.*, 2008), the relatively high numbers of some of these species in the original core study areas was unexpected.

Despite the relative proximity of the survey areas, as in previous years we were generally able to spatially distinguish these areas spatially based on community structure, although the distinction was greatest between Klondike and Burger, with Statoil stations forming a gradient between the two. Seasonal shifts in community structure were also apparent for each area. Particularly given the expanded environmental gradients encountered over the expanded 2011 study area, the physical environment, including water depth, are statistically correlated to the community structures. A more complete examination of these latter patterns will be undertaken following a second year of these expanded observations.

Inter-annual comparison

A notable feature of the zooplankton community for 2011 was the strong initial contribution by large copepods, while meroplankton groups typically declined. The expansion stations and sampling area also allowed us to collect several additional species known to be present in the region, but not yet collected by this program in previous years.

The most notable feature of the 2011 season was the incursion of significant numbers of the large Arctic Basin copepod *Calanus hyperboreus* into Burger and southeastern Statoil during September. While the average transport of water through the study region is to the north and northwest, particularly through the deeper channels in the region (Herald Valley, Central Channel, Barrow Canyon – Weingartner et al., 2005), the circulation patterns around Herald and Hanna Shoals are less understood. It has been proposed that water from the Central Channel flows clockwise around Hanna Shoal, potentially carrying water back toward Burger (Spall, 2007; Weingartner et al., *in press*). Furthermore, during September of 2011 HF radar along the coast (Sidebar: <http://www.ims.uaf.edu/hfradar/>) indicate that a period of northeasterly winds resulted in a sustained period of flow reversal and upwelling at the head of Barrow Canyon, with subsequent transport of waters westward. Aided by the tendency for southward transport along eastern boundary of Hanna Shoal, this situation would create the mechanism to carry basin species up Barrow Canyon and toward the study area. Our observations of *Calanus hyperboreus* at Burger are consistent with such a mechanism. The frequency and intensity with which such a transport mechanism occurs will be better understood as the duration of HF radar observations, and concurrent oceanographic measurements increases.



Sidebar: High-Frequency Radar estimates of daily surface currents in the Northeastern Chukchi Sea during the period when zooplankton sampling occurred over the Burger survey area (Figures courtesy of Tom Weingartner).

It is believed that the inter-annual variability observed for the planktonic communities from 2008-2011 is related to a combination of physical parameters observed at the study area and the intensity of physical transport from the Bering Strait. Onset conditions during 2011 appeared to favor zooplankton, with abundance and biomass during August comparable to 2010, however both these parameters declined during September, falling below 2010 values. Sea surface temperatures in 2011 were warm when sampling commenced, and temperature gradients were apparent across the survey area, declining from south to north, particularly during the second survey (Weingartner and Danielson, 2011). Warmer temperatures should have allowed more rapid growth and reproduction of zooplankton, but as in previous years, the region remains poor in phytoplankton biomass to support this potential. Advection of Basin waters into Burger and Statoil during September may have contributed to the declines in neritic zooplankton abundance and biomass by simple displacement.

CONCLUSIONS

Significant differences in water temperatures and timing of the phytoplankton bloom from 2008-2011 resulted in variations among both seasonally and spatially averaged zooplankton community values. It is likely that both the intensity of transport of zooplankton from more southern waters, and their productivity while en route to the study region are also important, although 2011 demonstrates transport from other directions may also have significant impacts. In addition to confirming the known importance of crustacean zooplankton as abundant resources for higher trophic levels, these surveys are establishing the unappreciated importance of both larvaceans and meroplankton in the northeastern Chukchi Sea. Sampling during four years of the ice-free period in the Chukchi Sea has allowed us to recognize the level of inter- and intra-annual variability of a plankton community primarily Pacific in faunal character. Surveys during 2012 will further help to refine the scales of spatial variability and our understanding of inter-annual variability, and it is likely that across these 5 years we will have observed the range of productivity experienced by this ecosystem.

Data collected during the 1980s by the ISHTAR program (Turco, 1992a,b) suggests that large seasonal and inter-annual difference can occur in the northern Bering and southern Chukchi Seas, however their conclusions are somewhat qualitative as they lacked a consistent set of stations on which to standardize their data. A major strength of this program is the use of a consistent sampling design capable of capturing differences in both timing and intensity of the planktonic communities and other ecosystem components. This design lays a solid foundation for accessing any potential perturbation associated with exploration and production activities in the northeastern Chukchi region.

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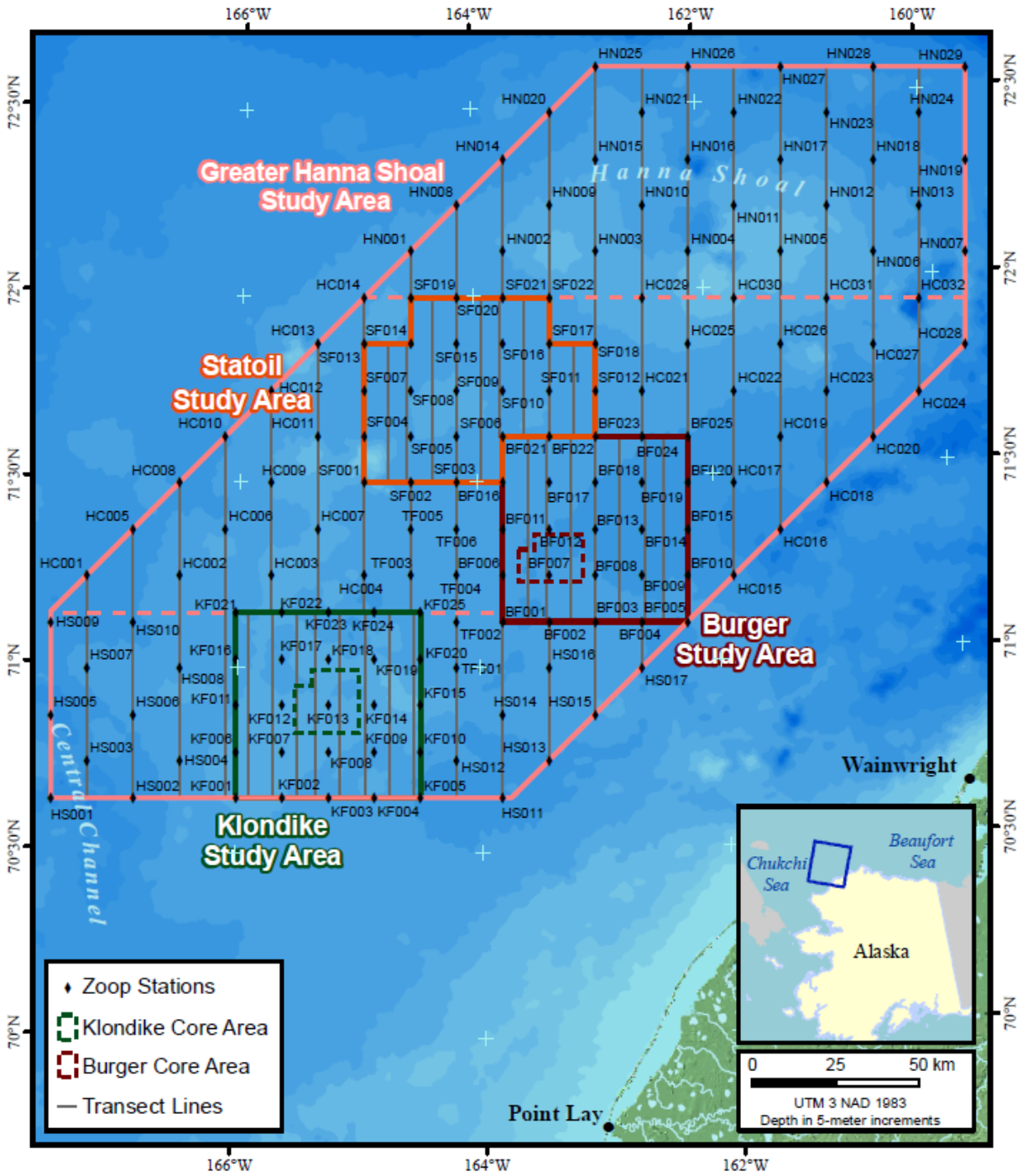


Fig. 1 Locations of the CESP survey area in the northeastern Chukchi Sea. Survey grids Klondike, Burger, and Statoil are approximately 900-NM².

August Klondike 2011

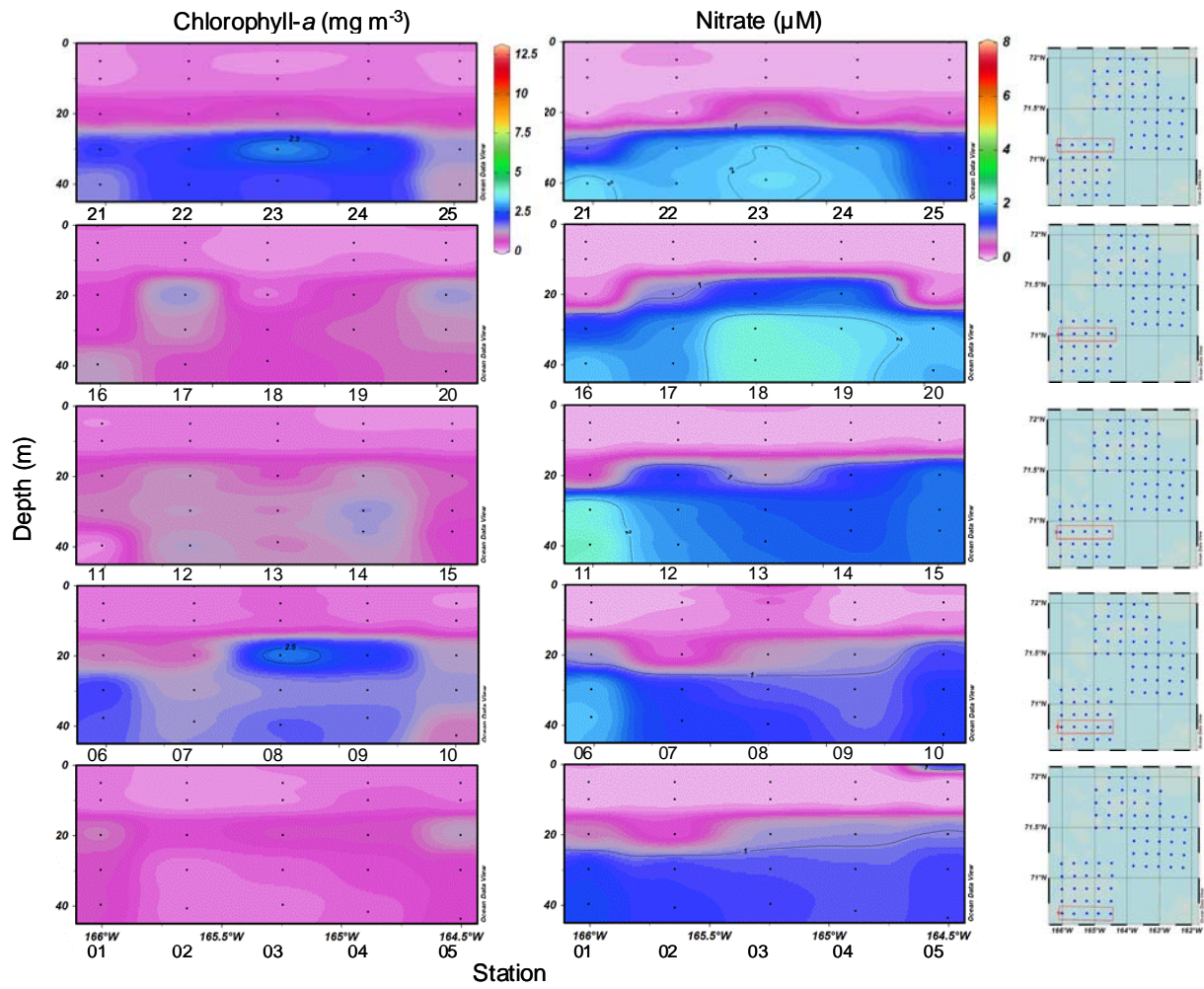


Fig. 2 Chlorophyll-*a* and nitrate profile concentrations observed at the Klondike survey area during the August cruise 2011 (WWW1102).

August Klondike 2011

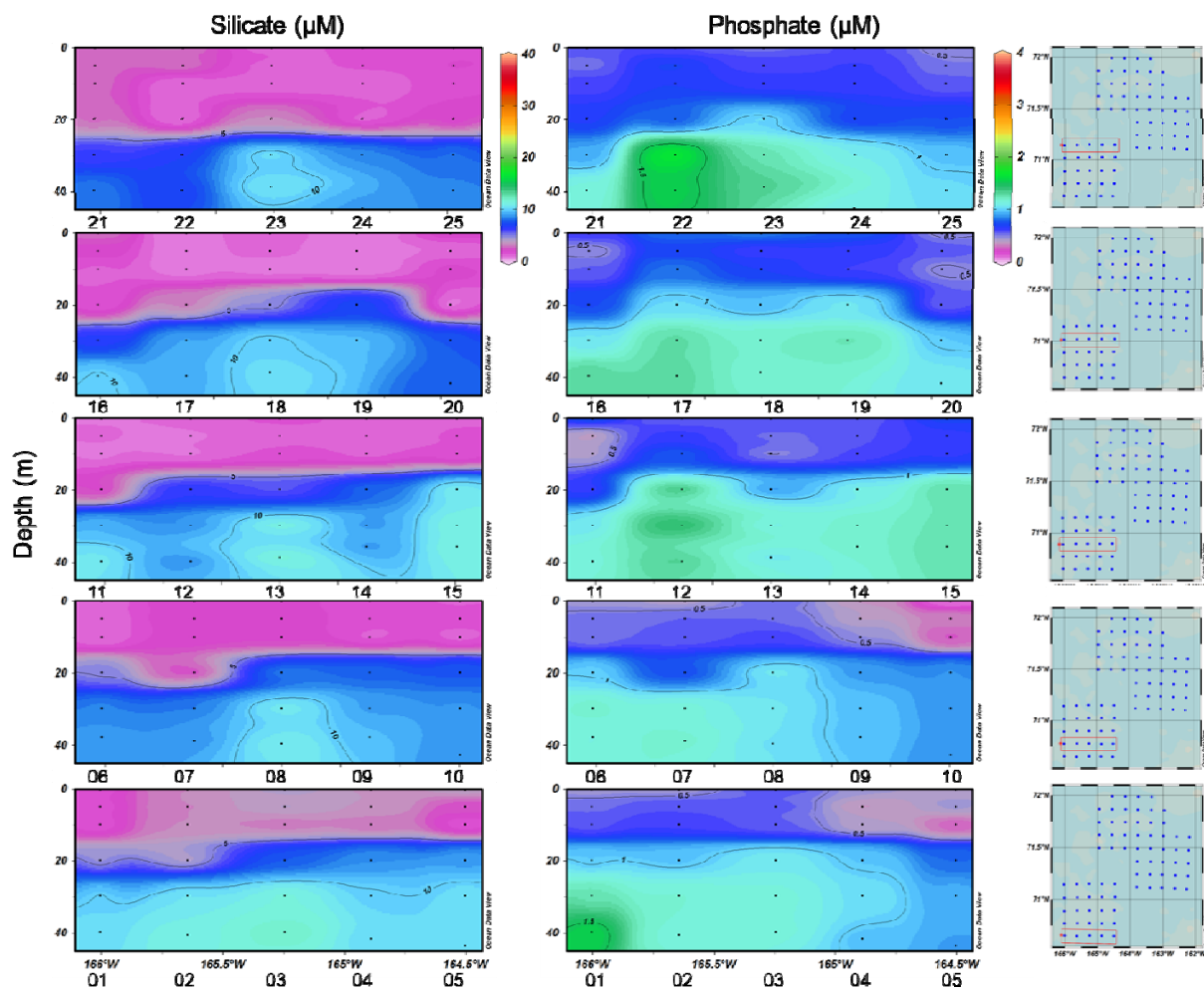


Fig. 3 Silicate and phosphate profile concentrations observed at the Klondike survey area during the August cruise 2011 (WWW1102).

August Burger 2011

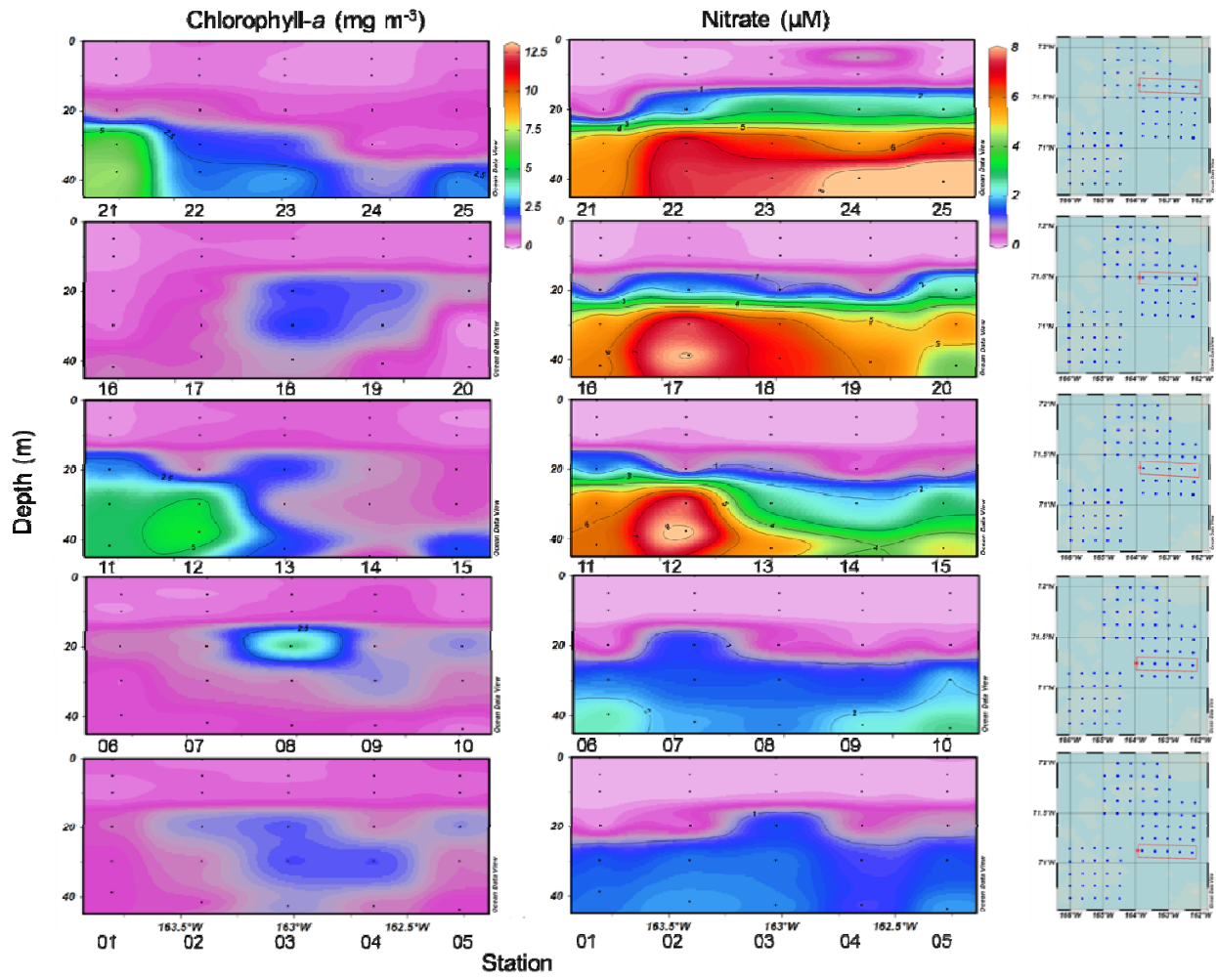


Fig. 4 Chlorophyll-*a* and nitrate profile concentrations observed at the Burger survey area during the August cruise 2011 (WWW1102).

August Burger 2011

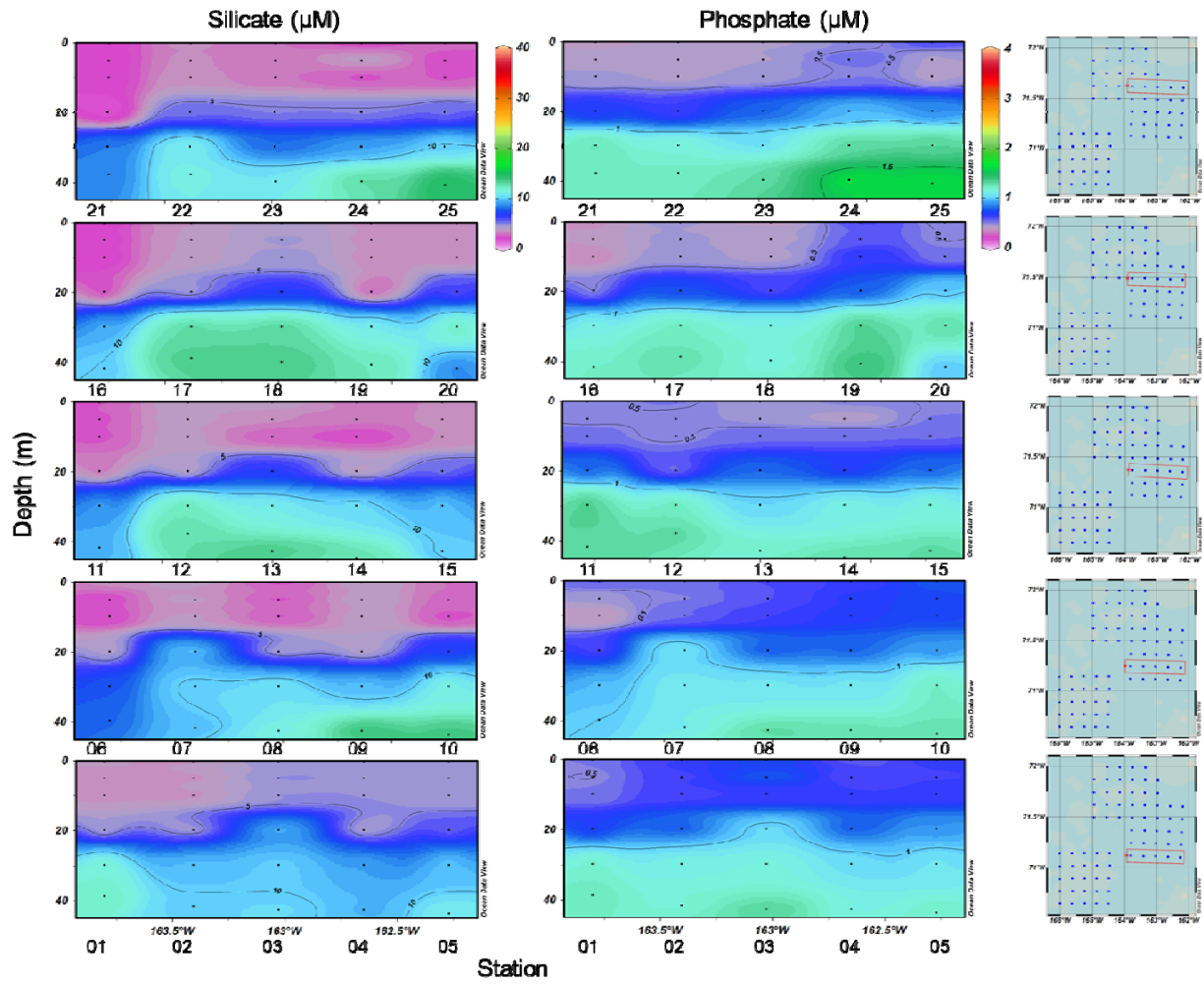


Fig. 5 Silicate and phosphate profile concentrations observed at the Burger survey area during the August cruise 2011 (WWW1102).

August Statoil 2011

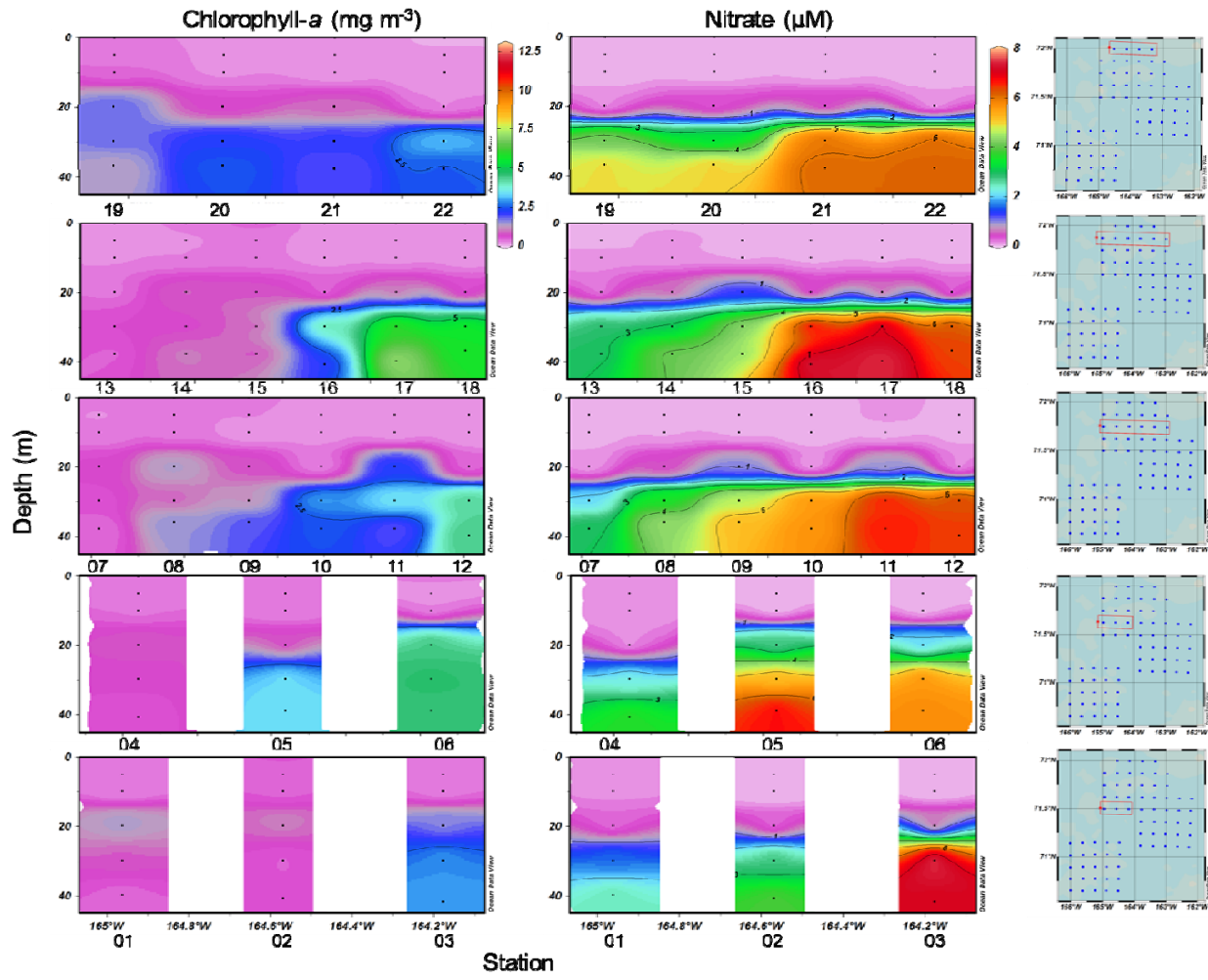


Fig. 6 Chlorophyll-*a* and nitrate profile concentrations observed at the Statoil survey area during the August cruise 2011 (WWW1102).

August Statoi 2011

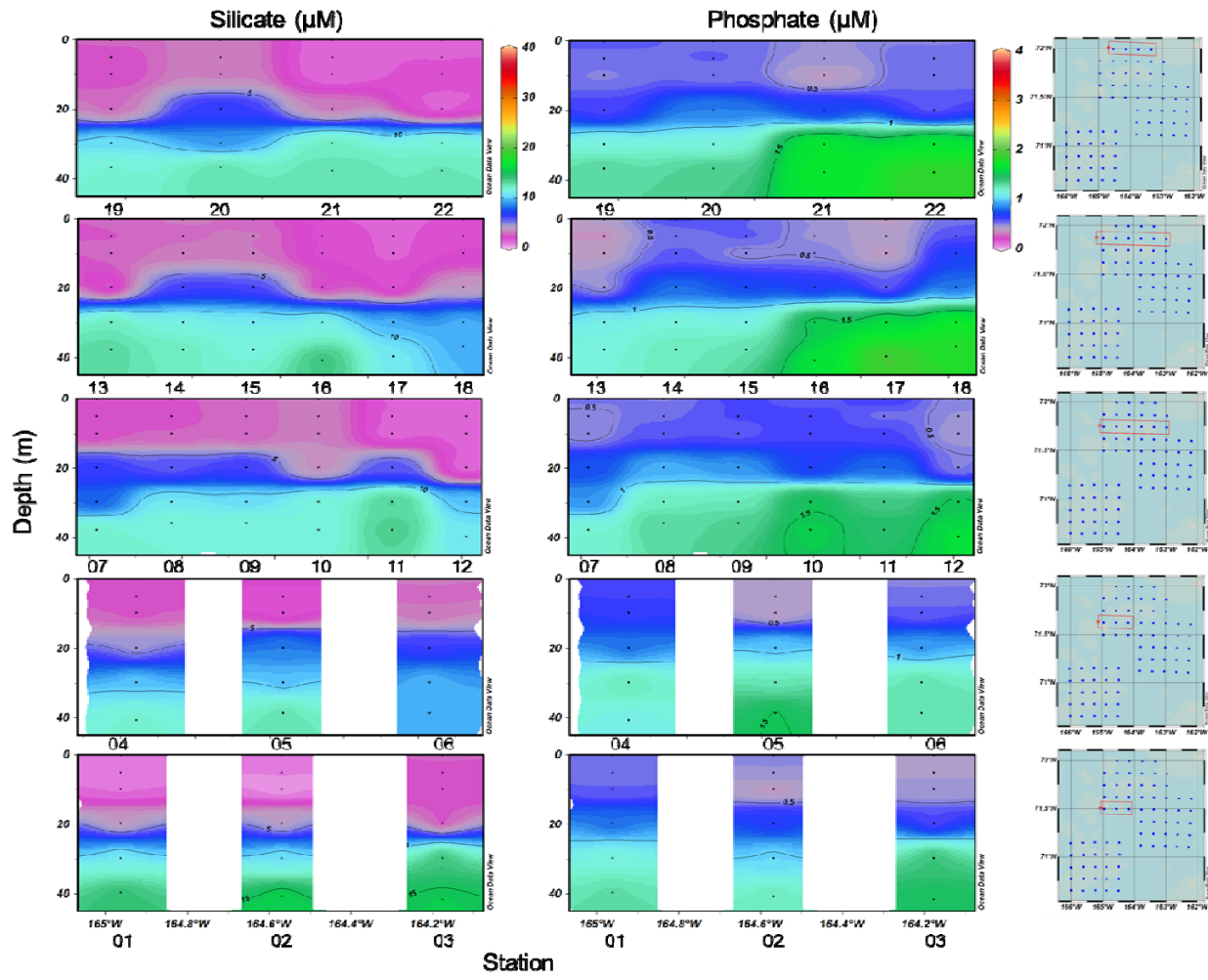


Fig. 7 Silicate and phosphate profile concentrations observed at the Statoi survey area during the August cruise 2011 (WWW1102)

Sept-October Klondike 2011

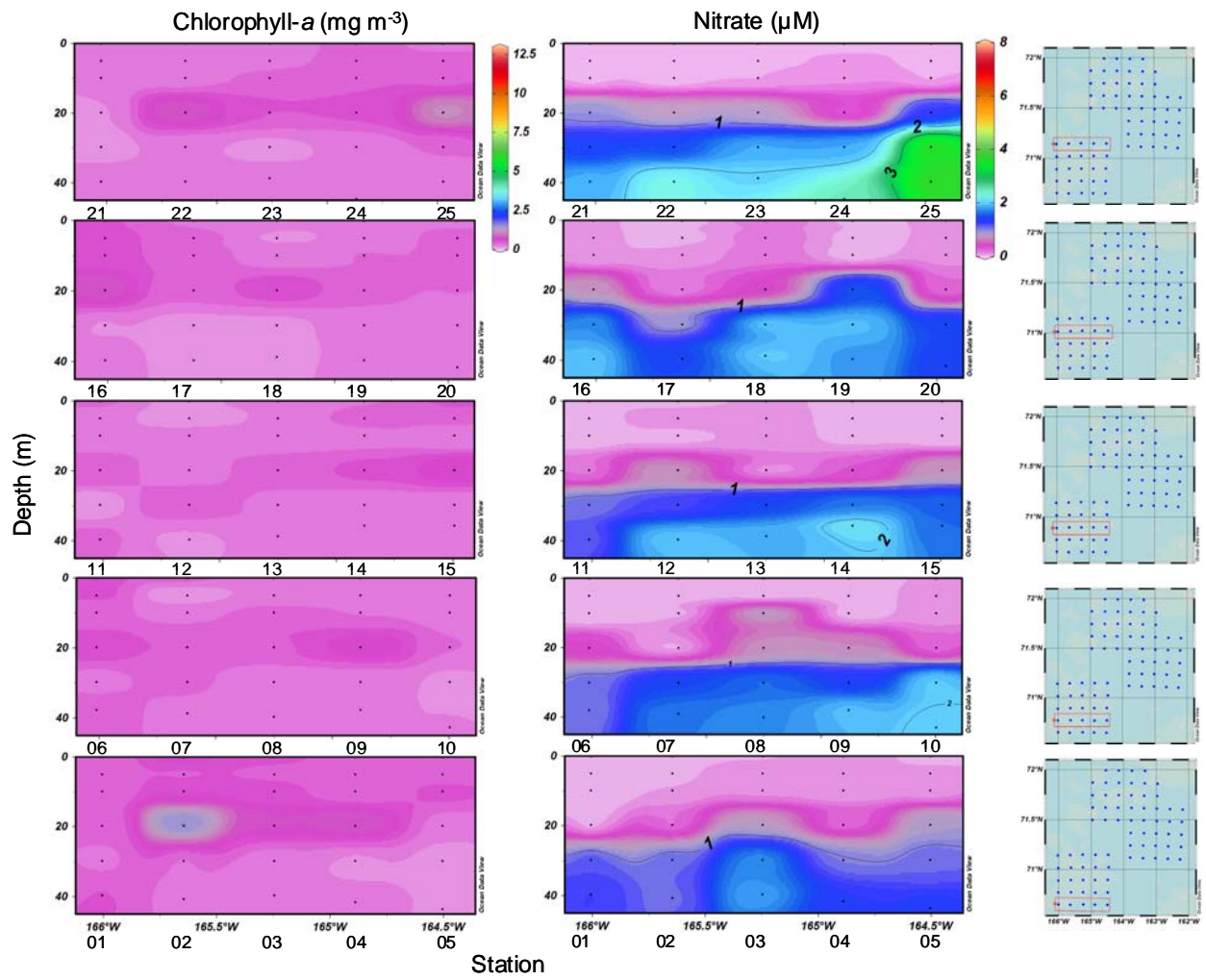


Fig. 8 Chlorophyll-a and nitrate profile concentrations observed at the Klondike survey area during the Sept-October cruise 2011 (WWW1104).

Sept-October Klondike 2011

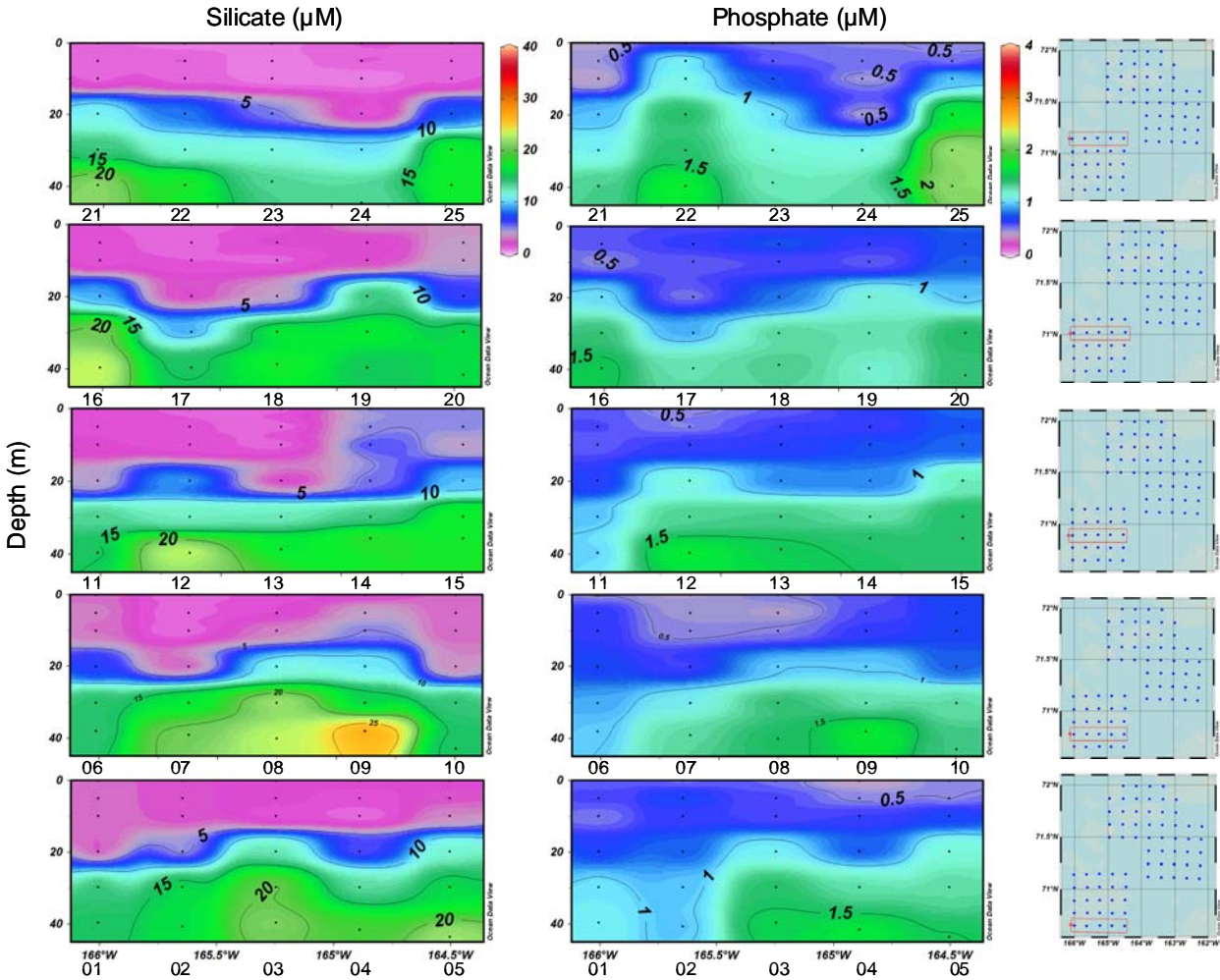


Fig. 9 Silicate and phosphate profile concentrations observed at the Klondike survey area during the Sept-October cruise 2011 (WWW1103).

Sept-October Burger 2011

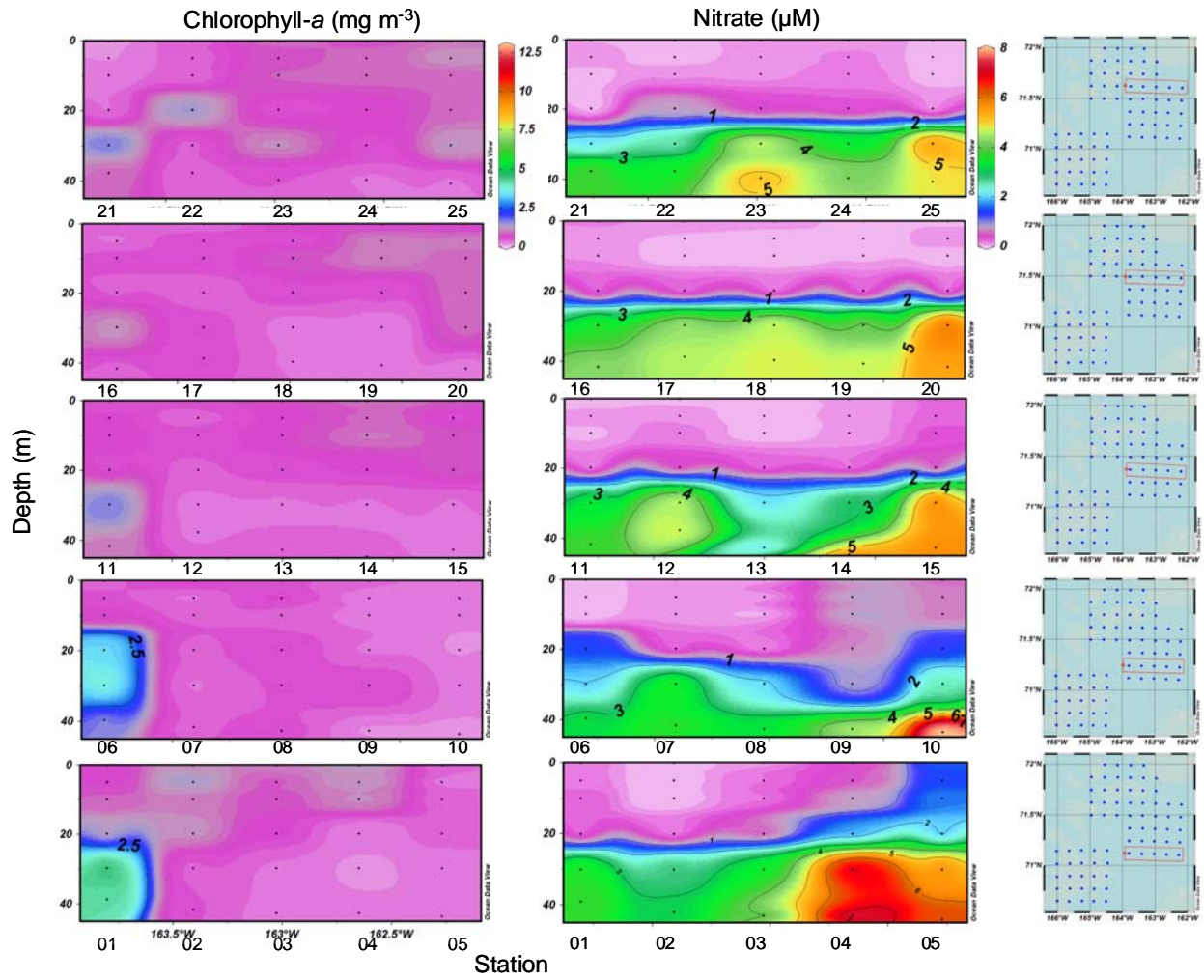


Fig. 10 Chlorophyll-*a* and nitrate profile concentrations observed at the Burger survey area during the Sept–October cruise 2011 (WWW1104).

Sept-October Burger 2011

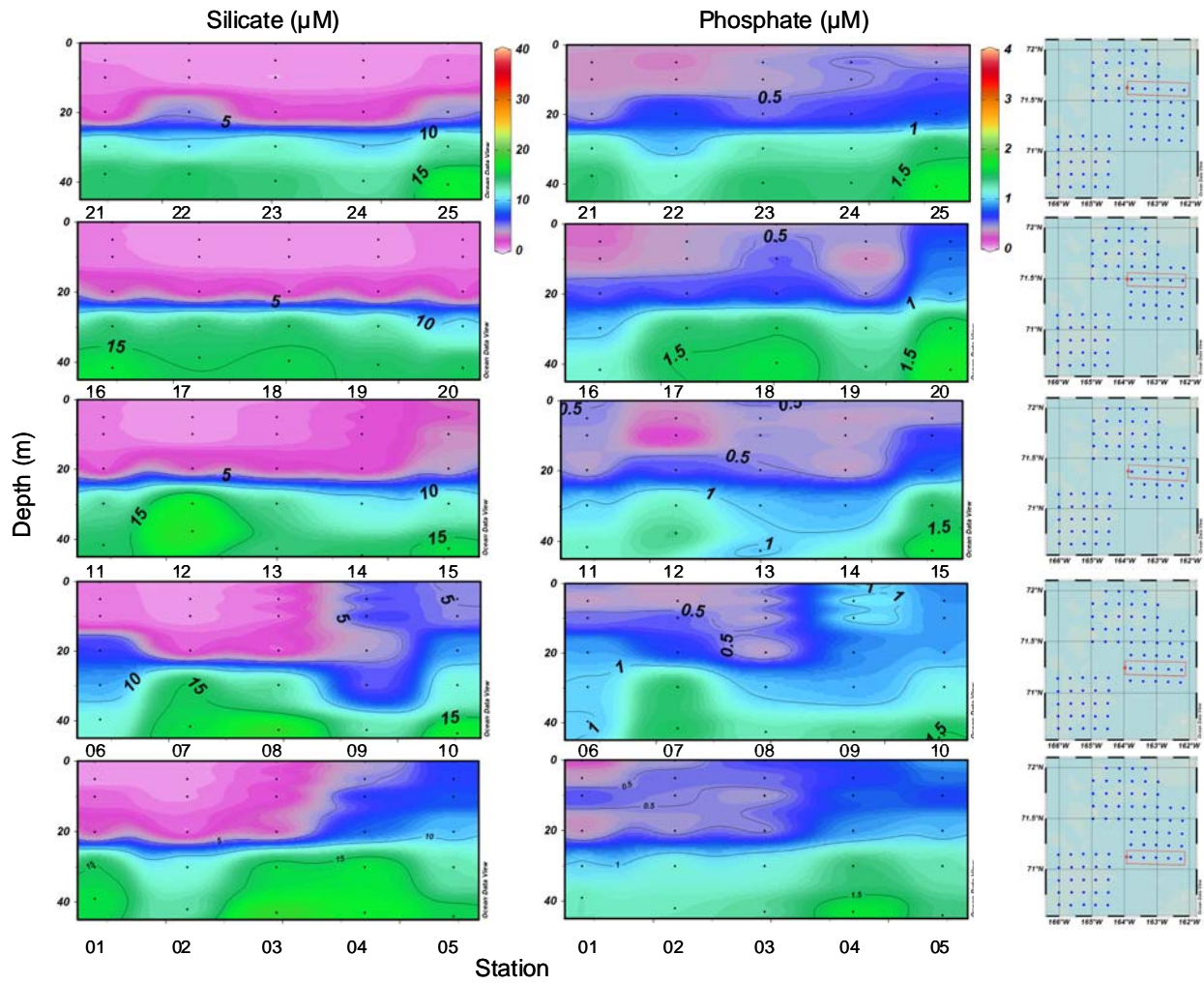


Fig. 11 Silicate and phosphate profile concentrations observed at the Burger survey area during the Sept-October cruise 2011 (WWW1103).

Sept-October Statoil 2011

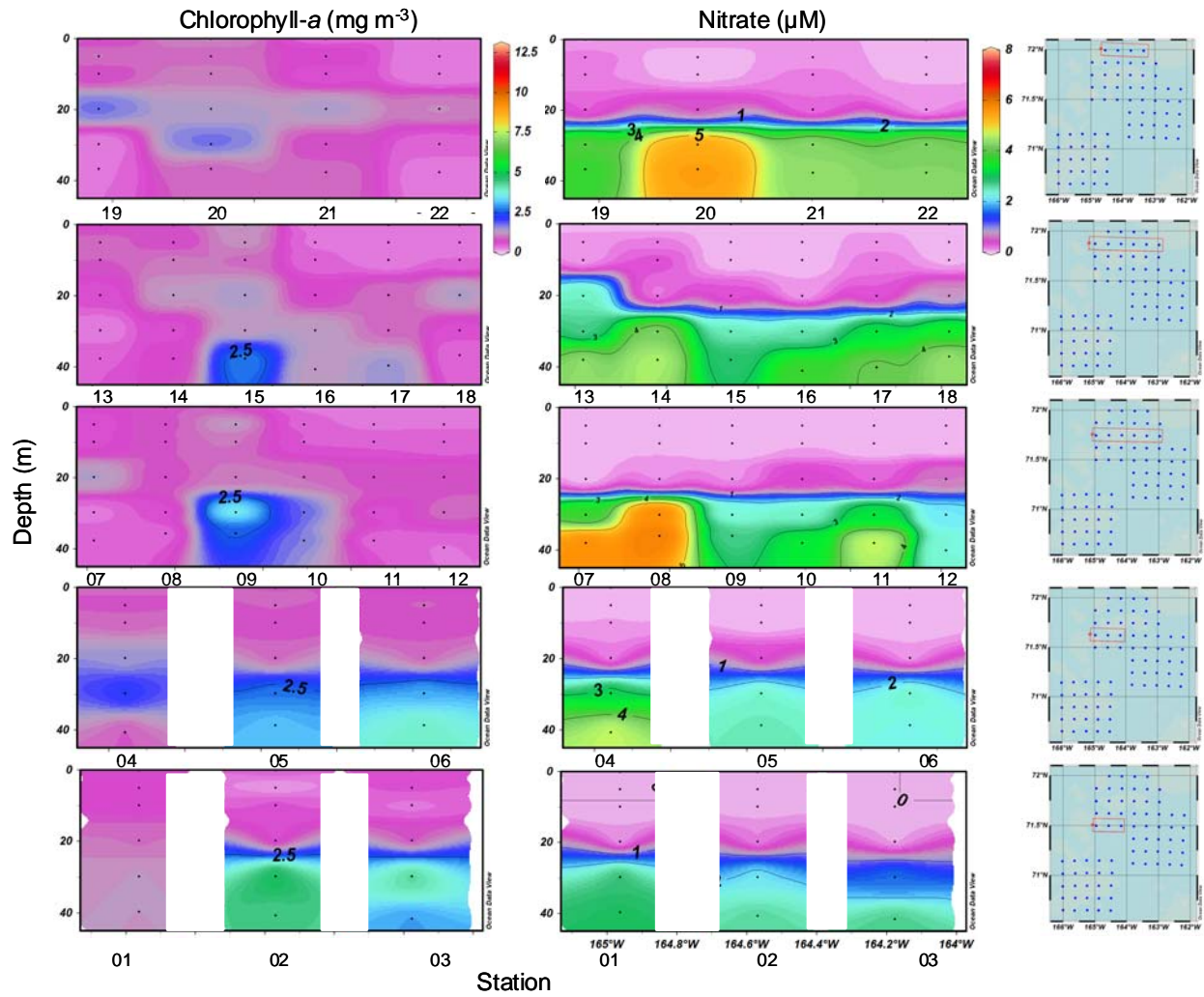


Fig. 12 Chlorophyll-*a* and nitrate profile concentrations observed at the Statoil survey area during the Sept–October cruise 2011 (WWW1104).

Sept-October Statoil 2011

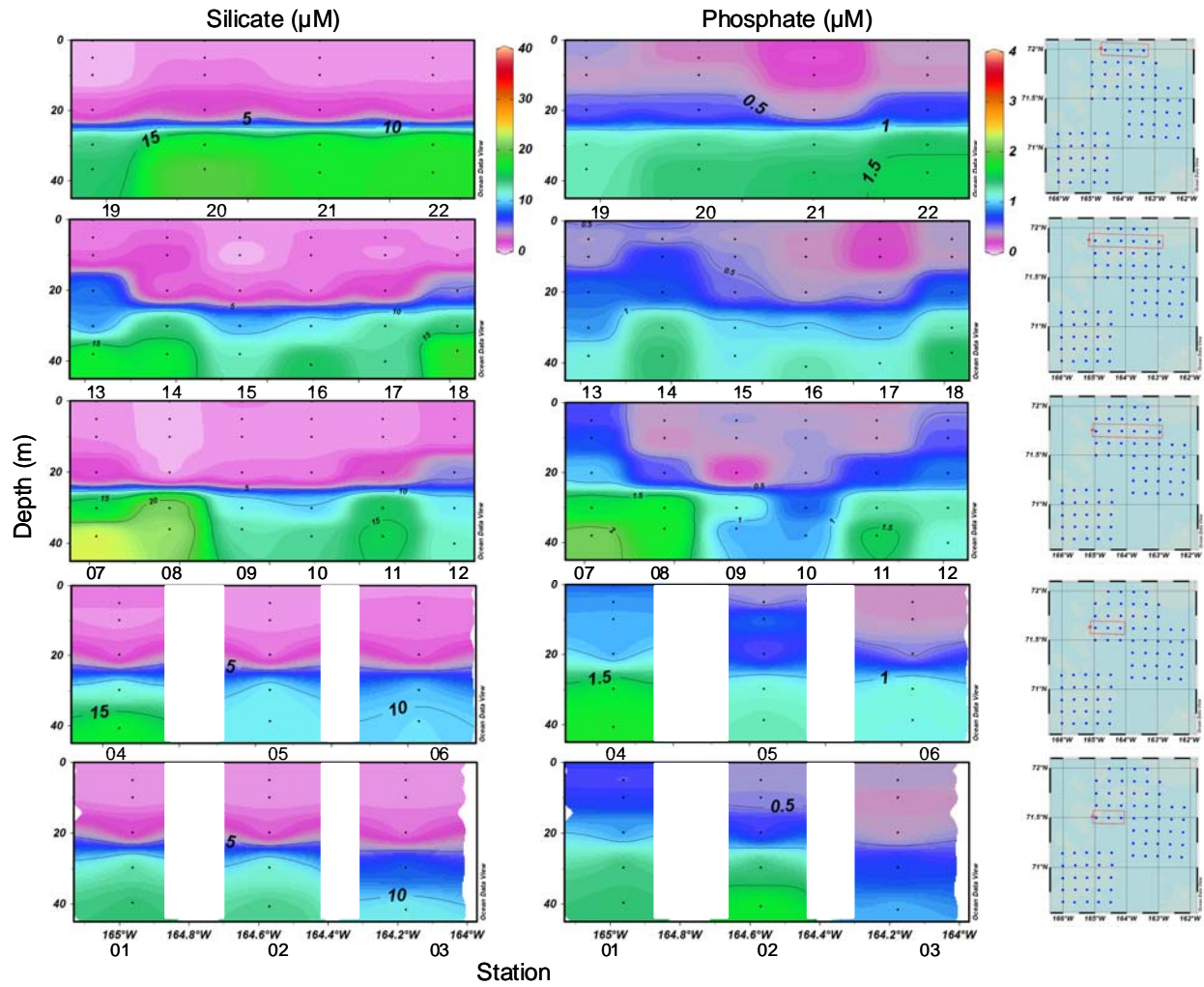


Fig. 13 Silicate and phosphate profile concentrations observed at the Statoil survey area during the Sept-October cruise 2011 (WWW1103).

Sept-October Hanna Shoal

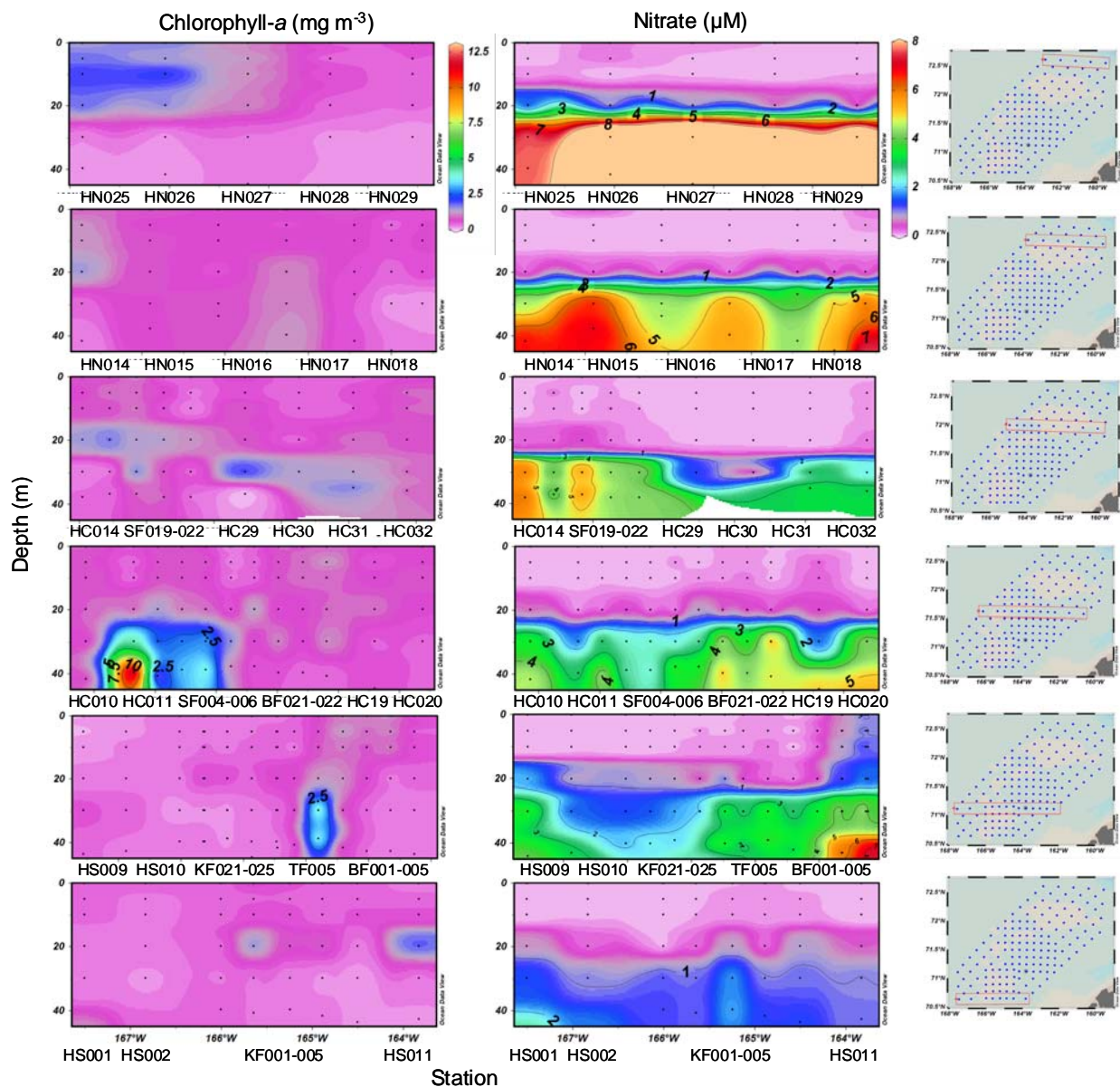


Fig. 14 Chlorophyll-*a* and nitrate profile concentrations observed throughout the Hanna Shoal survey area during the Sept–October cruise 2011 (WWW1104).

Sept-October Hanna Shoal

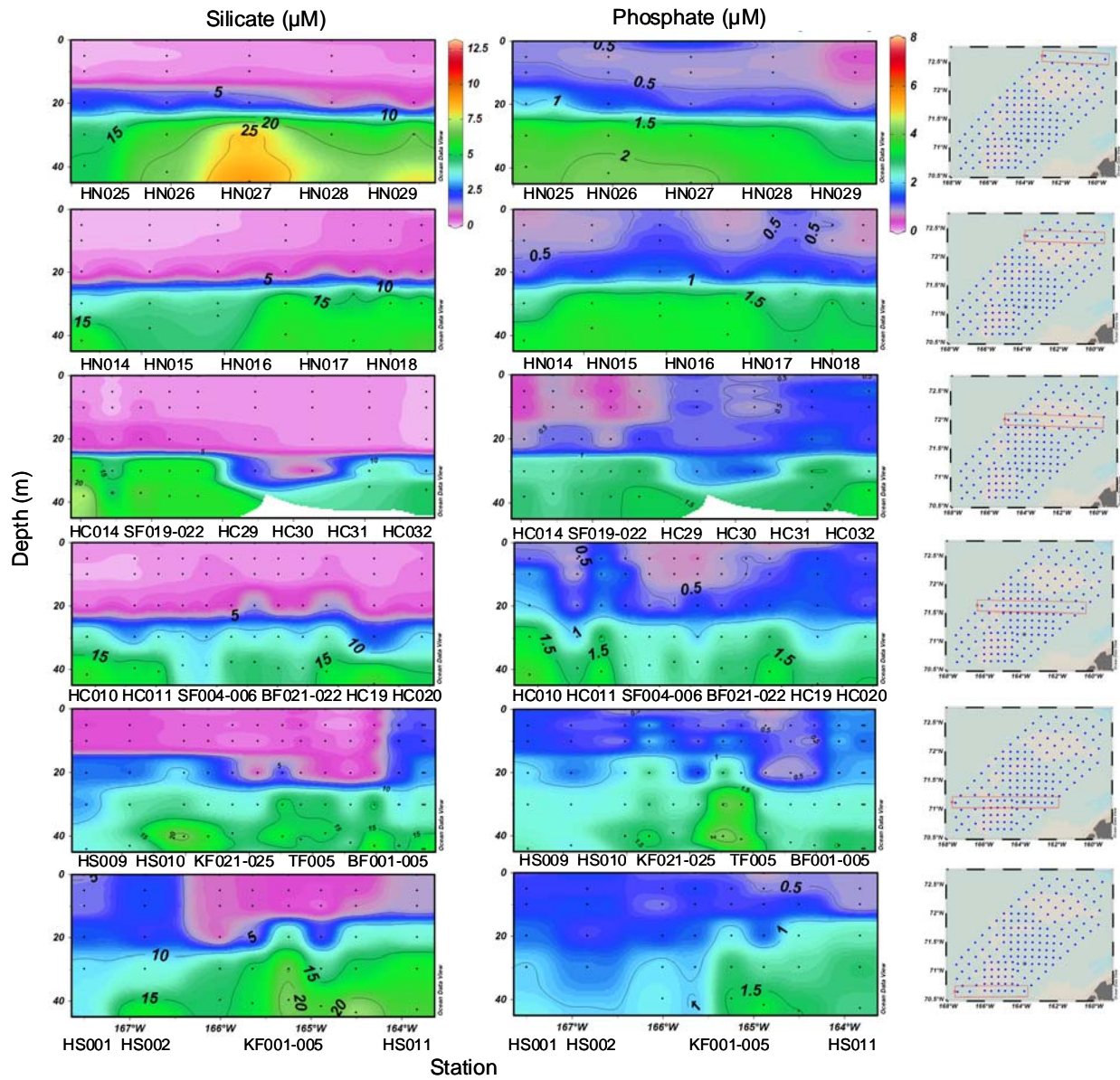


Fig. 15 Silicate and phosphate profile concentrations observed throughout the Hanna Shoal survey area during the Sept-October cruise 2011 (WWW1103).

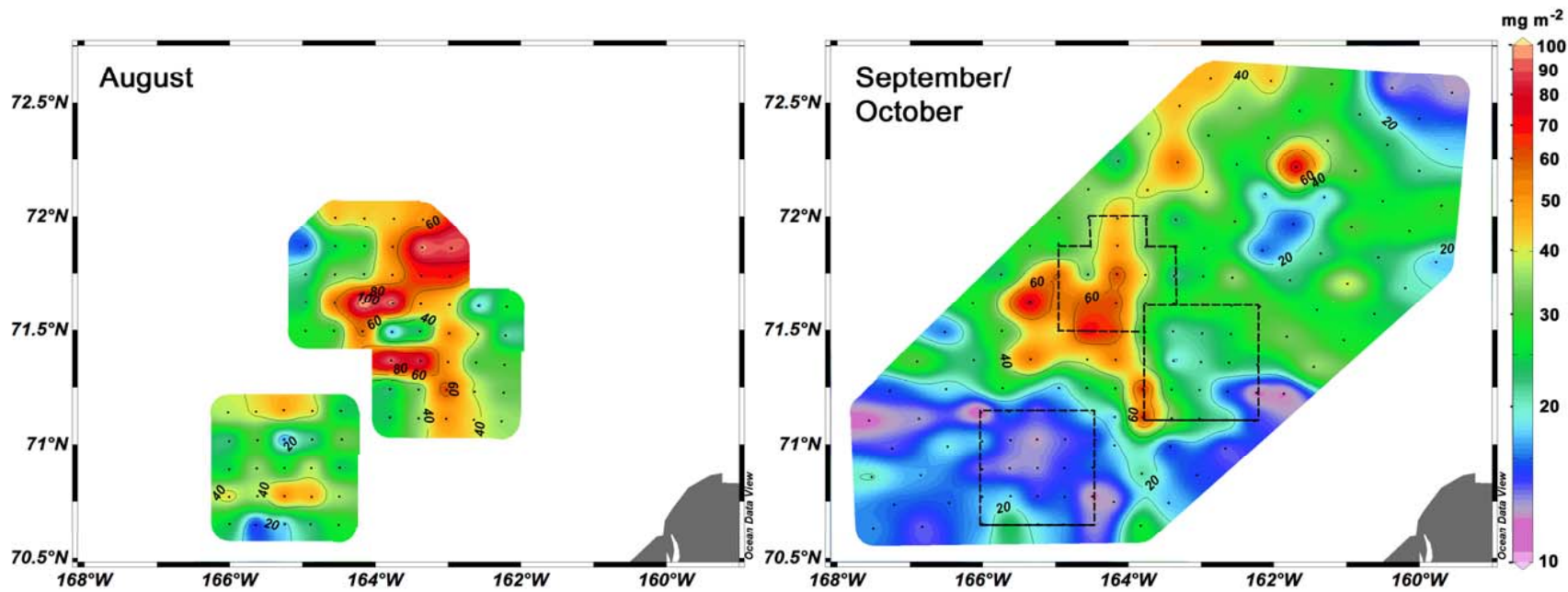


Fig. 16 Integrated chlorophyll-*a* observed over the CSESP study area in 2011.

Sept-October Hanna Shoal 2011

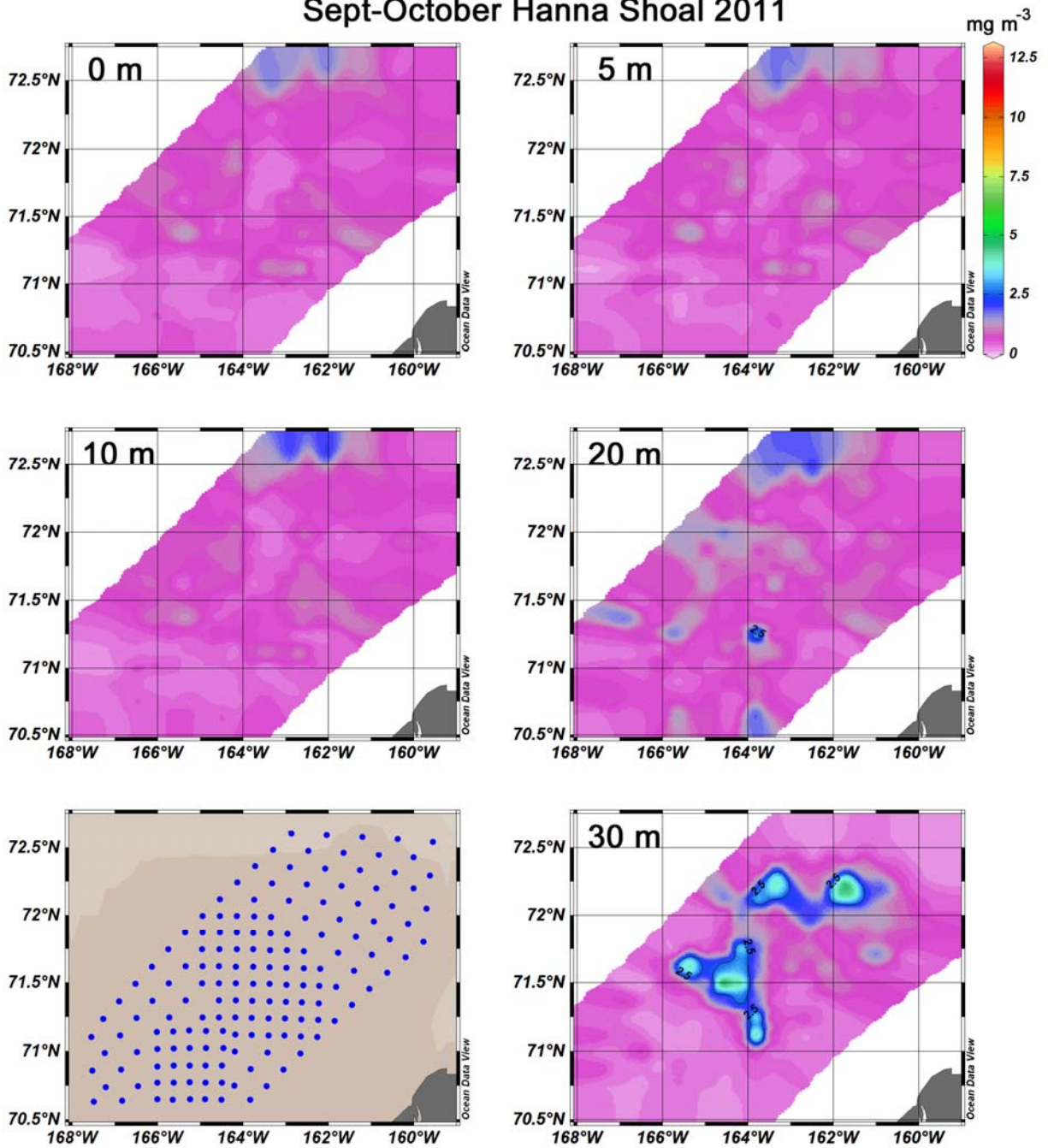


Fig. 17 Chlorophyll-*a* concentrations observed throughout the water column (0, 5, 10, 20, & 30 m) over the Hanna Shoal study area during the Sept-October cruise 2011 (WWW1104).

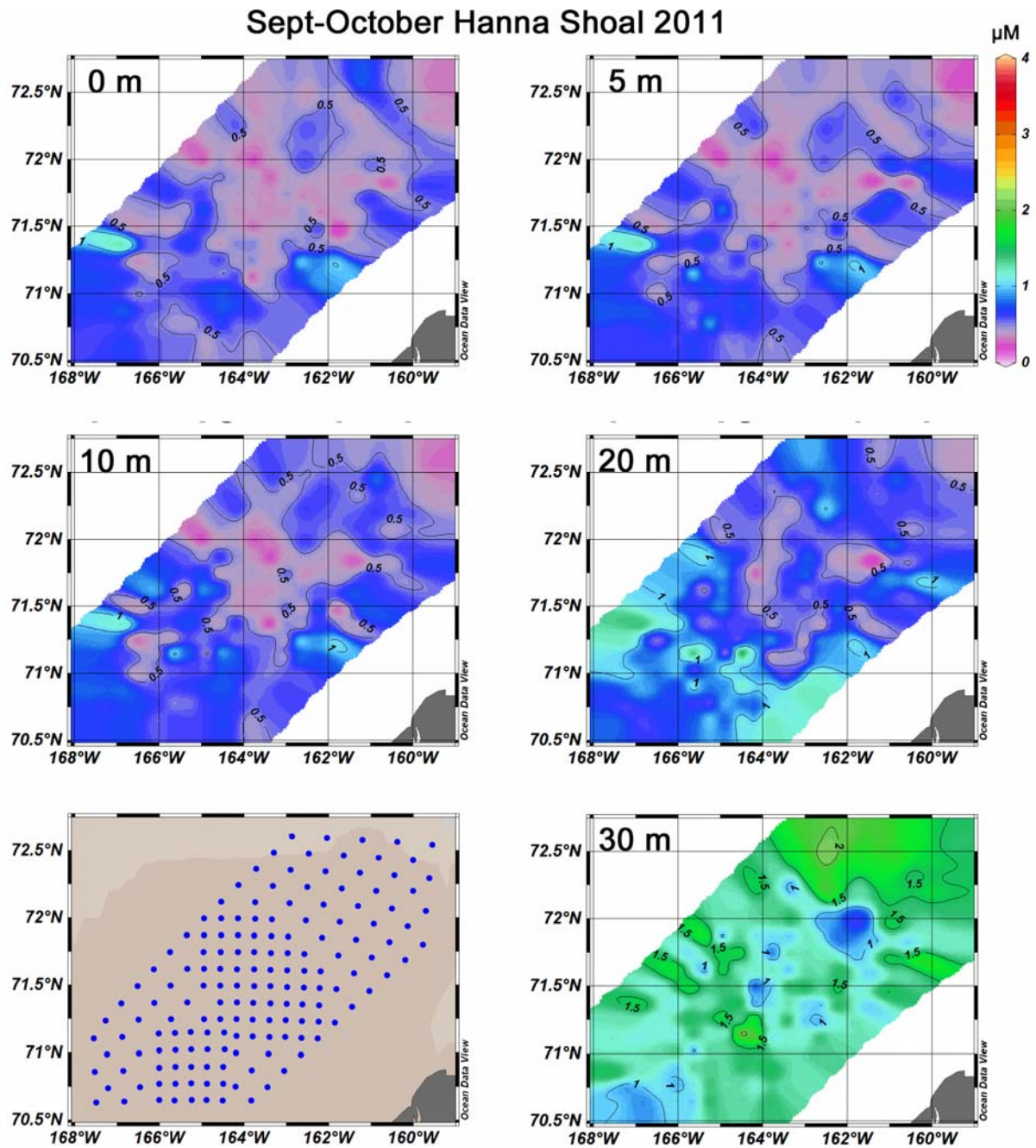


Fig. 19 Silicate concentrations observed throughout the water column (0, 5, 10, 20, & 30 m) over the Hanna Shoal study area during the Sept-October cruise 2011 (WWW1104).

Sept-October Hanna Shoal 2011

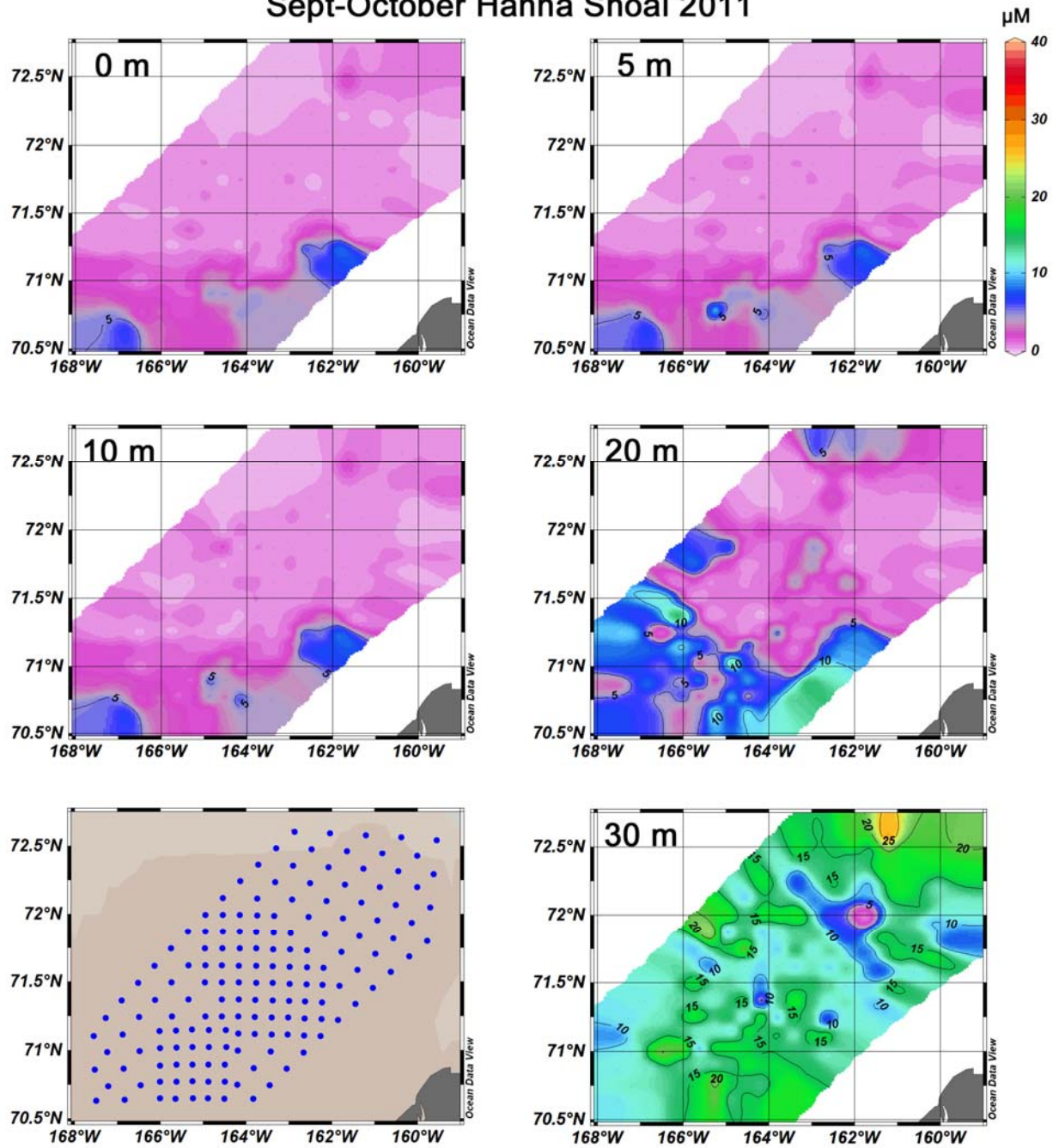


Fig. 20 Phosphate concentrations observed throughout the water column (0, 5, 10, 20, & 30 m) over the Hanna Shoal study area during the Sept-October cruise 2011 (WWW1104).

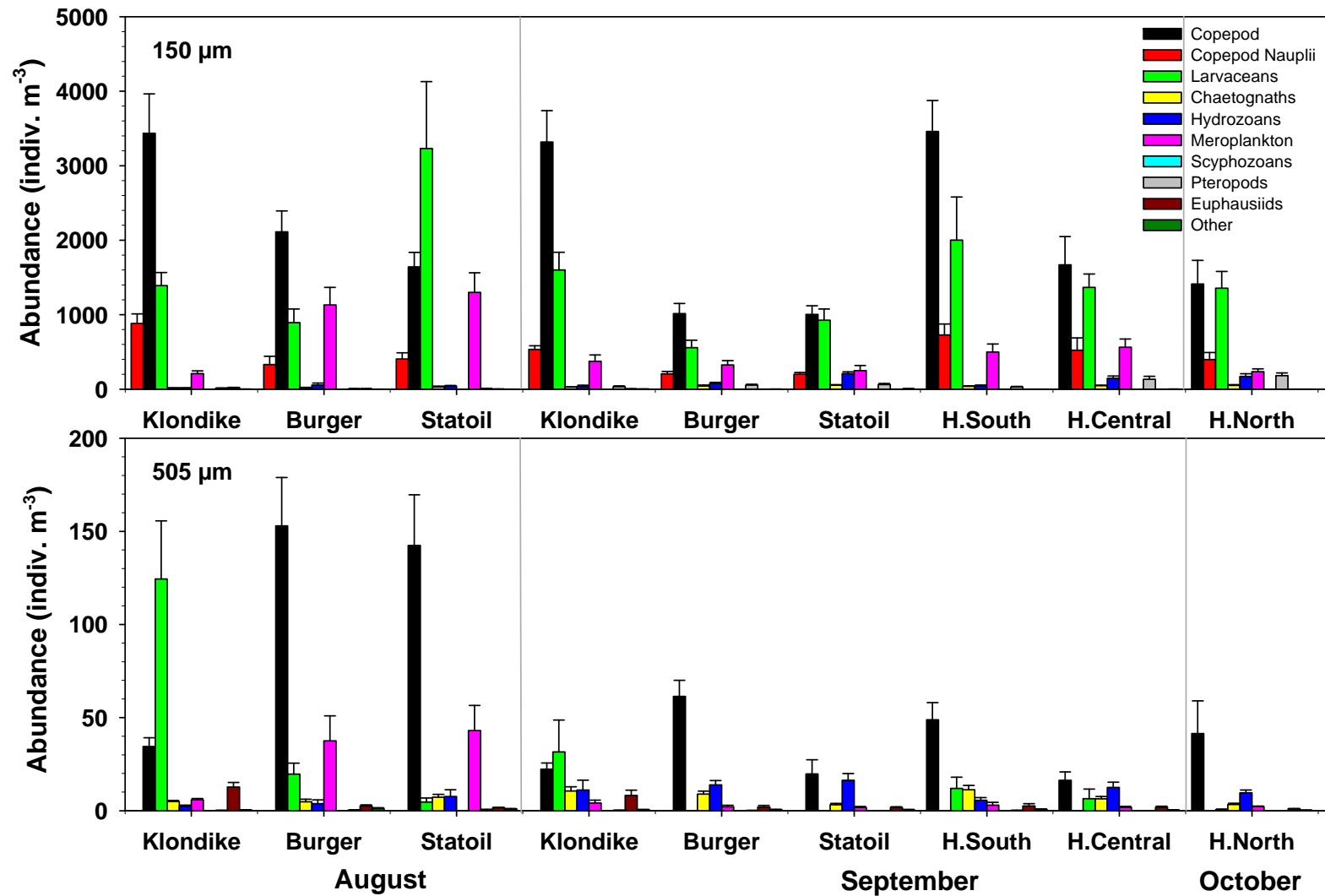


Fig. 21 Contribution of the major groups to the community abundance at each survey grid during 2011 as determined for both plankton nets. Error bars are standard error of the means.

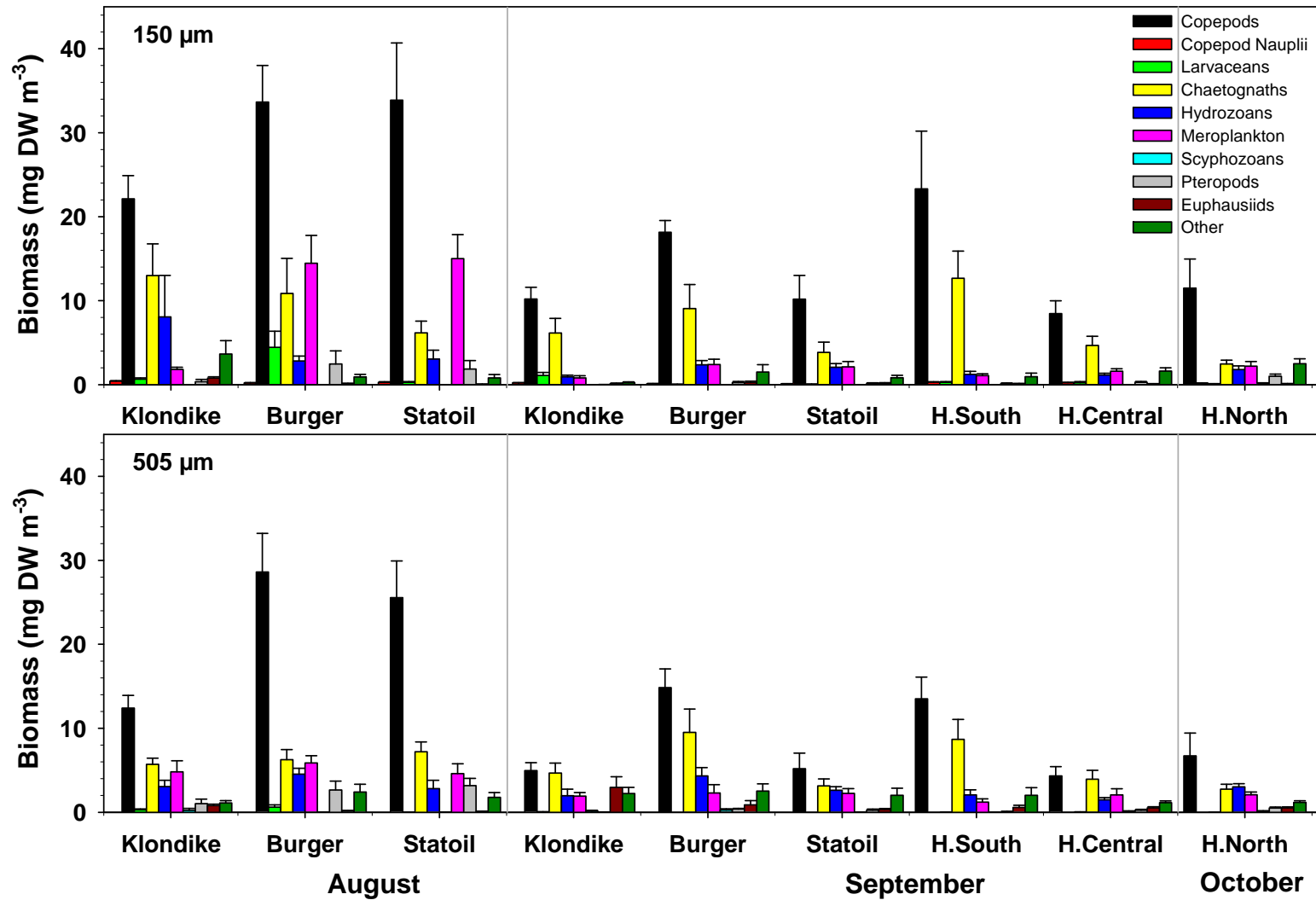


Fig. 22 Contribution of the major groups to the community biomass at each survey grid during 2011 as determined for both plankton nets. Error bars are standard error of the means.

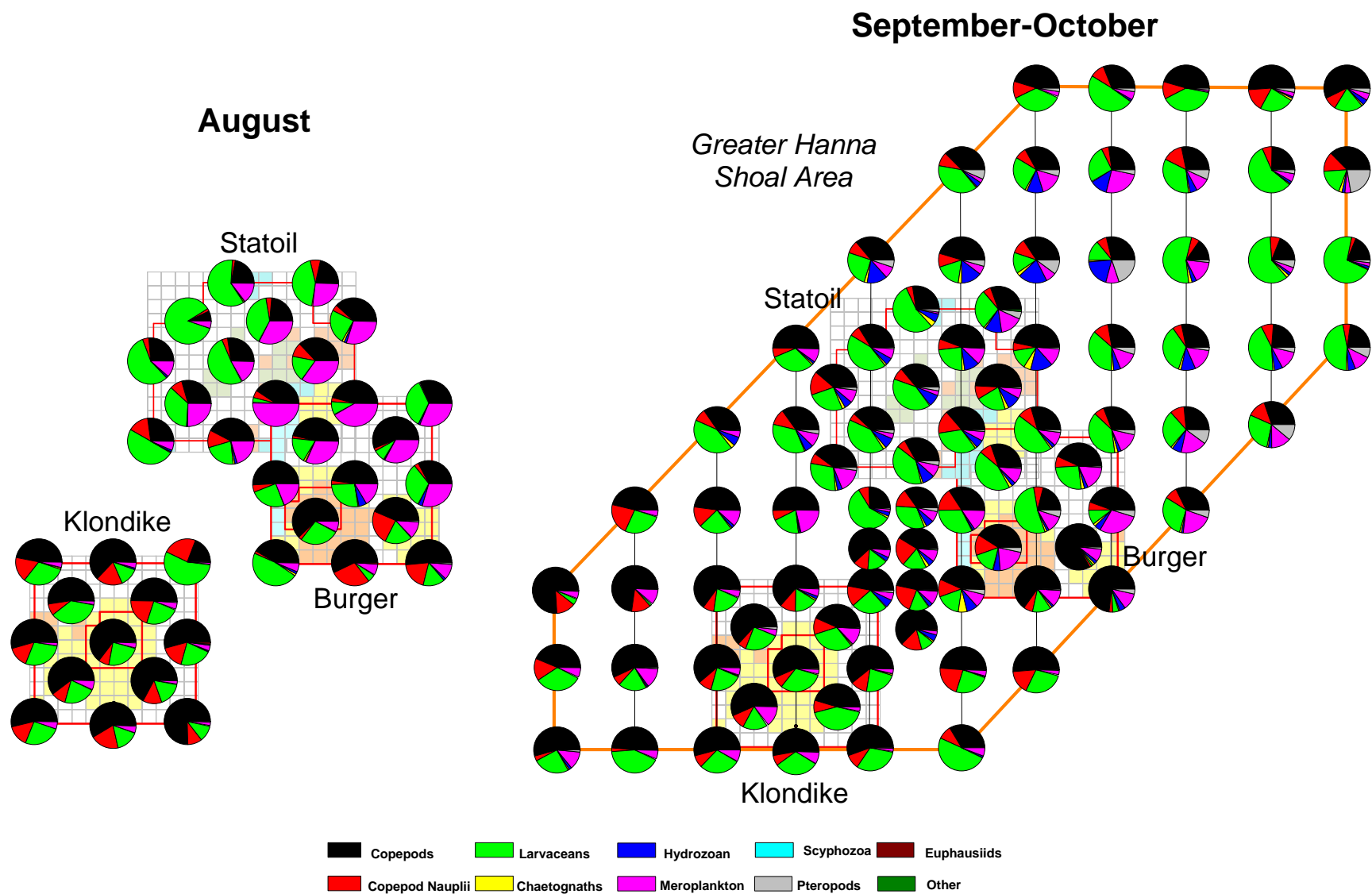


Fig. 23. Relative contribution of major taxonomic groups to the community abundance captured by the 150-µm net at each survey grid during 2011.

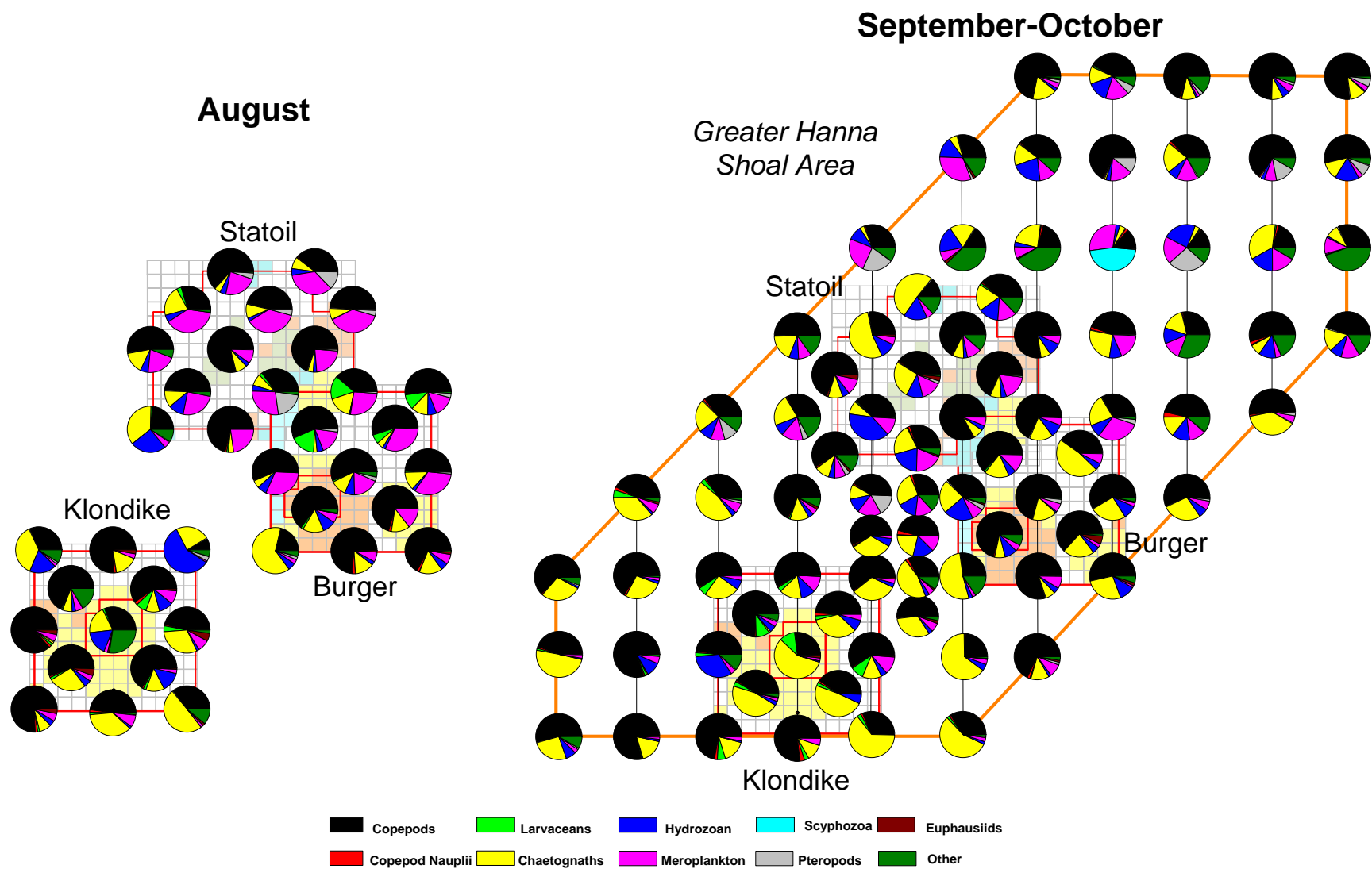


Fig. 24 Relative contribution of major taxonomic groups to the community biomass captured by the 150- μ m net at each survey grid during 2011.

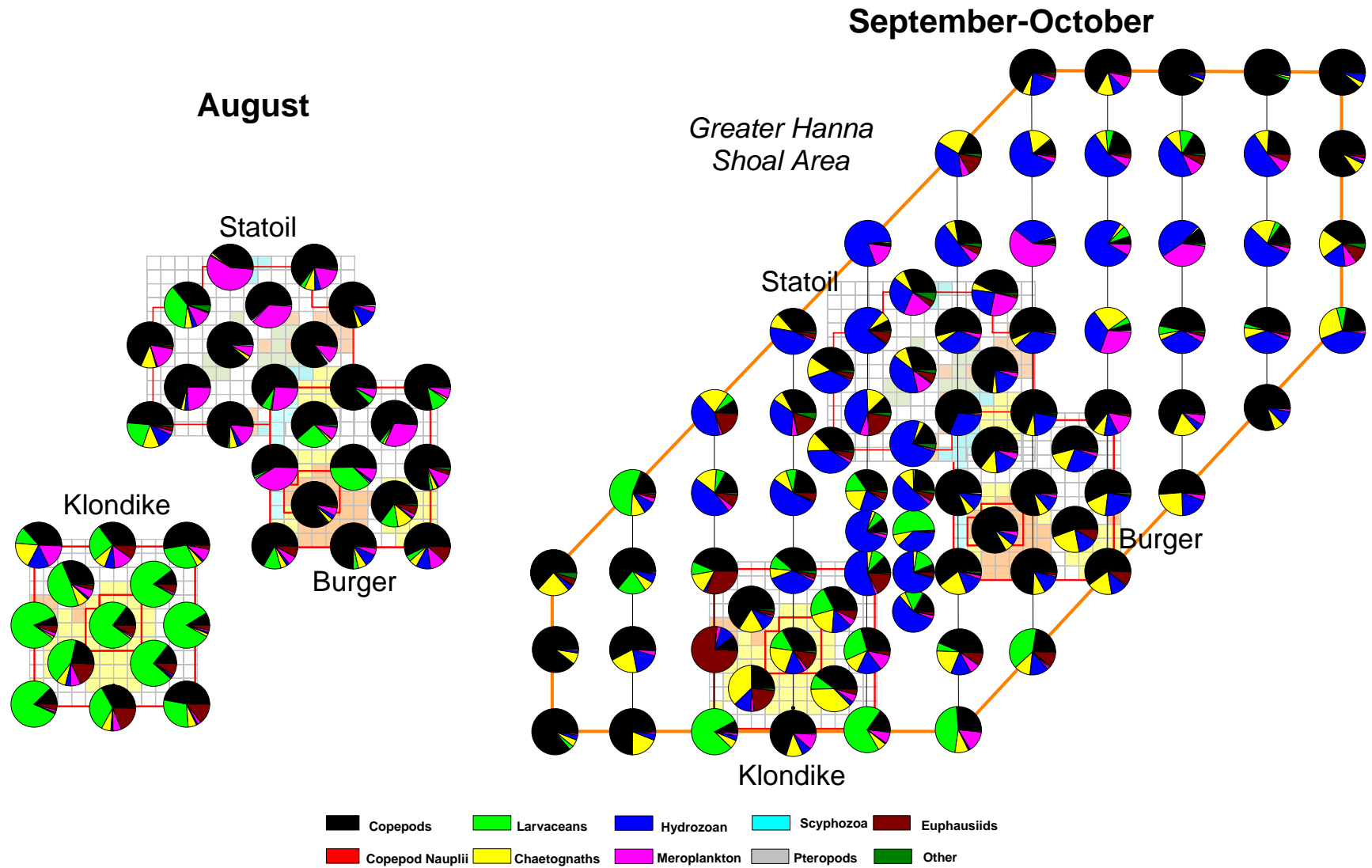


Fig. 25 Relative contribution of major taxonomic groups to the community abundance captured by the 505- μ m net at each survey grid during 2011.

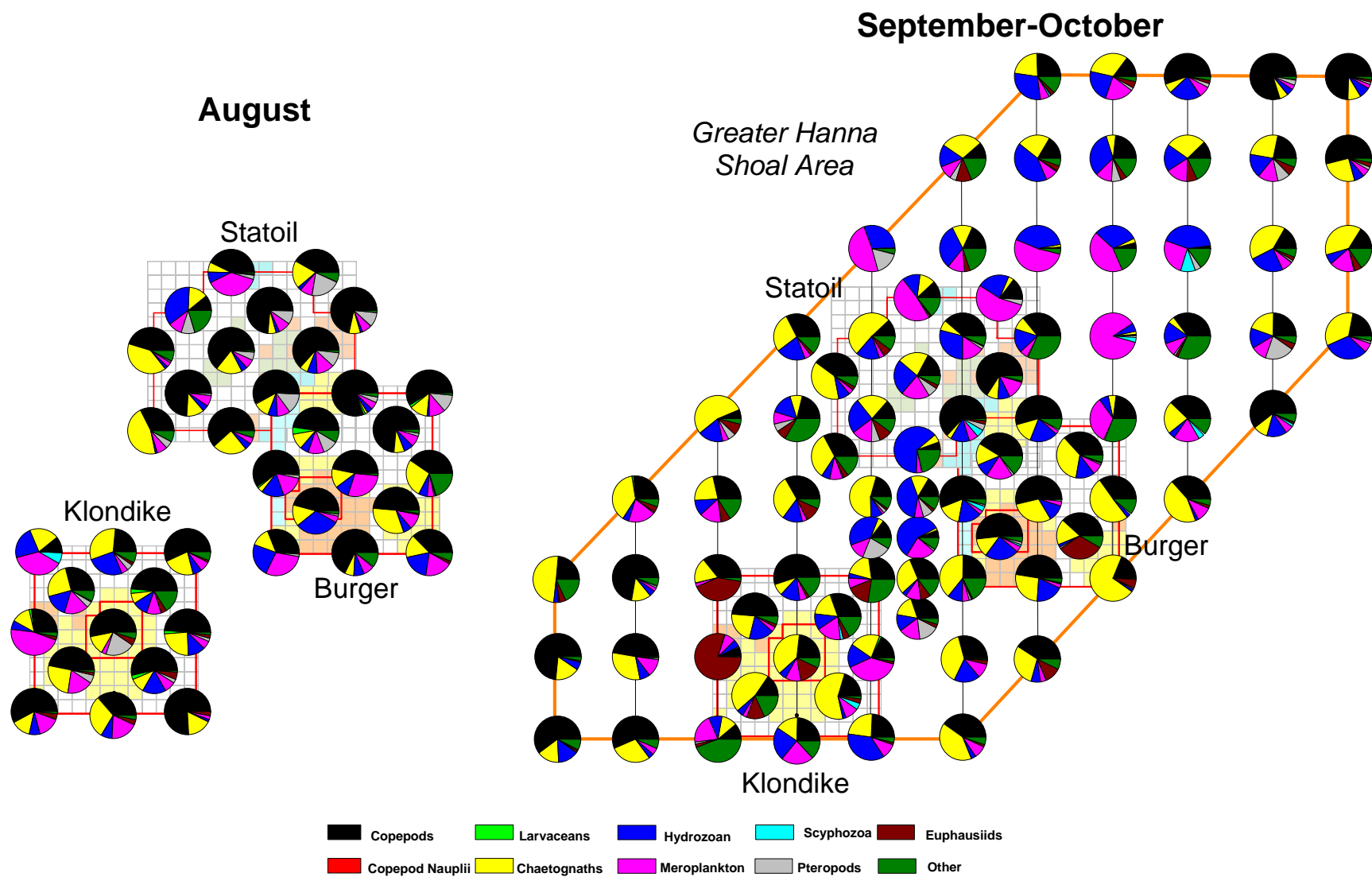


Fig. 26 Relative contribution of major taxonomic groups to the community biomass captured by the 505- μ m net at each survey grid during 2011.

150- μ m

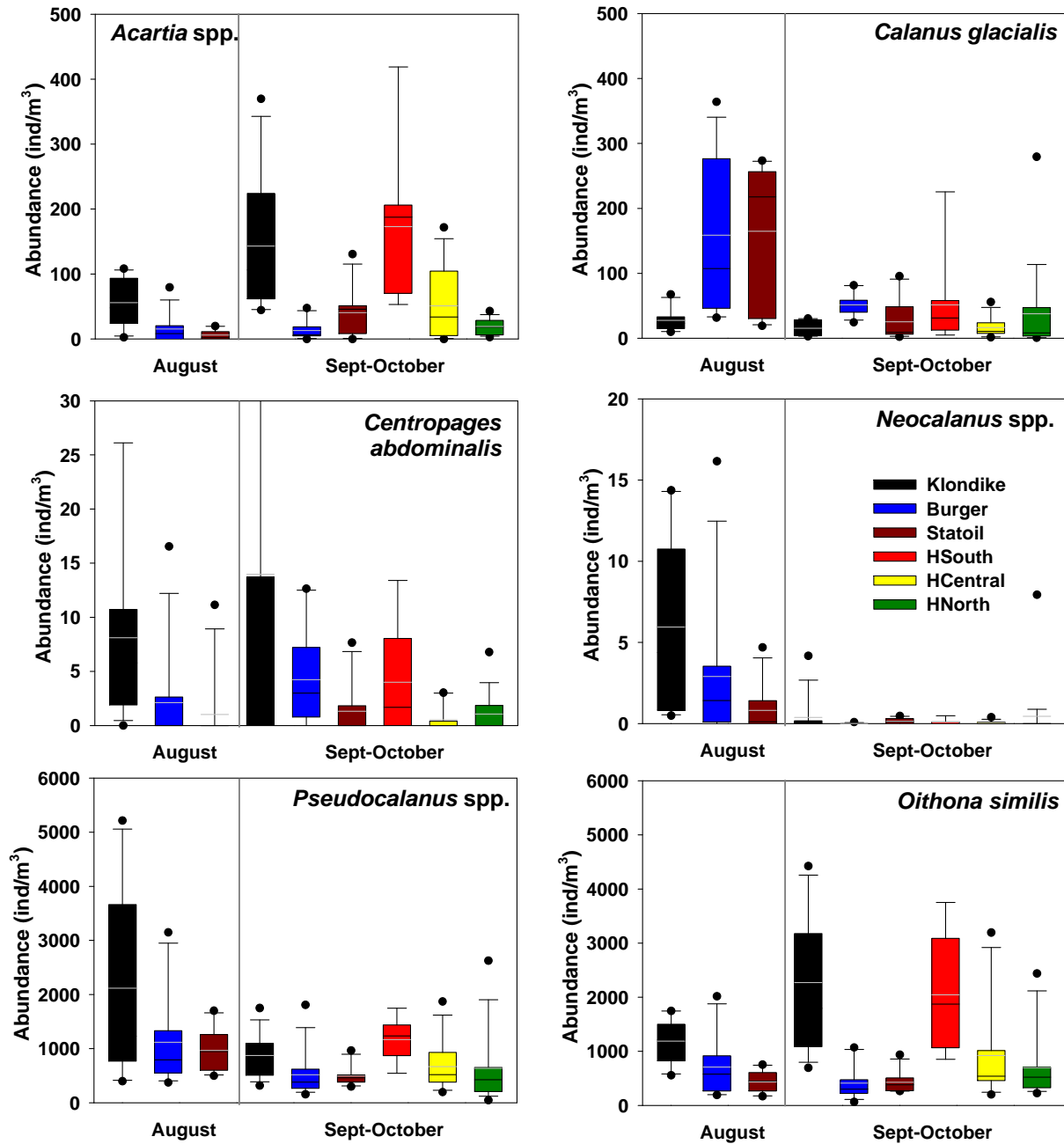


Fig. 27 Abundance of the dominant copepod species or genera during each survey grid in 2011 as captured by the 150- μ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25th and 75th percentile. Whiskers are the 10th and 90th percentiles and the single points are the 5th and 95th percentiles. Features may be absent where number of samples with occurrence is low.

150- μ m

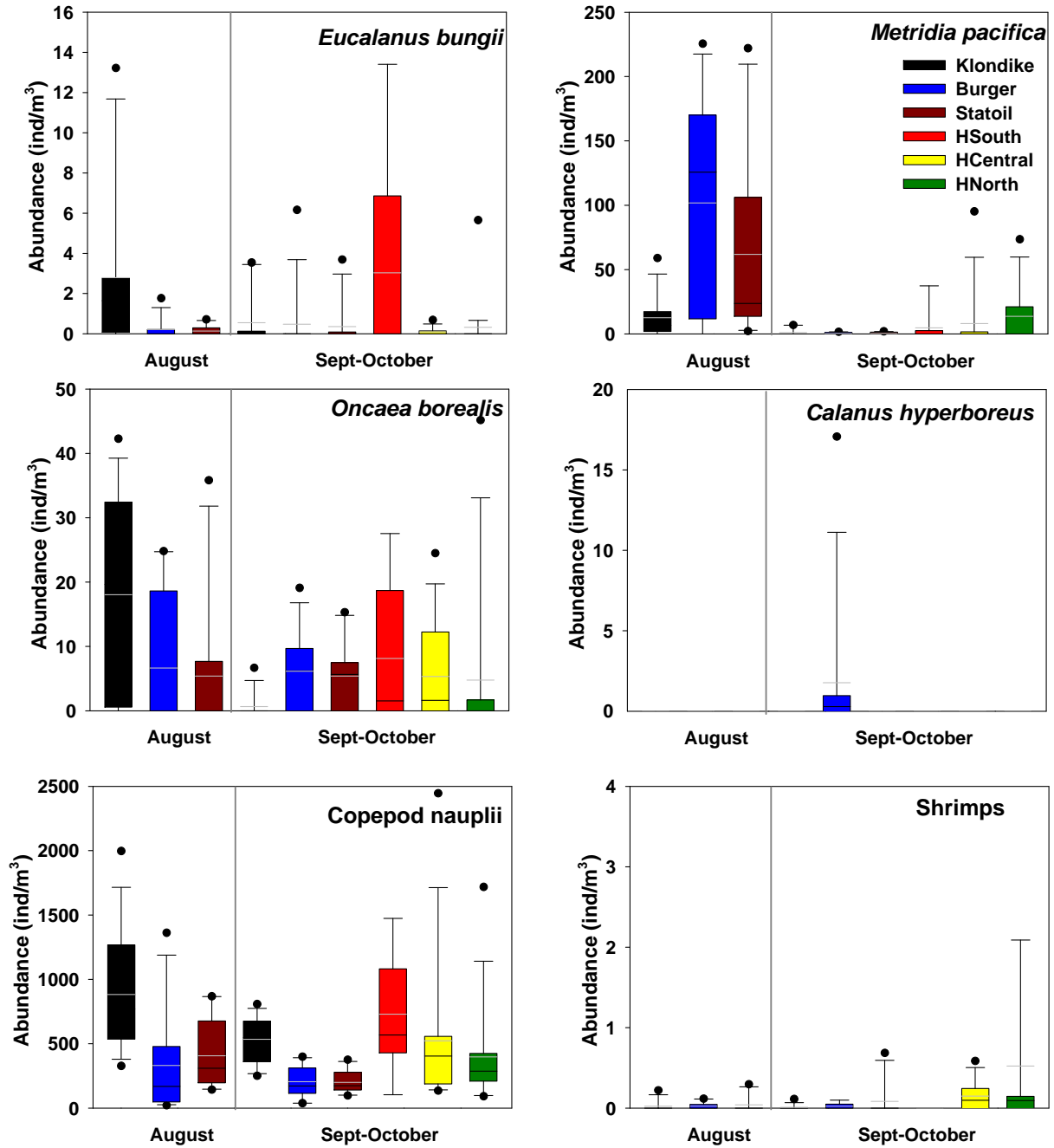


Fig. 28 Abundance of the dominant copepod species/stages, and non-copepod crustaceans during each survey grid in 2011 as captured by the 150- μ m net.

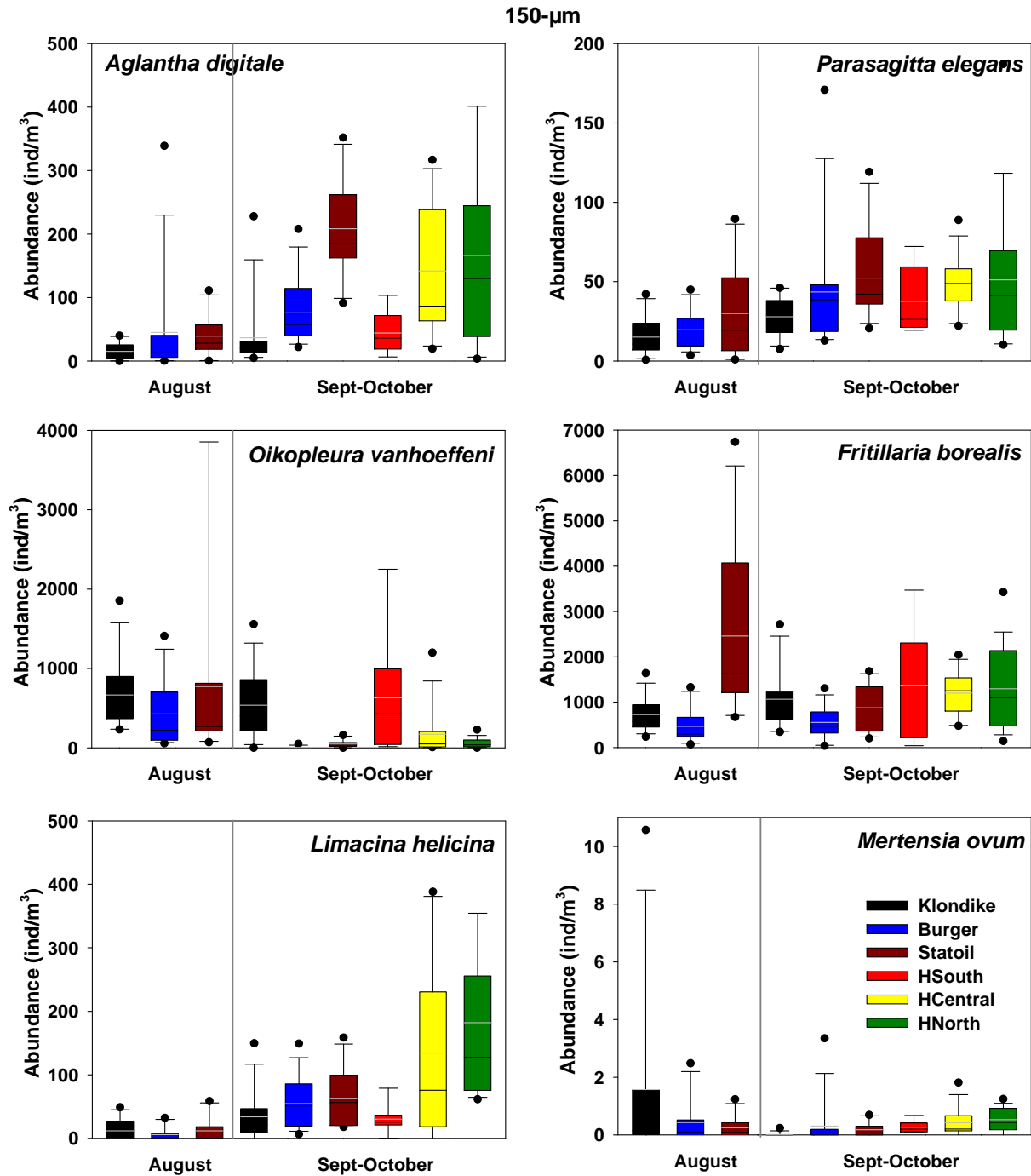


Fig. 29 Abundance of the dominant cnidarians, chaetognaths, larvaceans and pteropods during each survey grid in 2011 as captured by the 150- μ m net.

150- μm

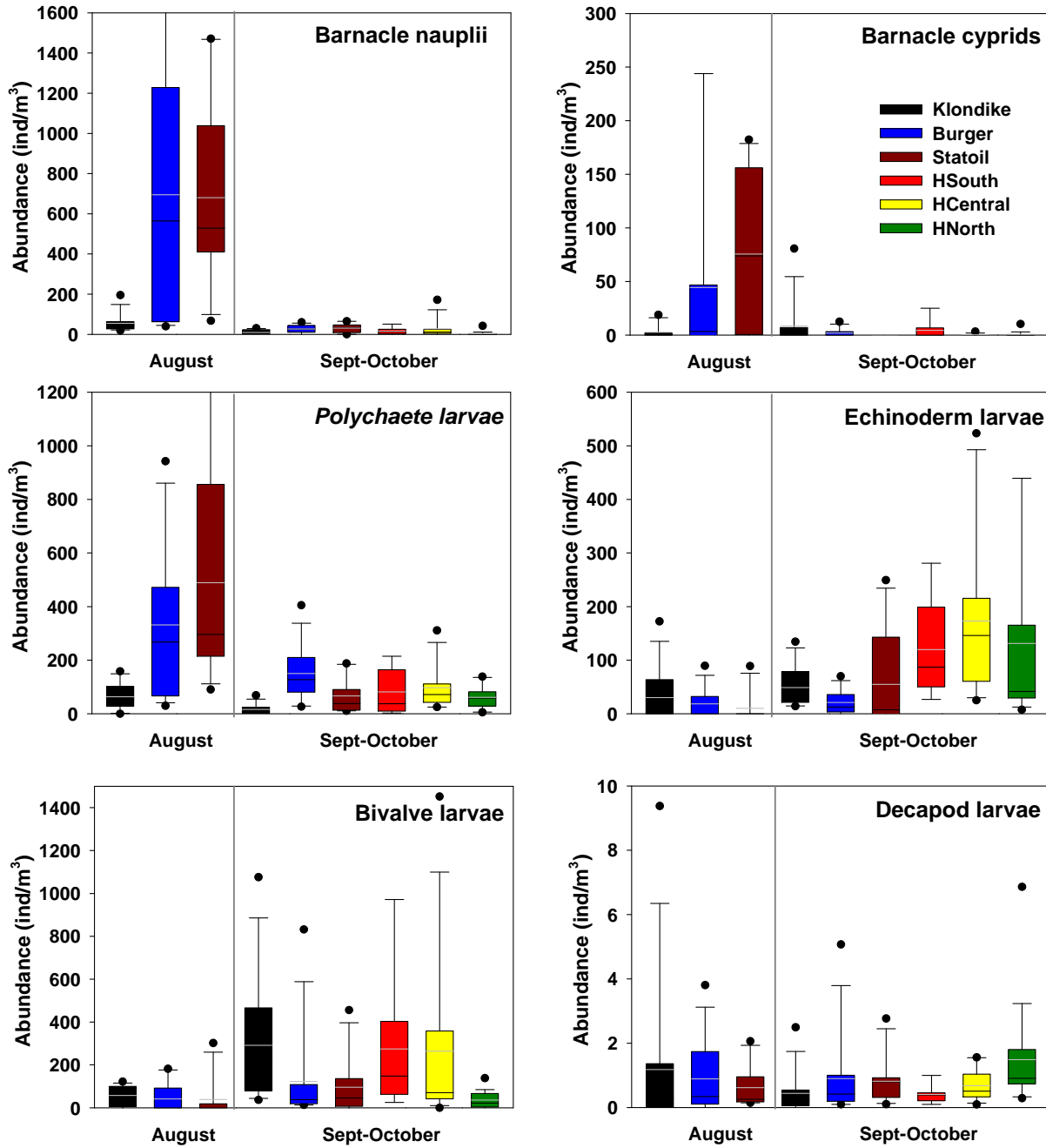


Fig. 30 Abundance of the dominant meroplankton during each survey grid in 2011 as captured by the 150- μm net.

505- μm

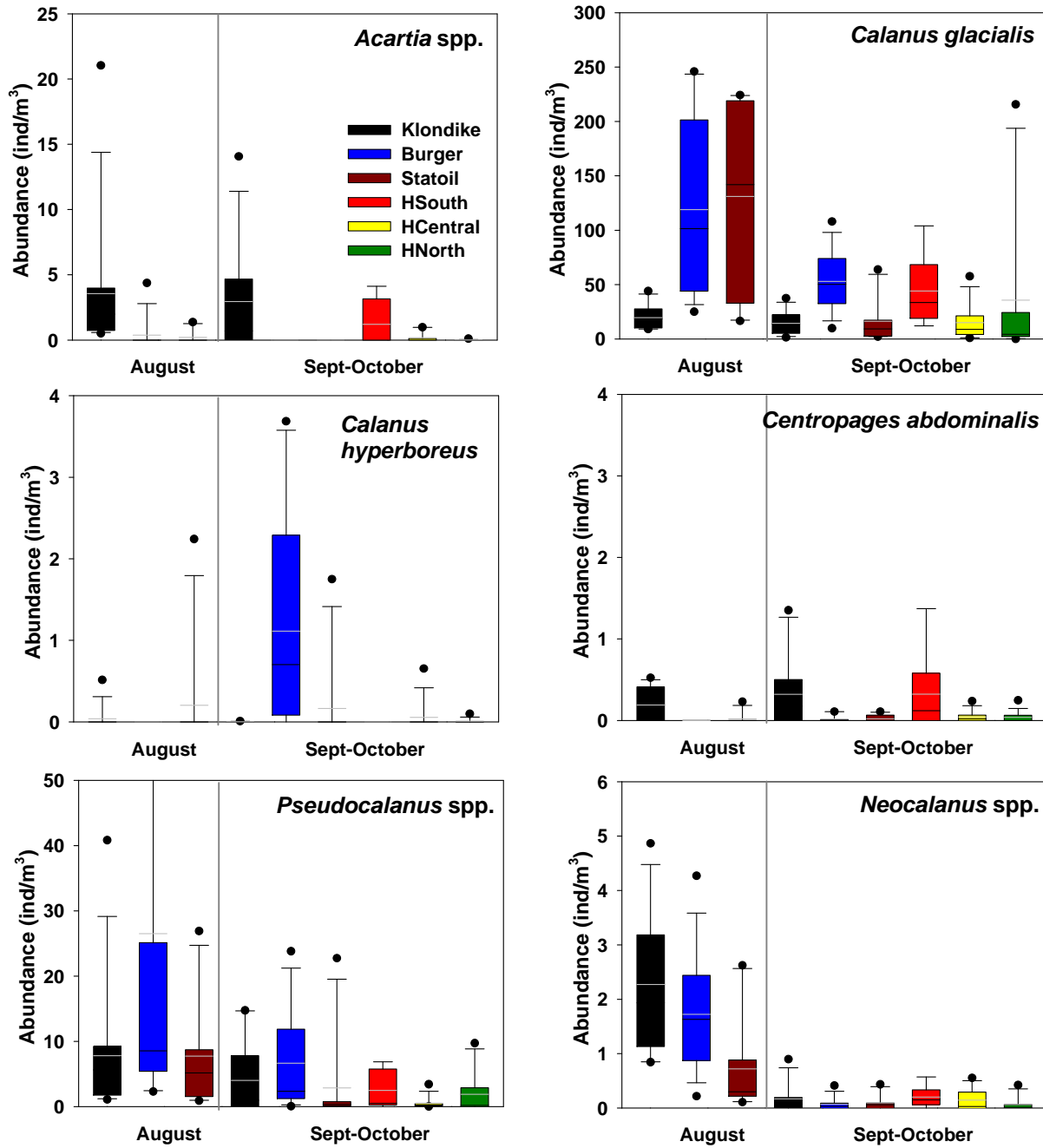


Fig.31 Abundance of the dominant copepods during each survey grid in 2011 as captured by the 505- μm net.

505- μ m

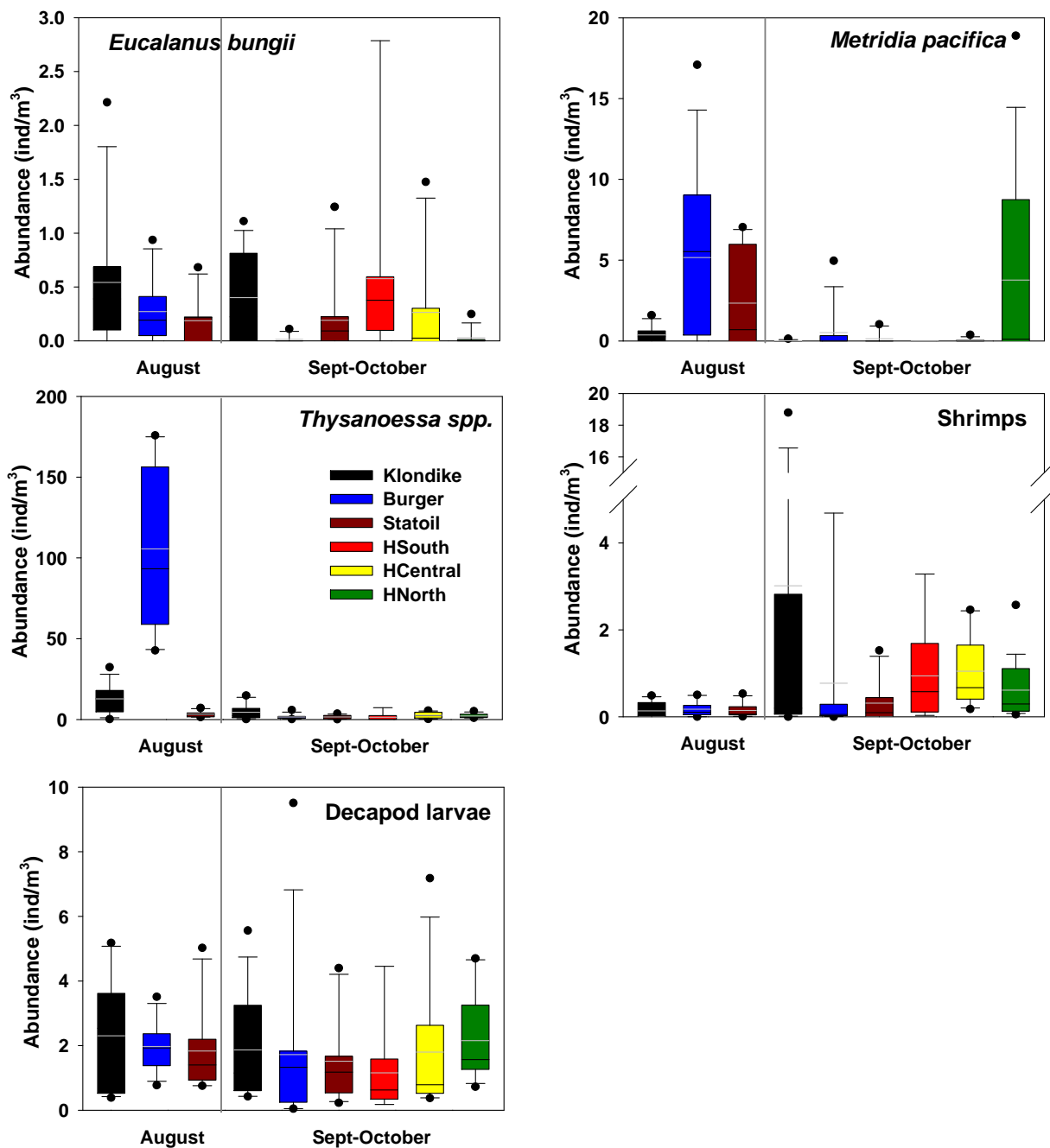


Fig. 32 Abundance of the dominant crustacean zooplankton during each survey grid in 2011 as captured by the 505- μ m net.

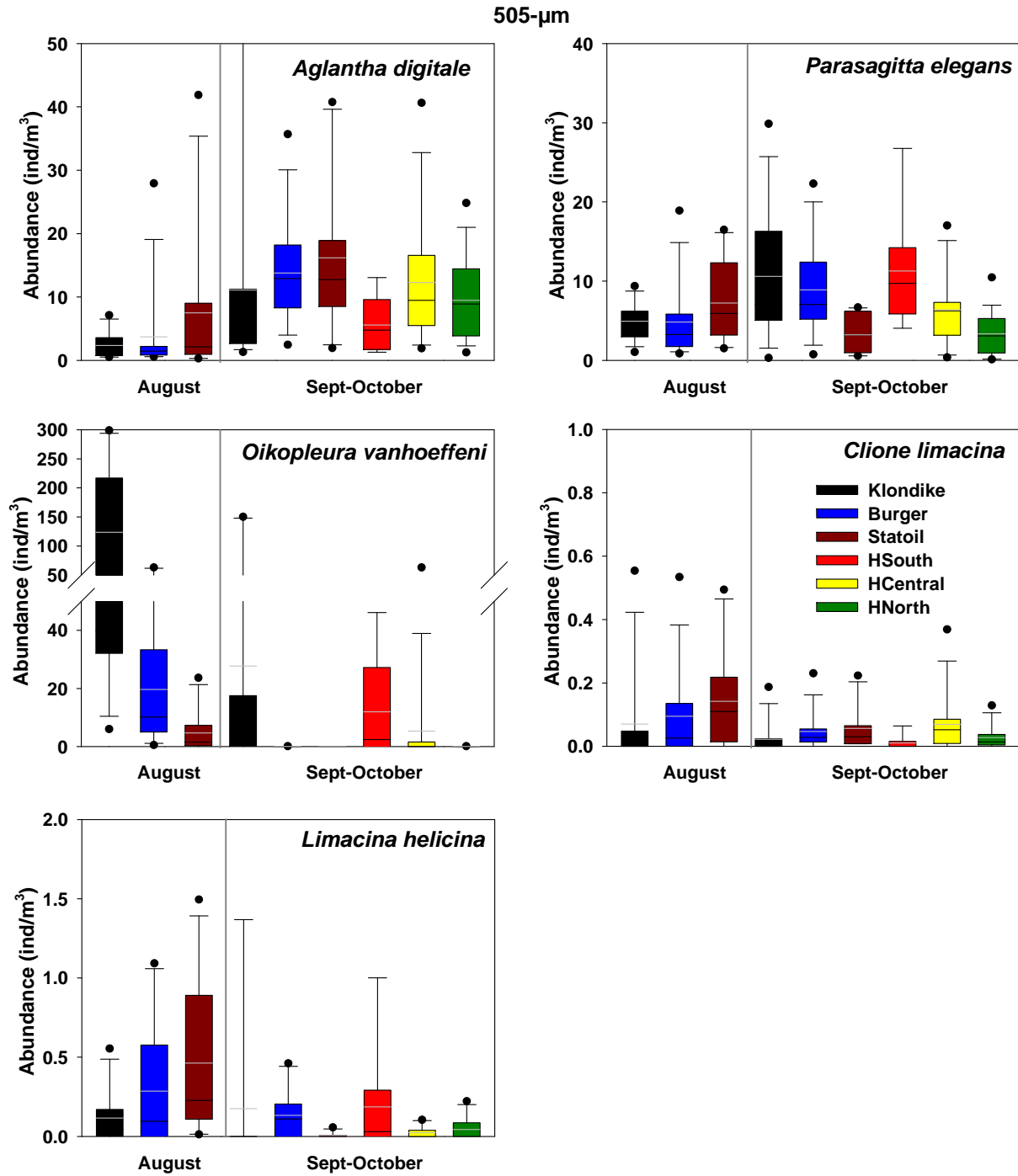


Fig. 33 Abundance of the dominant non-copepod zooplankton during each survey grid in 2011 as captured by the 505- μ m net.

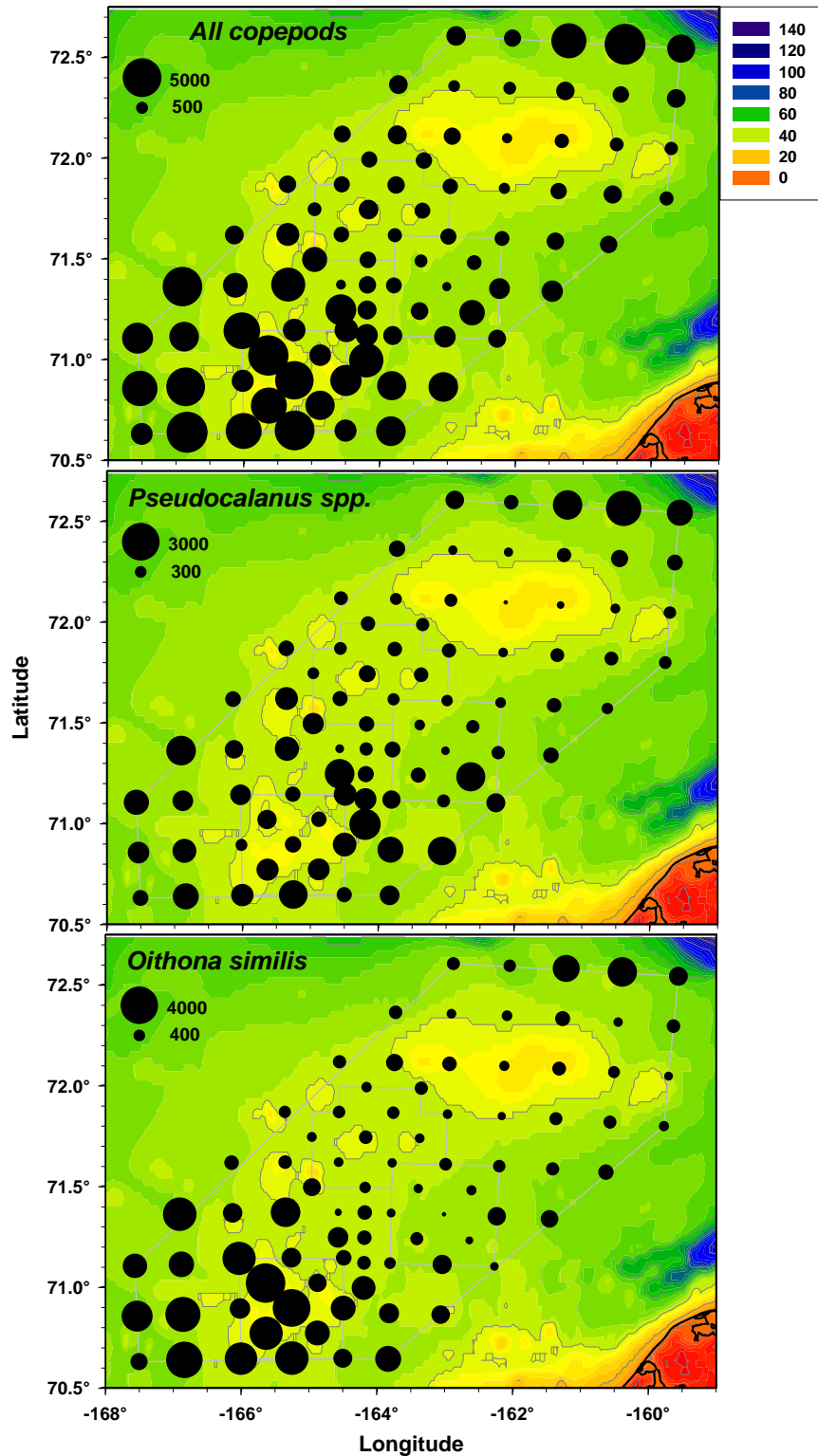


Fig. 34. Abundance of all copepods, and their most abundant species, over the Greater Hanna Shoal study area in 2011 as assessed using the 150- μ m mesh nets. Area of bubbles is proportional to abundance (individuals m^{-3}). Color fills represent bathymetry in meters.

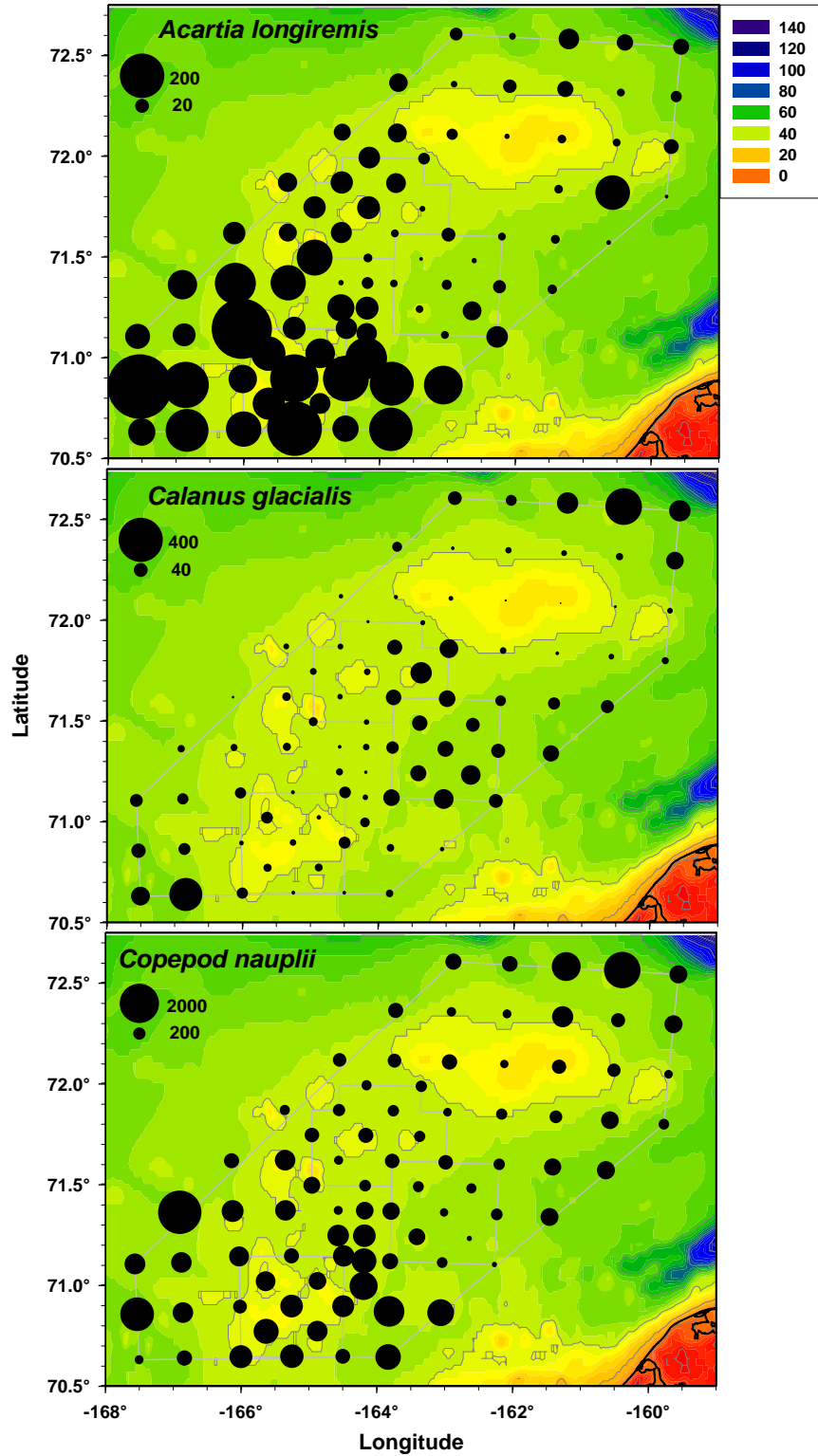


Fig. 35. Abundance of *Calanus* copepod species and copepod nauplii over the Greater Hanna Shoal study area in 2011 as assessed using the 150- μ m mesh nets. Area of bubbles is proportional to abundance (individuals m^{-3}). Color fills represent bathymetry in meters.

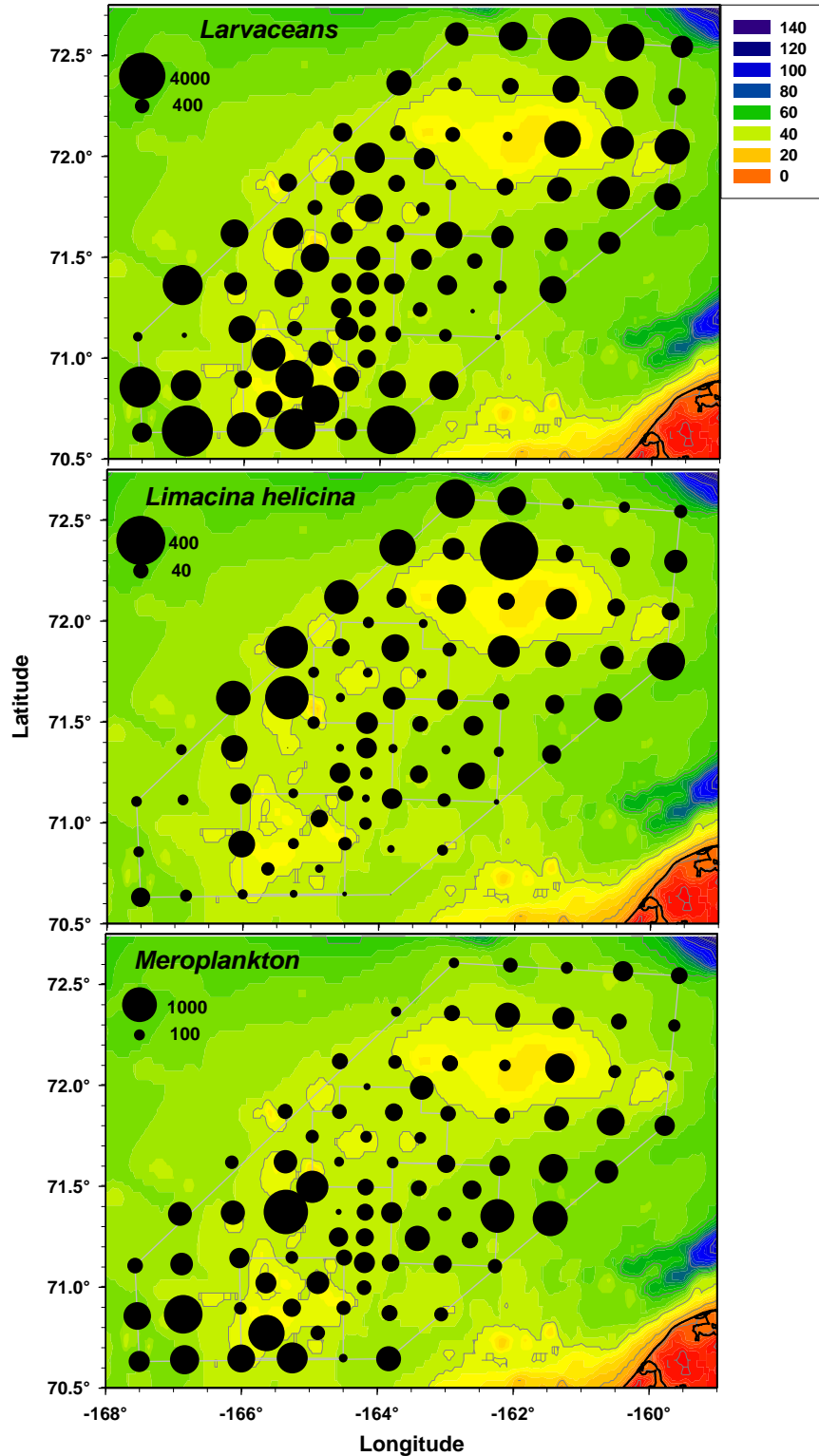


Fig. 36. Abundance of larvaceans, the pteropod *Limacina helicina*, and meroplankton over the Greater Hanna Shoal study area in 2011 as assessed using the 150- μ m mesh nets. Area of bubbles is proportional to abundance (individuals m^{-3}). Color fills represent bathymetry in meters.

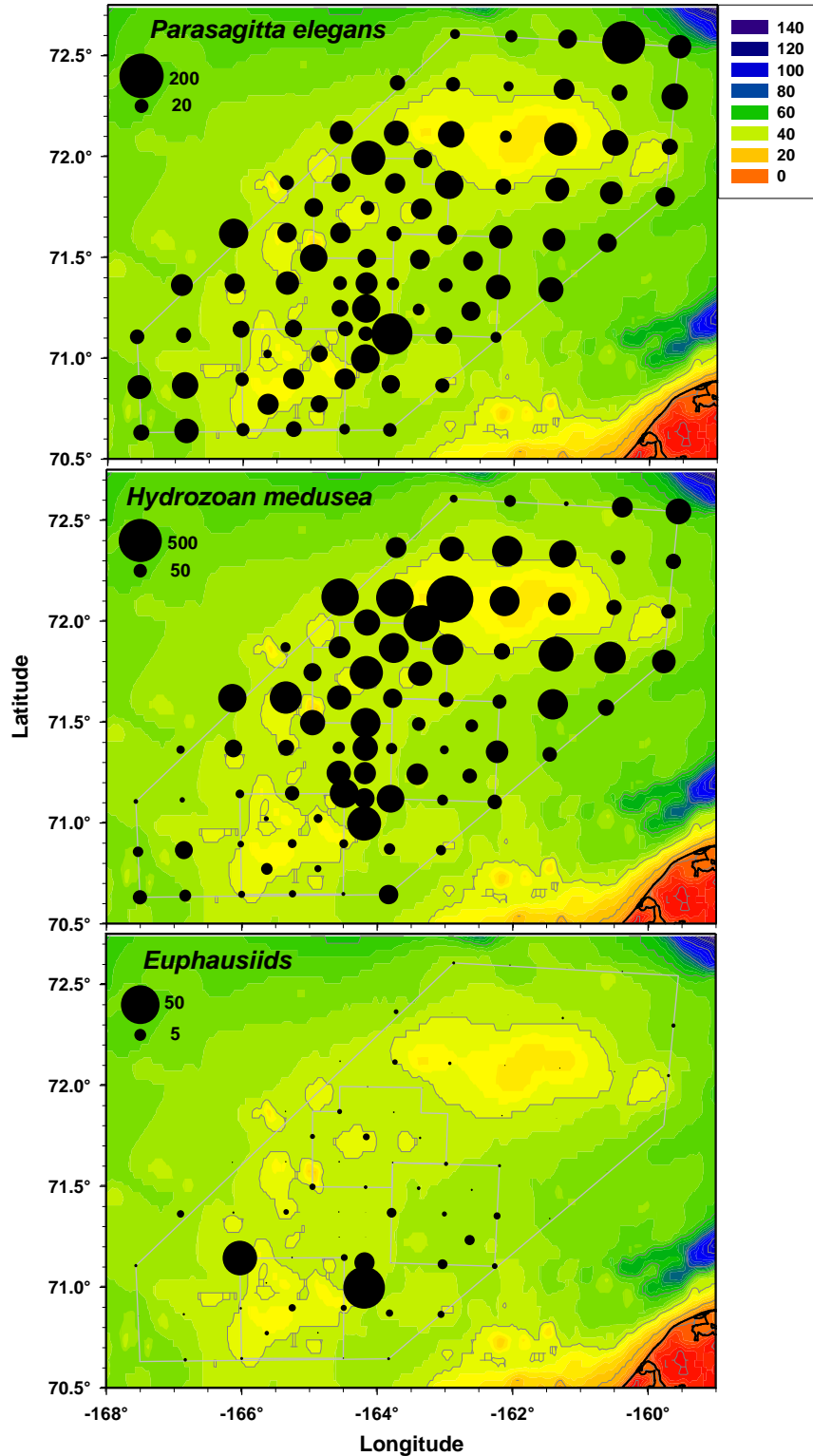


Fig. 37. Abundance of the chaetognath *Parasagitta elegans*, hydrozoan medusae and euphausiids over the Greater Hanna Shoal study area in 2011 as assessed using the 150- μ m mesh nets. Area of bubbles is proportional to abundance (individuals m⁻³). Color fills represent bathymetry in meters.

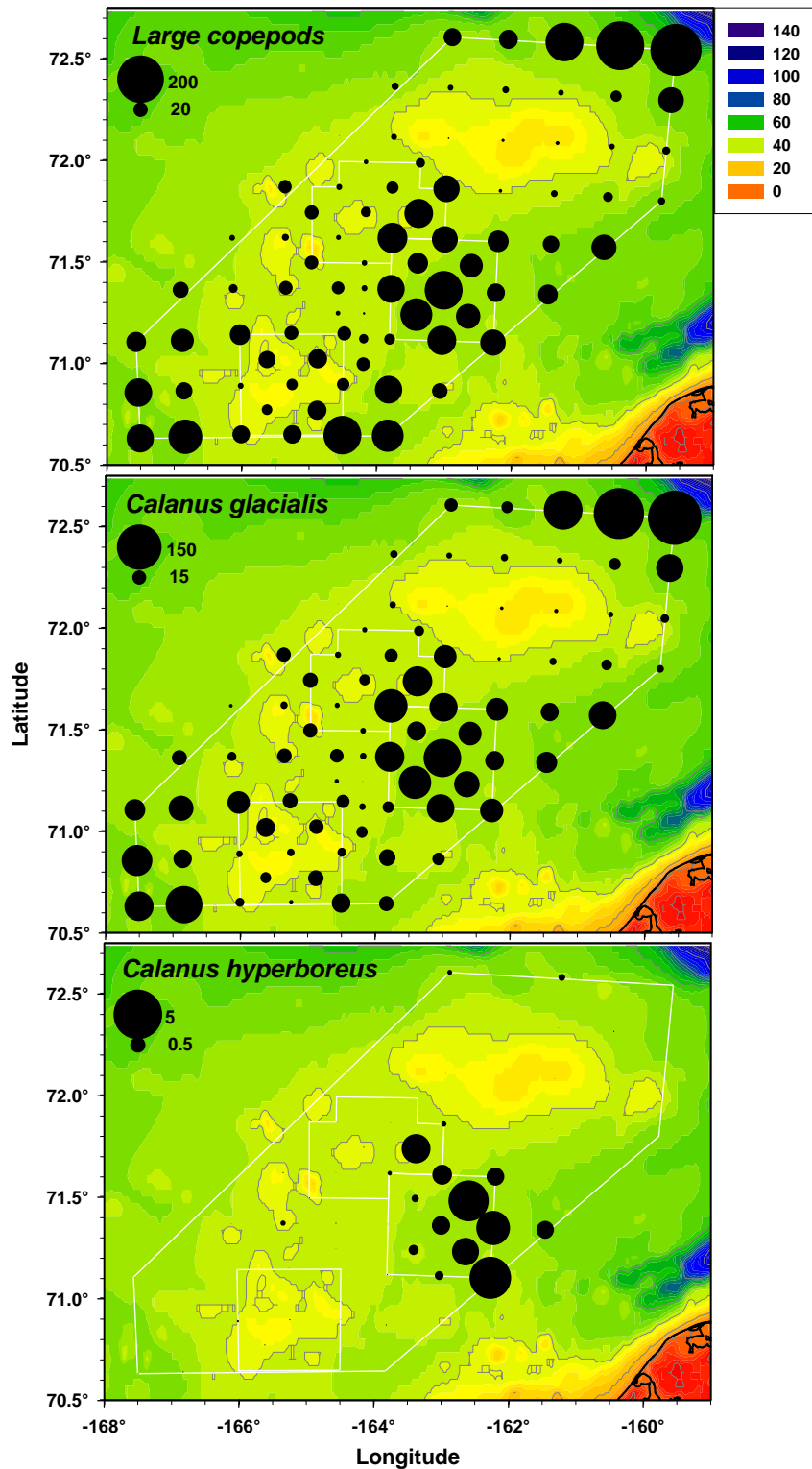


Fig. 38. Abundance of all copepods, and their *Calanus* species, over the Greater Hanna Shoal study area in 2011 as assessed using the 505- μm mesh nets. Area of bubbles is proportional to abundance (individuals m^{-3}). Color fills represent bathymetry in meters.

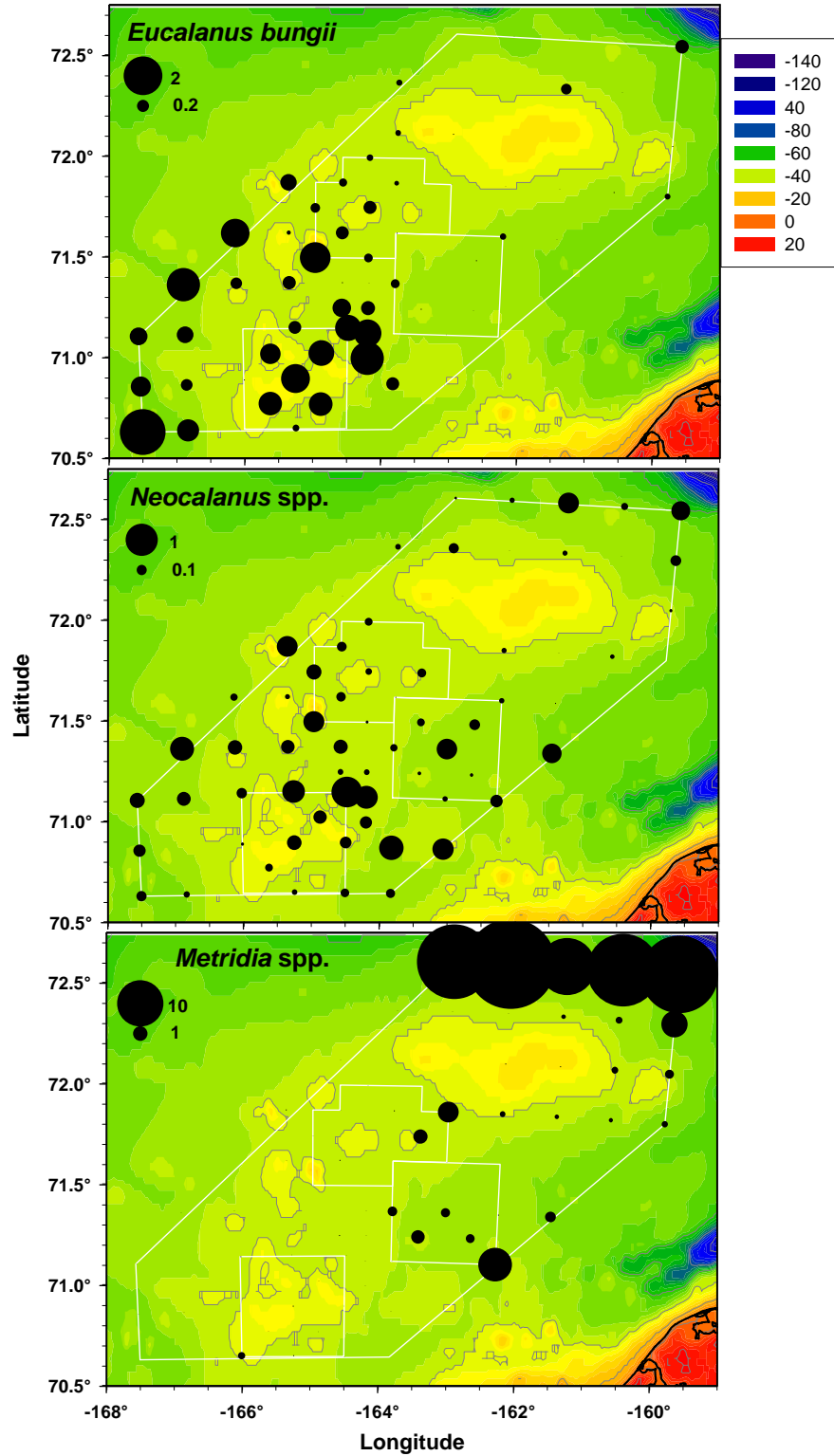


Fig. 39. Abundance of three large-bodied Pacific copepods over the Greater Hanna Shoal study area in 2011 as assessed using the 505- μ m mesh nets. Area of bubbles is proportional to abundance (individuals m^{-3}). Color fills represent bathymetry in meters.

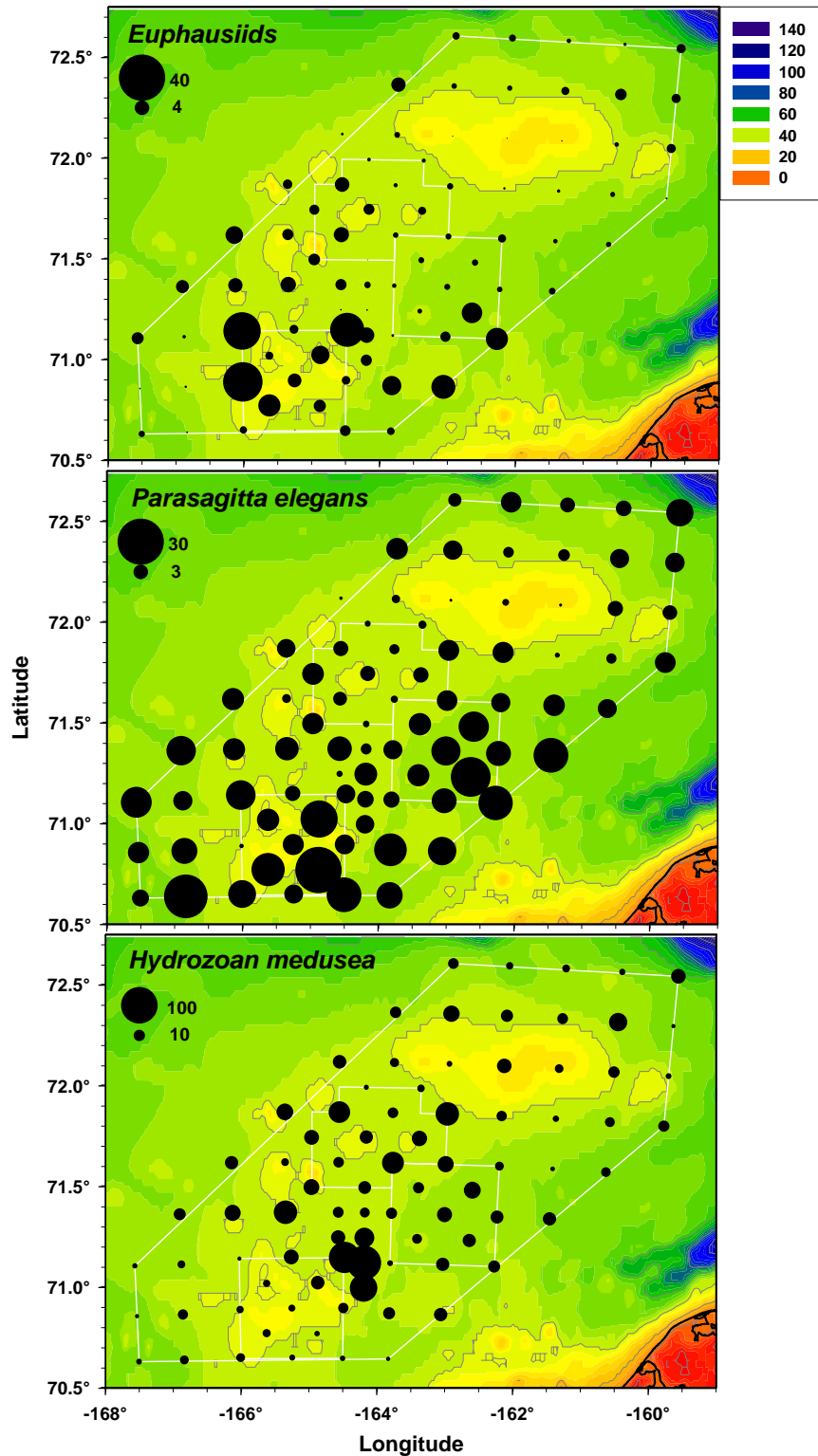


Fig. 40. Abundance of euphausiids, the chaetognath *Parasagitta elegans* and hydrozoan medusea over the Greater Hanna Shoal study area in 2011 as assessed using the 505- μm mesh nets. Area of bubbles is proportional to abundance (individuals m^{-3}). Color fills represent bathymetry in meters.

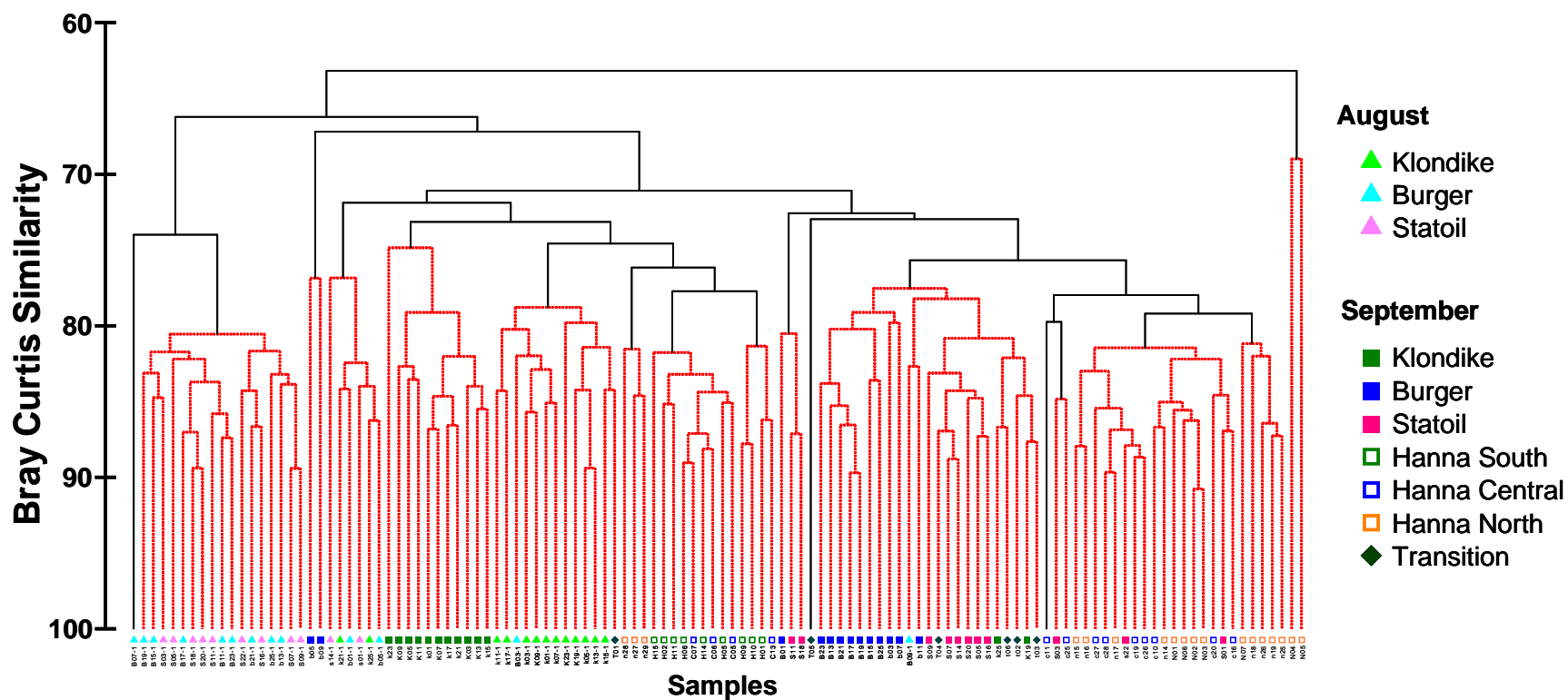


Fig. 41 Station similarity as determined by hierarchical clustering of fourth-root transformed zooplankton abundance for the 150- μ m net. Red lines connect stations that are not statistically unique ($P < 0.05$). Stations color-coded by survey grid to aid interpretation. First cruise is distinguished by the suffix “1.” Stations numbers are last two digits of sample ID number.

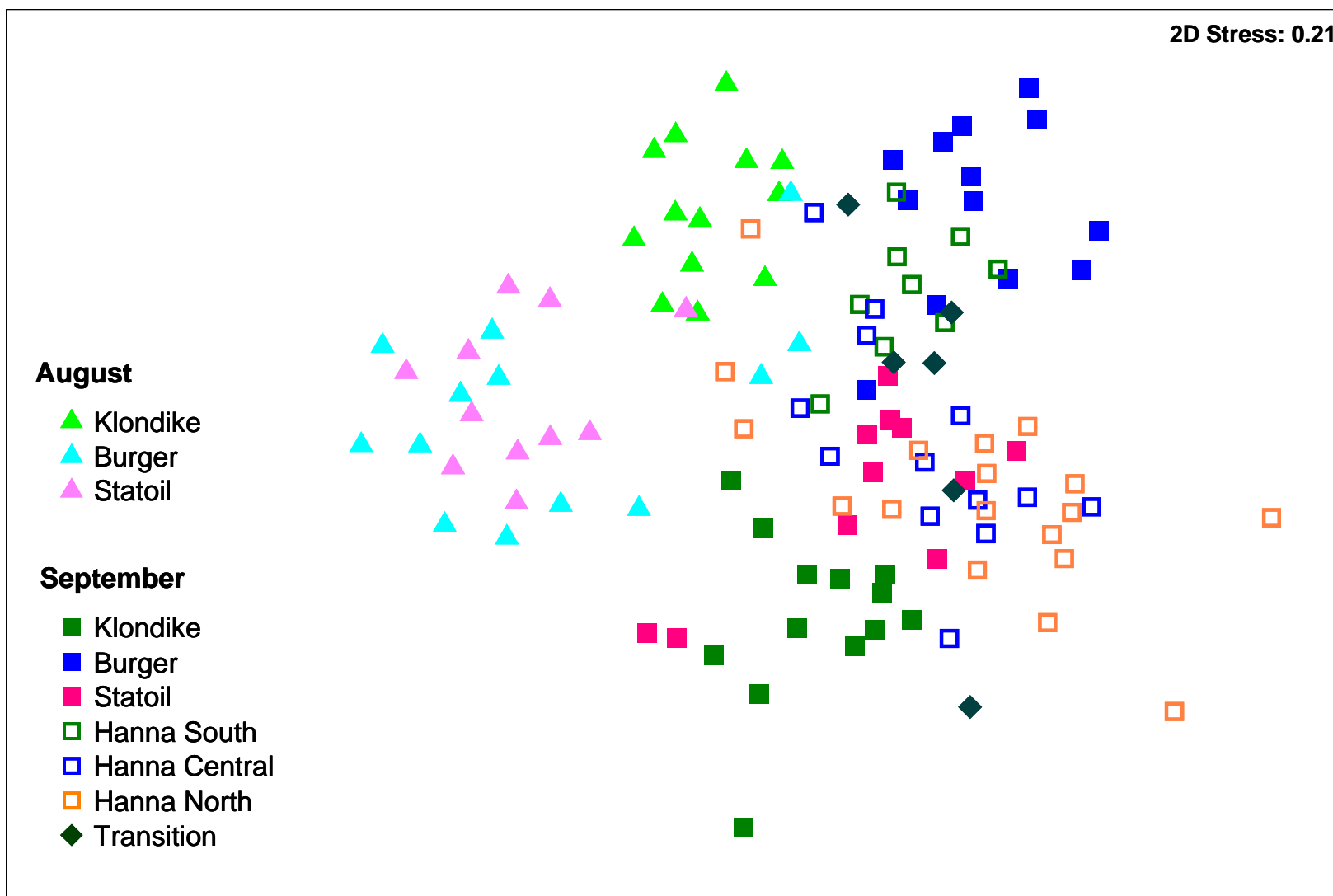


Fig. 42. Multidimensional scaling of zooplankton community abundances for the 150- μ m net based on clustering performed in Fig. 41. Axes are arbitrary, spacing of samples represents the best 2-D projection of the distance in similarity between each sample. Stations color-coded by survey grid to aid interpretation.

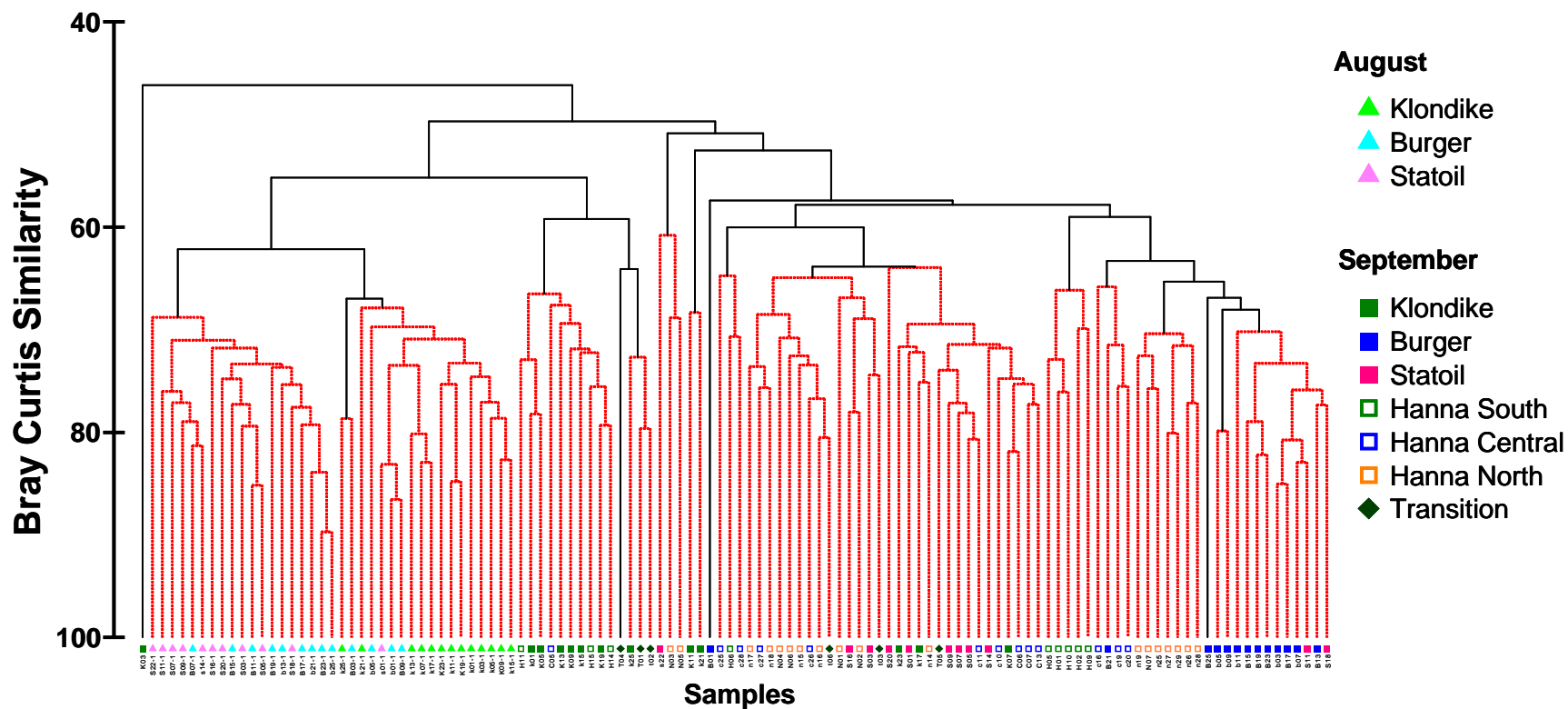


Fig. 43. Station similarity as determined by hierarchical clustering of fourth-root transformed zooplankton abundance for the 505- μm net. Red lines connect stations that are not statistically unique ($P < 0.05$). Stations are color-coded by survey grid to aid interpretation. First cruise is distinguished by the suffix “1.” Station numbers are last two digits of sample ID number.

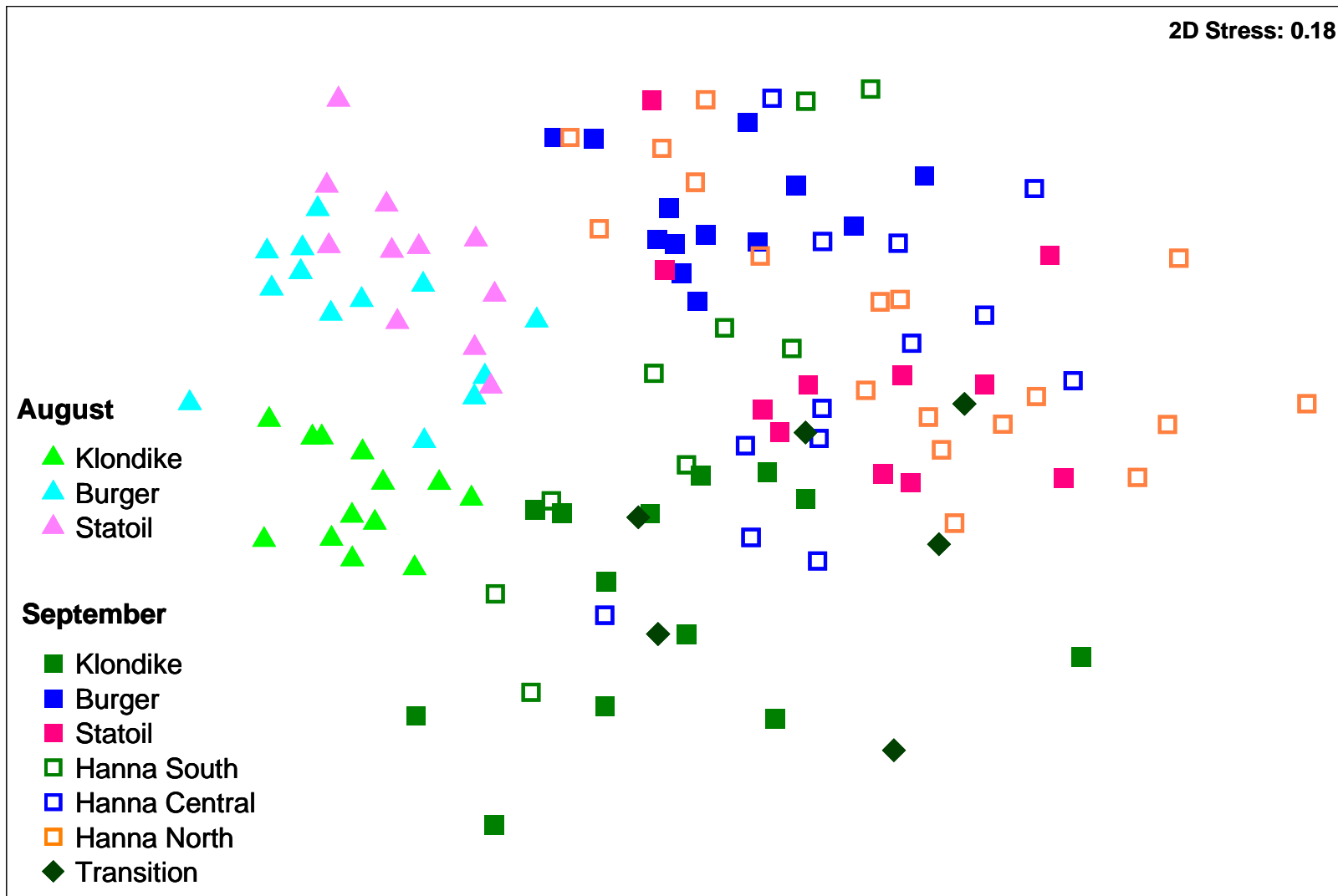


Fig. 44. Multidimensional scaling of zooplankton community abundances for the 150- μ m net based on clustering performed in Fig. 43. Axes are arbitrary, spacing of samples represents the best 2-D projection of the distance in similarity between each sample. Stations color-coded by survey grid to aid interpretation.

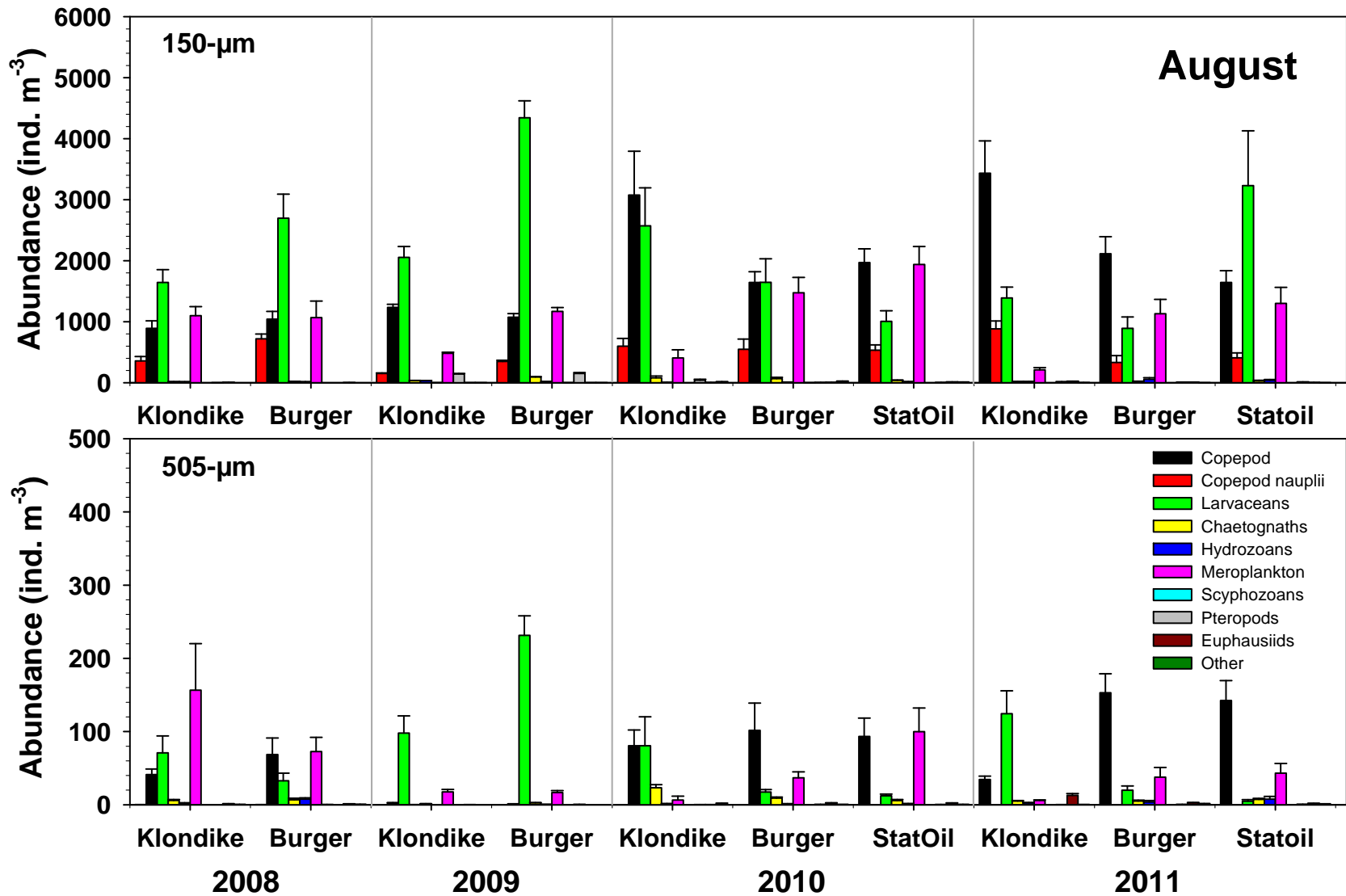


Fig. 45 Contribution of the major groups to the community abundance during August at each survey grid spanning the 2008–2011 season as determined for both plankton nets. Error bars are standard error of the means.

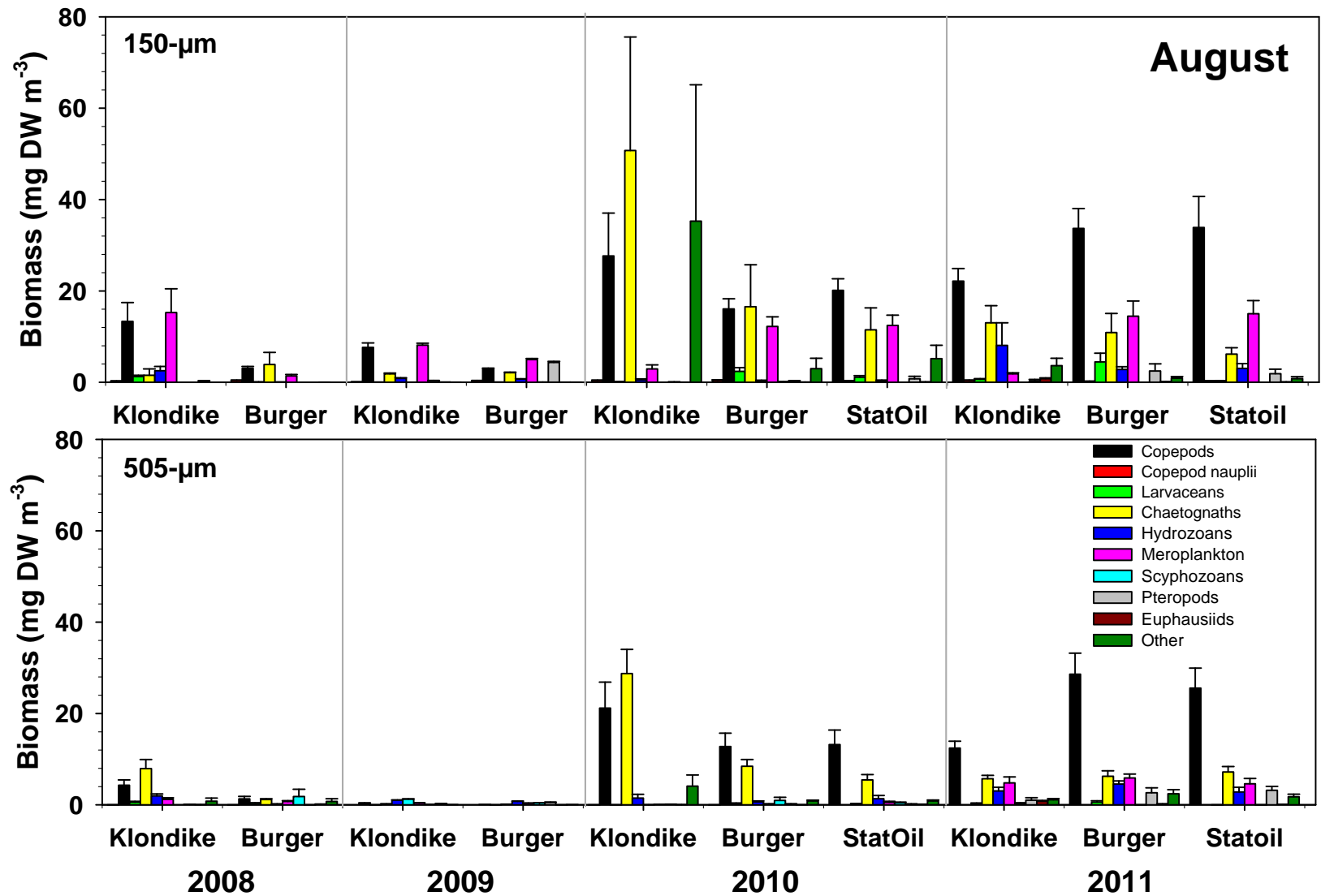


Fig. 46. Contribution of the major groups to the community biomass during August at each survey grid spanning the 2008–2011 season as determined for both plankton nets. Error bars are standard error of the means.

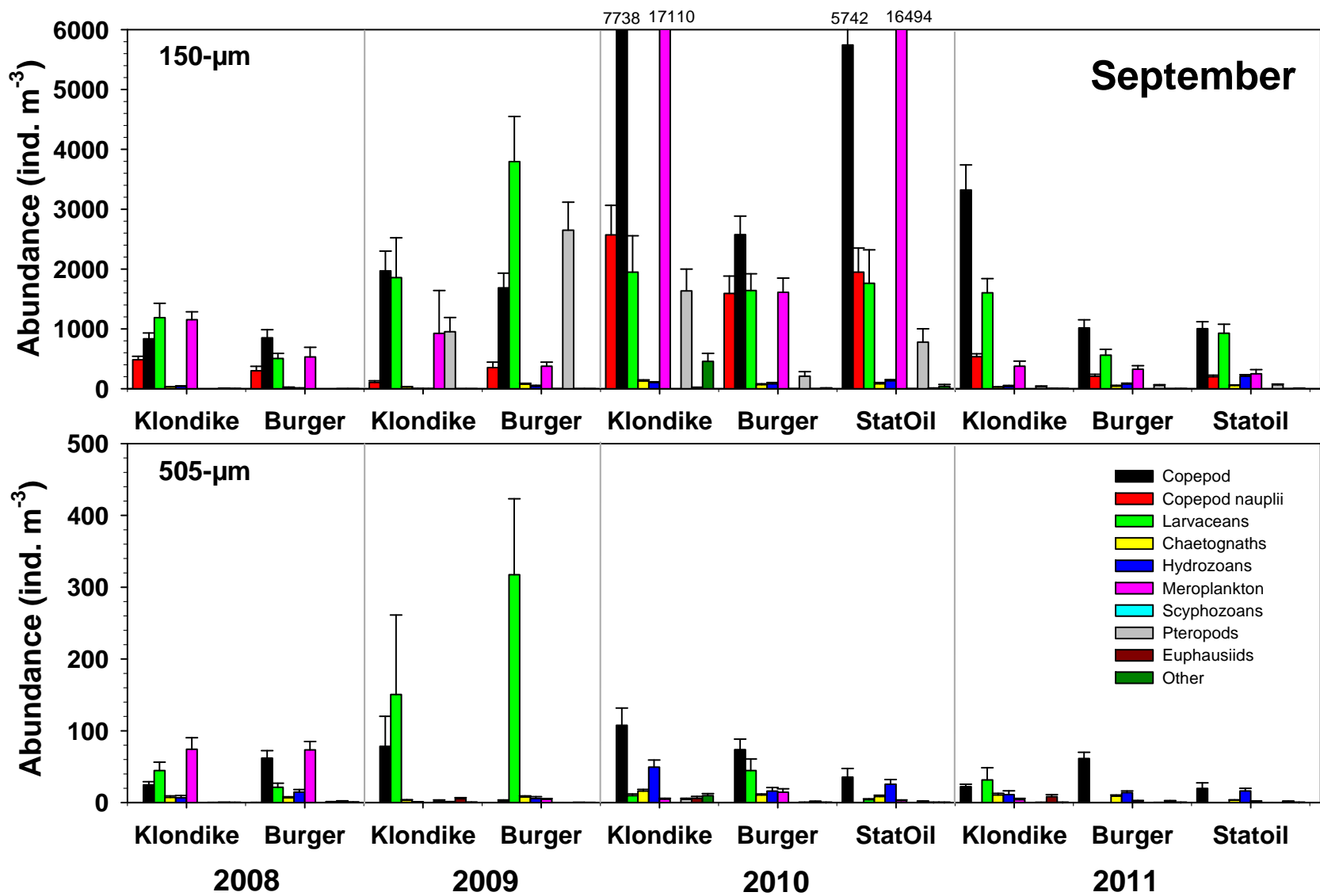


Fig. 47. Contribution of the major groups to the community abundance during September at each survey grid spanning the 2008–2011 season as determined for both plankton nets. Error bars are standard error of the means.

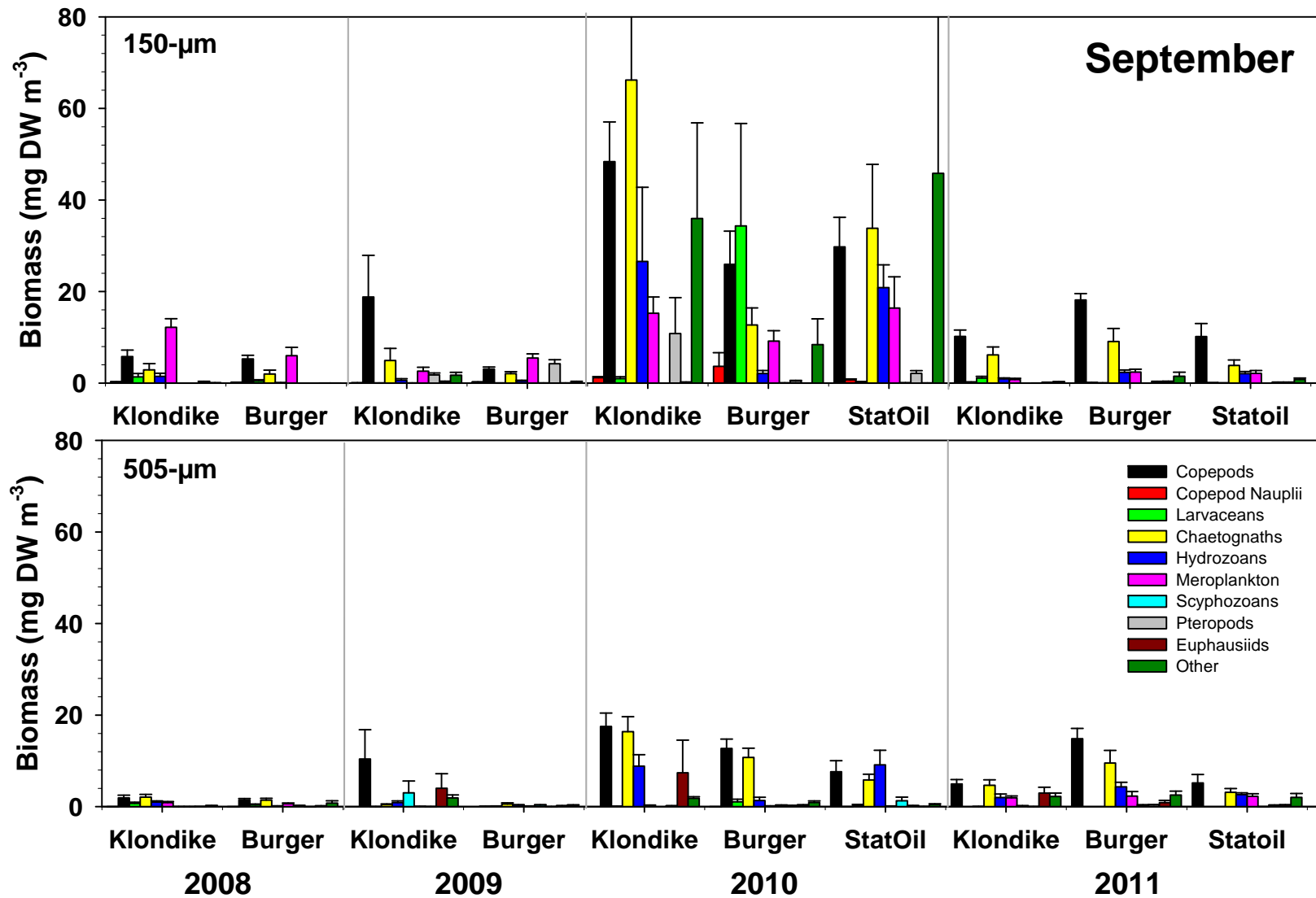


Fig. 48. Contribution of the major groups to the community biomass during September at each survey grid spanning the 2008–2011 season as determined for both plankton nets. Error bars are standard error of the means.

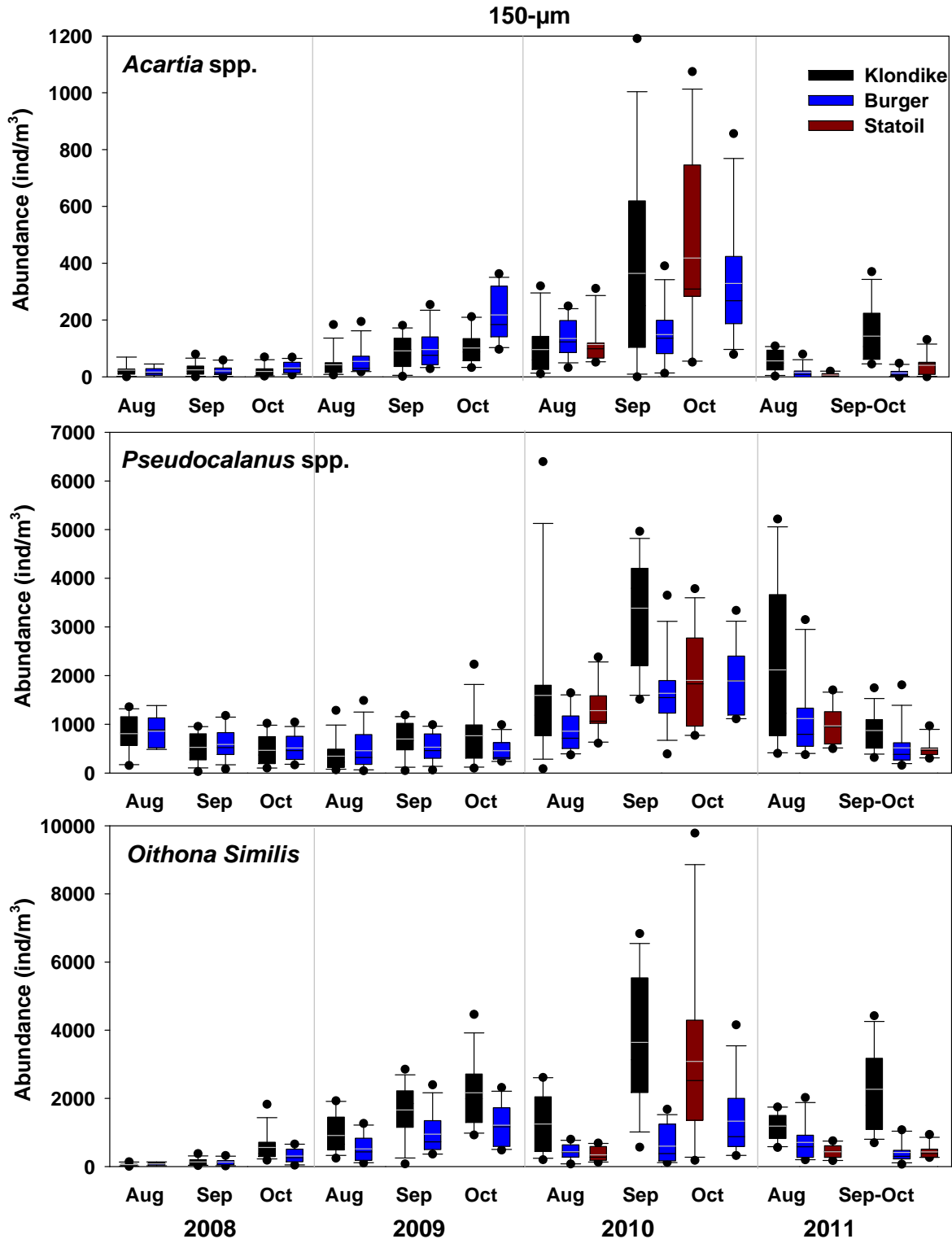


Fig. 49a. Abundance of the dominant copepod and larvacean species during each survey grid spanning the 2008-2011 seasons as captured by the 150- μ m net. The black or white line through the box is the sample median; grey line is the mean, limits of the box are the 25th and 75th percentile. Whiskers are the 10th and 90th percentiles and the single points are the 5th and 95th percentiles.

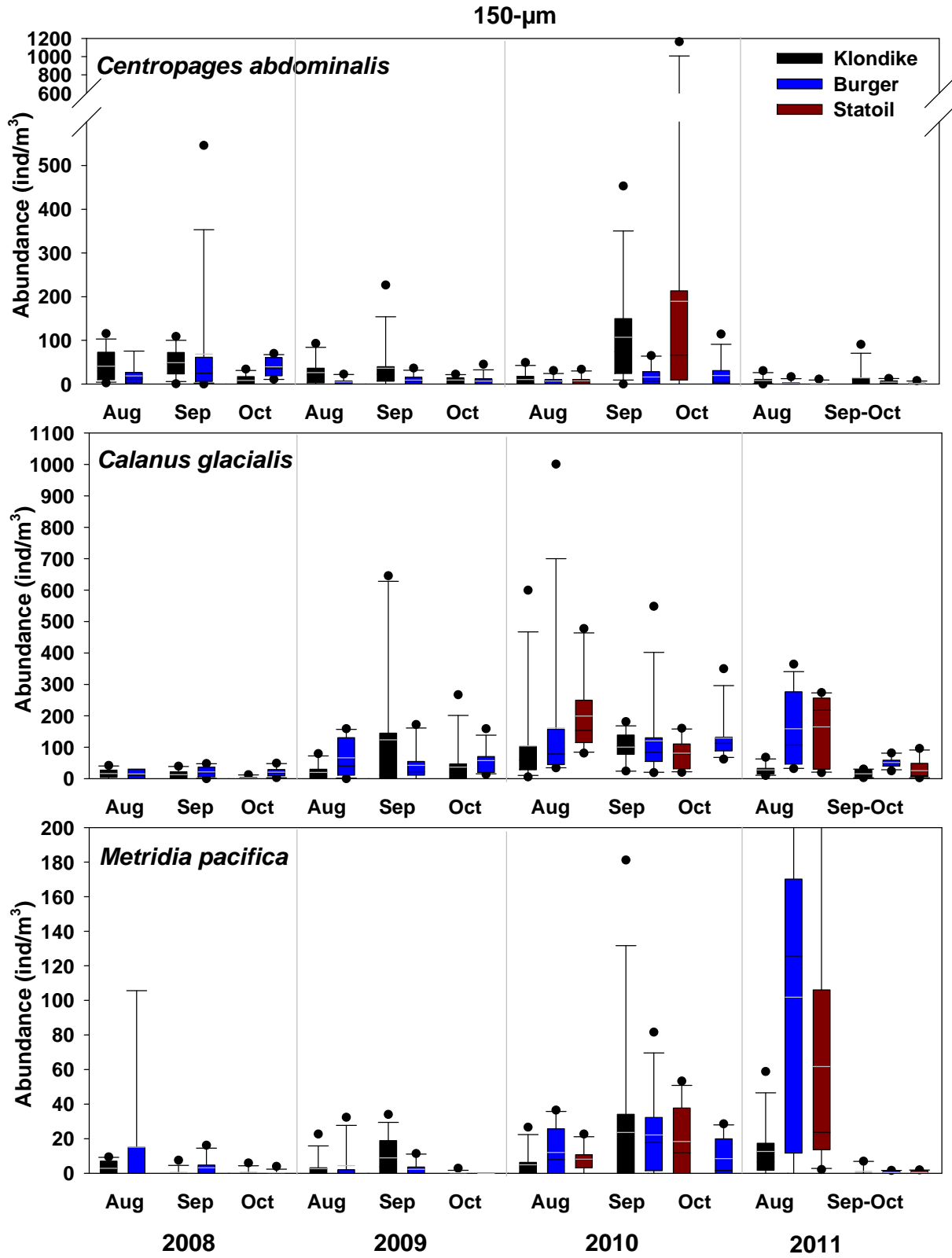


Fig. 49b. Abundance of the dominant copepod and larvacean species during each survey grid spanning the 2008-2011 seasons as captured by the 150- μ m net.

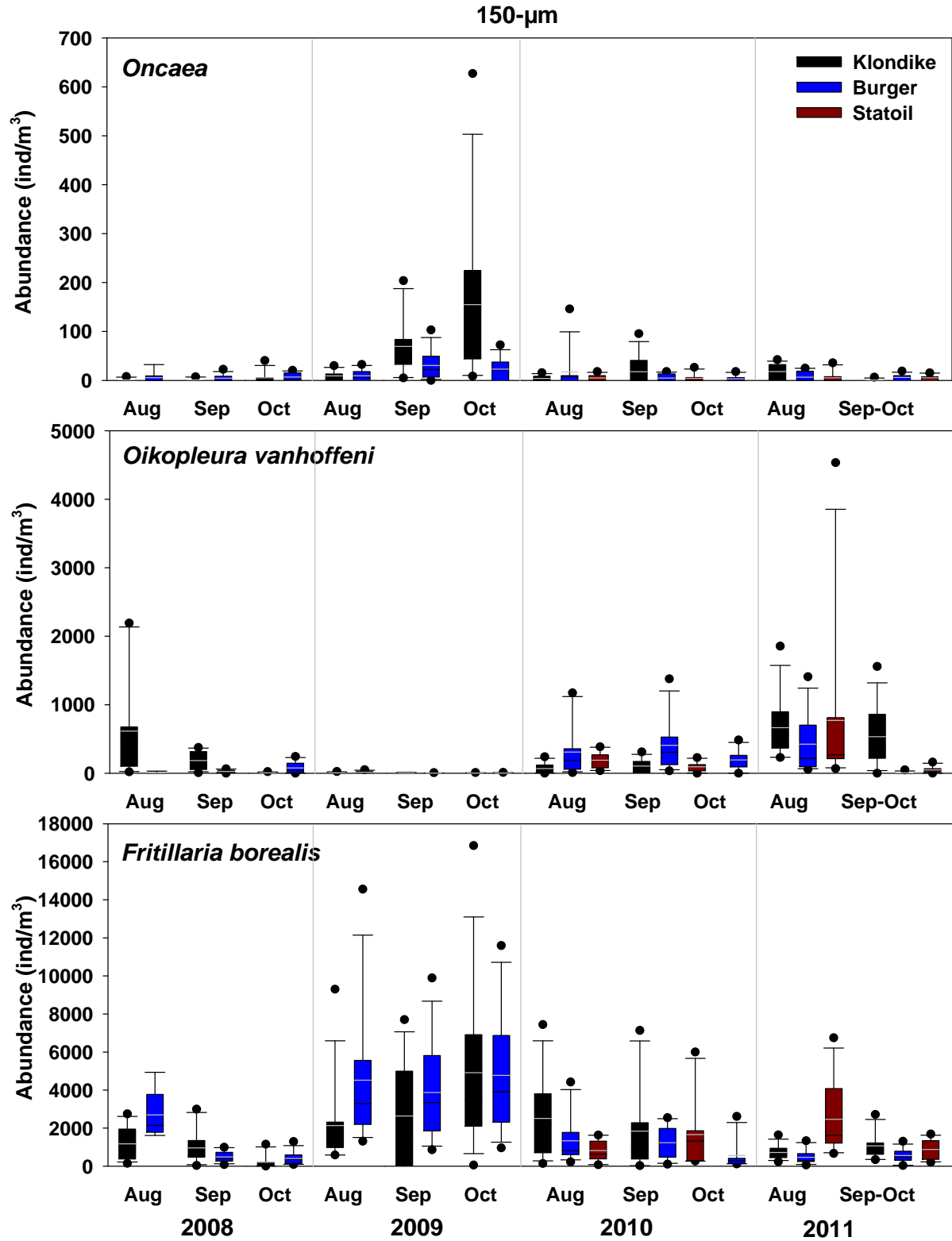


Fig. 49c. Abundance of the dominant copepod and larvacean species during each survey grid spanning the 2008-2011 seasons as captured by the 150- μ m net.

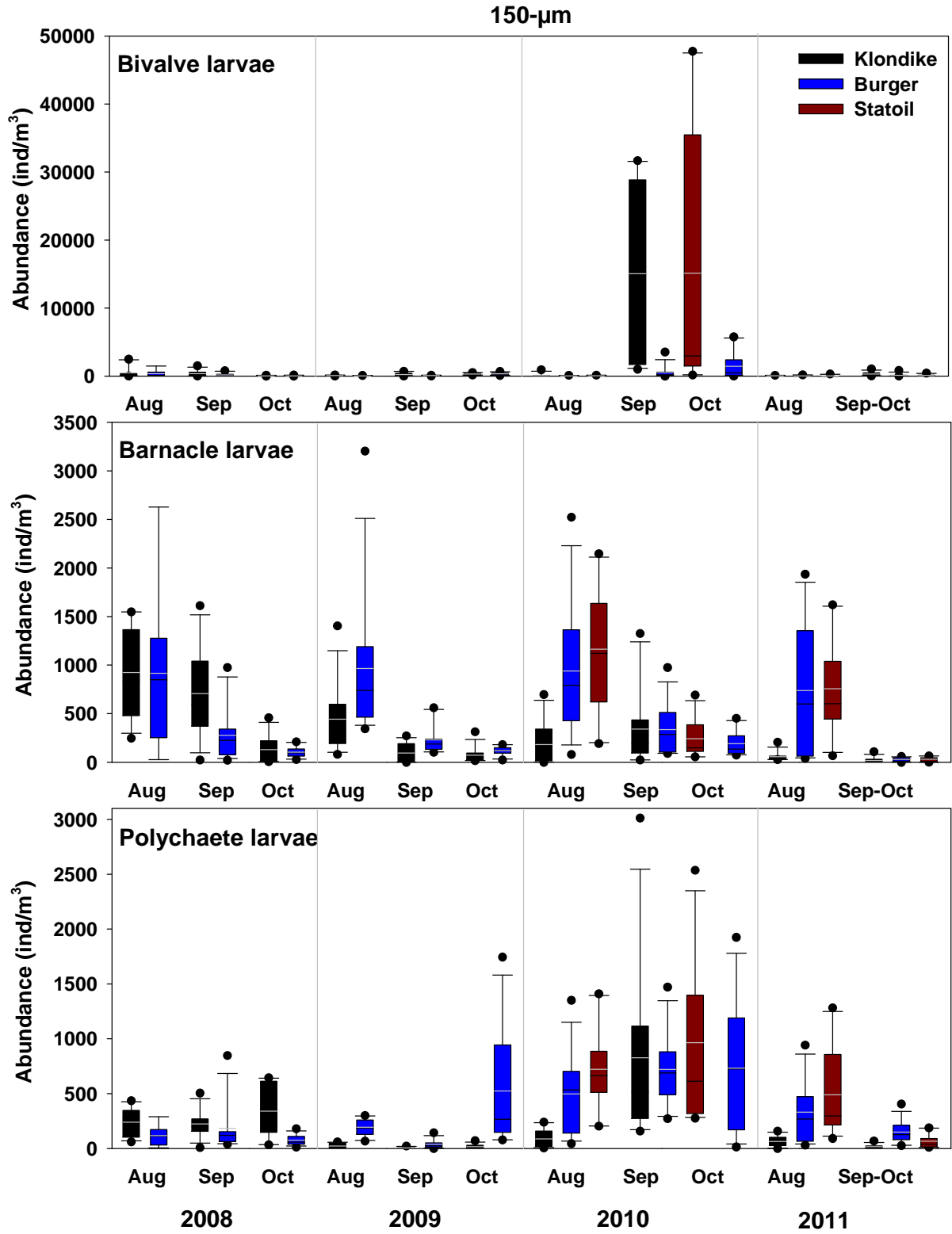


Fig. 50. Abundance of the dominant meroplankton during each survey grid spanning the 2008-2011 seasons as captured by the 150- μ m net.

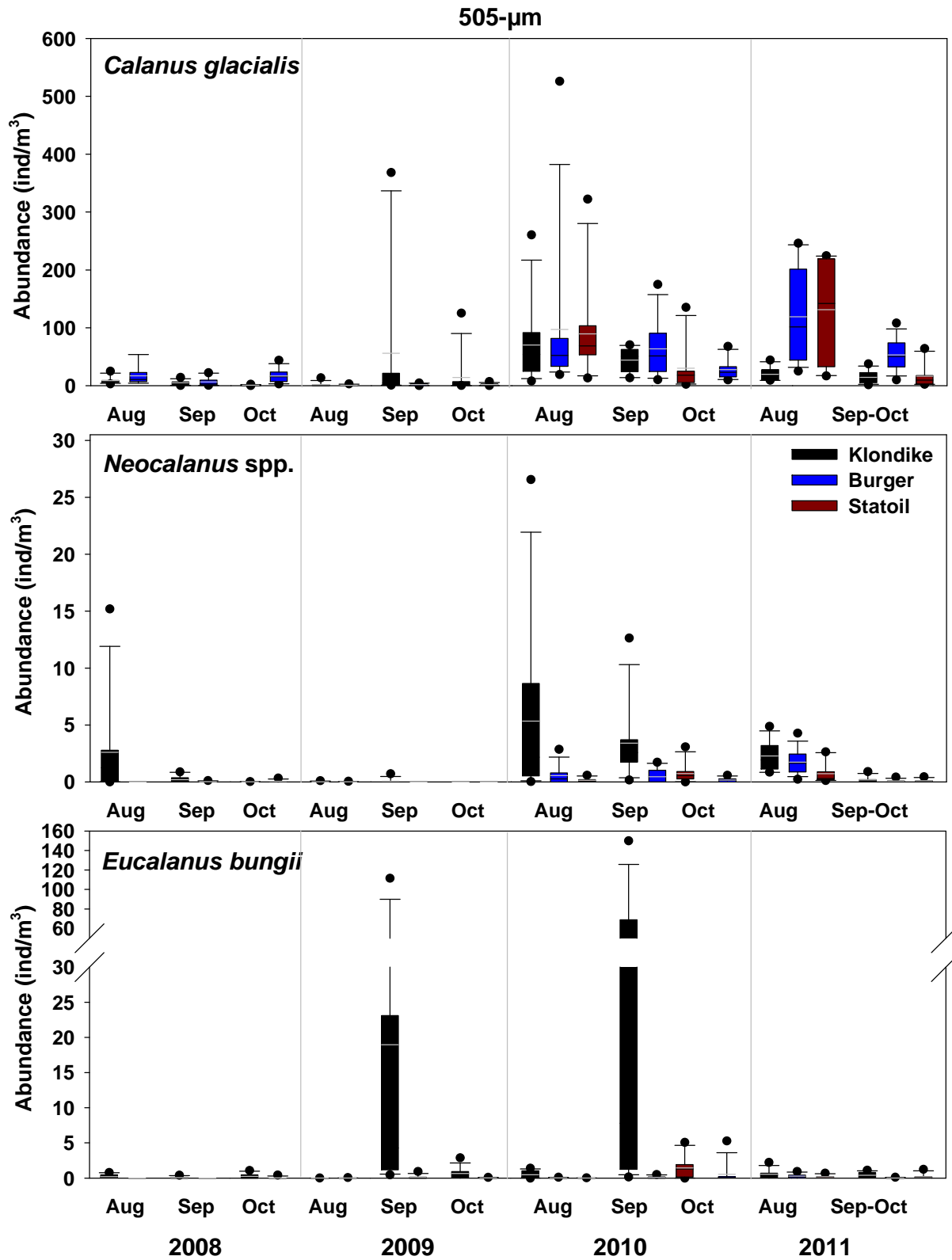


Fig. 51 Abundance of the dominant copepod species during each survey grid spanning the 2008-2011 seasons as captured by the 505- μ m net.

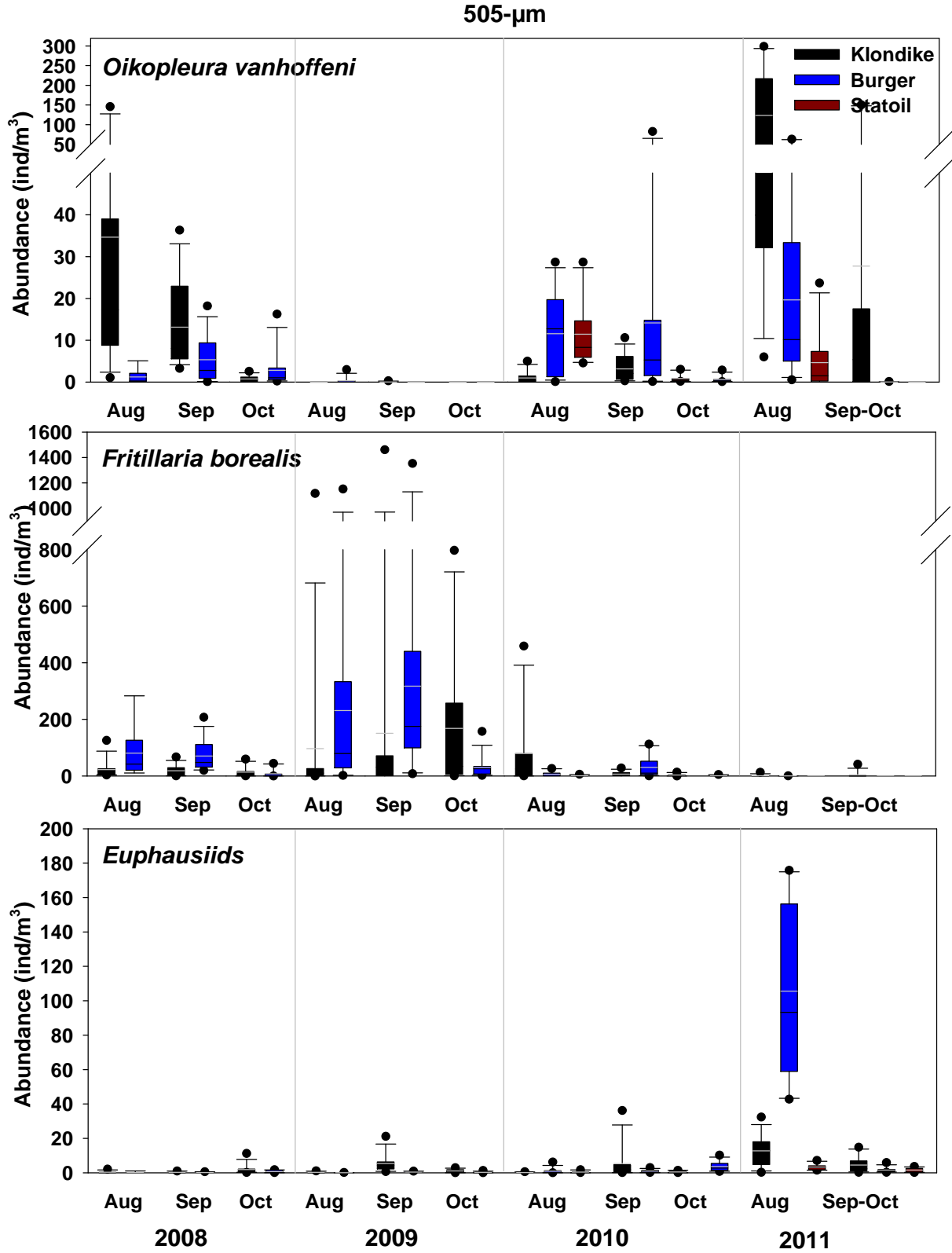


Fig. 52. Abundance of the dominant larvacean species and euphausiids (juveniles plus adults) during each survey grid spanning the 2008-2011 seasons as captured by the 505- μ m net.

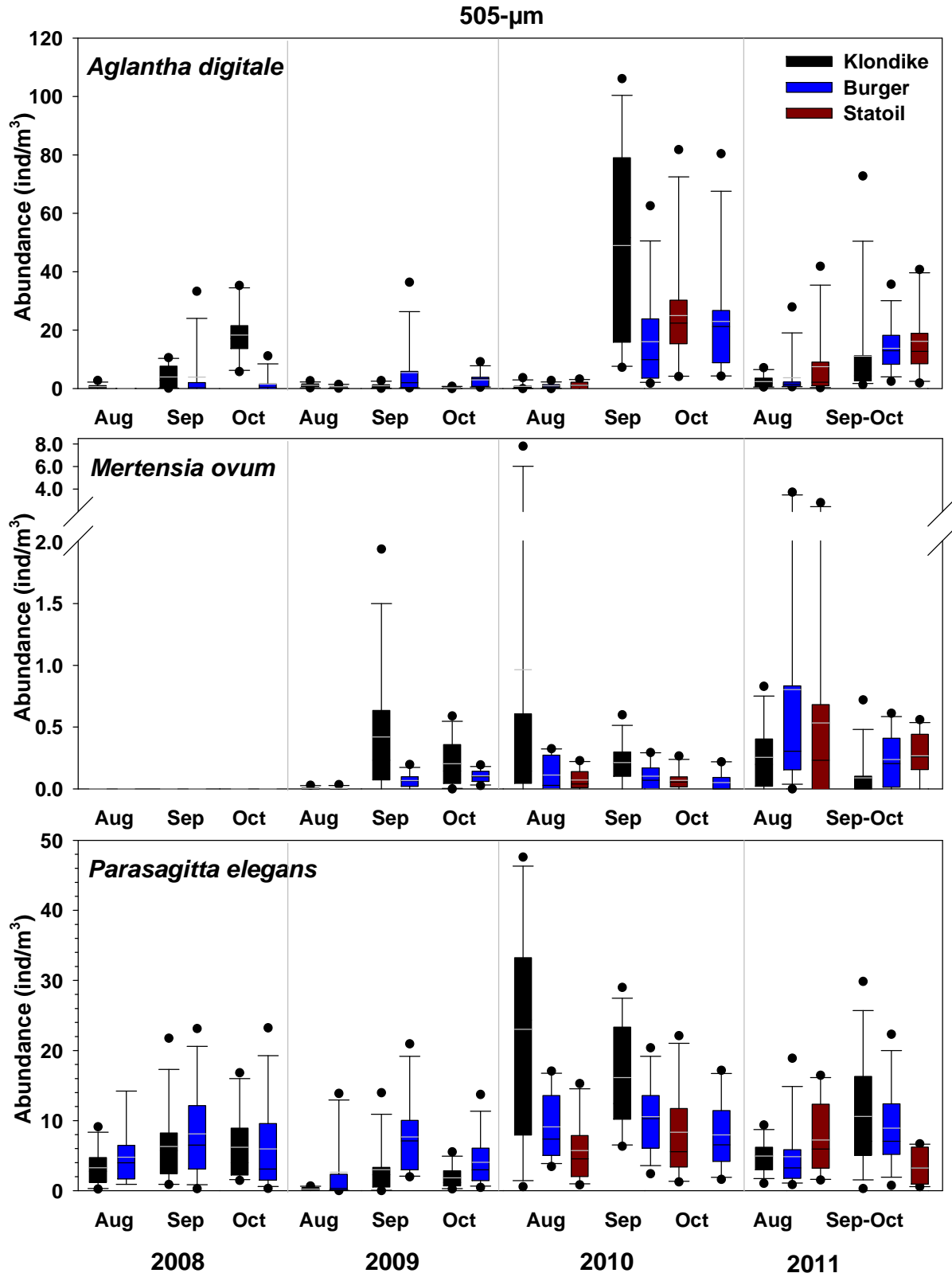


Fig. 53. Abundance of the dominant cnidarian, ctenophore and chaetognath species during each survey grid spanning the 2008-2011 seasons as captured by the 505- μ m net.