



5

*J. Plankton Res.* (2014) 0(0): 1–8. First published online Month 00, 0000 doi:10.1093/plankt/fbu049

60

10

# Did the iron fertilization near Haida Gwaii in 2012 affect the pelagic lower trophic level ecosystem?

15

20

SONIA D. BATTEN<sup>1</sup>\* AND JAMES F. R. GOWER<sup>2</sup>

<sup>1</sup>SIR ALISTER HARDY FOUNDATION FOR OCEAN SCIENCE C/O 4737 VISTAVIEW CR, NANAIMO, BC, CANADA V9V 1N8 AND <sup>2</sup>INSTITUTE OF OCEAN SCIENCES, 9860 W SAANICH RD, SIDNEY, BC, CANADA V8L 5T5

25

\*CORRESPONDING AUTHOR: soba@sahfos.ac.uk

75

Received January 9, 2014; accepted May 6, 2014

30

Corresponding editor: Roger Harris

35

40

Deliberate fertilization of a patch of water west of Haida Gwaii, British Columbia, with iron sulphate and oxide occurred in summer 2012 and triggered a phytoplankton bloom strongly visible in satellite imagery in late August and detectable through September 2012. Routine sampling by the Continuous Plankton Recorder Survey from commercial ships occurred in the vicinity of the fertilized patch between April and October that year. Comparisons with samples from the same region in the years 2000–2011 showed that phytoplankton and microzooplankton abundance indices were the lowest recorded over the time series in the autumn of 2012, while crustacean zooplankton were higher than average, and often higher than previously recorded in the autumn. Possible other contributory factors are discussed but this evidence suggests that the iron-induced bloom could have caused an increase in zooplankton that in turn exerted a heavy grazing pressure on the large phytoplankton and microzooplankton by the autumn of 2012.

85

90

KEYWORDS: continuous plankton recorder; iron fertilization; northeast pacific

95

45

## INTRODUCTION

50

The subarctic Northeast Pacific is low in naturally occurring iron so that while the surface waters have sufficient other essential nutrients such as nitrate, the levels of chlorophyll from phytoplankton production are kept relatively low. An experiment carried out at Ocean Station Papa (50°N, 145°W) in 2002 confirmed that iron does

play an important role in determining phytoplankton concentrations in this region (Boyd *et al.*, 2004). A volcanic eruption in the Aleutian Island chain in summer 2008 deposited iron-containing ash over a wide area of the subarctic NE Pacific and has been shown to have triggered a widespread phytoplankton bloom (Hamme, *et al.*, 2010). There has been speculation since that the bloom

100

105

was largely responsible for the return of the largest run in almost a century of sockeye salmon to the Fraser River (Parsons and Whitney, 2012) in British Columbia through the enhanced phytoplankton production being transmitted through the oceanic ecosystem to the out-migrating sockeye juveniles. This conclusion has also been disputed and attributed to other factors (McKinnell, 2013). The Haida Salmon Restoration Corporation (HSRC), largely on the basis of the volcanic ash-induced bloom and subsequent high salmon returns, fertilized a patch of water west of Haida Gwaii, British Columbia, with iron in an effort to restore salmon. Bird *et al.* (Bird *et al.*, 2013) report that between 22 and 30 July 2012, 90 tons of iron sulphate (monohydrate, 30% iron) were spread in an area roughly 1° of longitude by 0.5° of latitude, centred at about 52.7°N and 139.3°W. A second fertilization took place in the same vicinity on 16/17 August involving 10 tons of iron oxide (70% iron) and a third involving 10 tons of iron sulphate and 10 tons of iron oxide on 18/19 August. Resulting bloom conditions were measured in transects of the region by a glider between 17 August and 4 September (Bird *et al.*, 2013). Gower (Gower, 2013) summarizes the satellite-derived imagery from the aftermath of this event. Xiu *et al.* (Xiu *et al.*, 2014) report that the fertilization occurred in a second-year anticyclonic Haida eddy, typical of the region, resulting in chlorophyll concentrations within the eddy 10 times that of previous months and twice the value of September 2011 when chlorophyll was stimulated by natural iron inputs from the shelf as a second Haida eddy merged with the first.

Routine lower trophic level sampling of the near-surface North Pacific is undertaken each year, spring through autumn, by the North Pacific Continuous Plankton Recorder (CPR) Survey. The CPR is deployed behind commercial ships along two transects that originate in the entrance to Juan de Fuca Strait. It collects samples that are analysed for zooplankton and some larger phytoplankton taxa (see Batten *et al.*, 2003 for full details on CPR sampling methodology). Each sample represents the plankton from 18.5 km of the transect collected close to the surface (about 7 m) and in the ship's wake. Although there is some variability between the ship transects from month to month, one route (N-S) typically heads off the shelf in a NW direction and on towards Cook Inlet, and the second (E-W) heads more directly west across the Gulf of Alaska to the Aleutian Islands *en route* to Japan. The sampling schedule was not modified in order to investigate the effects of the iron fertilization, largely because the event occurred with no prior warning. Satellite imagery and CPR samples represent independent observations of the impacts on phytoplankton (satellites and the CPR) and zooplankton (from the CPR only). We investigated whether the availability of

such data after the event (within about 1–3 months) is adequate to detect a lower trophic level response.

## METHOD

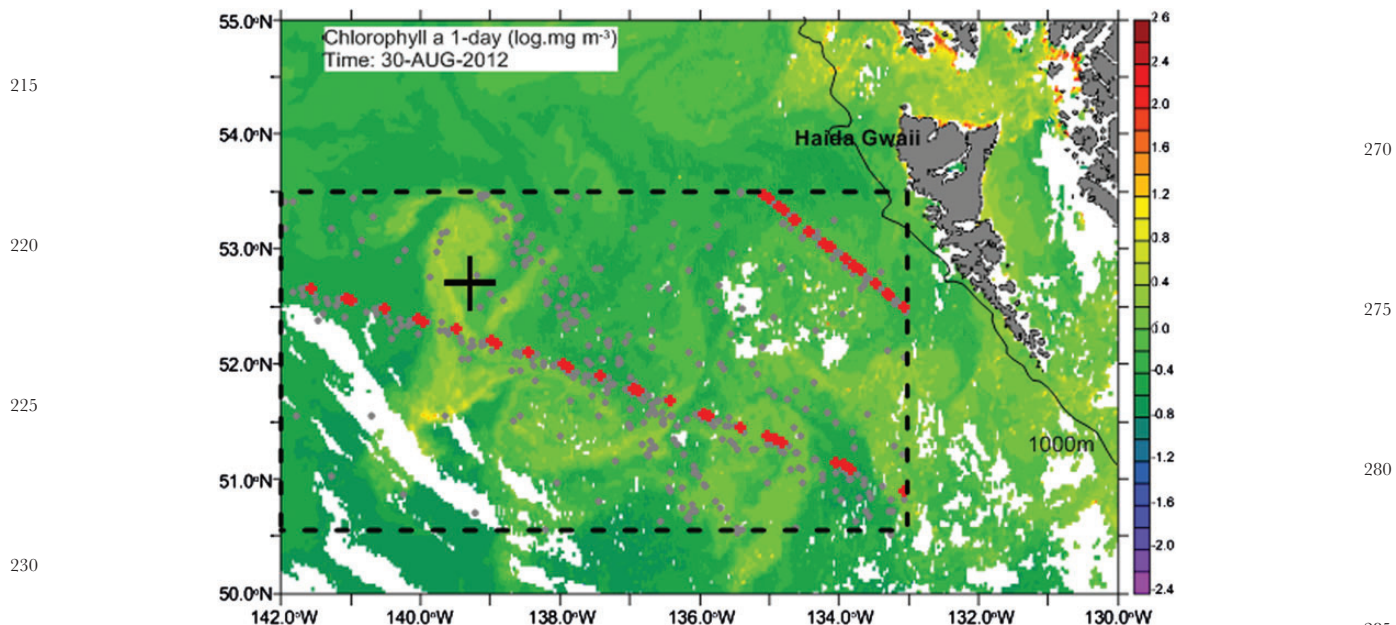
### CPR sampling in 2012

The N–S transect passes just to the north-east of the fertilized region and is normally sampled monthly between April to September. No samples were collected in the region on this transect in August 2012, but the sampling schedule was extended into October. The July sampling occurred on 13 July, before the iron fertilization first took place starting on 22 July. The E–W transect typically samples through the fertilized region, and is normally sampled in spring, summer and autumn. In 2012, the summer transect was sampled before the fertilization and the autumn transect not until October, some 3 months afterwards.

Cloud cover prevented synoptic chlorophyll images from satellites for late July and most of early August, but a circular bloom was visible at the fertilized location on 8 August, showing the first evidence of phytoplankton growth due to the fertilization. Images show that a phytoplankton bloom was still evident in late August, while some had also drifted mostly to the east of the fertilized region (Fig. 1). Assuming that any zooplankton responding to the increased phytoplankton levels were somewhat dispersed by the autumn, we designated a box that encompasses the two CPR transects (the N–S transect in the NE quadrant, the E–W transect crossing from SE to NW) and the bloom area, but still remains oceanic to avoid influence of the shelf (Fig. 1). Overlaid on this image also are the historic CPR samples in this region (grey dots), from 2000 to 2011, and the samples collected before and after the fertilization event in 2012 (red crosses). CPR data from 2012 are compared with data from previous years for the same region.

### Plankton indices

Some 300+ individual taxa are recorded from CPR samples and taxonomic resolution varies widely depending on organism preservation during the sampling process. For example, most copepods are identified to species but chaetognaths are not classified any further. For this study, we have examined summary indices of phytoplankton and zooplankton (Table I) to establish whether or not values in the post-bloom samples fell outside the range seen in previous years. The CPR was designed to catch mesozooplankton. It retains only the larger, hard-shelled forms of phytoplankton, which may make up just a small proportion of the community in this part of the NE Pacific, but



**Fig. 1.** Satellite chlorophyll-*a* image showing regions of elevated chlorophyll on 30 August 2012. The colour bar is  $\log_{10}$  Chlorophyll in  $\text{mg m}^{-3}$ , so that the yellow colour in the fertilized patch represents  $10 \text{ mg m}^{-3}$  and the green and dark green background colours represent  $1 \text{ mg m}^{-3}$  and below. The large + indicates the approximate centre of the patch fertilized with iron sulphate in late July. Historic (2000–2011) CPR samples are overlaid as grey dots, while 2012 CPR samples are overlaid as red+. Dashed rectangle delimits region for which monthly CPR data have been averaged. The 1000 m isobath is also shown, indicating that all CPR samples were well off-shore.

sampling is internally consistent. Relative changes in phytoplankton between years should therefore also be meaningful.

For each index, monthly means of samples from 2000 to 2011 were calculated, and then a mean of each month of the year (March to October) together with the minimum and maximum values seen for each month. The 2012 values were then compared with these values to see first of all whether they fell outside the range seen before, and if not then how they compared with the mean value. This is still a relatively small area for averaging CPR samples over; the CPR sampler is designed to cover large spatial scales. However, we believe that sufficient data for 2012 were available for a meaningful study, with the number of samples per month being (in parentheses): April (8), June (12), July (2), September (10) and October (5).

## RESULTS AND DISCUSSION

The region outlined in Fig. 1 was sampled in 2012 in the months of April, June, July, September and October. July CPR sampling occurred around the 13th of the month, so before the fertilization event. We therefore consider April, June and July sampling as pre-fertilization and September and October as post-fertilization. Note that April, July and September were sampled by only the N–S transect, while June and October were sampled by both. Note also that

CPR sampling usually ends in September, and in only 2002, 03, 04 as well as 2012 did it continue into October. Comparisons between the October 2012 data and the historic October data are therefore more limited than the other monthly comparisons. There was also no autumn sampling in the years 2000 and 2009.

Considering phytoplankton indices first (Fig. 2), it is clear that none of the indices was outside of the historic values pre-fertilization although some indices were higher than the historic mean values. However, all the autumn indices were lower than the historic means and in October all were lower than previously recorded for this month (in September total phytoplankton cells and number of phytoplankton taxa were lower than previously recorded for this month). Elevated surface chlorophyll signatures were certainly evident from satellite images at the end of August (Fig. 1) and throughout September. There are signs of the bloom in images from 19, 20, 21, 22, 23, 27 and 29 September, before dispersal and increasing cloud cover make it undetectable. What the CPR catches may not represent the phytoplankton community as seen by satellites especially as the CPR best retains larger cells which may not have contributed much to the bloom, and this may explain the discrepancy between the satellite imagery and the autumn CPR phytoplankton counts. It must also be remembered that higher productivity is not always visible as higher standing stocks if the phytoplankton is being grazed as quickly as it is being generated (see later).

Table I: Summary CPR indices examined for this report, together with a definition

Zooplankton indices	
Biomass (mg dry weight)	Estimated from taxon specific dry weights and abundances
Mesozooplankton abundance	Total abundance of mesozooplankton
Mean copepod size	An indication of the copepod community structure based on female prosome lengths in mm. See (Richardson <i>et al.</i> , 2006) for derivation
Small copepods	Total abundance of copepods <2 mm in total length
Large copepods	Total abundance of copepods >2 mm in total length
Euphausiids	Total abundance of euphausiids, excluding free floating eggs
Hyperiid	Total abundance of hyperiid amphipods
Chaetognaths	Total abundance of chaetognaths
Pteropods	Total abundance of pteropods
Microzooplankton	Total abundance of microzooplankton (e.g. hard-shelled protists such as foraminifera, radiolaria, tintinnids)
Phytoplankton indices	
Phytoplankton colour index	Unique CPR index, corresponds to the green staining by phytoplankton cells and correlated with chlorophyll levels. See Raitsos <i>et al.</i> (Raitsos <i>et al.</i> , 2013) for further details
Total cells	Abundance of all phytoplankton cells enumerated
Total diatoms	Abundance of all diatom cells enumerated
Total dinoflagellates	Abundance of all dinoflagellate cells enumerated
Number of taxa	Number of individual taxa counted per sample. Often identified to species level but sometimes to genus or above

In each case, the number obtained is the mean abundance/biomass/value per sample, which is estimated to be 3 m<sup>3</sup>.

350

The zooplankton indices are shown graphically in Figure 3. Most of the mesozooplankton groups [e.g. total mesozooplankton, small and large copepods, hyperiids, euphausiids (both are not identified beyond this taxonomic level but juveniles and adults are included)] had their highest recorded abundances for that month in the post-fertilization sampling, and if not the highest, then higher than the historic mean. Microzooplankton were much lower than average however; they usually peak in CPR samples in this region in the autumn, but post-fertilization values were very low, particularly in October which was only a third of the previous minimum value for this month. It should again be noted that only hard-shelled ciliates are recorded in the CPR samples, not the full microzooplankton community. Pteropods (*Limacina helicina* made up the majority of pteropods in the samples) were below average through most of the year and chaetognaths generally within normal range except for an unusual peak in June. Mean copepod size was close to average, suggesting the copepod community was not

370

unusual in its species composition. The autumn community is usually biased towards small species since the larger subarctic species have generally descended to diapause depths by late summer. While large copepods were unusually abundant in autumn 2012, so also were small copepods so that the size composition remained close to normal.

375

The evidence suggests that the iron-induced phytoplankton bloom in August fuelled the increase of crustacean zooplankton. Small copepods have relatively short generation times; the species recorded in these CPR samples were principally from the genera *Acartia*, *Oithona* and *Para-* or *Pseudocalanus*, and published generation times for these species at moderate temperatures (SST in this region in summer ranges from about 14 to 16°C) vary from 23.3 days [*Pseudocalanus* at 15°C, Lee *et al.* (2003)] to 30 days [*Oithona* at 15°C, Uye and Sano (1998), *Acartia* at 13.8°C, Uye (1982)]. There was thus ample time for a reproductive response to the bloom which could have resulted in high numbers of late stage copepodites in the surface waters in mid September.

380

385

390

The increase in large copepods is likely not a reproductive response, since these species typically have one generation per year, but as was speculated during investigations into the August 2008 volcanic eruption response, more likely they spent more time in surface waters or were higher in the water column to feed, increasing the chances of the CPR catching them (Hamme *et al.*, 2010). Unchanged species composition but a shallower depth distribution of larger copepods was also noted in the zooplankton response to an earlier fertilization experiment in the NE Pacific in 2002 (Tsuda *et al.*, 2006). This study, while too short to detect a reproductive response, suggested that an increase in juvenile euphausiids and *Eucalanus bungi* copepodites was likely because of decreased mortality in the egg and naupliar stages.

395

400

405

Hyperiid were very numerous in September and October, much more so than previously noted in this region in any month. As carnivorous predators on smaller zooplankton, this result also suggests a response to the increased numbers of copepods.

410

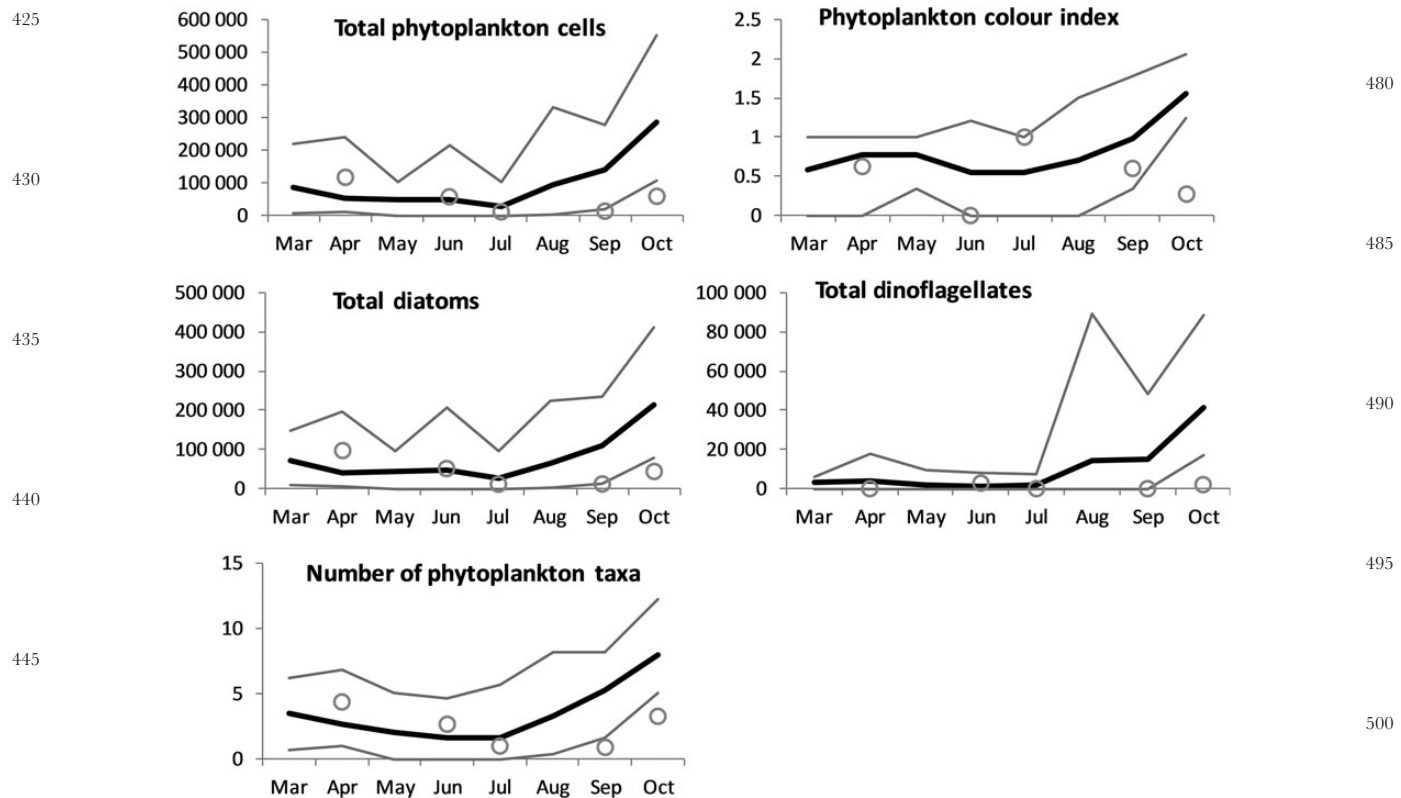
At the same time as the crustacea were elevated, the lower than usual microzooplankton abundance suggests that this group was either being grazed themselves by the increased copepod populations, or outcompeted for food by the crustacea. The larger phytoplankton retained by the CPR were also unusually depressed in the post-bloom data (Fig. 2) also suggesting increased grazing pressure.

415

These results are consistent with the hypothesis that fertilizing the region with iron sulphate triggered a phytoplankton bloom that subsequently resulted in an increase in zooplankton and a corresponding decrease in large phytoplankton and ciliates as grazing pressure increased

420



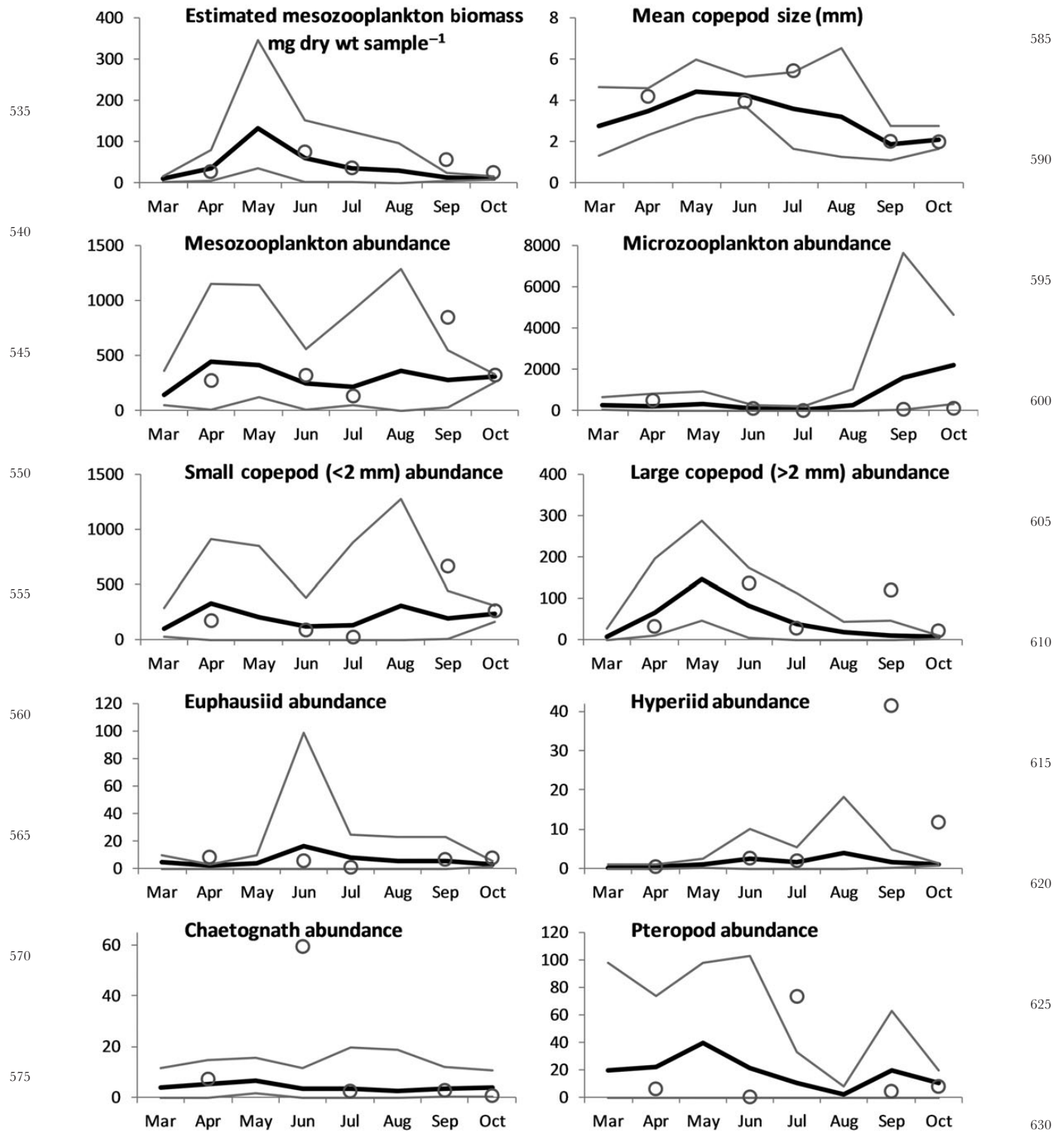


**Fig. 2.** Plots showing CPR phytoplankton data (See Table I for derivation of indices). Solid black line is mean monthly value (2000–2011), while grey lines are the minimum and maximum monthly value (2000–2011). Open circles are the monthly mean for 2012. Units on y-axes are abundances, or value, per sample. See online supplementary data for a colour version of this figure.

into the autumn. There are a number of other factors that need to be discussed however.

The patch of water fertilized by iron sulphate was located in a second year Haida eddy. Haida eddies are known to trap coastally derived water and, together with its biological and chemical properties, transport it offshore. Xiu *et al.* (Xiu *et al.*, 2014) studied the fertilized 2012 eddy, comparing it to historical eddies and found that it was not unusual in its characteristics but had a considerably longer lifespan and a relatively weaker surface elevation than other eddies. None of the historical eddies studied by Xiu *et al.* (Xiu *et al.*, 2014) showed elevated chlorophyll as late in life as this eddy after fertilization. The weaker surface elevation would result in a weaker rotation and therefore poor retention of the higher chlorophyll concentrations in its interior, with increased advection or mixing with surrounding waters. During August 2012, the chlorophyll was about 10 times higher than previous months and twice as high as the previous year when natural iron inputs from coastal water had stimulated an increase in chlorophyll (Xiu *et al.*, 2014). Haida eddies have also been shown to contain higher numbers of both coastal and oceanic zooplankton (Mackas and Galbraith, 2002; Batten and Crawford,

2005). Most zooplankton enhancement occurs in the first few months of the eddy's life after it detaches from the shelf, when chlorophyll levels are increased relative to surrounding waters. Seeding by coastal species and colonization by oceanic species occurs during the first spring and although Mackas *et al.* (Mackas *et al.*, 2005) refers to Haida eddies as a productive but “leaky” environment, they also discuss retention mechanisms whereby zooplankton can avoid the surface dispersing layer and remain within the eddy into the first autumn. Small numbers of coastal species have been found in some second year eddies (Mackas and Galbraith, 2002). However, given the relatively weak nature of the fertilized eddy as well as its age, it is highly doubtful whether the high zooplankton numbers described here were a result of the initial water properties some 16 months previously. Xiu *et al.* (Xiu *et al.*, 2014) also mention a new eddy forming in the region in August 2012, although they do not characterize it any further in their study. It is possible that coastal organisms could have been seeded into the region by another eddy, especially influencing the samples in the NE quadrant of our study region; however, we would expect large phytoplankton and microzooplankton to also be enhanced if this were the case,



**Fig. 3.** Plots showing CPR zooplankton data. See Table I for derivation of indices. Solid black line is mean monthly value (2000–2011), while grey lines are the minimum and maximum monthly value (2000–2011). Open circles are the monthly mean for 2012. Units on y-axes are all abundances per sample, except for mesozooplankton biomass which is estimated dry weight, in mg sample<sup>-1</sup> and copepod community size which is mean copepod length (mm). See online supplementary data for a colour version of this figure.

whereas their numbers were anomalously low and only crustacean zooplankton were anomalously high.

There is also the wider-scale CPR sampling to consider. Data from the British Columbia (BC) shelf further south and east, and the Alaskan Shelf (AK) further north (data not shown) also showed higher than average meso-zooplankton biomass in 2012. On the BC shelf, highest ever monthly means were recorded for July and October 2012, though spring and September values were close to average. On the AK shelf spring values were average, July was the highest recorded and the autumn months were close to average. Clearly, the iron-fuelled bloom's influence in the small area west of Haida Gwaii could not stretch across the NE Pacific, but the generally higher than average zooplankton recorded in the CPR zooplankton data may be a large, basin-scale response to a climate signal. Total phytoplankton cells were within the range previously recorded in autumn but higher than average in both the BC and AK shelf regions. While the full number of plankton indices listed in Table I has not yet been studied for these other regions, the preliminary conclusion is that both zooplankton and phytoplankton were generally high in the autumn of 2012 on the shelf of the NE Pacific, in contrast to the oceanic region west of Haida Gwaii which had high zooplankton but very low large phytoplankton and microzooplankton in the autumn.

In conclusion, while other factors may have had a role to play and we cannot exclude them based on the data we have available, it seems that the phytoplankton bloom induced in August 2012 could have been responsible for the high zooplankton numbers and subsequent low large phytoplankton and microzooplankton concentrations recorded by the CPR in the autumn of that year for the region considered here. Whether or not this in turn could lead to an increase in fish, or other higher trophic level, productivity in the region given the small size of the fertilized area, is outside the scope of this study, but the authors would like to see a full exploration of the data collected by the HSRC during this event.

## SUPPLEMENTARY DATA

Supplementary data can be found online at <http://plankt.oxfordjournals.org>.

## ACKNOWLEDGEMENTS

We are grateful to the volunteer vessels which tow the CPR, and their parent companies, specifically the officers and crew of the *Horizon Kodiak* and the Sea Board International ships *Skaubryn* and *Morning Cedar*.

## FUNDING

Pacific CPR data collection is supported by a consortium for the North Pacific CPR survey coordinated by the North Pacific Marine Science Organisation (PICES) and comprising the North Pacific Research Board (NPRB), Exxon Valdez Oil Spill Trustee Council (EVOS TC), Canadian Department of Fisheries and Oceans (DFO) and the Sir Alister Hardy Foundation for Ocean Science (SAHFOS).

## REFERENCES

- Batten, S. D., Clarke, R. A., Flinkman, J. *et al.* (2003) CPR sampling—the technical background, materials and methods, consistency and comparability. *Prog. Oceanogr.*, **58**, 193–215.
- Batten, S. D. and Crawford, W. R. (2005) The influence of coastal origin eddies on oceanic plankton distributions in the eastern Gulf of Alaska. *Deep Sea Res. II*, **52**, 991–1009.
- Bird, J. S., Gross, P., McNea, W. *et al.* (2013) *Initial Investigation of the North East Pacific Salmon Feeding Waters with Slocum Gliders*. Oceans, San Diego, pp. 1–10, 23–27 September 2013. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6740994&isnumber=6740936>.
- Boyd, P. W., Law, C. S., Wong, C. S. *et al.* (2004) The decline and fate of an iron-induced subarctic phytoplankton bloom. *Nature*, **428**, 549–553. <http://dx.doi.org/10.1038/nature02437>.
- Gower. (2013) Gulf of Alaska fertilization monitored by satellite ocean colour and in-situ measurements. In Irvine, J. R., Crawford, W. R. *State of Physical, Biological, and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2012*. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/032. viii + 140 p. see [http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2013/2013\\_032-eng.pdf](http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2013/2013_032-eng.pdf).
- Hamme, R. C., Webley, P. W., Crawford, W. R. *et al.* (2010) Volcanic ash fuels anomalous plankton bloom in subarctic Northeast Pacific. *Geophys. Res. Lett.*, **37**, L19604. doi:10.1029/2010GL044629, 2010.
- Lee, H., Ban, S., Ikeda, T. *et al.* (2003) Effect of temperature on development, growth and reproduction in the marine copepod *Pseudocalanus neomani* at satiating food condition. *J. Plankton Res.*, **25**, 261–271.
- Mackas, D. L., Tsurumi, M., Galbraith, M. D. *et al.* (2005) Zooplankton distribution and dynamics in a North Pacific Eddy of coastal origin: II. Mechanisms of eddy colonisation by and retention of offshore species. *Deep-Sea Res. II*, **52**, 1011–1035.
- Mackas, D. M. and Galbraith, M. (2002) Zooplankton distribution and dynamics in a North Pacific eddy of coastal origin: I. Transport and loss of continental species. *J. Oceanogr.*, **58**, 725–738.
- McKinnell, S. (2013) Challenges for the Kasatoshi volcano hypothesis as the cause of a large return of sockeye salmon (*Oncorhynchus nerka*) to the Fraser River in 2010. *Fish. Oceanogr.*, **22**, 337–344.
- Parsons, T. R. and Whitney, F. A. (2012) Did volcanic ash from Mt. Kasatoshi in 2008 contribute to a phenomenal increase in Fraser River sockeye salmon (*Oncorhynchus nerka*) in 2010? *Fish. Oceanogr.*, **21**, 374–377.
- Raitsos, D. E., Walne, A., Lavender, S. J. *et al.* (2013) A 60-year ocean colour data set from the Continuous Plankton Recorder. *J. Plankton Res.*, **35**, 158–164.
- Richardson, A. J., Walne, A. W., John, A. W. G. J., Jonas, T. D., Lindley, J. A., Sims, D. W., Stevens, D. and Witt, M. (2006) Using continuous plankton recorder data. *Prog. Oceanogr.*, **68**, 27–74.

745 Tsuda, A., Saito, H., Nishioka, J. *et al.* (2006) Mesozooplankton response to mesoscale iron enrichment during the diatom bloom and bloom decline during SERIES (NE Pacific). *Deep-Sea Res. II*, **53**. doi:10.1016/j.dsr2.2006.05.041.

Uye, S. (1982) Population dynamics and production of *Acartia clausi* Giesbrecht (Copepoda: Calanoida) in inlet waters. *J. Exp. Mar. Biol. Ecol.*, **57**, 55–83.

750

755

760

765

770

775

780

785

790

795

Uye, S. and Sano, K. (1998) Seasonal variations in biomass, growth rate and production rate of the small cyclopoid copepod *Oithona davisae* in a temperate eutrophic inlet. *Mar. Ecol. Prog. Ser.*, **163**, 37–44.

Xiu, P., Thomas, A. C. and Chai, F. (2014) Satellite bio-optical and altimeter comparisons of phytoplankton blooms induced by natural and artificial iron addition in the Gulf of Alaska. *Remote Sens. Environ.*, **145**, 38–46.

800

805

810

815

820

825

830

835

840

845