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Evaluating benthic recovery decades after a major oil spill in the Laurentian Great Lakes

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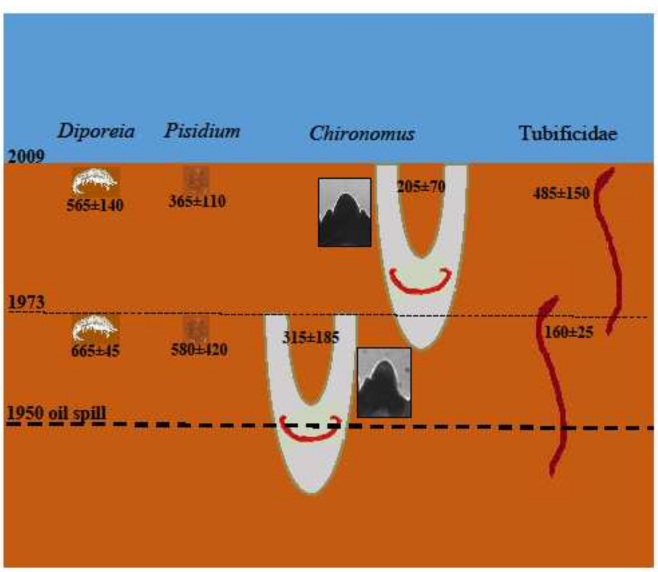
ABSTRACT: The long-term effects of oil spills on freshwater organisms have been little studied. In 1950, a large oil spill (10 million L) covered the harbor area of Parry Sound, Ontario, the deepest port in the Laurentian Great Lakes. Ecological impacts were not studied at the time, but 25 years later three-quarters of the *Chironomus cucini* larvae (Insecta, Diptera, Chironomidae) living in the harbor area were reported to be deformed. We returned six decades after the spill and found that the frequency of deformities had returned to background levels, and that the community of burrowing invertebrates has largely recovered. By dating sediment cores and measuring the depth distribution of oils, we conclude that, although the oil persists six decades after the spill, sufficient uncontaminated sediment has covered the oil thereby putting it out of reach of most burrowing animals. Provided that the sediment remains undisturbed, the buried oil is unlikely to exert further negative effects on the biota in spite of the fact that it will likely persist for centuries.

TOC (Figure 3 of manuscript):



Introduction

Large oil spills in marine systems have made names such as Amoco Cadiz (France 1978), Exxon Valdez (Alaska 1989), and Deepwater Horizon (Gulf of Mexico 2010) infamous, and the effects of such spills have been extensively documented.[1] Oil spills in fresh waters, while not of this scale, can have major impacts in the short term,[2] whereas their long-term impacts and the persistence of oil in freshwater ecosystems are unknown. There is an urgent need for such information given the increasing rate at which oil sands and other terrestrial sources of oil are being exploited and their products transported over great distances by pipelines, trains and ships.

In 1950, one of the largest oil spills in the history of the Laurentian Great Lakes occurred in Parry Sound, Ontario, Canada, when the rupture of an oil storage tank spilled 10 million L of heavy bunker oil into Parry Sound Harbor.[3] To put this spill in perspective, a very large oil spill into the Kalamazoo River, Michigan, involved less than half this amount (≈4 million L; Detroit Free Press, 23 July 2011). Response measures after the 1950 Parry Sound spill were limited to a few booms, ineffective attempts to burn-off the oil, and the use of sand to sink the oil to the lake bottom.[3] Two and a half decades after the spill, sediment collected in the profundal zone of Parry Sound Harbor contained substantial quantities of oil.[4] Furthermore, three-quarters of the *Chironomus cucini* (Webb 1969) larvae (Insecta, Diptera, Chironomidae) collected from these sediments had deformed mouthparts.[4] The results of many studies have evoked contaminants such as oil as the cause of high proportions of deformities in field populations of *Chironomus* larvae[4,5,6,7] and this supposition is supported by the results of laboratory experiments.[8,9,10]

Six decades after the 1950 oil spill, we revisited Parry Sound where we collected large numbers of *Chironomus cucini* larvae to determine if the frequency of larval deformities had declined in the intervening decades. We also collected other invertebrates to determine if benthic community composition had changed since it was measured in the 1970s. Lastly, we collected cores that allowed us to determine the depth of sediment that has been deposited since the oil spill, as well as to measure the vertical distribution of oil in the sediments and describe the history of the chironomid populations at the contaminated site. Overall, these measurements should allow us to relate the depth-distribution of oil in the sediment to the history and present state of benthic invertebrate populations in the impacted area. Given the lack of long-term studies on the impact of oil spills on freshwater biota, our data should be useful for estimating response times for benthic recovery in comparable systems.

MATERIALS AND METHODS

Study site and sampling rationale. Parry Sound Harbor (45° 20' 0" N, 80° 2' 0" W; surface area ~3 km^2) is located at the eastern extremity of Parry Sound, a large bay (50 km^2) on the eastern shore of Georgian Bay, Lake Huron. Beginning in the 19th century, this major port received contaminants from activities such as shipping, forestry, and sewage from the town of Parry Sound.[3,4] In 1950, the rupture of a shore-side storage tank released ~10 million L of heavy bunker oil that covered much of the harbor and spread to the Sound itself.[3] Two and a half decades later (1973), three-quarters of the *Chironomus cucini* larvae collected from harbor sediments were deformed.[4]

To determine if insects were still deformed 6 decades after the oil spill, we collected *C. cucini* larvae in 2006 and 2009 from the station (station 1; 22-m depth) originally sampled by Hare and Carter[4] (station 8; see map in Hare and Carter[4]). In 2009, we also collected *C. cucini* at an additional station situated ~0.7 km to the east (station 2; 24-m depth) as well as sediment cores and grab samples for the determination of benthic community structure and the measurement of contaminants. Historical and current values are compared to those for a reference station in Parry Sound (14-m depth; sampled in 2009) that is located beyond the reach of the oil spill (station 34 in Hare and Carter[4]). All stations sampled are in the profundal zone, and larvae of *C. cucini* are reported to be limited to this zone in Parry Sound.[4] *Chironomus cucini* are recognizable as members of the *salinarius* group of *Chironomus* species by the fact that larvae lack ventral and lateral tubules on their abdomen.[11] *Chironomus cucini* was reported to be the only salinarius-group *Chironomus* species present in the hypolimnion of Parry Sound Harbor,[4] and this identification has since been confirmed using a combination of morphological, cytological and genetic techniques.[12]

Sediment cores. We collected two sediment cores (A and B; length 50 cm) at station 1 using a gravity corer. To avoid sediment displacement during transport, the ends of the core samples were plugged using floral foam. In the laboratory, the polyvinyl-chloride core tubes (6.7-cm diameter) were cut lengthwise into halves using a miniature circular saw and a wire was used to separate the sediment lengthwise into two halves. For ^{210}Pb dating and ^{137}Cs measurements, half of core A was cut into 0.5-cm lengths for the first 10 cm and then into 1 cm lengths for the remainder of the core. These fresh samples were weighed, freeze dried, weighed again and ground to a powder of which a minimum of 1 g was placed into a pre-weighed vial and counted for 24 h in an ultra-low-background, high-purity, germanium, gamma spectrophotometer (ORTEC). Counts were treated and data interpreted according to Appleby[13] and Couture et al.[14]

Total lead (Pb) measurements were obtained using an ITRAX X-ray fluorescence scanner (Cox Analytical Systems). Measurements were made at intervals of 100 µm and the resulting data were treated using ImageJ (http://rsbweb.nih.gov/ij/).

Total greases and oils were measured in subsamples collected at 0.5-cm intervals along one of the longitudinal halves of core B. To glass vials we added 4 g of homogenized sediment, 0.8 g of anhydrous magnesium sulfate ($MgSO_4$), and 16 mL of hexane. Vials were held in an ultrasonic bath for 10 min, shaken for 10 min, and set aside to allow the $MgSO_4$ to precipitate. The supernatant was pipetted through a Millex 0.8-µm filter into a preweighed glass vial and then evaporated in a rotary evaporator at a temperature above that of hexane volatilization (69 °C). The containers were held overnight in a desiccator and then weighed to obtain the weight of total greases and oils in the each sample; this value was divided by the weight of the whole sample to obtain the concentration of total greases and oils.

Trace metals in sediments and larvae. Since trace metals are reported to cause deformities in *Chironomus* larvae,[8,10] we measured cadmium (Cd), copper (Cu), nickel (Ni), thallium (Tl) and zinc (Zn) in surface sediments and in larvae collected in 2009 at station 1 in Parry Sound Harbor and at the reference site. At each site, oxic sediment was collected by scraping a small plastic spatula along the surface (0-0.5 cm) of intact Ekman grab (15 x 15 x 23 cm) samples and then remaining sediment was sieved through a 0.5-mm mesh-aperture net to concentrate *C. cucini* larvae. In the laboratory, larvae were held in lake water for 4 days to allow them to evacuate their gut contents. Fifteen well-depurated fourth-instar larvae were chosen from each site and their head capsules were detached and preserved in alcohol for later examination for deformities. Larval bodies and sediment samples were frozen at -20 °C on pieces of pre-weighed acid-washed Teflon sheeting held in acid-washed 1.5 mL Eppendorf tubes then freeze dried and weighed. We then added Omni Trace nitric acid (100 µL per mg of sample) to each larval and sediment sample as well as to samples of similar weight of certified reference materials (MESS-3 and PACS-2 for sediments and TORT-2 (lobster hepatopancreas) and bovine liver for biological samples). After five days at room temperature, hydrogen peroxide (60 µL of Trace Select Ultra per mg of samples) was added and samples were held for a further two days. Samples were topped up with ultra-pure water to a volume of 1 mL per mg of sample. Trace metals were measured by inductively coupled plasma – mass spectrometry; values of certified standards fell within the range of certified values.[15]

Collection and study of benthic invertebrates. In 2009, we collected 10 Ekman grab (15 x 15 x 23 cm) samples at each of stations 1 and 2 to measure the composition of the extant benthic community. Samples were sieved using a 0.5-mm mesh-aperture net and preserved in 10% formalin to which we added a vital stain (Rose Bengal) to facilitate recovery of the invertebrates. We compared the population densities obtained with those from samples collected in 1973 (triplicate samples collected by Ekman grab in July).[16]

To retrieve subfossil chironomid head capsules, we cut a longitudinal half of core A into 5-mm long slices that were sieved through a 100-µm mesh-aperture sieve. Material retained was examined in a Bogorov dish under a microscope and head capsules found were mounted in Canada balsam on microscope slides.

In 2006 and 2009, we collected large numbers of *Chironomus cucini* larvae at station 1 in Parry Sound Harbor. In 2009, *C. cucini* larvae were also collected at station 2 in Parry Sound Harbor and at the reference site. Larvae were collected by Ekman grab, the contents of which were sieved using a 0.5-mm mesh-aperture net and held in lake water at field temperatures for transport back to the laboratory where larvae were removed and preserved in 10% formalin. To measure deformities, the head capsule of each larva was removed and held in 10% potassium hydroxide (KOH) for 30 minutes to digest soft tissues. The KOH was neutralized by holding the head capsule in concentrated acetic acid for 30 seconds and then it was transferred to 95% ethanol before being placed in Canada balsam on a microscope slide where it was cut laterally to separate it into dorsal and ventral halves. The mandibles and antennae were removed and all parts were covered with cover glasses and the slide was left to dry at room temperature for several weeks. Several parts of the larval head capsule were found to be deformed including the mentum, mandibles, pectin epipharyngis and the antennae as illustrated in Fig. S1.

RESULTS AND DISCUSSION

Sediment Chronology. To estimate the chronology of events in Parry Sound Harbor and to determine the depth of sediment that had accumulated since the oil spill, we measured ^{210}Pb activity in a sediment core collected at station 1. The cumulative curve of unsupported ^{210}Pb activity (not shown) indicated that sedimentation rates in Parry Sound Harbor have varied somewhat over time. Using the Constant Rate of Supply model,[13,14] sediment depth was related to the year in which the sediment was deposited (Fig. 1). The reliability of the resulting ^{210}Pb profile (Fig. 1) is supported by the fact that peak ^{137}Cs values occurred in the early 1960s (Fig. 2a) when inputs of fallout from atmospheric nuclear testing would have been at a maximum.[13] Further support for the ^{210}Pb dates comes from the relative concentrations of total Pb that increase sharply through the 1920s, reach a maximum between the 1950s and the 1980s, and then decline up to the present day (Fig. 2b). Such a pattern is coherent with the use of Pb as an additive in gasoline.[17]

Concentrations of total greases and oils in sediment were below the detection limit at sediment depths greater than 6.5 cm and less than 4 cm, whereas between these depths concentrations ranged from 75 to 175 mg/kg (Fig. 2c). The large depth range of the oil suggests that there was some mixing of oil and previously deposited sediment at the time of the spill.

Measurements of ^{210}Pb, ^{137}Cs, total Pb and total greases and oils were consistent in suggesting that ≈4.5 cm of sediment has accumulated at station 1 in Parry Sound Harbor since the 1950 oil spill. The relationship between sediment depth and ^{210}Pb dates (Fig. 1) is consistent with a published value for mean sedimentation rates (0.78 mm per year) in the near-shore waters of Georgian Bay,[18] since, at this rate, ≈4.5 cm of sediment would have accumulated between 1950 and 2009. The upper boundary of sediment rich in oil was also found at a depth of ≈4.5 cm (Fig. 2c), which suggests that oil from the 1950 spill has remained buried below this depth in the sediment of Parry Sound Harbor.

Trace metals in sediments and in *Chironomus cucini*. We measured the trace metals Cd, Cu, Ni, Tl and Zn in sediments and larvae of *C. cucini* to determine if these contaminants could be responsible for deformities (as illustrated in Fig. S1). Concentrations of all trace metals, except copper, were significantly higher in sediments from Parry Sound Harbor (station 1, 2009) than at a reference site (Table 1), which is explained by the harbor's history as a centre of transport and industry for the region.[3] In contrast, larvae from station 1 and the reference site showed no significant differences in their concentrations of most trace metals (Table 1; exceptionally, cadmium concentrations were marginally higher in larvae from Parry Sound Harbor). These results suggest that metals alone cannot explain the biological effects measured in Parry Sound Harbor. Indeed, much higher concentrations of Cd, Cu, Ni and Zn have been measured in *Chironomus* larvae from lakes in a mining area near Parry Sound (Sudbury, Ontario) and these larvae did not have elevated levels of deformities ([19]; Proulx and Hare, unpublished). Likewise, laboratory experiments have shown that high incidences of deformities in *Chironomus* larvae collected from contaminated lake sediments could not be explained by the high lead content of the sediments.[20] Although trace metals are reported to cause deformities in *Chironomus* larvae in the laboratory,[8,9,10,21] caution should be used when inferring cause and effect relationships between high concentrations of trace metals in field sediments and indicidences of larval deformities. Measurements of trace metal concentrations in burrowing insects such as *Chironomus* would provide better estimates of metal bioavailability,[22,23] which could then be compared to the prevailing incidence of deformities. In conclusion, our data suggest that the trace metals we measured are not the cause of deformities in *C. cucini* larvae, however, we cannot rule out synergistic interactions between trace metals and oil in Parry Sound Harbor.

Changes in benthic community composition over time. Benthic communities have been severely impacted by oil spills in both marine[24,25] and freshwater[26] ecosystems. Their recovery is reported to be more rapid in shallow, hard, substrates subject to strong currents than in deeper regions characterized by soft sediments in both marine[24,25] and freshwater[26] systems. Thus recovery of the benthic community in the cold, deep water, soft muds that we studied is likely to relatively slow.

We compared densities of the numerically-dominant benthic taxa collected both 23 years after the 1950 oil spill (in 1973)[16] and 59 years after the spill (in 2009) to determine if they had changed in the intervening decades. Note that the value of these comparisons is limited by the small sample sizes in 1973 (n = 3)[16] and the lack of data from intervening years.

Densities of the amphipod crustacean *Diporeia hoyi* S. I. Smith, 1874, and the sphaeriid mollusk *Pisidium* spp. were not significantly different in 1973 and 2009 (Fig. 3), which suggests that populations of these taxa were well-established 23 years after the oil spill. Larvae of *Chironomus cucini* were also present at station 1 in similar densities in 1973 and in 2009 (Fig. 3), which suggests that its population density, if the same at the time of the spill, had recovered by 1973. However, the high incidence of deformities reported for this species in the mid-1970s,[4] suggests continued contact with oily sediment at this time (as discussed below). Mean densities of Tubificidae were lower in 1973 than in 2009 (Fig. 3), which suggests that populations of these deep burrowing, sediment feeding, worms were affected by the spill but may not have recovered by 1973.

We hypothesized that the recovery of a given benthic taxon in Parry Sound Harbor will depend on the depth to which it burrows and feeds, with species living in near-surface sediments recovering first as uncontaminated sediment gradually buries the spilled oil.

Given that the amphipod crustacean *Diporeia hoyi* (Fig. 3) feeds on freshly deposited sediment and burrows little below the sediment surface,[27,28] this species was likely one of the first to recover from the oil spill. The sphaeriid mollusk *Pisidium* spp. (Fig. 3) should be one of the next taxa to colonize station 1 since it lives within the first 5 mm of sediment where it is reported to filter interstitial water to feed on micro-organisms.[29] Judging from the similarity between the densities of these two taxa in 1973 and 2009, we assume that if they were affected by the 1950 spill they had recovered sometime prior to 1973. By this date ≈2-2.5 cm of uncontaminated sediment should have covered the oil (Fig. 1), which should be sufficient for these shallow-burrowing taxa (Fig. 3).

Several lines of evidence suggest that although the population densities of *Chironomus cucini* were similar in 1973 and 2009 (Fig. 3), larvae of this species continued to contact oily sediment in the mid-1970s. First, final-instar *Chironomus* larvae are reported to construct tubes to mean depths of ~4 cm in fine sediment,[19] whereas only ≈2-2.5 cm of uncontaminated sediment had been deposited by 1973 (Figs. 1 and 3). Second, at ~2 cm in maximum length, vertically-oriented larvae would have been close to the contaminated zone. Third, *C. cucini* larvae do not feed in the water-column or on surface sediment, but on anoxic sediment below the surface oxic zone.[30] Fourth, the high incidence of deformities (Fig. S1) reported for this species two and a half decades after the oil spill,[4] indicates continued contact with oily sediment at this time (as discussed below).

Tubificid oligochaetes (Fig. 3), and the tubificid genera reported to occur at station 1 in Parry Sound Harbor (*Ilyodrilus, Limnodrilus, Rhyacodrilus,* and *Tubifex*),[31] are thought to construct vertical burrows in soft sediments and to consume deep sediment in a head-down position.[32.33] The fact that the mean values of Tubificidae reported for 1973 were lower than those we measured in 2009 (Fig. 3) suggests that populations of these deep burrowing and feeding worms were affected by the spill but may not have fully recovered by 1973.

Temporal changes in the chironomid community. We also evaluated historical trends in Parry Sound Harbor by studying changes in the chironomid community as revealed by head capsules collected at various depths in a sediment core collected at station 1. In the decade or so following the oil spill (corresponding to a core depth of ≈4 to 4.5 cm), the numbers of the numerically-dominant chironomid groups, that is, the Orthocladiinae (mainly *Heterotrissocladius*), the Chironomini (mainly *Chironomus, Dicrotendipes, Phaenopsectra*, and

Polypedilum), and the Tanytarsini (mainly *Micropsectra* and *Tanytarsus*) were reduced but returned to their previous densities after this time (Fig. 4, upper panels). Exceptionally, Diamesinae (all *Protanypus*) were absent prior to the oil spill but present thereafter (Fig. 4). The low numbers of this taxon and the lack of ecological data on *Protanypus* make interpretation of this pattern difficult. Larvae of Tanypodinae were in low and varying abundances over the time interval studied (Fig. 4). Overall, the total numbers of subfossil Chironomidae show a minimum near the estimated depth of the buried oil (Fig. 4), which suggests that the chironomid community was decimated by the oil spill but had recovered within a decade or two after the spill.

Of the 34 subfossil head capsules of *C. cucini* found at all depths in the sediment cores, only 5 were deformed and, of these, 3 were found at the 4-4.5 cm depth interval, that is, near the time of the oil spill.

Temporal changes in deformed *Chironomus cucini*. Examination of larval head capsules showed that teeth on the mandibles, the mentum and the pecten epipharyngis were subject to loss or deformation, as were the antennae (Fig. S1). Approximately two and a half decades after the oil spill, 77% of the *C. cucini* larvae collected at station 1 in Parry Sound Harbor (Fig. 5A; 85 larvae measured) had a deformed mentum, mandibles or both[4] suggesting that contaminants were still having an effect on this population. At that time, the comparable figure for a reference site outside of Parry Sound Harbor was 2.5% (Fig. 5A; 41 larvae measured). The results of other studies also suggest that high incidences of deformities in *Chironomus* larvae are caused by exposure to contaminants,[34,35,36] whereas background levels of deformities are reported to be much lower. For example, in nearby Georgian Bay, only 5.3% of *Chironomus* larvae were reported to have a deformed mentum and 1.3% deformed mandibles.[37]

In 2009, the percentage of deformed individuals in Parry Sound Harbor was 12% (of a total of 146 larvae) at both stations 1 and 2 (Fig. 5A). We note that in 2006 a higher percentage of deformed larvae was measured at station 1 (28.5% of 81 larvae), which suggests that the depth of uncontaminated sediments covering the oil is spatially variable (the exact position of the sampling site varied somewhat from year to year). The percentage of *C. cucini* larvae having a deformed mentum or mandibles was very similar at the reference site (9% of 129 larvae) and at the two contaminated sites in Parry Sound Harbor (12% of 103 in 2009; Fig. 5A), which suggests that the majority of the Parry Sound Harbor population is no longer affected by contaminants. At the reference site, the lower percentage of deformed individuals in the mid-1970s (2.5% of 41 larvae)[4] compared to 2009 (9%; Fig. 5A) is likely explained by the fact that the evaluator in 2009 (K. Bertrand) categorized a wider range of differences as being deformities that did the evaluator of the earlier samples (L. Hare).

We found that deformities were not limited to the mentum and mandibles but that the antennae and the pecten epipharyngis (part of the labium) could also be deformed (Fig. S1). In 3 of 4 cases (Fig. 5B), antennal deformities were at least as common as deformities of the mentum and mandible. Individuals with deformities of the pecten epipharyngis were uncommon and were recorded only in Parry Sound Harbor in 2009 (Fig. 5B). The fact that parts other than the mentum and mandibles can be deformed suggests that the value of 77% deformed larvae in the mid-1970s (Fig. 5A) would have been even higher if other head-capsule parts had been examined. For a given part, deformities were further classified according to type (Figs. S1,6). The only clear trend was that antennal deformities in larvae from Parry Sound Harbor mainly involved the loss of segments, whereas those from the reference site had multiple ring organs in the basal segment (Figs. S1,6).

The deformities we observed do not appear to have hindered *C. cucini* larvae, since their population density was similar in the mid-1970s and in 2009 and because deformed larvae were able to pupate successfully as determined by the fact that 5 of the 7 pupae that we collected had attached larval head capsules with deformed mouthparts.

A persistent population of deformed larvae suggests tolerance to oil. If so, *C. cucini* larvae could be used as sentinels to monitor recovery in the decades following an oil spill, since their tolerance allows them to persist in the presence of buried oil and yet their developmental sensitivity to the oil, as evidenced by deformities, allows for the quantification of contaminant exposure. Six decades after the oil spill, the low background level of deformities suggests that sufficient uncontaminated sediment has accumulated to allow *C. cucini* larvae to burrow and feed without contacting oil-contaminated sediment (Fig. 3).

Extrapolation from the Parry Sound Harbor oil spill. Our data suggest that biological effects on the benthos were extreme during the first decade or two following the oil spill, likely due to invertebrates contacting the oil either directly or indirectly through volatile components diffusing towards the sediment-water interface. If we assume that the burial of oily sediment allowed recovery of the benthic community, then recolonization likely proceeded according to the depths to which various taxa burrow, with surface-dwelling taxa reestablishing themselves first. At a given site, the greater the sedimentation rate the faster the benthic community will be able to completely recolonize sediments after an oil spill.

In the absence of light and at 4° C, the oil at our study site is sufficiently stable that it continues to persist 6 decades after the oil spill. Although, it does not appear to be a current threat to most benthic invertebrates this could change in the future if, for example, sediments were disturbed by dredging or by the arrival of a deep-burrowing invading species. In lakes where bottom sediments are subject to disturbance by wind-induced currents, much longer time frames could be required before oil is safely buried at depth. Such considerations will be important in designing and evaluating the effectiveness of artificial lakes that are created to cover oil-rich tailings, such as those being planned for use in the oil sands of northern Alberta.[38] Since our study is the first to address the long-term effects of oil in lakes, it will be useful for evaluating the feasibility of such projects as well as the long-term recovery of freshwater benthic communities impacted by oil.

Supporting Information.

The Supporting Information is available free of charge on the ACS Publications website at DOI xxxx.

Figure S1. Deformed and normal structures of final instar *Chironomus cucini* larvae collected from station 1 in Parry Sound Harbor.

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Table 1. Mean (± 95% CI) concentrations (nmol/g dry weight) of the trace metals Cd, Cu, Ni, Tl and Zn in sediments and in larvae of *Chironomus cucini* collected in 2009 at a reference site in Parry Sound and in Parry Sound Harbor (station 1). Overlap of confidence intervals indicates no significant difference between means.

Metal: Medium / station	Cd (nmol/g)	Cu (nmol/g)	Ni (nmol/g)	Tl (nmol/g)	Zn (nmol/g)
Sediment - reference	17±2	578±294	435±94	0.8±0.03	2987±703
Sediment - Parry Sound Harbor	37±3	884±79	703±99	1.7±0.03	8883±1014
C. cucini - reference	23±6	330±97	15±7	0.08±0.04	842±272
C. cucini - Parry Sound Harbor	63±29	217±127	26±5	0.04±0.02	1191±816

FIGURE CAPTIONS

Figure 1. Changes in sediment age with depth in core A collected at station 1 in 2009 from Parry Sound Harbor, as determined by ^{210}Pb measurements. Error bars are standard deviations (SD).

Figure 2. Depth profiles of variables in cores collected at station 1 in 2009 from Parry Sound Harbor: (a) ^{137}Cs activity (±SD, core A); (b) total Pb (core A); (c) total greases and oils (core B). Dates are derived from ^{210}Pb geochronology.

Figure 3. Schematic representation of presumed burrowing and feeding depths of the four numerically-dominant benthic invertebrates at station 1 in Parry Sound Harbor as related to the depths of the 1950 oil spill and to the sediment-water interface in 1973 and 2009 as well as their mean densities (± 95% confidence interval) in these two years. Also pictured is the middle tooth of the mentum of deformed (1973) and normal (2009) *Chironomus cucini* larvae.

Figure 4. Numbers of chironomid head capsules in 0.5-cm slices of core A collected from station 1 in Parry Sound Harbor. The 1950 oil spill corresponds to a sediment depth of ≈4.5 cm.

Figure 5. Deformities in *Chironomus cucini* from a reference station and two stations in Parry Sound Harbor. Larvae were collected in either the 1970s (1973 and 1976[4]) or 2009 (this study). a: percentage of larvae having either a deformed mentum or deformed mandibles (numbers examined given above bars). b: percentage of deformed larvae exhibiting various types of deformities (totals can exceed 100%, since individuals can have more than one deformed part).

Figure 6. Percentages of various types of deformities observed in the various parts of deformed *Chironomus cucini* larvae collected at two stations in Parry Sound Harbor (1 and 2) and at a reference station outside of Parry Sound Harbor. Larvae were collected in 2009 from all stations and in 2006 from station 1.

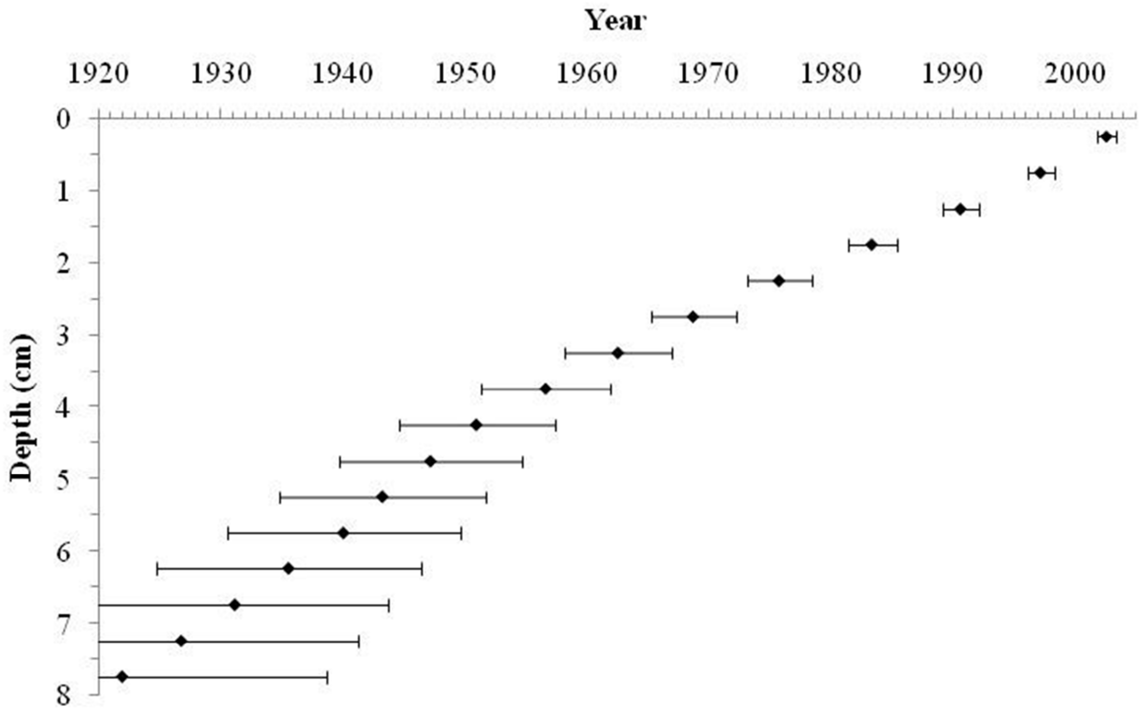
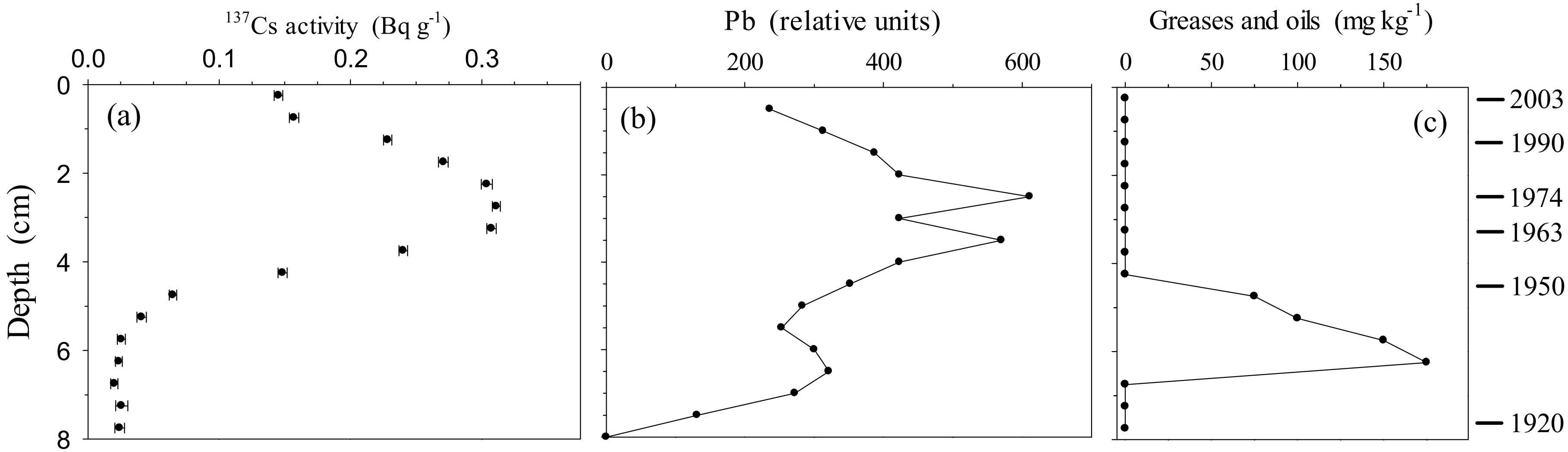

Year
1920
1930
1940
1950
1960
1970
1980
1990
2000
Depth (cm)
0
1
2
3
4
5
6
7
8

Figure 1.



^{137}Cs activity (Bq g^{-1})
0.0
0.1
0.2
0.3
Depth (cm)
0
2
4
6
8
(a)
Pb (relative units)
0
200
400
600
(b)
Greases and oils (mg kg^{-1})
0
50
100
150
(c)
2003
1990
1974
1963
1950
1920

Figure 2.

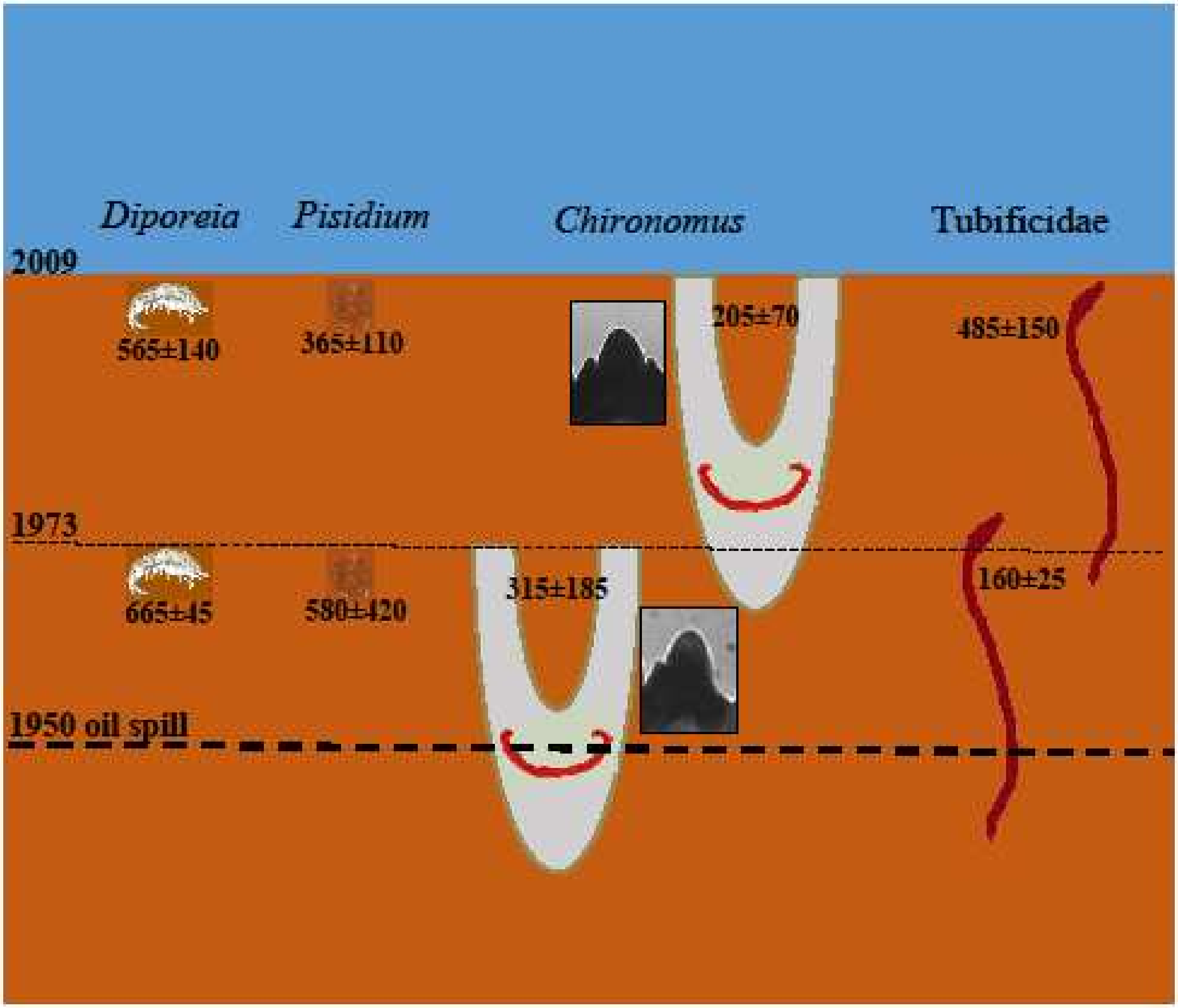

Diporeia
Pisidium
Chironomus
Tubificidae
2009
565±140
365±110
205±70
485±150
1973
665±45
580±420
315±185
160±25
1950 oil spill

Figure 3.

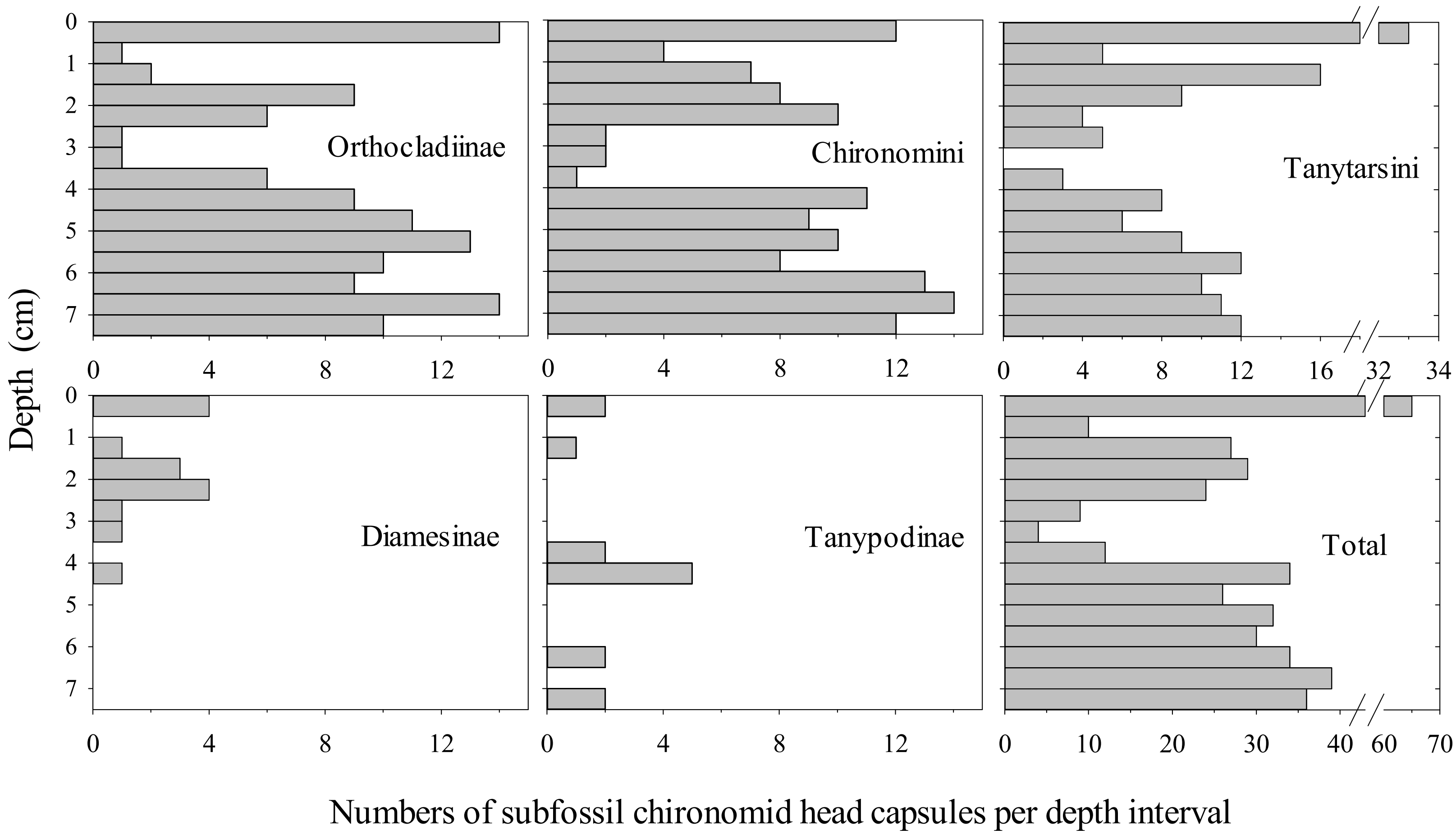

Orthocladiinae
Chironomini
Tanytarsini
Diamesinae
Tanypodinae
Total
Depth (cm)
0
1
2
3
4
5
6
7
0
4
8
12
16
32
34
10
20
30
40
60
70
Numbers of subfossil chironomid head capsules per depth interval

Figure 4.

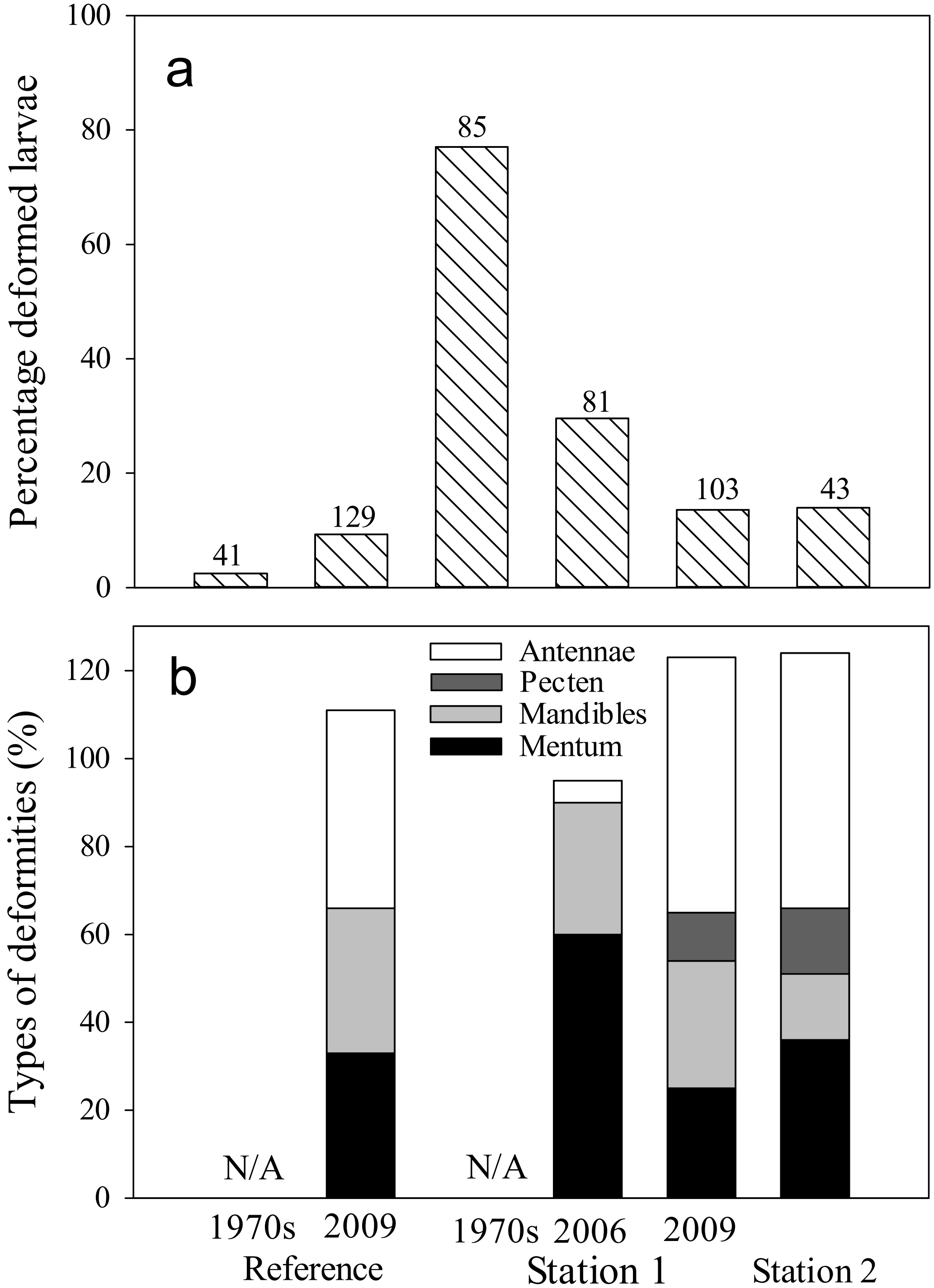

a
100
80
60
40
20
0
Percentage deformed larvae
85
81
129
41
103
43
b
120
100
80
60
40
20
0
Types of deformities (%)
Antennae
Pecten
Mandibles
Mentum
N/A
N/A
1970s 2009
Reference
1970s 2006 2009
Station 1
Station 2

Figure 5.

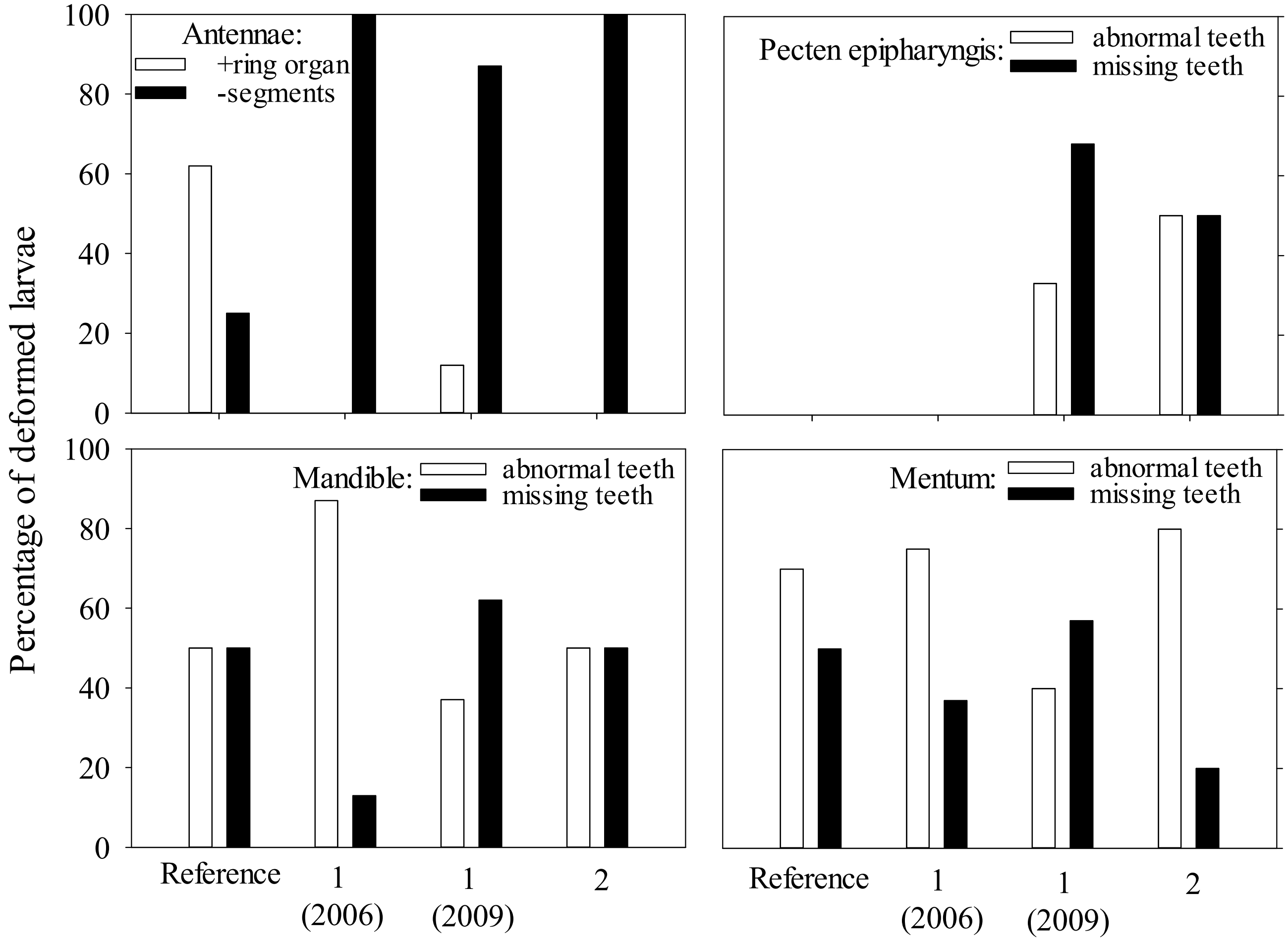

Percentage of deformed larvae
100
80
60
40
20
0
Antennae:
+ring organ
-segments
Pecten epipharyngis:
abnormal teeth
missing teeth
Mandible:
abnormal teeth
missing teeth
Mentum:
abnormal teeth
missing teeth
Reference
1 (2006)
1 (2009)
2

Figure 6.