



Minimal incorporation of Deepwater Horizon oil by estuarine filter feeders[☆]



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ABSTRACT

Natural abundance carbon isotope analyses are sensitive tracers for fates and use of oil in aquatic environments. Use of oil carbon in estuarine food webs should lead to isotope values approaching those of oil itself, -27‰ for stable carbon isotopes reflecting oil origins and -1000‰ for carbon-14 reflecting oil age. To test for transfer of oil from the 2010 Deepwater Horizon spill into estuarine food webs, filter-feeding barnacles (*Balanus* sp.) and marsh mussels (*Geukensia demissa*) were collected from Louisiana estuaries near the site of the oil spill. Carbon-14 analyses of these animals from open waters and oiled marshes showed that oil use was $<1\%$ and near detection limits estimated at 0.3% oil incorporation. Respiration studies showed no evidence for enhanced microbial activity in bay waters. Results are consistent with low dietary impacts of oil for filter feeders and little overall impact on respiration in the productive Louisiana estuarine systems.

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1. Introduction

Biological degradation of oil is an ongoing process in marine waters (Camilli et al., 2010; Hazen et al., 2010), and oil and oil-derived hydrocarbons can be important sources of carbon in marine food webs (Spies and DesMarais, 1983; Brooks et al., 1987). We used natural abundance carbon isotope measurements ($\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$) as tracers for incorporation of hydrocarbon-derived carbon from the Deepwater Horizon spill into estuarine food webs. We tested whether the warm summer temperatures prevailing during this spill would increase uptake of oil carbon. Water temperatures are near 30 °C during the summer in the Gulf of Mexico, and previous work showed rapid oil degradation, with $>95\%$ of oil loss in 5 months following a summer oil spill in Galveston Bay, Texas (Rozas et al., 2000). We hypothesized that similar rapid metabolism of oil might occur after the Deepwater Horizon spill entered Louisiana bays, and that rapid metabolism of oil would result in strong uptake of oil carbon into warm-water estuarine food webs. This would be in contrast to results from the aftermath of the Exxon Valdez oil spill in Alaskan waters where very little uptake of oil

carbon into cold-water food webs was documented (Coffin et al., 1997).

The Deepwater Horizon oil spill lasted almost 3 months (April 20 to July 15, 2010) and tides and storm surges brought oil from this largest accidental marine oil spill into coastal waters of the northern Gulf of Mexico. Estuaries of the central Louisiana coast were closest to the spill, and storm surges associated with Tropical Storm Alex in late June 2010 brought oil into some of these water bodies, including Barataria Bay and Terrebonne Bay. Oil stranded in northern and western Barataria Bay and in northern Terrebonne Bay, where the oil visibly coated marsh edges (<http://gomex.er-ma.noaa.gov>, <http://www.noaa.gov/deepwaterhorizon/maps/>, Fig. 1 in Whitehead et al., 2011). As part of the effort to assess possible ecosystem-level effects of this oil, we collected barnacles and mussels from these two bays and from a third nearby estuarine system which received little oil, Breton Sound. We hypothesized that bacterial breakdown of oil was occurring where oil entered estuaries, and previous work (Wright et al., 1982; Kirchman et al., 1984; Peterson et al., 1985) has shown that mussels are capable of directly filtering such bacteria. Barnacles generally graze larger organisms, but could also use oil-derived carbon if they were grazing microzooplankton that ate bacteria (Head et al., 2006; Graham et al., 2010). These microbial and grazing activities might also increase overall ecosystem respiration (Coffin et al., 1997). Our hypotheses were (1) enhanced ecosystem-level respiration would occur in Barataria Bay due to the presence of oil substrates from the Deepwater Horizon spill, (2) oil would be strongly incorporated

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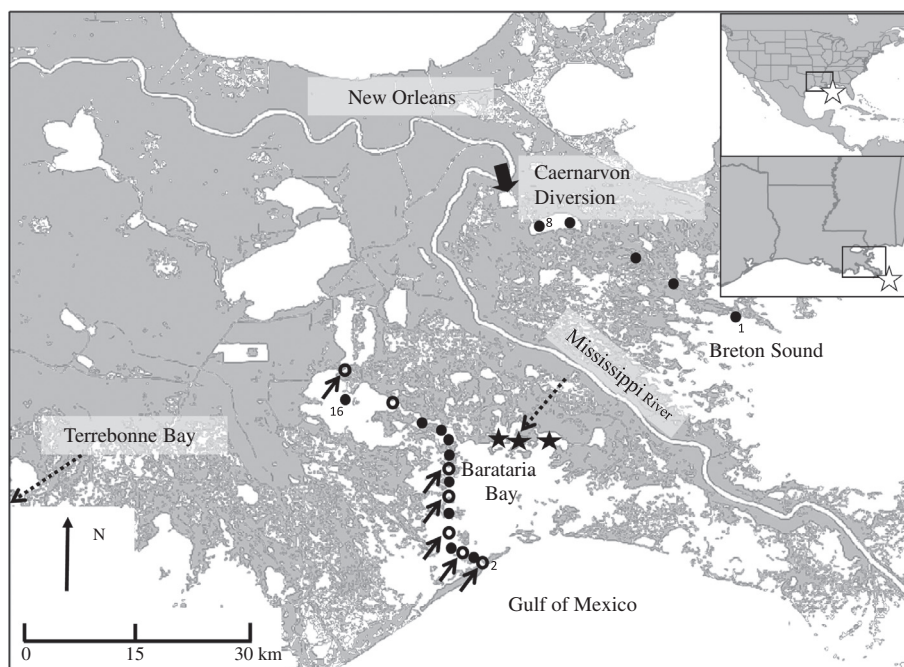


Fig. 1. Study site locations. Open stars in insets show site of Deepwater Horizon oil rig, closed stars in upper Barataria Bay indicate marsh areas visibly contaminated with oil, circles mark sampling locations for barnacles (open circles for barnacles collected in both 2000 and 2010; closed circles for barnacles collected only in 2010), small solid arrows show locations where barnacle shells were collected, larger dashed arrows indicate areas where mussels were collected in paired oiled and unoiled marshes. Station numbers for barnacle samples are given starting at marine ends of transects.

by mussels collected from visibly oiled marshes, and (3) barnacles collected near the mouth of Barataria estuary where tides most regularly advected oil into the estuary (Whitehead et al., 2011) would strongly show oil signals.

We sampled barnacles widely in Barataria Bay to try to detect oil that might be entering food webs from visible deposits on marshes but also from less obvious deposits that can form in bottom sediments by wave action (Macko and Parker, 1983). Barnacle data was used to screen larger areas for possible oil inputs to food webs, while mussel data were used to investigate hypothesized maximal oil uptake in marshes visibly coated with oil. Incorporation of oil carbon into food webs leading to barnacles and mussels, or into the respired CO_2 pools of dissolved inorganic carbon from which barnacle and mussel shells are constructed, was expected to shift ambient isotope values towards those of oil. End member oil values for radiocarbon $\Delta^{14}\text{C}$ are -1000‰ because no radioactive carbon remains in this ancient geological substance (White et al., 2005). For stable carbon isotopes, a -27‰ $\delta^{13}\text{C}$ value has been determined previously for Deepwater Horizon oil (Graham et al., 2010). The separation between ambient values and radiocarbon oil values is very large at about 1020‰ , compared to the $2\text{--}10\text{‰}$ for stable isotopes, so that resolution of oil use is much better with the radiocarbon measurements. However, stable isotope measurements are much less expensive ($<\$10$ US/sample for stable isotopes vs. $>\$500$ /sample for radiocarbon), so that we used stable isotope results to screen samples for radiocarbon analyses.

2. Materials and methods

2.1. Respiration samples

Samples for planktonic respiration were collected along Barataria Bay and Breton Sound transects in late August and early October, 2010 (Fig. 1). Whole-water samples were used without filtration or size fractionation. Planktonic respiration was measured as oxygen decreases in dark bottles incubated 24 h at field

temperatures (Wissel et al., 2008). Results are expressed in units of $\text{mmol oxygen consumed m}^{-3}\text{d}^{-1}$.

2.2. Mussel collections

Filter-feeding estuarine mussels (*Geukensia demissa*) were collected directly from oiled and unoled marsh sites in May and September 2010. A size range of mussels (from 40 to 110 mm total length) was collected at each site to study any size-related oil uptake. Mussels were collected from among marshgrass (*Spartina*) root mats, typically from within 5 m of marsh edges. Animals were placed on ice in the field and later frozen whole. Marsh sites in Terrebonne Bay were located near Cocodrie, Louisiana, with an oiled site (site terr 50; oil visibly present) along the northwestern shore of Lake Barre and unoled sites about 4 and 14 km to the southeast and nearer Cocodrie (sites terr 49 and terr 53 initial, respectively). Collections at one site (terr 53) were made in May before any oil entered the bay for an initial pre-spill baseline, with post-spill September collections at this site showing elevated aromatic hydrocarbon values in sediment samples from the edge (R.E. Turner, personal communication). Marsh sites in Barataria Bay were located in the north-central part of the bay, with an oiled site (site bar 66; visibly oiled but without elevated hydrocarbon readings in marsh edge sediment) located across a bayou channel from a paired unoled site (site bar 65; no visible oil and without elevated hydrocarbon readings in marsh edge sediment) in northeastern Wilkinson Bay. Two other unoled sites (sites bar 67 and bar 68) were located respectively 3 km to the southwest in Wilkinson Bay and 5 km to the southeast along the north shore of Bay Jimmy.

2.3. Barnacle collections

Barnacles were collected August 28–30, 2010, six weeks after the Deepwater Horizon well was capped. Most samples were collected along a long transect through western Barataria Bay (Fig. 1). For reference, pre-oil barnacle tissue samples from

10 years earlier (May 2000) were available from the same transect. Reference barnacle samples also were collected in late August 2010 in a second Louisiana estuary, Breton Sound, that also was close to the Deepwater Horizon spill site (Fig. 1). Introduction of Mississippi River water at the head of the Breton Sound estuary through a river diversion structure (Day et al., 2009) at Caernarvon, Louisiana, largely kept oil from entering this estuary.

Barnacles were collected from pilings by divers and were composed mostly of the species *Balanus eburneus*, with some *Balanus amphitrite* at the most seaward stations of Barataria Bay and Breton Sound. Samples were placed on ice in the field, then later frozen.

2.4. Laboratory analysis

In the laboratory, mussels were measured for shell total length, thawed and dissected. Adductor muscle tissue was dissected from individual animals, rinsed in deionized water (DI), and dried at 60 °C. The outermost 10 mm of mussel shells that represented the most recent growth was broken off and treated with bleach to remove organic matter. Shells were soaked overnight in household bleach (Clorox, 6% sodium hypochlorite) to remove soft tissues, crushed into coarse fragments and soaked again overnight with bleach, then rinsed extensively with DI prior to drying at 60 °C.

Barnacles were thawed, basal diameters were measured, and for each station approximately 50–100 animals with basal diameters of 5–20 mm were separated from their shells and combined into a composite site sample. Soft tissues were placed briefly in 1 N HCl and any carbonate shell detected by bubble evolution was removed under a dissecting microscope. Cleaned soft tissues were then rinsed with deionized water and dried at 60 °C. Barnacle shells were treated with bleach as described above for mussels.

Barnacle soft tissues were pulverized with a steel rod in glass vials. All other samples including shells and tissues of mussels were pulverized with a Wig-L-Bug automated grinder (Dentsply International). Shells and tissues were analyzed for $\delta^{13}\text{C}$ by standard combustion methods with isotope ratio mass spectrometry (Fry, 2007), and results are reported as $\delta^{13}\text{C}$ values using the VPDB reference (Coplen, 1994) where $\delta^{13}\text{C} = (R_{\text{SAMPLE}}/R_{\text{STANDARD}} - 1) \times 1000$ and $R = {}^{13}\text{C}/{}^{12}\text{C}$. Samples for radiocarbon analyses were sent to the Rafter Radiocarbon Laboratory in Lower Hutt, New Zealand for measurement with accelerator mass spectrometry; results are reported as $\Delta^{14}\text{C}$ values (Stuiver and Polach, 1977).

2.5. Isotope mixing models and $\Delta^{14}\text{C}$ corrections

For $\delta^{13}\text{C}$, both diet and inorganic carbon dynamics have been shown to affect filter feeder isotope values (Fry, 2002), with the inorganic carbon dynamics at the base of food webs leading to higher $\delta^{13}\text{C}$ values for plants and animals in more marine portions of estuaries. To account for this basal or baseline effect which is conveniently recorded by inorganic carbon in shell carbonate, the fractionation between shells and filter feeder tissues was calculated as

$${}^{13}\epsilon = (R_{\text{SHELL}}/R_{\text{TISSUE}} - 1) \times 1000$$

where R is the ${}^{13}\text{C}/{}^{12}\text{C}$ isotope ratio in the $\delta^{13}\text{C}$ definition. The ${}^{13}\epsilon$ values can be thought of as the baseline-corrected fractionation through the food web leading to filter feeders, and can be compared to the fractionation expected for dietary reliance on 100% non-oil normal estuarine foods versus fractionation expected from a 100% oil-based diet. Results from control no-oil samples indicated an average ${}^{13}\epsilon$ value of about 18‰ for un-oiled filter feeders, whereas larger ${}^{13}\epsilon$ values of 22–25‰ generally were estimated for a 100% oil diet from shell $\delta^{13}\text{C}$ and –27‰ oil. Measured ${}^{13}\epsilon$ values were

used to investigate shifts towards larger fractionations expected for oil uptake and in mass-balance isotope mixing models (Spies and DesMarais, 1983) to calculate % oil use:

$$\% \text{ oil} = 100 * ({}^{13}\epsilon_{\text{CONTROL}} - {}^{13}\epsilon_{\text{SAMPLE}}) / ({}^{13}\epsilon_{\text{CONTROL}} - {}^{13}\epsilon_{\text{OIL}})$$

A similar mass balance mixing equation was used to calculate % oil use from $\Delta^{14}\text{C}$ data:

$$\% \text{ oil} = 100 * (\Delta^{14}\text{C}_{\text{CONTROL}} - \Delta^{14}\text{C}_{\text{SAMPLE}}) / (\Delta^{14}\text{C}_{\text{CONTROL}} - (-1000))$$

For $\Delta^{14}\text{C}$ results for barnacles collected in 2000, a post-analysis decay correction was extrapolated from published data (Druffel et al., 2010) and applied to account for the higher ${}^{14}\text{C}$ activity of seawater in 2000 than in 2010. This change in seawater ${}^{14}\text{C}$ activity is due to ongoing loss of bomb radiocarbon that was added to the atmosphere and biosphere during aboveground nuclear bomb tests in the 1950s and 1960s. To account for this change in activity, 29‰ has been subtracted from the measured $\Delta^{14}\text{C}$ values for year 2000 results, to give a common baseline for comparison with all 2010 results, which are reported as analyzed. The detection limit for the % oil calculations was about 0.3% oil incorporation, based on the average 95% confidence limits for $\Delta^{14}\text{C}$ means of triplicate individual samples listed in Table 1.

3. Results

3.1. Respiration

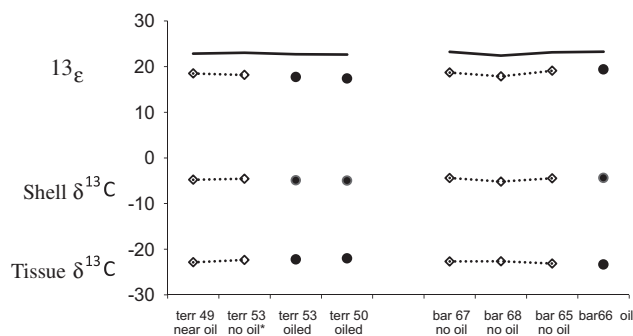
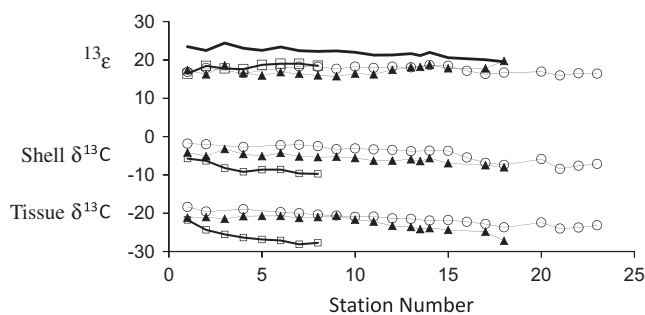
Incubations of estuarine water showed no evidence for enhanced respiration in Barataria Bay due to microbial use of Deepwater Horizon oil. Incubations were performed at multiple stations (Fig. 1) along the Barataria transect hypothesized to be impacted by oil and along the Breton Sound transect that lacked oil inputs. Respiration rates for the transects, given in average mmol oxygen consumed $\text{m}^{-3} \text{d}^{-1} \pm$ standard error of the mean (N), were 28 ± 2 (10) for Barataria in late August, 27 ± 2 (17) for Barataria in early October, and 41 ± 5 (9) for Breton Sound in early October. Barataria respiration rates were significantly lower ($P < 0.05$, unpaired t test) rather than higher than Breton Sound respiration rates.

3.2. Barnacle and mussel $\delta^{13}\text{C}$

Barnacles and mussels were analyzed initially for $\delta^{13}\text{C}$ to test for oil uptake in comparisons of animals collected from oiled vs. un-oiled control sites. Mussel $\delta^{13}\text{C}$ values were very similar at oiled and un-oiled sites and animals from oiled sites did not show shifts towards larger ${}^{13}\epsilon$ values expected for oil incorporation (Fig. 2). Barnacle $\delta^{13}\text{C}$ values were more variable across the salinity gradients of the transects, and the 2010 Barataria samples collected after the spill had lower $\delta^{13}\text{C}$ values that would be consistent with oil uptake (Fig. 3). But this apparent shift towards oil values largely disappeared after baseline inorganic carbon effects were normalized out using shell $\delta^{13}\text{C}$ values, and ${}^{13}\epsilon$ values were similar for all collections (Fig. 3). Thus, ${}^{13}\epsilon$ averages \pm SEM (N) for the 2010 post-spill barnacles were $17.2 \pm 0.3\%$ (18) and not significantly different ($P > 0.05$, t tests) than control values of $17.4 \pm 0.2\%$ (20) for collections along the same transect in May 2000, or control values of $18.2 \pm 0.4\%$ (8) for barnacles collected in Breton Sound in 2010. In particular, the Barataria 2010 collection did not show the expected shifts towards larger ${}^{13}\epsilon$ values indicative of strong oil incorporation nor the hypothesized stronger oil signals and larger ${}^{13}\epsilon$ values towards the mouth of the estuary (Fig. 3). Overall, ${}^{13}\epsilon$ results for both mussels and barnacles showed no significant ($P > 0.05$, unpaired t test) negative shifts towards larger ${}^{13}\epsilon$ values calculated for use of the –27‰ value measured by Graham et al.

Table 1 $\Delta^{14}\text{C}$ values and estimates for % oil incorporated by mussels and barnacles from Barataria and Terrebonne Bays.

		Average	S.E.M.	N	^{14}C depression ^a	% Oil incorporated ^b
<i>Marsh Mussel (Geukensia demissa) tissues:</i>						
Terrebonne Bay, terr 53	Un-oiled	27.5	2.2	3		
Terrebonne Bay, terr 50	Oiled	23.4	1.5	3	−4.1	0.4
Barataria Bay, bar 65	Un-oiled	23.8	0.9	3		
Barataria Bay, bar 66	Oiled	19.9	0.9	3	−3.9	0.4
<i>Marsh Mussel (Geukensia demissa) shells:</i>						
Terrebonne Bay, terr 53	Un-oiled	23.6		1		
Terrebonne Bay, terr 50	Oiled	19.2		1	−4.4	0.4
Barataria Bay, bar 65	Un-oiled	24.3		1		
Barataria Bay, bar 66	Oiled	15.2		1	−9.1	0.9
<i>Barnacle (Balanus eburneus + amphitrite) tissues:</i>						
Barataria Bay, 2000 (with 29‰ subtracted)	Un-oiled	19.7	0.9	7		
Breton Sound, 2010	Un-oiled	16.5	1.8	5		
Barataria Bay, 2010	Oiled	17.5	2.1	17	1.0	−0.1
<i>Barnacle (Balanus eburneus + amphitrite) shells:</i>						
Barataria Bay, 2010	Oiled	15.7	3.3	6		
					Average	0.40
					SD	0.35
					N	5
					SEM	0.16
					95% cl	0.31

^a ^{14}C depression is calculated pairwise between samples, i.e. between un-oiled reference and potentially oiled samples as $\Delta^{14}\text{C}_{\text{REFERENCE}} - \Delta^{14}\text{C}_{\text{OILED}}$.^b % Oil incorporated is calculated as: $100 * (\Delta^{14}\text{C}_{\text{REFERENCE}} - \Delta^{14}\text{C}_{\text{OILED}}) / (\Delta^{14}\text{C}_{\text{REFERENCE}} - (-1000))$.**Fig. 2.** Stable carbon isotope results for marsh mussels collected from sites in Terrebonne Bay and Barataria Bay. Values are averages of 3 individuals collected at each site. * denotes collection before oil came ashore; solid line indicates ^{13}C values expected for 100% oil use. Solid circles indicate data for oiled sites.**Fig. 3.** Stable carbon isotope results for barnacles collected from Barataria Bay and Breton Sound, with station numbers starting at the coast and increasing up-estuary into fresher water (see Fig. 1). Closed triangles represent data from oil-impacted Barataria Bay in 2010, while open squares and open circles represent control (no oil) data from, respectively, Breton Sound in 2010 and Barataria Bay in May 2000. Solid line indicates ^{13}C values expected for 100% oil use.

(2010) for oil from Deepwater Horizon (Figs. 2 and 3). Average shifts were close to zero (+0.5 to +0.1‰ for barnacles and +1.0 to −0.3‰ for mussels), compared to larger 1–4‰ shifts measured previously for plankton samples affected by the Deepwater

Horizon oil spill (Graham et al., 2010). Sensitivity analyses indicated that consistent shifts of at least 0.5–1.0‰ and at least 10–30% incorporation of oil would be necessary before a significant result of detectable oil would be achieved with the $\delta^{13}\text{C}$ analyses of barnacles or mussels.

3.3. Barnacle and mussel $\Delta^{14}\text{C}$

Based on the $\delta^{13}\text{C}$ results, selected samples were analyzed further for the more sensitive radiocarbon tracer. The radiocarbon results confirmed low use of oil by the filter feeders, with maximum uptake calculated for paired mussel samples as <1% (Table 1). All the various barnacle tissue and shell samples from control and potential oil impact areas had nearly identical $\Delta^{14}\text{C}$ results and showed no geographic trends (Fig. 4). We did not detect any size-related $\Delta^{14}\text{C}$ variation for mussels. The overall average for filter feeder use of oil from the $\Delta^{14}\text{C}$ results was slightly above zero at $0.4 \pm 0.3\%$ (Table 1; mean \pm 95% confidence level).

4. Discussion

Although stranded oil locally coated some marshes in Terrebonne and Barataria Bays, bay-wide respiration rates measured in this study did not show a strong enhancement associated with the oil. Measured respiration rates were within the central median range of respiration rates observed in unpolluted estuarine waters (Hopkinson and Smith, 2005). Higher respiration rates in Breton Sound may be due to enhanced productivity in that system, which is fertilized by inputs of nutrient-rich Mississippi River water from the Caernarvon diversion (Day et al., 2009). Respiration results were not consistent with ideas of large-scale submarine deposition of oil and subsequent high summertime metabolism of this oil in well-mixed estuaries. Nonetheless, metabolic contributions of 10–30% for oil would not be ruled out by the respiration measurements, making results from isotope analyses of filter feeding barnacles and mussels important additional data for in tracking the fate of oil in these food webs.

It was surprising that so little oil (<1%) entered estuarine food webs, but there are several possible factors that could combine

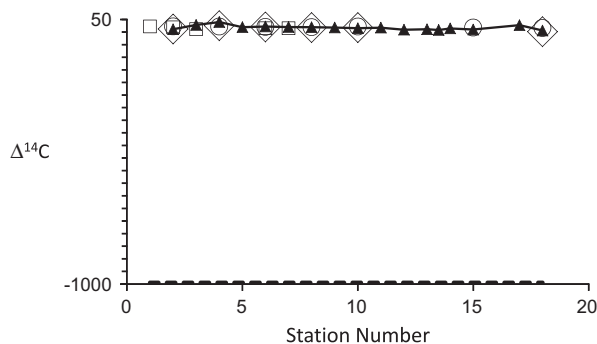


Fig. 4. $\Delta^{14}\text{C}$ results for barnacles (symbols at top) and oil (dotted line at -1000‰) along marine-to-freshwater transects in Louisiana bays. Closed triangles and open diamonds represent, respectively, tissue and shell data from oil-impacted Barataria Bay in 2010, while open squares and circles represent control (no oil) data from respectively Breton Sound in 2010 and Barataria Bay in May 2000. Station numbers refer to locations in Fig. 1, starting at the coast and increasing up-estuary into fresher water.

to explain the lack of oil incorporation. Mitigating factors could include: (1) low hydrographic dispersion of oil-degrading bacteria, with most bacteria adhering to marsh and oil surfaces and not mixed into the water column by waves and tides; (2) food web dilution, with known rapid rates of phytoplankton production in Louisiana estuaries (Day et al., 1989) providing a much greater food supply for barnacles and mussels than carbon derived from oil metabolism; (3) low microbial growth efficiencies, with relatively little microbial biomass resulting from growth on hydrocarbons (Wegener et al., 2008); (4) low use of microbial foods in metazoan food webs, with most bacterial carbon in aquatic food webs mineralized by viruses (Almeida et al., 2001); (5) the adductor muscle tissue sampled in mussels may accumulate less oil than other tissues such as the hepatopancreas, and (6) slow microbial metabolism of oil combined with slow growth and turnover by barnacles and mussels, so that there is a long time delay before oil carbon is measurable in filter feeders. Because of the sensitivity of the natural radiocarbon tracing technique, it is likely that several of these mechanisms operated together to result in the estimate of <1% incorporation of oil into filter feeders.

The explanation of slow turnover of barnacle tissues could be important especially if oil were interfering with normal feeding behavior. At the time of collection, however, visual observations by divers showed that barnacles were actively filter feeding at all stations. No visual observations were made to confirm that mussels were feeding at or near the time of collection. Carmichael et al. (2012) found normal patterns of filter feeder (oyster) growth in nearby Mississippi waters impacted by the Deepwater Horizon spill, and Soniat et al. (2011) also found normal patterns of condition and mortality for oysters in spill-affected areas of eastern Louisiana. Those two investigations and this one agree that studied estuarine filter feeders showed no apparent strong effects from the Deepwater Horizon spill.

Recent modeling of isotope turnover times for coastal invertebrate filter-feeders indicates that 4 summer months are needed for complete turnover of all tissues (Fertig et al., 2010), in the same range as the approximately 4 months of time elapsed since the start of the spill (April 20, 2010) and the late August/early September time of collection for barnacles and mussels. However, a recent report that oil from Deepwater Horizon was entering some planktonic food web samples in nearby Mississippi Sound (Graham et al., 2010) is consistent with turnover of smaller-sized plankton being generally faster than that of larger animals such as barnacles and mussels. Stable carbon isotope data in that study (Graham et al., 2010) were consistent with up to 20–45% oil incorporation into

planktonic food webs, and it may be that more rapid bacterial use of oil occurs when oil is relatively fresh and dispersed in the water column (Hazen et al., 2010). Burial of oil in marsh sediments can be associated with very slow rates of oil degradation (Slater et al., 2005; White et al., 2005), even in relatively warm marshes of the northern Gulf of Mexico (Macko et al., 1981). Also, oil arriving in Louisiana marshes had been at sea for several days or weeks before stranding, and while at sea, oil undergoes initial microbial attack and physical weathering to form tar balls and mousse. Subsequent metabolism of such weathered globular oil is likely is slower than that of fresh, dispersed oil (Macko et al., 1981; Hazen et al., 2010). Slow bacterial metabolism of oil to CO_2 combined with relatively strong hydrographic flushing of Louisiana estuaries (Das et al., 2010) may account for the result that oil signals also were only weakly evident (were <1%) in radiocarbon analyses of shell materials and did not significantly elevate planktonic respiration rates. Overall, it seems likely that metabolism of oil that stranded in Louisiana marshes proceeds mostly in a local benthic environment rather than strongly influencing planktonic food webs, that oil-degrading bacteria are not an important food source for estuarine filter feeders, and that oil carbon respired by microbes is lost to atmospheric CO_2 pools rather than aquatic CO_2 pools.

5. Conclusions

Oil spill effects can be strong when even small amounts of toxins or contaminants are involved (Joye and MacDonald, 2010; Diercks et al., 2010; Whitehead et al., 2011), but may be generally weaker in food webs where much larger amounts of material must be incorporated to produce strong tracer signals (Coffin et al., 1997; Carmichael et al., 2012). Nonetheless, it may be that strong food web effects exist in the deep sea near the site of the Deepwater Horizon spill because in deep waters, metabolism is generally slow and food is often limiting, in contrast to the results for estuarine waters studied here. The generally small effects we observed were consistent with other reports that there was little uptake of oil by Louisiana coastal species (State of Louisiana, 2011).

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