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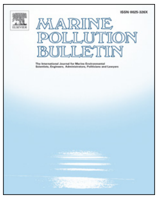

Sources and fate of organic matter in constructed versus natural coastal waterways

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ABSTRACT

Coastal wetlands are increasingly being converted into canal estates with potential consequences for ecosystem functioning. We compared the sources and fate of organic matter and water quality at four types of canal habitats (entrances and ends of canals, canal lakes and lake edges) and shallow and deep natural habitats (four replicates of each habitat). The fate of labile organic matter was assessed by measuring rates of scavenging of carrion. Surface sediments were analysed for organic carbon content and stable carbon isotopes, fatty acid biomarkers and compound specific stable isotope analysis of selected fatty acids were used to elucidate sources of sedimentary organic matter. Canal lakes differed from other habitats and were characterised by negligible scavenging, larger quantities of organic matter comprised of higher contributions from diatoms, and hypoxia. Despite some trends, natural habitats were statistically indistinguishable from canal entrances and ends. Variation among replicate habitats was large.

1. Introduction

Coastal wetlands, such as mangroves, saltmarshes and seagrass meadows, provide important ecosystem services. For example, they are habitat for macrofauna, support coastal food webs, maintain water quality by trapping sediments and organic matter, and efficiently recycle organic matter or sequester it (Barbier et al., 2011; McLeod et al., 2011). Growing demand for waterfront residential property has seen increasing areas of coastal wetlands being converted to residential canal estates and 4000 linear km of canal estates now occur globally (Waltham and Connolly, 2011). Understanding the sources and fates of organic matter in artificial versus natural coastal systems is a key aspect of determining how the proliferation of artificial waterways affects coastal ecosystem functioning and is needed to inform policy on the design and construction of artificial waterways (Harvey and Stocker, 2015).

Canal estates are an extreme form of coastal modification because the natural complex, vegetated coastline is converted to narrow, blind-ending channels and deep lakes (Waltham and Connolly, 2013) that limit tidal exchange and are prone to sedimentation, the accumulation of organic matter and hypoxia (Azzoni et al., 2015; Cosser, 1989; Waltham and Connolly, 2011). These conditions make canal estates less hospitable for fish and macroinvertebrates and the biomass of these taxa is usually less than in nearby unmodified coastal waterways (Maxted et al., 1997; Morton, 1989).

Several of the important primary producers in coastal wetlands, including mangroves, saltmarsh plants and seagrasses are usually absent in constructed waterways. Primary producers in canal estates are thus dominated by phytoplankton, benthic microalgae and some novel sources, such as urban grasses (Connolly, 2003). This can lead to food webs within constructed waterways being supported by basal carbon sources that are different from those in natural waterways (Connolly, 2003; Waltham and Connolly, 2006). Moreover, the particulate organic matter that is deposited in sediments in constructed vs natural waterways may differ in lability, since phytoplankton and microalgae typically have lower C:N than highly refractory mangrove leaves and seagrasses (Enriquez et al., 1993).

A variety of methods can be used to identify the sources of carbon within sediments including stable isotopes and lipid biomarkers. Stable isotopes are useful when different sources have distinct isotopic signatures (Fry, 2013). Fatty acid biomarkers can usually identify a larger range of sources than stable isotopes (e.g. bacteria and different types of

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algae) but the assignment of different types of fatty acids to their sources is sometimes ambiguous (Dalsgaard et al., 2003). Isotopic analysis of particular fatty acids (i.e. compound-specific isotope analysis) can more reliably resolve the sources of different fatty acids. Moreover, isotopic analysis of fatty acids unique to bacteria (e.g. odd carbon-numbered and branched-chain fatty acids and the monounsaturated fatty acid (MUFA) 18:1ω7) can help elucidate the source of organic matter being used by bacteria (Boschker et al., 1999).

Recycling of particulate organic matter is a critical ecosystem function. Particulate organic matter that accumulates on the benthos may have several fates: it may be consumed by scavengers or remineralised by microbes and thus recycled to the environment, or it may be buried in sediments. In natural waterways that support an abundant and diverse community of scavengers, most detritus is probably consumed. Because canals support fewer fish and macroinvertebrates overall and fewer detritivores (Maxted et al., 1997; Morton, 1989), less detritus is probably scavenged and a larger proportion of the decaying organic material may be remineralised by microbes or accumulate in sediments. Scavenging rates may vary through time, however, as consumption rates of organisms often vary seasonally (e.g. Micheli, 1997). Moreover, deep lakes and the ends of canals that are poorly flushed may act as sinks for fine sediments and organic matter (Cosser, 1989) and if the organic matter content is high, the deep lakes may experience net respiration and hypoxia. Consequently, compared to natural waterways sediments in artificial waterways potentially contain more organic matter and bacterial biomass, have a different composition of organic matter and their bottom waters may be more prone to hypoxia.

The Gold Coast region of southeast Queensland, Australia, supports > 150 linear km of artificial waterways (Waltham and Connolly, 2011). Canal systems have been established within the Nerang River, Tallebudgera River and Currumbin River estuaries and have replaced extensive mangrove forests, saltmarshes and seagrass meadows. The canal estates are comprised of flow-through and dead-end canals and deep lakes (some exceeding 25 m depth). The lakes were created when sediment was excavated during the construction of the canal system and used to elevate the adjacent low-lying residential land. The hydrology of the lakes is different to the canals and natural waterways since they are much deeper and some are located behind tidal gates that restrict tidal flows (Zigic et al., 2002; Waltham and Connolly, 2013).

Similar species of fish inhabit the Gold Coast canals and nearby natural waterways but the relative abundances of species vary (Morton, 1989; Morton, 1992; Morton et al., 1987). In particular, the dead-ends of canals support fewer macrobenthic carnivores (e.g. sparids and tetraodontids) and detritivores (mugilids) than canal entrances or rivers (Morton, 1989; Morton, 1992) and abundances of these groups are also reduced compared to nearby natural waterways (Morton et al., 1987). The ends of canals also support reduced species richness and diversity of benthic macroinvertebrates (Cosser, 1989). Fish assemblages are depauperate and sometimes absent in the deep lakes (Waltham and Connolly, 2013). Consequently, rates of scavenging in the canal system, and in the deep lakes in particular, are likely to be lower than in natural waterways.

The objective of this study was to investigate the sources and fate of particulate organic matter in different types of habitats within artificial and natural waterways of southeast Queensland, Australia to determine how the proliferation of artificial waterways affects coastal ecosystem functioning. We tested the following hypotheses:

1. That rates of scavenging of carrion would be greater in natural than canal habitats and lowest in deep lakes and that rates of scavenging would be greater in summer than in winter.
2. That canal habitats would contain more sedimentary organic matter, finer sediments and be more prone to hypoxia than natural habitats, with the most extreme values occurring in the deep lakes.
3. That sediment organic matter within the constructed waterways would have greater contributions from bacteria and microalgae and less from macrophytes than natural waterways.

2. Materials and methods

The study was done in the Gold Coast region of southeast Queensland, Australia. Six types of habitat were sampled: 1) canal lakes (depth range 8–23 m); 2) edges of canal lakes (< 2 m); 3) entrances of canals (where a canal intersected the river; depth range 1.4–5 m); 4) ends of canals (> 500 m from the canal entrance; depth range 1.5–2.1 m); 5) natural deep habitats (depth range 3.5–4.3 m); and 6) natural shallow habitats (depth range 0.7–1.0 m) (for examples see Fig. 1). Four independent replicate locations were sampled for each type of habitat from across the Gold Coast region (24 locations overall spread over 40 km of coastline). Except for deep lakes and edges of deep lakes, all locations were > 500 m apart. Latitude and longitudes of all 24 locations are provided in Supplementary Table 1. Natural habitats were located within the Broadwater of southern Moreton Bay and consisted of a network of channels containing extensive seagrass meadows (predominantly *Zostera muelleri*) fringed by mangroves (predominantly *Avicennia marina*) and saltmarsh flats (predominantly *Sporobolus virginicus*).

2.1. Rates of scavenging

Rates of scavenging were assessed at all habitats and locations, except for the edges of the deep lakes. Scavenging rates were measured twice during summer (December 2009 and February/March 2010) and twice during winter (June and July/August 2010) to assess temporal variation within one year. Scavenging was assessed using a commonly-employed assay (e.g. Porter and Scanes, 2015) by quantifying the mass of carrion consumed over 1 h. Fifteen ‘dillies’ (300 mm diameter flat rings covered in 20 mm mesh) were baited with a known mass (~50 g) of dead pilchards (*Sardinops sagax*) and lowered to the benthos. Any carrion remaining on the dillies was re-weighed after retrieval.

2.2. Sampling and analyses of sediments

Surface sediments (~15 cm depth) were sampled between December 2012 and January 2013 for analysis of % of particulate organic matter (%POM), percentage of organic carbon (%OC), $\delta^{13}C$, atomic C:N, sediment grain size distributions, profiles of fatty acid methyl esters (FAMES) and compound-specific isotopic analyses (CSIA; $\delta^{13}C$) of selected bacterial fatty acids. At every location, five samples of unvegetated surface sediment were collected using a van Veen grab and immediately cooled and then frozen when returned to the laboratory.

The percentage of organic matter was determined by wet-sieving sub-samples of sediment through a 2 mm sieve. Organic material retained on the sieve and sediments < 2 mm that passed through the sieve were retained and dried in an oven at 60 °C until constant weight. The %POM was determined as the proportion of the organic material relative to the total weight of the dried sample. Sediments analysed for %OC, $\delta^{13}C$ and atomic C:N were dried at 60 °C until constant weight, homogenised and subsamples were extracted. Sub-samples were acidified with 1 M HCl to remove inorganic carbonates and redried. Samples were then ground using a mortar and pestle, weighed and combusted on a Sercon Hydra 20–22 mass spectrometer. Isotope results were presented using standard δ notation (per mil ‰), defined as:

$$\delta^{13}C = ([R_{sample}/R_{standard}] - 1) \times 10^3$$

where R represents $^{13}C/^{12}C$. PDB limestone was the standard reference for carbon. Atomic C:N was calculated based on percentage dry weight of the two elements. Sediment grain size distribution was determined from volumetric particle size distribution (0.1–2000 μm) measurements. The five replicate samples collected at each location