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A novel approach to model exposure of coastal-marine ecosystems to riverine flood plumes based on remote sensing techniques

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ABSTRACT

Increased loads of land-based pollutants are a major threat to coastal-marine ecosystems. Identifying the affected marine areas and the scale of influence on ecosystems is critical to assess the impacts of degraded water quality and to inform planning for catchment management and marine conservation. Studies using remotely-sensed data have contributed to our understanding of the occurrence and influence of river plumes, and to our ability to assess exposure of marine ecosystems to land-based pollutants. However, refinement of plume modeling techniques is required to improve risk assessments. We developed a novel, complementary, approach to model exposure of coastal-marine ecosystems to land-based pollutants. We used supervised classification of MODIS-Aqua true-color satellite imagery to map the extent of plumes and to qualitatively assess the dispersal of pollutants in plumes. We used the Great Barrier Reef (GBR), the world's largest coral reef system, to test our approach. We combined frequency of plume occurrence with spatially distributed loads (based on a cost-distance function) to create maps of exposure to suspended sediment and dissolved inorganic nitrogen. We then compared annual exposure maps (2007–2011) to assess inter-annual variability in the exposure of coral reefs and seagrass beds to these pollutants. We found this method useful to map plumes and qualitatively assess exposure to land-based pollutants. We observed inter-annual variation in exposure of ecosystems to pollutants in the GBR, stressing the need to incorporate a temporal component into plume exposure/risk models. Our study contributes to our understanding of plume spatial–temporal dynamics of the GBR and offers a method that can also be applied to monitor exposure of coastal-marine ecosystems to plumes and explore their ecological influences.

1. Introduction

Land-based pollution poses a major threat to marine ecosystems globally and is projected to increase with the expansion and intensification of agriculture, mining, and urbanization (Butchart et al., 2010; CBD, 2006; Halpern et al., 2008; MEA, 2005). Increasing loads of land-based pollutants (e.g., nutrients, sediment, pesticides) associated with land use change are causing major ecological impacts, potentially interacting with other stressors (e.g., overfishing, increased ocean temperature, ocean acidification, sea level rise). Improving coastal-marine water quality is therefore a global priority (UNEP, 2012). Nutrient runoff from intensive use of fertilizers in agriculture can cause severe eutrophication, toxic phytoplankton blooms, and hypoxia in coastal and marine

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ecosystems (Cloern, 1996; Diaz and Rosenberg, 2008; Gabric and Bell, 1993; Howarth, 2008). Nutrient enrichment of coastal waters has also been related to increased risk of coral bleaching (Wooldridge, 2009) and outbreaks of the reef-destroying crown-of-thorns starfish (COTS) (Brodie et al., 2005; Fabricius et al., 2010). Globally, land use change associated with agriculture, forestry, and urbanization have led to significant soil loss, resulting in increased sediment loads and turbidity of coastal waters (Croke and Hairsine, 2006; Thrush et al., 2004; Walling, 2006), which in turn have been related to reduced coral recruitment (Hutchings et al., 2005), increased seagrass mortality (Cabaco et al., 2008), and declines in invertebrate densities (Reid et al., 2011). Pesticides are a major concern, particularly for sites adjacent to coastal catchments with intensive agriculture or forestry plantations, and have been related to dieback in mangroves, as well as reduced photosynthesis and expulsion of the symbiotic algae (bleaching) from corals (Duke et al., 2005; Haynes et al., 2007; Hutchings et al., 2005).

Dispersal of land-based pollutants has been traced to offshore waters, sometimes hundreds of kilometers distant from river mouths (Beman et al., 2005; Brodie et al., 2010; Devlin and Schaffelke, 2009), highlighting the need to consider such threats in marine conservation planning. The ecological impacts of land-based pollutants vary with the magnitude and extent of river plumes – i.e., masses of turbid freshwater discharged by rivers and extending into the sea –, but also with the coastal-marine ecosystems being affected (Halpern et al., 2007, 2008), and the frequency and duration of river plumes (McKenzie and Unsworth, 2011). Thus considering land-based threats is of utmost importance when planning for coastal-marine conservation and catchment management (Alvarez-Romero et al., 2011). Ignoring the potential impacts of land-based threats can reduce the effectiveness of marine conservation areas (Stoms et al., 2005; Wilson et al., 2005), especially when these threats are extensive (Brodie, Kroon, et al., 2012; Halpern et al., 2009). Furthermore, land-based pollution impacts not only marine biodiversity but also human livelihoods by compromising marine ecosystem services, such as food provisioning, recreation, and protection against coastal hazards (Lubchenco et al., 2003; Worm et al., 2006).

Identifying marine areas and ecosystems affected by land-based impacts is crucial if management is to address those impacts, but current methods have limitations. Mapping river plumes – their extent and surface water characteristics – is key to understanding the flow of land-based pollutants into marine systems (Devlin et al., 2011). Several approaches have been developed to map river plumes, but improvements are possible and desirable. A common approach has been visual delineation of plumes based on aerial photography and satellite imagery (Devlin and Schaffelke, 2009; Devlin et al., 2011; Evans et al., 2012), but requires considerable experience, is time-consuming, and inevitably incurs human error. Advances have been made in automating the process of identifying plumes with ocean-color products derived from satellite images, for example to map the freshwater extent of plumes (Schroeder et al., 2012) and to monitor variations in surface water parameters (Brando et al., 2010). However, to date these methods are limited because estimated parameters (e.g., chlorophyll, suspended sediment) can be associated with processes other than river plumes, and they generally perform poorly under atmospheric and water conditions such as moderate cloud cover and sun glint and high turbidity characteristic of the initial phases of plumes. Hydrodynamic models have also been used, in combination with estimated pollutant loads discharged by rivers, to estimate the dispersal of pollutants and hence to assess exposure of marine ecosystems to pollutants (e.g., Cherubin et al., 2008), but require significant expertise and computational resources and, in most cases, have not been validated against *in situ* data.

The purpose of our study was to develop a new method to assess exposure of coastal-marine ecosystems to land-based pollutants. Our approach, based on the automated classification of true-color satellite imagery, offers a way of mapping plumes under moderate cloud cover and with sun glint, as well as in highly turbid waters where the performance of other remote sensing methods is limited. More specifically, we aim to improve existing plume mapping and estimating exposure to river-borne pollutants in two ways: (1) by developing an automated method to map the extent of plumes, characterize surface plume waters, and qualitatively assess the dispersal of land-based pollutants; and (2) by assessing spatial–temporal variability in the exposure of marine ecosystems (coral reefs and seagrass beds) to plumes, necessary for estimating potential impacts. Our study contributes to understanding the spatial–temporal dynamics of plumes in the Great Barrier Reef (GBR), Australia, but describes a method that is widely applicable. We discuss the application of our method to monitor exposure of marine ecosystems to plumes and to study ecological responses to land-based pollutants.

2. Material and methods

2.1. Study region

Our study focuses on the GBR, the world's largest coral reef system, located in the Coral Sea, off the coast of Queensland in north-east Australia, and a World Heritage Site since 1981. The GBR is globally recognized for its outstanding ecological, cultural and socioeconomic values (GBRMPA, 2009) and since 1975 a large part of the reef is protected by the Great Barrier Reef Marine Park (GBRMP). While the rezoning of the GBRMP vastly increased the area under strict protection (i.e., no-take areas) from 4.5% to >33% (Fernandes et al., 2005), threats originating from land-based activities and from global climate change are major concerns (Brodie, Kroon, et al., 2012; GBRMPA, 2009). Since the arrival of Europeans in Australia, loads of suspended sediments delivered to the GBR have increased drastically following extensive land clearing for grazing, agriculture and coastal development (Joo et al., 2012; Kroon et al., 2012). Similarly, fertilized cropping has significantly increased the loads of nutrients (particularly dissolved inorganic nitrogen and phosphorus), thus resulting in eutrophication of estuarine and marine environments (Brodie et al., 2011; Brodie, Kroon, et al., 2012). Most of the pollutants are delivered during the wet season and in particular during peak-flow periods, when large plumes can be identified along the coast (Devlin and Brodie, 2005), occasionally reaching offshore reefs (Devlin et al., 2012b; Schroeder et al., 2012).

We focus our 5-year study (2007–2011) on four of the six Natural Resource Management regions (hereafter NRMs) of the GBR: Wet Tropics, Burdekin, Mackay-Whitsundays, and Fitzroy (Fig. 1). The Cape York and Mary-Burnett NRMs were excluded because information on estimated annual loads was not available or incomplete. The four selected NRMs illustrate a range of land use and landscape characteristics (e.g., climate, soils, topography) that result in different patterns of delivery of pollutants by major rivers across the GBR (Brodie et al., 2009; Kroon et al., 2012). Differences in flow are reflected in the spatial and temporal distribution and composition of river plumes observed along the GBR coast (Devlin et al., 2001, 2011). Along this wide latitudinal range (10°41′20″ S–24°30′00″ S) are also differences in the distribution of marine ecosystems (e.g., coral reefs in the north are closer to the coast), which means that some of these ecosystems are more likely to be affected by plumes. These characteristics make the GBR an ideal area to study plume dynamics across large areas and to illustrate the application of our plume exposure model for regional planning.