Review: Sediment-Related Controls on the Health of the Great Barrier Reef

Peter B. Hairsine*

Linking terrestrial soil erosion to the degradation of marine ecosystems relies on a long chain of evidence. Here, this chain of evidence is reviewed for Australia’s Great Barrier Reef and its catchments. Excessive sediment delivery to the marine environment is one component of an interlinked group of stressors that include coral bleaching, damage by storms, and plagues of crown-of-thorns starfish. Sediment and the pollutants they carry are one of the drivers of marine ecosystem decline and adversely impact recovery following disturbance by other stressors. Significantly, a portion of the N species carried by fine sediment in the freshwater system is released in the marine environment, thereby perturbing marine ecology. Available controls on sediment and pollutant delivery are hillslope erosion rates, gully and streambank erosion rates, sediment deposition rates in sediment sinks including footslopes, floodplains, and water reservoirs, and the application rates of pesticides and fertilizers. By reducing sediment fluxes through the combined strategies of erosion control and deposition enhancement, near- and offshore impacts can be reduced. Gully and streambank erosion are more significant sources of fine sediment than hillslope erosion. Fertilizer and non-fertilizer N and pesticides carried by sediment play an important role in coral reef degradation. A graphic summary of the spatial configuration the sources and sinks is provided to guide the prioritization of interventions. The scale of intervention required to achieve the desired marine outcome is so large that a combined voluntary and regulatory approach is needed.

Abbreviations: COTS, crown-of-thorns starfish; DIN, dissolved inorganic nitrogen; GBR, Great Barrier Reef; OSL, optically stimulated luminescence.

Coral reef ecosystems are in global decline (Bellwood et al., 2004). The quality of runoff from non-urban land is one of the stressors impacting the world’s marine systems (Halpern et al., 2008). There are many examples of concern about this relationship and responses from governments, organizations, and communities (Lotze et al., 2006). Knowledge concerning this relationship and its controls is extensive but appears primarily as fragments of a long chain of links in the land–stream–estuary–marine–reef continuum.

In this review, I have structured the knowledge concerning this chain, drawing on the extensive peer-reviewed publications concerning the Great Barrier Reef (GBR) and its contributing catchments. First I address the foundation question: Does excess land-derived sediment impact on the health of the GBR? Using the accumulated assessments of the sediment budgets and its components, I have constructed a description of the fluxes of sediment and sediment-bound nutrients through the catchment–estuary system. Finally, I have identified and comment on the available management controls on sediment delivery within this system.

Does Excess Land-Derived Sediment Impact the Great Barrier Reef?

A causal relationship between elevated river sediment loads and degradation of coastal ecosystems is assumed in public discussion and many publications. Here, I briefly review the evidence in the case of the GBR and the watersheds that drain into it.
A snapshot of the movement and influence of terrestrial sediment in the coastal environment of the GBR can be obtained from remotely sensed images in the days following the passage of a flood down the river network. Figure 1 shows an example of the influence of floods carrying sediment and nutrients into the GBR lagoon via major and minor rivers.

The responses to excess terrestrial sediment in the GBR ecosystem can be grouped into impacts on seagrass beds, impacts on nearshore reefs, and impacts on offshore reefs and will be briefly summarized below.

**Impacts on Seagrass**

Shallow-water seagrass meadows are estimated to occupy 5700 km² in the GBR lagoon (Great Barrier Reef Marine Park Authority, 2014) and provide habitat for many species including dugongs and sea turtles. The area of deep-water seagrass is estimated as 40,000 km² (Great Barrier Reef Marine Park Authority, 2014). In its most recent outlook, the Great Barrier Reef Marine Park Authority (2014) found “monitoring of about 30 intertidal seagrass meadows along the central and southern coast indicates that their overall abundance has declined” when comparing the 2014 data with the 2009 data. Seagrass growth is influenced by the availability of light and nutrients and the impacts of physical disturbances including tropical storms and water quality problems (Waycott et al., 2005).

Pesticide use has been implicated in the decline of seagrass communities (Haynes et al., 2000a). Specifically, the historical use of the herbicide diuron \([N'-(3,4-dichlorophenyl)-N,N-dimethylurea]\) produced concentrations in the near-coastal environment that have been shown to have a significant impact on the photosynthesis of three species of seagrass common in the lagoon of the GBR (Haynes et al., 2000b). Lewis et al. (2012) reported on the results from passive chemical samplers deployed for several years in the seagrass beds adjacent to islands in the central and southern GBR lagoon. They found toxic levels of a range of pesticides used in cropping (including sugarcane \([Saccharum officinarum L.]\)) and horticulture, which would probably impact the ability of seagrass to grow.

Pesticides can be transported by a variety of pathways, including in overland flow and groundwater. Giacomazzi and Cochet (2004) reviewed the mobilization and transport of diuron. This pesticide and its breakdown products take a variety of pathways from agricultural fields to waterways. Sediment carries much of the chemical in freshwater. In the marine environment, diuron appears persistent. Reducing the flux of fine sediment in and downstream of diuron application sites will mitigate further accumulation of this pesticide in sensitive ecosystems.

**Impacts on Nearshore Reefs**

McCulloch et al. (2003) used coral dating techniques on a nearshore reef complex in the central GBR lagoon to assess reef growth for the period 1750 to 1998. They found that sediment reached the reef only occasionally from 1750 to 1870. After 1870 there was a five- to 10-fold increase in sediment delivered to the reef. They attributed this change to the increase in livestock and cropping in the catchments draining to that location and specifically implicated drought-breaking runoff events. Although they suggested that the increase in sediment load is of concern to coral reefs, they provided no direct evidence for its role in reef degradation.

Indirect evidence for sediment impacts on nearshore reefs was provided by Roff et al. (2013). They investigated a reef approximately 25 km offshore and adjacent to the estuaries of the Burdekin and Herbert rivers (Fig. 2 shows this and other locations mentioned), using uranium isotopes to date the growth patterns of coral. They found a very stable baseline of growth for many centuries before
1900, followed by a decline in the period 1920 to 1955. No growth was observed in the period after 1980. Roff et al. (2013) attributed the decline in coral growth of the pre-European coral species assemblages to the inability of the coral to recover from disturbances associated with storms and extreme sea surface temperature events. They also suggested that the coral failed to recover as a result of the frequent presence of poor quality water. Their field study is consistent with the laboratory studies of Fabricius and Wolanski (2000), who observed the death of barnacles and coral polyps associated with the settling of aggregated estuarine fine sediment.

In apparent contrast with these findings, Morgan et al. (2016) reported extensive areas of active coral growth in the turbid zone adjacent to the central GBR lagoon. They suggested that "these coral communities may exhibit an unexpected capacity to tolerate documented declines in water quality." Furthermore, Larcombe and Woolfe (1999) concluded that turbidity and sediment accumulation at nearshore reefs was not influenced by sediment supply from rivers. Taken together, this suggests that at least some nearshore reef ecosystems are well adapted to turbid conditions.
The conclusions of Roff et al. (2013) and Morgan et al. (2016) are not necessarily contradictory. Different sites within the “inner-reef” environment were sampled and may consist of different species mixes and hydrodynamic conditions.

Sediment loads in the nearshore zone can be influenced by both river flows (e.g., Fig. 1) and resuspension (e.g., Fig. 3). Larcombe et al. (1995) attributed suspended sediment in the water column adjacent to near-coastal reefs to resuspension of bottom sediments. This attribution was confirmed by the field observations of Webster and Ford (2010), who observed resuspension associated with ebb tides in the Fitzroy River estuary. If the store of bottom sediments has a residence time of decades or more, then it can be expected that resuspension will persist even if river sediment loads are dramatically cut. This issue is discussed below.

The role of ocean upwelling in driving seasonal variations of available nutrients and phytoplankton responses was described by Furnas and Mitchell (1986). This source of nutrients is one that operated in the pre- and post-European settlement periods. Phytoplankton was found to take up all the newly available N and P within hours to days. Furnas et al. (2005) compared the contribution of different nutrient sources in the nearshore reef environment in the central GBR lagoon. They found that the main sources of dissolved inorganic N (DIN) were, from largest to smallest, benthic release (i.e., release from sediment already on the sea bed), river runoff, upwelling from the deep water edge of the outer reef, N in rainfall, and urban wastewater. Furthermore, they estimated that the river runoff contribution of DIN to this environment had doubled in the post-European settlement period. These results suggest that the GBR lagoon ecosystems experience strong variations in bioavailable N supply with time and that terrestrial sediment plays a key role in the delivery of peak N loads.

**Offshore Impacts**

The overall decline of coral biodiversity and cover on the GBR was documented by De’ath and Fabricius (2010) and De’ath et al. (2012). Using a statistical analysis of a record of 2114 reefs, De’ath et al. (2012) found a 51% decline in the initial coral cover between 1985 and 2012. They used statistical analysis to attribute this decline to the physical damage from tropical storms, coral bleaching, and increasingly frequent plagues of crown-of-thorn starfish (COTS, Acanthaster planci). They also concluded that the coral cover would recover in the absence of plagues of COTS. In turn, Fabricius et al. (2010) provided laboratory, field monitoring, and modeling evidence to link outbreaks of COTS plagues to the increased frequency and concentration of phytoplankton in the waters adjacent to the coral reefs. They described how increased phytoplankton abundance leads to the abundance of zooplankton, which in turn permitted the juvenile phase of COTS to survive in much-increased numbers.

Fig. 3. Three sequential true-color images of the Whitsunday Island region of the southern Great Barrier Reef Lagoon captured 5 d apart by the ENVISAT MERIS satellite sensor in June 2011. This southern-hemisphere winter period had no major river flows in the weeks preceding the image acquisition, and therefore turbidity is attributed to tidal resuspension of sediment from the lagoon floor. The proximity of fine sediment to the reef (shown as white) is apparent in these images. (Images courtesy of Thomas Schroeder, CSIRO.)
It has been widely observed (e.g., Devlin and Brodie, 2005; Brodie et al., 2007, 2010) that flood plumes from the river are followed by blooms of phytoplankton in the GBR lagoon. The greatest abundance of phytoplankton occurs where fresh surface water mixes with seawater at the outer edge of the plume, where turbidity is relatively low compared with the river sediment plume behind it. Radke et al. (2010) termed this zone the coastal transition zone, where settling of flocculated fine sediment coincides with increased availability of nutrients and light penetration, resulting in a large increase in the abundance of phytoplankton.

The three groups of coral-degrading processes identified by De’ath et al. (2012) (i.e., storms, bleaching, and COTS) are not independent. Wooldridge (2016) found that coral reefs exposed to excess nutrients were less tolerant of the extreme water temperatures associated with coral bleaching. McCook (1999) found that it is possible following a major disturbance by storms, COTS, or coral bleaching for a state shift to occur where macro-algal communities replace coral ecosystems. This state or phase shift is influenced by many factors including the presence of herbivorous fish that graze on macro-algae. Phase shifts in reef ecosystems during the recovery from major disturbances have been observed globally (Bellwood et al., 2004).

The lines of evidence above support the conclusion that elevated loads of N carried by fine sediment, and nutrients carried as solutes, are linked to the increased frequency and abundance of phytoplankton blooms near the outer reef during and after major river floods. In turn, the link between this outcome and the frequency of COTS outbreaks, as described by De’ath et al. (2012), provides a chain of links between elevated river sediment loads during floods and the decline of coral cover on the outer reef. The interactions between stressors make it probable that overall ecosystem resilience (i.e., recovery following any form of disturbance) is negatively affected by the increased nutrient availability. The association between excess sediment and excess nutrients is further addressed below.

**Sediment Budgets within the Watersheds of the Great Barrier Reef**

By understanding the relative magnitude and location of components of the sediment budget, it becomes possible to better inform investments in sediment management focused on marine water quality improvements. Here, I review the components of the sediment budget of the GBR watersheds and the approaches to quantifying and assembling these components.

**Hillslopes**

Cropping in the GBR catchments consists predominantly of sugarcane (3784 km²), horticulture (691 km² including tree fruits and banana [Musa L.]) in coastal regions, and grain cropping (6192 km²), predominantly in the central areas of the Fitzroy catchment (Thorburn and Wilkinson, 2013). This compares with 338,119 km² of grazing land across the GBR catchments.

Erosion rates in the cane lands have been high historically. Prove et al. (1995) found that hillslope erosion rates in the conventionally tilled sugar fields averaged 148 t ha⁻¹ yr⁻¹ and <15 t ha⁻¹ yr⁻¹ for no-till practices. The increase in green cane harvesting and reduced tillage in sugarcane management practices from 1980 onward has significantly reduced the rates of hillslope erosion occurring in these near-coastal landscapes (Hunter and Walton, 2008). Bare soil fallowing for some time around sugarcane planting remains standard practice in the GBR region (Smartcane, 2017).

A long-term paired catchment study in Brigalow open woodland in the Fitzroy catchment provides a rich data source for understanding the consequences of developing natural landscapes into cropping and grazing landscapes. Cowie et al. (2007) described three adjoining microcatchments (12–17 ha) that were monitored for 17 yr before one catchment was converted to pasture and another converted to cropping in 1982. Monitoring then continued for a further 23 yr. The climate at this site is semiarid, with mean annual rainfall of 697 mm. As well as finding changes to the magnitude and temporal patterns of runoff, Thornton et al. (2012) found suspended sediment yields from the cropped catchments to be twice that of the natural control treatment. In contrast, the suspended sediment yield for the pasture treatment was half of the control treatment. It is noted that the size and morphology of the catchments used in this study means the yields are likely to be influenced by both hillslope erosion and deposition prior to flow entering a natural stream channel.

Grazing occupies 97% of the total GBR catchment area and occurs almost exclusively as extensive cattle grazing with no significant inputs of fertilizer (Thorburn and Wilkinson, 2013). Long-term monitoring of soil erosion rates in grazing landscapes of the GBR catchment was reported by McIlvor et al. (1995), Scanlan et al. (1996), Bartley et al. (2010), and Silburn et al. (2011). All these studies noted that the combination of strong rainfall variability and commonly high stocking rates caused periods of poor vegetation cover and correspondingly high erosion risk. Each study also recommended a minimum vegetative cover of 30 to 50%. Silburn et al. (2011) reported 7 yr of monitoring of 12 treatments in the semiarid grazed landscapes, and concluded that the long-term run down in soil structure and cover had an impact on the rates of runoff and, consequently, suspended sediment yield.

Lu et al. (2003) and Teng et al. (2016) provided spatial estimates of mean annual hillslope (sheet and rill) soil erosion rates for the Australian continent. These assessments were done using a version of the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1994). Lu et al. (2003) estimated the cover factor using a remote sensing classification for the period 1981 to 1994. By contrast, Teng et al. (2016) estimated the cover factor by combining the Dynamic Land Cover product (Lyburner et al., 2010) based on interpretation of remote sensing for the period 2000 to 2008, estimating the RUSLE cover factor from land cover type. Teng et
al. (2016) estimated hillslope erosion rates for extensive grazing lands that were considerably less than the estimates of Lu et al. (2003). Both national assessments identified the Burdekin River catchment and adjacent areas of the GBR watersheds as having relatively high hillslope erosion rates compared with the Australian average (1.86 t ha⁻¹ yr⁻¹ as presented by Teng et al., 2016).

Yang (2014) provided a method for combining remotely sensed estimates of bare soil, photosynthetic vegetation, and non-photosynthetic vegetation (from Guerschman et al., 2009) with monthly rainfall erosivity estimates to estimate the cover factor. This development suggests that dry bleached vegetation may have been misclassified as bare soil in previous predictions, including Lu et al. (2003). The method provided by Yang (2014) appears to be highly suited to hillslope erosion estimates in tropical and subtropical environments where seasonal patterns of both rainfall and vegetative cover combine with the importance of non-green cover. This method awaits application in the GBR catchments.

Footslope Deposition

Walling (1983) identified different sediment stores that influence sediment delivery within watersheds: “deposition and temporary or permanent storage may occur on the slope, particularly where gradients decline downslope, at the base of the slope, in swales ...” Together, these sediment stores are described here as footslopes.

In modeling the sediment budget for the GBR catchments, McKergow et al. (2005) assumed a uniform 10% sediment delivery ratio between model-estimated sheet and rill sediment mobilization at the “field” scale and delivery into the nearest stream as represented in the model. This assumption was partly based on the dilution of surface soil tracers in stream flows from small catchments (e.g., Wallbrink et al., 2003). In modeling small catchments, the hillslope delivery ratio is adjusted so that the blend of hillslope erosion, with a high surface soil signal, and gully and streambank erosion, with a mainly subsurface soil signal, is matched.

Distinct types of footslope deposits have not been quantified separately in the GBR watersheds. The exception is the study of McKergow et al. (2004), who investigated the performance of grass and natural rainforests as riparian buffers. Their approach was to monitor grass buffers on planar and convergent slopes below banana crops in a steep tropical setting. For the planar grass buffer, >80% of the sediment load and between 25 and 60% of the total nutrient load were captured in a 15-m-wide grass strip along the base of a cropped field. The convergent slopes and natural rainforest buffers were largely unsuccessful in capturing the pollutants leaving the cropping zone, however.

Gully Erosion

A series of sediment tracer studies have identified subsurface erosion as the source of the majority of sediment to the coast of northern Australia (e.g., Hughes et al., 2008; Caitcheon et al., 2012; Olley et al., 2013; Wilkinson et al., 2013). These studies compared the soil tracer signal of surface and subsurface soils with that of sediment in deposits near the coast. Subsurface erosion includes gully erosion, streambank erosion, and hillslope erosion of subsoils exposed by removal of the surface soil layers. Wilkinson et al. (2013) and Olley et al. (2013) both concluded that this evidence demands a major revision of assumptions in sediment modeling in these environments, which previously predicted that surface erosion was the predominant source of sediment in the GBR lagoon.

There are an estimated 80,000 km of gullies in the GBR catchments (Thorburn and Wilkinson, 2013). The formation of these gullies is largely a legacy of land development by early European settlers (Saxton et al., 2012) from the late 1800s onward. The initiation of gullies was probably the combined result of drought and overgrazing after native vegetation clearing (Bartley et al., 2014).

Gullies continue to evolve by lengthening, then widening, resulting in elevated levels of sediment yield for many decades after their initiation (Bull and Kirkby, 1997). Hughes et al. (2010) used sediment dating of a floodplain accumulated below a gully network in the central Fitzroy watershed to conclude that the rates of gully erosion have decreased on the order of 60 to 70% since the mid-20th century.

A special class of gully erosion is alluvial gullies, which often form in sodic soils in alluvial settings. Brooks et al. (2009) reported on the morphology and sediment yield of a highly active alluvial gully in a catchment adjacent to the GBR catchments. Alluvial gullies have also been reported in the Normanby catchment (Olley et al., 2013) and the Burdekin catchment (Wilkinson et al., 2013). These researchers reported alluvial gullies to be highly active erosion features that are directly connected to the stream network.

Streambanks

Streambanks contribute sediment directly to the river network and thus are not subject to footslope deposition. Furnas (2003) reported that 60% of native riparian vegetation in the tropical cropping zones of the GBR catchments had been cleared. Johansen and Phinn (2006) combined IKONOS and Landsat ETM+ satellite imagery to map extensive riparian vegetation removal and degradation in the grazing lands of the Burdekin catchment since European settlement. Also using remote sensing methods, Lymburner (2008) found widespread degradation of riparian functions in the extensively grazed lands of the Fitzroy catchment.

Beyond these studies, streambank erosion remains an under-investigated component of the sediment budget in Australia’s tropical catchments (Bartley et al., 2015). Bartley et al. (2008) used direct measurement during a 3-yr period and air photo interpretation for a 28-yr period (1972–2000) to assess the contribution of streambank erosion along the Daintree River. There was an 85% reduction in the rate of streambank erosion where riparian vegetation was intact compared with where the streambank had been
cleared. River width increased throughout the short-duration detailed survey but decreased during the longer period spanned by the air photos. Bartley et al. (2008) concluded that in this tropical setting it was difficult to predict short-term behavior of stream-banks and channel width.

**Floodplains**

Floodplains are extensive throughout the GBR catchments and range from extensively grazed semiarid plains in the central Fitzroy catchment to intensively cropped coastal floodplains in the wet tropics. Hughes et al. (2008, 2009, 2010) investigated the accumulation of sediment on a floodplain adjacent to Theresa Creek, a tributary of the Fitzroy River. This study used optically stimulated luminescence (OSL) dating techniques to obtain precise contemporary dates for the sediment stores. They found that floodplain accretion rates had increased three- to fourfold after European settlement around 1850 CE. Hughes et al. (2010) also noted that in-channel deposits in Theresa Creek contained volumes of fine sediment that are significant at the catchment scale and appear stable on a decadal time scale.

Also using OSL techniques, Bostock et al. (2007) estimated a mean accretion rate of 1 mm yr\(^{-1}\) for the coastal floodplain of the Fitzroy River in the last 100 yr. The resulting mean annual net deposition rate on this floodplain was estimated at 640 kt yr\(^{-1}\), which represents 13\% of the sum of floodplain deposition and estimated mean sediment discharge from the river mouth (4162 kt yr\(^{-1}\)).

Wallace et al. (2009) monitored 13 floods that inundated the coastal floodplain of the Tully–Murray rivers that drain into the central GBR lagoon. By comparison of river fluxes and those estimated across the floodplain, they found that a significant portion of the total sediment and nutrient load was carried by overbank flows. Although they did not estimate net erosion or deposition on the floodplain, they did conclude that restoration of wetland and riparian vegetation to slow the passage of flows are likely to have significant impacts on the downstream fluxes of sediment and particularly on dissolved organic N.

**Reservoirs**

Most major rivers draining the GBR lagoon are dammed upstream for irrigation water supply, town water, hydroelectric purposes, or a combination of these (Australian National Committee of Large Dams, 2010). Reservoirs are generally in the headwaters or mid-reaches of the watershed and divide the stream network into an upper part that drains into a reservoir and a lower part that does not. The largest reservoir in the GBR catchments is Lake Dalrymple, as formed by the Burdekin Falls Dam, with a maximum capacity of 1,860,000 ML and an upstream catchment area of 114,220 km\(^2\) (Australian National Committee of Large Dams, 2010). This represents 88\% of the total Burdekin River catchment area (129,700 km\(^2\)) and 27\% of the total GBR catchment area (423,122 km\(^2\)).

The trapping of fine sediment in large reservoirs is normally calculated using empirical relationships that relate trapping efficiency to some combined metric of annual river flow and maximum reservoir capacity (e.g., Brune, 1953). Lewis et al. (2013) empirically found that the trapping efficiency of the Burdekin Falls Reservoir for 2006 to 2010 was 66\%, less than the 91\% predicted by the method of Brune (1953). The researchers suggested that the combined effects of highly variable inflows from the semiarid tropical watershed and the stratification of the reservoir may explain this difference. They proposed a variant to the Churchill (1948) equation to better predict reservoir sediment trapping where the identified effects are in place.

**Processes within Estuaries**

As a river enters an estuary, the river sediment is subject to additional influences including a reduction in the flow speed, buoyancy of freshwater in seawater, the mixing of river flow with saltwater, and changes to the ionic environment of the sediments.

Bostock et al. (2007) used sediment dating techniques to assess the accumulation of sediment within the estuary of the Fitzroy River. They found that the net deposition rate in this estuary for the past 100 yr was 2350 kt yr\(^{-1}\), equivalent to 56\% of the estimated mean sediment discharge from the river mouth. This rate of accumulation in the modern period is approximately double the average rate estimated for the past 8000 yr.

Webster and Ford (2010) sampled transects along the lower Fitzroy River, estuary, and ocean during both high river flows and inter-flood periods. The overall pattern they described during flood events is one of fine sediment delivery coincident with flocculation triggered by the mixing of fresh and marine waters. This pattern was also observed by Bainbridge et al. (2012) for flood plumes exiting the Burdekin River. The location of the mixing zone varies as the flood enters the lagoon. Between flood events, sediments that remain in the direct influence of the river mouth tidal flows are drawn back into the estuary by the asymmetric tidal velocities. Sediments that escape this influence are dispersed by successive resuspension and deposition, as influenced by the prevailing wind and currents (Webster and Ford, 2010).

The transport and impacts of fine sediment and nutrients in this environment are interlinked. Webster and Ford (2010) confirmed mechanisms for this linkage in the Fitzroy estuary: fine sediment carries the majority of the nutrient load in the freshwater environment and can restrict the availability of light for primary production. Furthermore, they observed two important processes at the transition between freshwater and seawater: the neutralization of the surface charge on clay and organic surfaces and the flocculation and resulting accelerated settling of fine sediments associated with this change in surface charge.

Radke et al. (2010) presented a detailed examination of the biogeochemistry of the estuary and adjacent zones surrounding the
mouth of the Fitzroy River. Although the sampling of this study was confined to the dry season, it elucidates the nutrient cycling processes in the estuary that cause part of the nutrients carried by the river to become available to the food web in the lagoon. In the freshwater–marine transition zone, a large portion of the particulate nutrients is carried into the saltwater by sediment and then detached. Radke et al. (2010) asserted that “based on measured sedimentation rates and nutrient concentrations within the sediment column, the amount of nutrient buried appears to be approximately 30 and 50% of the modern inputs of TN (total nitrogen) and TP (total phosphorus) by the Fitzroy River to its estuary.” Furthermore, the released nutrients are primarily taken up by phytoplankton in the coastal transitional and more offshore “blue water” parts of the lagoon. This study supports the hypothesis that changes to the flux of fine sediment in the river will result in similar changes in the flux of nutrients introduced to coastal ecosystems.

The relationship between particulate nutrients, specifically particulate-carried N, and the growth of phytoplankton in the GBR lagoon is a critical link in the causal relationships from soil erosion to the deteriorating health of the GBR. Brodie et al. (2015) commented: “A large portion of both marine and terrestrial-sourced PN [particulate N] is potentially bioavailable (time frame days to months) after bacterial mineralization to DIN or ingestion by filter feeders. However, a significant fraction may be removed through denitrification in sediments (nearly all nitrogen is ultimately returned to the atmosphere via denitrification). The bioavailability of DON [dissolved organic nitrogen] spans a wide spectrum. A significant proportion of DON, however, may be unavailable over timeframes longer than water residence times in the GBR system. Given our conclusions that almost all the PN discharged from rivers to the GBR, and some of the DON is likely to be bioavailable within its residence time in the GBR lagoon, we suggest management of anthropogenic sources of PN (mainly fine sediment erosion) may be equally important to the health of the GBR as is management of anthropogenic sources of DIN.”

Additionally, they suggested a combined strategy of fertilizer management (nitrogenous fertilizer primarily applied in cropping lands) and soil erosion management across all rural land uses as an appropriate approach to reducing the impact on marine ecosystems. They concluded that a better understanding of nutrient mobilization and tracking through the fluvial system to impacted ecosystems remains a research priority.

Along the transport path, nutrients cycle through pools including organisms and sediments. Thus the control of one nutrient species at its source (e.g., NO₃) will be only partially related to the concentration of that same nutrient species at a downstream location. The concept of nutrient spiraling is important to understanding the relationships between different forms of nutrient mobilization (e.g., solute leaching, soil erosion) and the speciation into nutrient forms available to the marine food chain. Ensign and Doyle (2006) provided a review of the processes of nutrient spiraling that are widely observed in terrestrial, stream, and estuarine systems. They defined a characteristic uptake length as the average distance traveled by a nutrient molecule in the inorganic phase before uptake. Ensign and Doyle (2006) summarized 59 studies of nutrient spiraling in rivers and streams and found a mean uptake length for NO₃ of 86 m. Such highly dynamic cycling demands attention to all forms in which nutrients are mobilized and may become biologically available at a downstream problem location.

Transport beyond the Estuary

The boundary between the estuary and the wider GBR lagoon is an arbitrary one. The relative importance of different sediment and nutrient processes varies markedly, with spatially and temporally transient conditions. Specifically, the extent of freshwater in the marine environment (Schroeder et al., 2012) and tidal influences are highly variable in time (Webster and Ford, 2010).

The partitioning of fine sediment, between that which remains in the river estuary and that which contributes to the coastal sinks, is influenced strongly by the magnitude of the individual river flood events. Devlin and Schaffelke (2009) used remote sensing for a range of river flows to show that the dispersal of river sediment in the GBR is highly variable between events. For large river flows, there can be overlap in the extent of plumes from major rivers. Devlin and Schaffelke (2009) intersected the extent of river plumes with the main parts of the GBR ecosystem, coral reefs and seagrass meadows. Their work directly associated river plumes with the deposition of fine sediment within, or adjacent to, these ecosystems.

Devlin and Brodie (2005) sampled the river plumes of the Barron, Herbert, Johnstone, and Burdekin rivers during major runoff events, including in the wake of tropical cyclones. For low-salinity samples (i.e., close to the river mouth), concentrations of NOₓ (combined NO₃ and NO₂) followed a conservative relationship with salinity of the samples. This pattern is consistent with simple dilution associated with mixing of river water and seawater without net transformation or uptake of the NOₓ. For higher salinity values, the NOₓ concentrations were below that associated with simple dilution. Devlin and Brodie (2005) attributed this effect to the uptake of NOₓ by phytoplankton under more marine-like conditions.

As described above and shown in Fig. 3, resuspension of seafloor sediment is widely observed in the near-coastal parts of the GBR lagoon. The resuspension of this material contributes to the temporal patterns of turbidity in these locations. Larcombe et al. (1995) noted the persistence of the source of this resuspension and the importance of very large fine sediment stores in the north-facing bays.

Response Times to Changes in Inputs

The assessment of the response times from erosion control to marine response is an important factor in the design of future and
assessment of past catchment management strategies. This factor awaits investigation in the GBR watersheds.

Techniques for estimating the response time from changes to source erosion rates to changes in the fine sediment flux have been developed using combinations of sediment tracers (Smith et al., 2014). These techniques sample sediments in transport or recently deposited in a problem location and compare their tracer properties with those of the range of possible upstream sources. Two catchments immediately to the south of the GBR catchments have had such investigations of fine sediment response times. Wallbrink et al. (2002) sampled the lower reaches of the Brisbane and Logan rivers, upstream of the seawater mixing zone, and found residence times in the range of 0 to 21 yr. Douglas et al. (2009) sampled the estuary of the Maroochy River and found that all but one sample had a residence time in the range of 0 to 30 yr.

Assembling the Components around the Stream Network Modeling

A range of modeling styles have been applied to represent the generation and transport of sediment on the land and in the stream network of the GBR catchments. Most models (McKergow et al., 2005; Kroon et al., 2012; Wilkinson et al., 2014) used a distributed deterministic approach built around a representation of the stream network (Welsh et al., 2013) that includes sediment transport through major floodplains and water storage. This approach permits the use of established field-scale models of hillslope erosion and associated generation of nonpoint-source pollution for major land uses. Algorithms for stream sediment transport, floodplain deposition, and reservoir sediment trapping relationships have been drawn from the global literature. Each of these modeling efforts made extensive use of the flow gauging networks in the river to calibrate rainfall–runoff algorithms for each river. McKergow et al. (2005) found that the predicted fine sediment loads for each river compared favorably with the annual average results from long-term monitoring. Kroon et al. (2012) also evaluated the predictions of pollutant loads for fine sediment and a range of N and P species against the available data from near-coast monitoring stations. For each major river basin, each comparison was generally favorable.

Most implementations of distributed deterministic models used in the GBR catchments combine long periods of synthetic rainfall and runoff data together with current or historical land use data to assess mean annual loads. Spatial outputs include predictions of erosion rates, the relative contribution of subcatchments to sediment loads at the river mouth, and an inventory of the processes predicted to contribute to fine sediment loads at the mouth. The model of Wilkinson et al. (2014) provides a more dynamic simulation approach where actual events can be modeled and compared with field observations.

Over the years, distributed deterministic models have been revised considerably based on new evidence provided by sediment provenance and tracer studies. A series of studies that sampled sediment sinks have determined the proportion of the fine sediment that has come from soil types and sediment in the catchments (Hughes et al., 2009; Tims et al., 2010; Wilkinson et al., 2013) and the proportion of sediment mobilized by surface and subsurface erosion (Tims et al., 2010; Olley et al., 2013; Wilkinson et al., 2013). Comparison of these results with the proportions of sediment sources predicted by models has provided a logic for adjustments to model parameters. Significantly, since the modeling study of McKergow et al. (2005), the process tracing evidence has shifted the focus from predominantly hillslope erosion to predominantly subsurface (gully and streambank) erosion.

All distributed modeling studies to date have suggested that the majority of sediment arriving at the coast is sourced from near-coastal regions. This is a logical consequence of the spatial arrangement of sediment sinks, where sources of sediment well away from the coast are subject to multiple forms of deposition (e.g., on floodplains and in reservoirs).

McKergow et al. (2005) and Kroon et al. (2012) estimated contemporary and pre-European settlement erosion and sediment delivery rates using distributed process models. The ratio of these rates, 8 for McKergow et al. (2005) and 5.5 for Kroon et al. (2012), agrees with estimates based on sediment core analysis by McCulloch et al. (2003), who concluded there had been a five- to 10-fold increase in sediment loads since 1850. Both studies noted the uncertainty in estimating model inputs for the pre-European settlement period.

Other modeling approaches have further exploited the available monitoring data in their simulations. Kuhnert et al. (2012) developed a regression estimator tool approach to using streamflow and suspended sediment concentrations together with a dynamic measure of catchment condition (catchment vegetation cover) for the Burdekin catchment. This approach permits formal consideration of uncertainty and predictions while reducing the structural complexity of the model.

Also following a statistical approach, Pagendam et al. (2014) used Bayesian hierarchical modeling to represent a small subcatchment of the Burdekin catchment. Their method integrates information from a process model for runoff, a statistical model for sediment generation, and observed runoff and sediment load data. The approach showed promise for providing daily predictions of loads with uncertainty where data are relatively abundant. Gladish et al. (2016) built on the deterministic approach of Wilkinson et al. (2014) but included a Bayesian hierarchy to more fully exploit daily concentration and flow data. They claimed that the method is statistically rigorous for quantifying uncertainty through space and time. These new developments in modeling dramatically increase the use of monitoring data.
compared with previous approaches in the GBR catchments and offer formal consideration of uncertainty.

A Summary of Pollutant Movement through the Catchment–Estuary System

Figure 4 provides an overview of the movement of terrestrial sediment and associated pollutants to the lagoon of the GBR as drawn from the sources described above. The representation of the catchments and estuaries nominally uses two tributaries: one with and one without a reservoir. The size of the fluxes shown in the figure is indicative of the relative size of the long-term flux of pollutants including the influence of major runoff events. This figure enables consideration of the sequence of sources and sinks and their overall influence on marine locations.

Management of Pollutant Movement to the Lagoon of the Great Barrier Reef

Source Controls

In extensively grazed landscapes, the control of hillslope erosion is focused on maintaining ground cover. The combined temporal patterns of precipitation and markets for domestic animals means that ground cover tends to be low at the end of dry periods (Bartley et al., 2014) and drought-breaking rains are drivers for major erosion events. McIvor (2012) provided a detailed review of grazing management techniques to maintain ground cover above threshold values in these semiarid subtropical and tropical landscapes. The use of widely available seasonal forecasting of rainfall can increase the profitability of grazing enterprises and reduce the risk of widespread low ground cover (O’Reagain et al., 2011), although land managers in the GBR catchments are reluctant to adopt these techniques (Marshall et al., 2011).

Spatial patterns of vegetative cover also play a significant role in influencing the rates of hillslope erosion. Bartley et al. (2010) described a long-term trial where the spatial arrangements of bare soil patches resulted in markedly different rates of soil erosion as measured at the base of a hillslope. Furthermore, the placement of watering points away from waterways reduced the combined effects of bare areas of soil adjacent to watering points and stock tracks that lead overland flow to these points in the landscape (Hairsine et al., 2001).

Gully erosion in grazing landscapes can be controlled by a range of measures (Geyik, 1986). As mentioned above, Thorburn and Wilkinson (2013) estimated that there are 80,000 km of gullies in the catchments of the GBR. Consequential gully remediation with the objective of reducing marine impacts must be focused on gullies that combine a high erosion rate and efficient delivery to the lagoon. For non-alluvial gullies, remediation efforts in the GBR focus on stock exclusion fencing to remove direct disturbance (Wilkinson et al., 2015), reduction of grazing pressure in the contributing catchment upslope (Wilkinson et al., 2015), and the use of low-cost porous weirs to intercept sediment (Heede, 1979).

For alluvial gullies, the high rates of erosion and their more localized occurrence may well justify more costly techniques (Shellberg and Brooks, 2013). Shellberg and Brooks (2013) evaluated fencing, rock chutes, gully reshaping, porous weirs, and soil amelioration to address alluvial gullies formed in a semiarid tropical landscape. The long-term cost effectiveness of both low-cost extensive and higher cost local treatments in the GBR catchments awaits further investigation.

Bartley et al. (2015) reviewed management options available for reducing streambank erosion in the GBR catchment. They drew extensively on experiences outside the catchments because there are few studies of streambank erosion and its management in the GBR watersheds. The emphasis in most rehabilitation techniques is on fencing off riparian zones rather than the high-cost engineering of streambanks. Fencing encourages the natural recovery of vegetation, but active planting of trees and shrubs may still be required in some settings.

The importance of deep-rooted vegetation in providing bank stability was emphasized by Bartley et al. (2008) for the tropical Daintree River. They found that without intact riparian vegetation, the streambank erosion rate was 6.5 times higher than where there was intact vegetation. They also noted that fencing and alternative water sources for stock help to maintain riparian vegetation. Outside the GBR, McKergow et al. (2003) found that intact riparian vegetation has a major impact on water quality. In their study, treatment was imposed on a stream network that was previously grazed to the edge of the stream, and suspended sediment loads fell by a factor of 10 in the 10 following years. However, this study was done in a Mediterranean environment and may not transfer directly to the GBR catchments.

Controlling hillslope erosion on cropland remains a priority for downstream water quality management. Erosion rates per unit area are generally higher for cropping land than grazing land (Lu et al., 2003) and there is a wide range of established erosion mitigation options for cropping systems. Industry-wide adoption of trash blanket sugarcane harvesting in the GBR catchments has greatly reduced soil erosion rates, but erosion rates remain high by world standards. Rohde et al. (2013) assessed the erosion and nutrient losses for a range of machinery and plant inputs for sugarcane grown on two soils in the tropical part of the GBR watershed. For all treatments, they found a 10-fold difference in the suspended sediment load coming from the plant crop phase of the sugarcane, when the soil is recently tilled and unprotected, and the ratoon phase when the soil has settled and a trash blanket is in place. Current standard soil preparation practices do not include the use of trash handling machinery in the planting phase, which occurs typically once every 4 yr (Smartcane, 2017). Thus there is considerable scope to further reduce hillslope erosion rates for this land use.

In the subtropical grain cropping systems of the central Fitzroy catchment, Carroll et al. (1997) evaluated the effectiveness of
Fig. 4. An overview of the movement of terrestrial sediment and particle-attached nutrients to the lagoon of the Great Barrier Reef as drawn from the synthesis of the sources described in the text: (a) the configuration of the catchment identifying major forms of sources and sinks of nonpoint source pollutants—note that all catchments are aggregated and nominally depicted as being either on a tributary with a major reservoir or on a tributary without a major reservoir; (b) the size of the arrows is indicative of the relative size of the long-term flux of pollutants including the influence of major runoff events; and (c) the size of the arrows is indicative of the relative size of the long-term fluxes of particle-attached nutrients. Changes in the size of arrows from (b) to (c) are associated with the preferential erosion of surface sediment richer in nutrients and the sorting of sediment and associated enrichment of nutrients in some sinks.
reduced and zero tillage for a range of crop rotations. Across 21 yr of monitoring in a highly variable rainfall zone, reduced tillage was found to reduce hillslope erosion for all cropping rotations. Furthermore, zero tillage resulted in long-term average erosion that was 25% of that under traditional management practices.

Although tracer studies have found that the contribution of hillslope erosion to coastal sediment is much less than those of gully and streambank erosion (e.g., Wilkinson et al., 2013), the enrichment of hillslope sediment with nutrients increases the importance of hillslope erosion control to mitigate coastal water pollution. With this in mind, Thorburn et al. (2013) concluded that reducing N fertilizer inputs was a priority for changes to sugarcane and horticultural cropping in the GBR catchments. They advocate a combined strategy of erosion control and fertilizer management to reduce the flux of suspended sediment and nutrients leaving cropping fields and arriving at the river mouth.

Sink Controls

There are opportunities to manage and, in some instances, enhance the net sediment deposition that occurs between soil erosion sources and the coast. Above, I described the various sinks, including footslopes, buffers and riparian zones, floodplains, and water storage reservoirs, and the investigations of their behavior in the GBR catchments. Here, I describe the potential to manage these sinks with the goal of improving the marine water quality.

Buffer zones, including those located on footslopes or in riparian zones, are widely acknowledged as an effective control on sediment delivery, although there are few rigorous studies in tropical settings (Mekonnen et al., 2015). As described above, McKergow et al. (2004) used a field monitoring approach to assess the influence of grass and native vegetation buffers on the movement of runoff and sediment into the stream network. The results of this work suggest that the positioning of buffers in the local topography determines their effectiveness. Planar or near-planar slopes where overland flow is spread through the buffer greatly decreases flow velocities and increases net deposition rates.

Floodplains occur throughout the GBR catchments including in headwater catchments, mid-reaches, and near the river mouth. Macnish (1980) described the use of grain row cropping orthogonal to the direction of overland flow across floodplains in subtropical southern Queensland, Australia. Innovative row croppers developed these systems to prevent erosion and enhance net deposition on floodplains subject to infrequent flooding. Crops are organized in regular narrow strips typically one plow or harvester width. By sequencing farming operations across the strips, the floodplain soil never has contiguous bare soil, and adjacent strips with a mature crop provide a hydraulic backwater for strips recently planted. Smith et al. (1991) formalized the hydraulic design of these strip-cropping methods to adapt to differing overland flow rates and land surface slopes. To the best of my knowledge, such techniques are yet to be trialed in the GBR catchments.

The construction and operation of in-stream reservoirs can be designed to reduce the delivery of suspended sediment in the GBR. Most major reservoirs in the catchments are multipurpose structures whose primary purpose is to supply irrigation water downstream. As described, Lewis et al. (2013) found that reservoirs can have a considerable impact on the delivery of sediment. To the best of my knowledge, minimizing the delivery of sediment is not currently a design criterion in the construction of new reservoirs or the management of existing ones in the GBR catchments. It is noted that major flood events in the GBR catchments have a flood volume that typically exceeds the capacity of even the largest reservoirs by several times, which may limit the ability of reservoirs to reduce sediment delivery.

**Concluding Remarks**

The structuring of knowledge concerning the erosion and transport of sediment from the land to the marine environment may also inform research outside the GBR. Specifically, this review shows that combining process studies and tracer and dating studies with modeling and monitoring can greatly assist to provide an overall assessment of sediment budgets in a way that is not possible with any single research approach. The identification of the response functions between erosion processes, river sediment, and indicators of marine health is essential for sediment science to be practically applied. Without strong evidence for the causal links involved, terrestrial erosion control as an approach to protecting marine ecosystems remains speculative.

For the system of the GBR and its watersheds, some specific findings emerged from this review. There is a high degree of certainty that terrestrially eroded sediment contributes to the degradation of the various marine ecosystems. However, the declining health of the GBR is driven by multiple stressors. These include the influence of sediment-carried nutrients on plagues of COTS and the broader influence of elevated turbidity and nutrient concentrations on reef recovery after storm damage, bleaching, or starfish plague events.

The chain of dependencies from erosion of sediment to coral and seagrass decline is long, and many forms of sediment and ecosystem research have been required to develop a useful systems view. Sediment tracing and coral dating techniques have been vital to providing evidence of sediment provenance and pre-European context. This is especially true in an environment subject to infrequent but large-scale river flooding. Improvement in predictive modeling continues to rely on the constraints provided by dating and tracing.

The GBR catchments contain 10,000s of square kilometers of eroding hillslopes and 10,000s of kilometers of eroding gullies and streambanks. The value of the GBR, the rate of its decline,
the spatial scale of the change to sediment delivery required, and the high cost of mitigation all sustain the current trend of ongoing decline. A step change in the investment in improving water quality would be required to reverse this trend and may well require a shift to both voluntary and regulatory measures.

A question of considerable practical importance remains largely unanswered. The time lag between changes in land and waterway management and responses in the marine ecosystem is uncertain, although many studies assume it to be short. The influences of sediment storage in the river systems, estuaries, and sea floor, the observed role of resuspension, and the timing of desorption of nutrients and other pollutants from sediment are all likely to have a role in determining the actual lag time between mitigation and recovery.

Furthermore, the relative importance of different forms of terrestrial nutrients in marine degradation remains contested. The emphasis on fertilizer management vs. erosion control is a practical question for agencies tasked with reducing the impacts on the reef. While causal links between nutrients in solute form proximate to the reef and reef response are relatively well understood, the relative impact of fertilizer management and erosion control and the near-reef concentrations of solutes remains uncertain. Arguably, the current knowledge base supports a precautionary approach that combines sediment and fertilizer control.

Finally, the literature is poor in evidence to support sediment-sink management as a tool in mitigating terrestrial impacts on the marine environment. In principle, the GBR watersheds appear to have large potential for capturing sediment and pollutants before they reach the marine system. For example, studies of floodplains have shown that historically these sinks have served as an effective buffer between the sediment sources and the sea. While there are studies of the effectiveness of measures such as strip cropping and check dams elsewhere, there appears considerable practical scope for investigation and design of such measures in this tropical and subtropical setting.

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