

Supplementary material

Review and conceptual models of agricultural impacts and water quality in waterways of the Great Barrier Reef catchment area

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Table S1. Examples of catchment impacts on ecological patterns and processes in rivers and coastal waters

All agents may interact with each other, with additive or multiplicative effects. These interactions are largely unknown; especially concerning is the potential interaction of these agents with changes in climate (adapted from Pearson and Stork 2008)

Pressure (source of stressor)	Stressor (cause of impact)	Ecological response (proximal impact)	Outcomes (ultimate impact)
Water quality			
Land clearing	Suspended sediments	Smothering of habitats, plants and animals	Loss of <ul style="list-style-type: none"> ▪ habitat ▪ biodiversity ▪ productivity ▪ ecosystem services ▪ amenity values
Grazing – soil and creek damage		Reduction of light penetration, productivity, and dissolved oxygen	
Agriculture and horticulture			
Mining, infrastructure, recreation			
Agricultural fertilisers			
Breakdown of organic material	Nutrients	Increased plant production and weed infestation, increased hypoxia and fish kills	
Aerial input from industrial sources		Plankton blooms	
Point sources such as sewage treatment works, animal production units, dairies	Organic material		
Agricultural trash, sugarcane juice-sucrose, decaying weed masses		Increased oxygen demand by bacteria; fish kills	
Stock on land or in intensive units, industry, sewage treatment works		Change in ecological assemblages due to change in food supply	
Agriculture			
Mining and industrial effluents			
	Pesticides	Possibly toxicity to native plants and fauna	
	Toxic minerals	Toxicity and death to biota where not sufficiently diluted	
Irrigated agriculture, cleared landscapes, deep drainage channels	Salinity	Loss of intolerant plants and animals	
Deep drains penetrating acid sulfate soils	Acidity	Toxicity to plants and animals	
Altered flows including dam releases		Effect on fish breeding triggers	
Loss of riparian shade		Exclusion of intolerant species	
Climate change	Changed temperature regimes	Exacerbate hypoxia processes	
Dam releases	Low dissolved oxygen (hypoxia)	Fish kills	
Nutrients, weeds, algal blooms, organic inputs		Exclusion of intolerant species	
Suspended sediments			

Pressure (source of stressor)	Stressor (cause of impact)	Ecological response (proximal impact)	Outcomes (ultimate impact)
Other			
Climate change	Changed flow regimes	Changed geomorphology and bank stability	
Water infrastructure – e.g. dams, weirs		Sediment build up or scouring	
Irrigation channels and drains		Changed water quality	
Water harvesting		Weed invasion	
Urbanisation		Altered triggers for animal breeding	
		Unseasonable drying or inundation	
	Barriers to movement of animals	Changed habitat availability, loss of connectivity	
Infrastructure – dams, weirs, culverts, flow control structures		Water-logging or drying of riparian soils and dieback of vegetation	
Weeds		Exclusion of species from important habitats and	
Poor water quality	Weed infestation		
Loss of riparian shade and increase in nutrient availability		Changes in e.g. geomorphology, habitats, water quality, connectivity	
Intentional introduction of pasture grasses	Feral animals		
Pigs and other large mammals		Large mammals damage vegetation and benthic habitats, cause local pollution	
Exotic fish escapes or wilful introductions	Changes in light regime	Displacement of native species	
Loss of riparian shade through clearing for agriculture		Increase in stream temperature, weed growth and hypoxia leading to loss of habitat and barriers to connectivity	

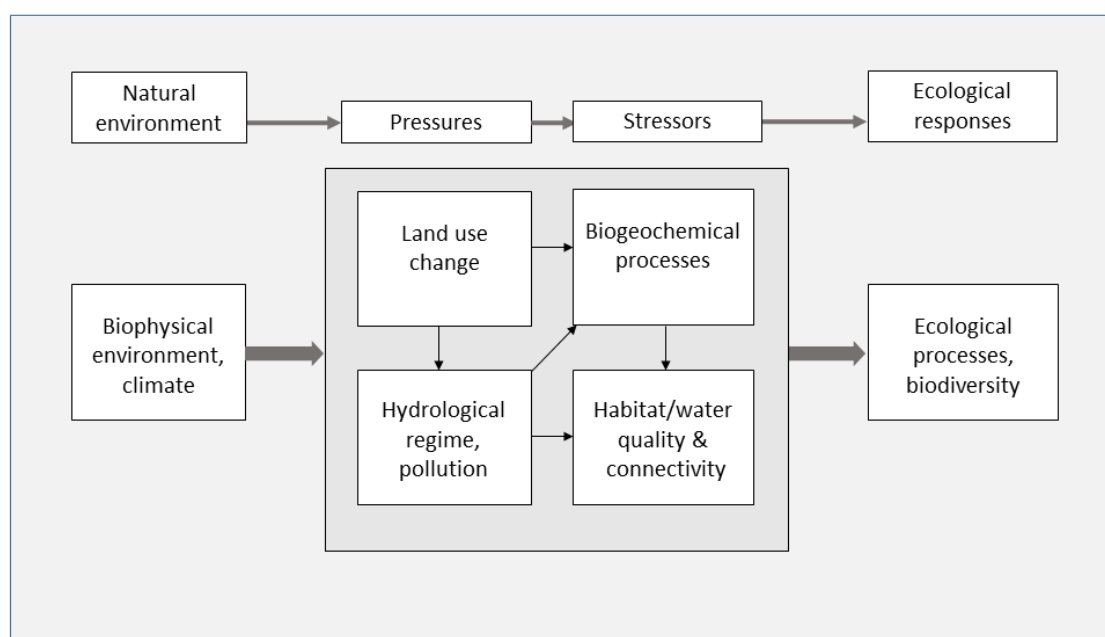


Fig. S1. Broad pressure–stressor–ecological response rationale for conceptual model development.

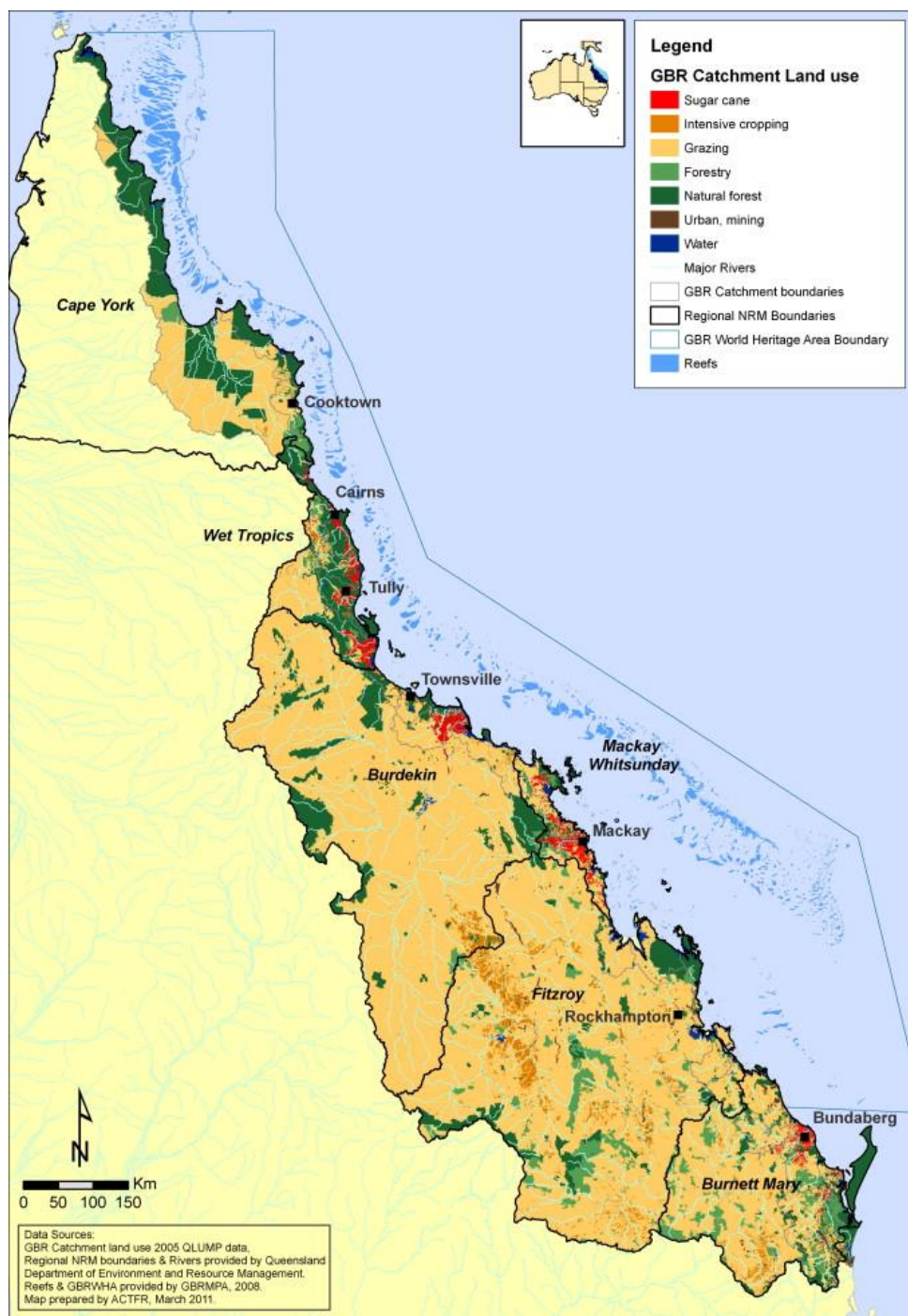


Fig. S2. The Great Barrier Reef catchment area, its primary land uses, and Regional Natural Resource Management regions.



Fig. S3. A waterhole in the upper Burdekin catchment pre- and post-cattle access (photo: Barry Butler).

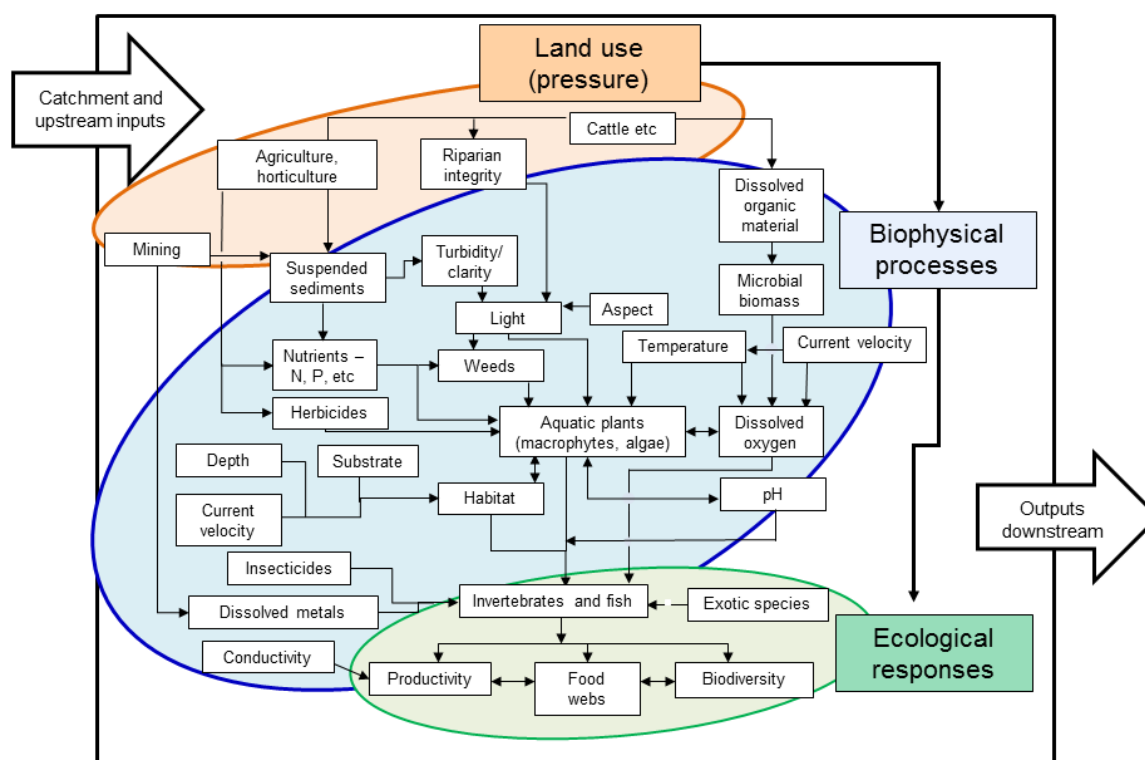


Fig. S4. Summary of typical processes affecting water quality and ecosystem health in a Great Barrier Reef catchment area (GBRCA) stream reach or waterhole. Not all factors or interactions can be shown; for example, riparian integrity has several influences on ecological responses that are not indicated here, and we omit influences of urban development. The large box represents a stream reach or discrete waterhole. Large arrows represent flow-related connectivity (which may be intermittent). Ovals represent pressures, biophysical processes (including stressors) and ecological responses to the interacting variables. Linkages between the aquatic environment and terrestrial landscape is implicit in some of the smaller boxes. Modified from R. G. Pearson, in Brodie *et al.* (2008)

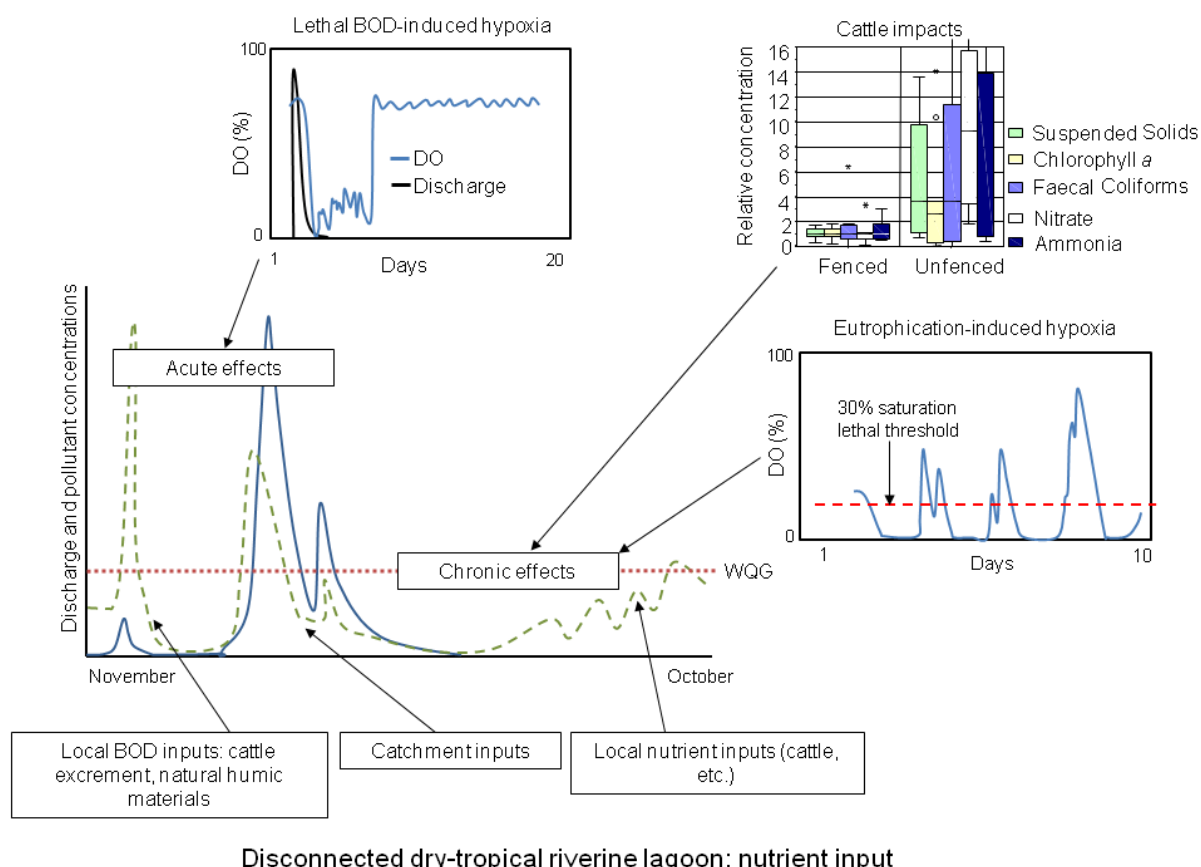
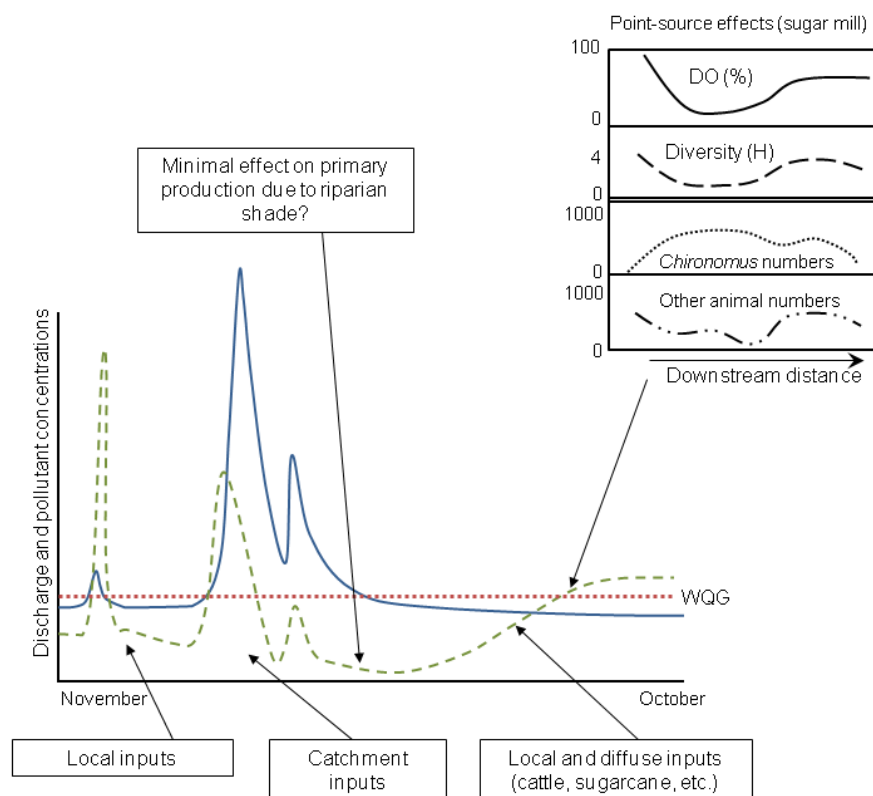


Fig. S5. Conceptual models summarising the dynamics of nutrient-delivery dynamics and ecological impacts across disconnected dry-tropical riverine lagoons in the Great Barrier Reef catchment area (GBRCA). Summary thumbnail water-quality relationships are derived from locally relevant studies (Butler 2008). WQG signifies parameter-relevant water-quality guideline.



Wet Tropics perennial stream: nutrient and organic inputs

Fig. S6. Conceptual models summarising the dynamics of nutrient-delivery dynamics and ecological impacts across perennial wet-tropical streams in the GBRCA Great Barrier Reef catchment area (GBRCA). Summary thumbnail water-quality relationships are derived from locally relevant studies (Pearson and Penridge 1987; Pearson *et al.* 2003). WQG signifies parameter-relevant water-quality guideline.

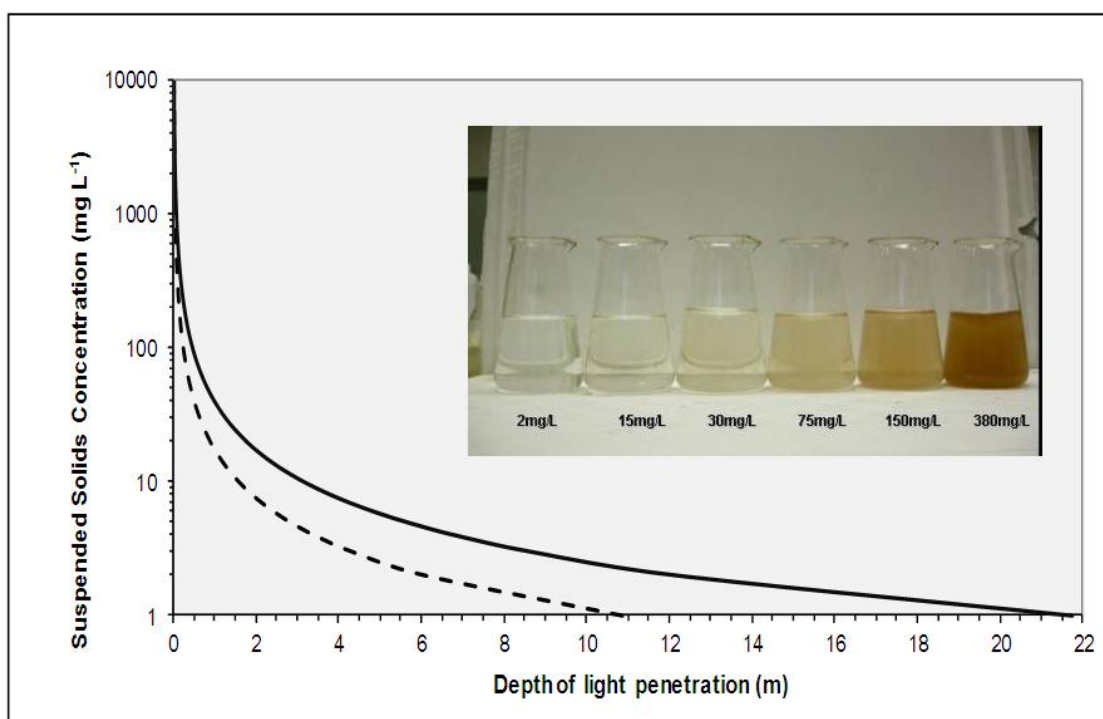
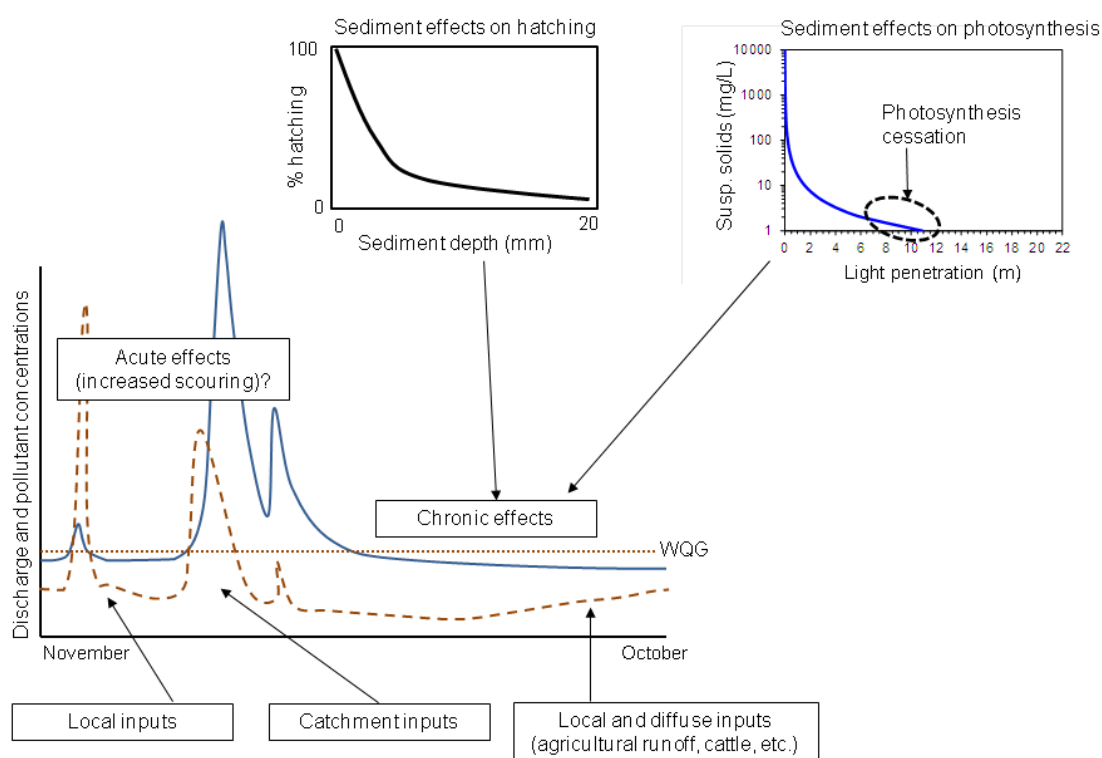


Fig. S7. Relationship among suspended-solid concentration, light penetration and aquatic plant growth in Great Barrier Reef catchment area (GBRCA) systems. The top (solid) curve marks the point at which photosynthesis will be measurably inhibited in the middle of the day. The bottom (dashed) curve is the point where net photosynthetic production will cease (on the basis of the compensation point of the most dark-adapted local species tested). The photograph illustrates turbidity under different concentrations of suspended solids. Adapted from Pearson *et al.* (2003).



Wet Tropics Perennial stream: sediment input

Fig. S8. Conceptual models summarising the dynamics of sediment delivery and ecological impacts across wet-tropical streams in the Great Barrier Reef catchment area (GBRCA). Summary thumbnail water-quality relationships are derived from locally relevant studies (Pearson *et al.* 2003; Connolly and Pearson 2007; Butler 2008; Kefford *et al.* 2010). WQG signifies parameter-relevant water-quality guideline.

Table S2. Adverse effects of eutrophication on freshwater plants and animals

Parameter	Physical habitat responses	Biological (ecosystem) responses	Sources
Acute effects	Increased nitrogen (N) and phosphorus (P) loading	Direct toxicity of unionized ammonia, nitrite and nitrate on aquatic animals (i.e. the conversion of oxygen-carrying pigments (haemoglobin, haemocyanin) to forms that are incapable of carrying oxygen)	Russo (1985); Camargo and Alonso (2006); Økelsrud and Pearson (2007)
	Pulses of organic matter entering waterbodies	Dissolved oxygen depletion (i.e. hypoxia), induced by biological oxygen demand	Bohl <i>et al.</i> (2002); Pearson <i>et al.</i> (2003); Rayment (2003)
Chronic effects	Increased N and P loading	High nitrate concentrations leading to the dominance of more competitive free-floating plant species and low species richness. Successional shifts in dominance from submerged macrophytes and periphyton towards complete dominance by phytoplankton	Barker <i>et al.</i> (2008); Feuchtmayr <i>et al.</i> (2009) Sand-Jensen and Borum (1991)
	Increased turbidity and light attenuation (phytoplankton blooms)	Denser stands of emergent and floating-leaved plants causing decline of submerged plants through light and space competition Light attenuation by epiphytes following nutrient enrichment Indirect negative impacts of eutrophication on macrophytes due to phytoplankton-induced turbidity	Moss <i>et al.</i> (2013) Smolders <i>et al.</i> (2002) Scheffer and van Nes (2007).
	Increased autotroph productivity through N and P enrichment	High ecosystem respiration rates, resulting in cyclical hypoxia, or poorly mixed water	Pearson <i>et al.</i> (2003); Perna and Burrows (2005); Perna <i>et al.</i> (2012)
		Consumer trait variation in response to ecosystem productivity gradients Shifts in community assemblage structure (decline in the percentage of piscivores, more omnivores and planktivores) Decline in average size of consumers (enhanced competition for food, reduced predation) The anoxic conditions under water hyacinth mats also favour the release of N and P from sediments which may further aid the rapid growth of water hyacinth. The decline in dissolved oxygen concentrations can also promote the formation of reduced compounds, such as hydrogen sulfide (H ₂ S), resulting in further adverse effects on aquatic animals (Camargo and Alonso 2006).	Tuckett <i>et al.</i> (2013) Moss <i>et al.</i> (2013)
	Enrichment of sediment with semi-labile, particulate organic matter (dead phytoplankton, terrestrially derived organic matter)	Increased biomass, and changes in productivity and species composition, of zooplankton, being usually favoured invertebrate grazers (e.g. <i>Daphnia</i>) at the expense of other trophic groups Biological oxygen demand induced dissolved-oxygen depletion (i.e. hypoxia), reduced root growth and anchorage of submerged plants and increases in root anoxia	Camargo and Alonso (2006) Sand-Jensen and Møller (2014)

Parameter	Physical habitat responses	Biological (ecosystem) responses	Sources
	Increased acidification (decrease in pH)	Increased mobilisation of metals	Smith <i>et al.</i> (1999); Camargo and Alonso (2006)

Table S3. Adverse effects of increased sedimentation on freshwater plants and animals

Parameter	Physical habitat responses	Biological (ecosystem) responses	Sources
Acute effects	Increased erosivity potential during spates	Increased riverbank erosion and slumping, channel-widening and sedimentation	
Suspended sediments	Increased turbidity	Damage to aquatic plants due to increased abrasion	Lewis (1973)
		Reductions in light penetration and temperature, with associated declines in photosynthesis and productivity	Van Nieuwenhuyse and LaPerriere (1986)
		Negative impacts on respiration through clogging of delicate structures such as gills and respiration effects	Lemly (1982); Bruton (1985); Bond and Downes (2003)
		Impacts on fish recruitment with eggs, larvae and juvenile stages more susceptible to suspended solids than adult fish	Chapman (1988), Moring (1982)
		Decreased water temperatures due to decreased light affecting temperature-sensitive species (altered breeding cues or direct physiological effects)	
		Temperature-induced water-column stratification	
		Net decrease in photochemical processes including the breakdown of contaminants by photolysis	
Deposited sediments	Increased sediment deposition	Limited disease resistance in poikilotherms	Pusey and Arthington (2003)
		Decreased temperature affecting growth rates and physiology of poikilotherms	Pusey and Arthington (2003)
		Increased invertebrate drift, loss of species	Connolly and Pearson (2007)
		Changes to substratum conditions and reductions in habitat space and food availability, resulting in altered community composition, reduced species richness	Matthaei <i>et al.</i> (2006)
		Altered community composition, including taxonomic shifts from insect orders Ephemeroptera, Plecoptera, and Trichoptera to Oligochaetes and burrowing non-tanypod chironomids	Wood and Armitage (1997); Larsen <i>et al.</i> (2009); Matthaei <i>et al.</i> (2006)
		Increased invertebrate drift from unfavourable habitat	
		Reductions in food availability and feeding efficiency	Broekhuizen <i>et al.</i> (2001)
		Preventing substrate attachment of algal cells	Brookes (1986).
		Loss of scrapers feed on attached algae (inhibited by surface sediment)	Brookes (1986).

Parameter	Physical habitat responses	Biological (ecosystem) responses	Sources
		Smothering and eliminating periphyton and aquatic macrophytes in extreme instances Reducing substrate porosity and hydrostatic permeability, leading to a decline in the volume of substratum water and reduced concentrations of dissolved oxygen	Wood and Armitage (1997)
		Burial under fine sediment increased leaf decay rates by stabilising the microenvironment for microbial processing	Shure <i>et al.</i> (1986)
		Reduction in suitability of fish spawning habitat Loss of invertebrate species	Connolly and Pearson (2007)

Table S4. Adverse effects of pesticide impact on freshwater plants and animals

Exposure period	Biological (ecosystem) responses	Sources
Acute effects	Death of non-resistant species and succession with resistant species of phytoplankton occurs	Graymore <i>et al.</i> (2001)
Sublethal effects	Marked decrease in the photosynthetic efficiency of autotrophs, reductions in individual cell size	Ricart <i>et al.</i> (2009); Graymore <i>et al.</i> (2001)
	Increased chlorophyll- <i>a</i> pigments and carbon incorporation in diatoms, the ‘dynamic balance theory’, also known as the ‘greening effect’	Ricart <i>et al.</i> (2009)
	Autotrophic community structural shifts due to toxicant-induced selection pressure on phototrophic communities (i.e. reductions in green algal biomass, increases in tolerant cyanobacteria)	Ricart <i>et al.</i> (2009); Pannard <i>et al.</i> (2009); Graymore <i>et al.</i> (2001).
	Toxicant-induced succession (TIS) selecting for progressive replacement of sensitive species with resistant ones. Indirect effects of pesticides on leaf breakdown mediated through a negative effect on sensitive detritivorous invertebrates	Blanck (2002); Pesce <i>et al.</i> (2012) Schäfer <i>et al.</i> (2007).
	Indirect cascade effects on community and trophic structure in zooplankton communities attributed to changes in the food source rather than direct physiological effects	Graymore <i>et al.</i> (2001)
	Reduced genetic variability within the adapted populations, possibly reducing adaptive capacity to other stressors	
	Decreased in dissolved oxygen due to depressed photosynthetic activity	Graymore <i>et al.</i> (2001)
	Anticholinergic effects and oxidative stress in fish	Kroon <i>et al.</i> (2015)
	Increased energy allocations and metabolic costs associated with detoxification mechanisms	
	Loss of macrophyte spawning areas and refuges as well as loss of periphyton food resources.	
	Behavioural alterations (elevated locomotory activity, reduced antipredator behaviours, reduced olfactory abilities)	Rohr and McCoy (2009)
	Alteration of gonadal morphology and function	Rohr and McCoy (2009)
	Increases in larval abnormalities, reductions in larval survival	Graymore <i>et al.</i> (2001); Rohr and McCoy (2009)
	Reductions in immune function, increases in infection end points	Rohr and McCoy (2009)

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