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Voyages of seaweeds: The role of macroalgae in sediment transport

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ABSTRACT

At least 26 genera of macroalgae have been observed attached to and carrying sedimentary materials (rock, veneer, or carbonate) to beaches and the sea floor. Most studies have been descriptive, with few quantifying flux rates. This study reviews and quantifies the mainly-biological literature on macroalgae-mediated sediment transport in coastal and marine environments. Dislodgement of macroalgae from a hard substrate can result in erosion up to 0.01 mm y^{-1}. The proportion of buoyant macroalgae carrying rock material (usually a thin veneer, but sometimes boulders up to 365 kg) varies by location, but can reach as high as 35%. Macroalgae carrying attached carbonate material (e.g., crustose coralline algae, shells) are more common: up to 85% of holdfasts on a beach may contain up to 116 g $CaCO_3$ each. Sand and carbonate trapped in haptera, along with encrusting carbonate-producing organisms, have a mass of up to tens of grammes. While most dislodged macroalgae land close to where they came from, others may be stranded many thousands of km from their place of origin. Sediment deposited by macroalgal transport depends largely on the characteristics of local source rocks. While hard rocks may only provide a few g m^{-2} y^{-1}, highly fractured basalt has been shown to provide up to 78 g m^{-2} y^{-1}. Rock transport by macroalgae is less than carbonate flux, which may reach over 8000 g m^{-2} y^{-1}. Based on the projected abundance of macroalgal rafts, some 350 tonnes of sediment (both carbonate and clastic) may be afloat in the Southern Ocean at any one time. Macroalgal transport may explain the presence of exotic rocks and shells found far from their source environment. While cold-climate rafting of sediment is dominated by glacial processes, in warm periods rafting may be limited to biological transport. Overall the transport of rock and carbonate by macroalgae has the potential in some environments of being a significant source of sediment.

1. Introduction

When biologists find an organism (living or dead) which has inadvertently carried inorganic material with it, they tend to regard it as a curiosity. Geologists may notice biological transport pathways but ordinarily do not consider them significant. Beach sediment budgets, for example, seldom explicitly include biological onshore transport of sand (e.g., Goodwin et al., 2006). Sedimentologists may be unaware of much of the biological literature; ecologists are often unclear on the needs and interests of those studying sediment dynamics.

Biologically-mediated transport is, nevertheless, very common. Thiel and Gutow (2005) described 1205 species that have been found rafting in the oceans, often attached to macroalgae, plastics, or wood. Such agents of transport range from algae and plants through invertebrates to vertebrates, and transported clasts range in size from mud and sand grains to pebbles and even boulders (Garden and Smith, 2011). Macroalgae are the most common rafting substrate in the mid-latitudes (Thiel and Gutow, 2004), carrying both clastic (rock) and carbonate (calcareous parts of animals and plants) materials sometimes for long distances (Garden et al., 2011), and yet few studies have quantified this transport mechanism, possibly because it is difficult and perceived as insignificant.

Macroalgae (large seaweeds) are largely confined to temperate coastlines of the world's oceans, between approximately 20° and 70° north and south (Woodborne et al., 1989). They grow from intertidal areas down to depths of 30 m or perhaps even deeper (e.g., North, 1971) and occupy habitats ranging from sheltered inlets to exposed coasts with severe wave impact. Although most species occur attached to rocky substrates, some species are free-living and may occur several hundred kilometres from land (e.g., Carpenter and Cox, 1974). Most rafting seaweeds are kelps and wracks of the Phaeophyceae (brown algae); some red and green algae may also transport material (Thiel and Gutow, 2004).

While there is little overall understanding of sediment transport rates by macroalgae, many studies worldwide have reported transport of rock material or shells by macroalgae over various distances (Table 1). At least 26 genera of macroalgae have been found carrying sedimentary material on beaches, floating at sea, and sunken on the sea floor. Older papers (e.g., Grieve, 1882) were usually reporting observations of a curiosity, whereas later studies tended to describe

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Table 1
Observations of sediment transport by dislodged macroalgae from the literature, organised in chronological order.

Taxa	Environment	Location	Amount/details	Distance	Reference
Fucus nodosus, *F. serratus*, *F. vesiculosus*	Shallow offshore	Colonsay–Oronsay, Scotland	Few ounces to half a hundredweight (c. 100 g to 25 kg)	Unknown	Grieve (1882)
Fucus serratus	Offshore	3 miles south of Falmouth Harbour, England	Large stone weighing 3/4 of a pound suspended from holdfast	Unknown	Vallentin (1895)
Chorda filum, *Fucus* spp.	Offshore	1 mile off Falmouth, England	Various bivalve molluscs, stones	Up to 4 miles	Vallentin (1895)
Macrocystis pyrifera	Beach	Port Phillip Bay, Victoria, Australia	4 1/4 inch pebble	Unknown	Dunn (1911)
Carpophyllum sp.	Beach	Mercury Bay, New Zealand	4 inch pebble	Unknown	Dunn (1911)
Unknown	Seafloor	Unknown	2 cm pebbles and shells	Several kilometres	Emery (1963)
Laminaria, *Fucus*, *Desmarestia*, *Ascophyllum*, *Rhodymenia*	Beach	Massachusetts	Pebbles and shells	Up to 250 km	Collins (1914)
Fucus, *Dictyota*, *Neurocarpus*, *Eisenia*, *Lessoniopsis*, *Pterygophora*	Beach	Unknown	Pebbles	Short distance	Emery and Tschudy (1941)
Sargassum vulgare or *S. bacciferum*	Offshore	Unknown	Stone	Unknown	Grieve (1929)
Chorda filum	Unknown	Unknown	Pebble	Unknown	Grieve (1929)
Egregia	Sea floor (215 m depth)	Palos Verdes, California	Two rocks with holdfast remains	c. 5 miles	Emery and Tschudy (1941)
Macrocystis, *Pelagophycus*	Beach	La Jolla, California	24 of 93 (26%) holdfasts had pebbles attached	1 mile from offshore bed	Emery and Tschudy (1941)
Egregia, *Dictyota*, *Neurocarpus*	Beach	South of La Jolla, California	Many with cobbles attached	Unknown	Emery and Tschudy (1941)
Egregia	Beach	La Jolla	72 of 207 (35%) holdfasts had pebbles attached	Unknown	Emery and Tschudy (1941)
Pterygophora	Beach	Point Conception, California	100 holdfasts with rock, up to 15 in and 13 lb, one had 25,000 pebbles	Unknown	Emery and Tschudy (1941)
Unknown	Beach	Unknown	Shells, pebbles	Unknown	Emery and Tschudy (1941)
Nereocystis	Offshore	Gulf of Alaska	8 cm pebble	500 km offshore	Menard (1953)
Unknown	Offshore	Near Northern Holiday Seamount, Pacific Ocean	8 × 5 × 4 cm rock	300 miles offshore	Shumway (1953)
Durvillaea antarctica	Beach	Little Papanui, Otago Peninsula, New Zealand	Some holdfasts washed ashore studded with barnacles	Unknown	Batham (1958)
Macrocystis pyrifera	Unknown	Unknown	Sand	Unknown	Thompson (1959)
Codium fragile spp. *tomentosoides*	Offshore	Falmouth	'Lifts oysters off the bottom and carries them off with the tide'	Unknown	Galstoff (1962)
Macrocystis pyrifera	Beach	California	Up to 10 kg, 40 cm rock, 10,000 pebbles in one holdfast	Unknown	Emery (1963)
Ulva, *Lessoniopsis*, *Laminaria*	Beach	Unknown	Pebbles, shells	Unknown	Emery (1963)
Fucus ceranoides, *Ascophyllum nodosum*	Beach	Northwest Scotland	Stones	Unknown	Darling and Boyd (1964)
Unknown	Unknown	Unknown	'Slivers of rock'	Unknown	Smith and Bayliss-Smith (1998)
Colpomenia perigrina	Offshore	Mediterranean Sea	Thallus can act as a balloon and carry oysters	Unknown	Blackler (1967)
Durvillaea antarctica	Beach	Macquarie Island	Large pieces of granite attached to holdfasts	Unknown	Cumpston (1968)
Codium fragile (also *Fucus vesiculosus*, *Chondrus crispus*)	Beach	Nobska Beach, Woods Hole, Massachusetts	Stones 0.5–25 cm and up to 5 kg; mostly attached to *Codium*; also transports scallops, oysters and clams	Unknown	Ben-Avraham (1971)
Macrocystis pyrifera	Beach	San Diego, California	Large stones (up to 25 lb) and shells	Offshore to beach	Zobell (1971)
Ectocarpus fasciculatus or *Chorda filum*	Unknown	Sandend Bay, Moray Firth, Scotland	24–29 mm *Donax vittatus* shells dislodged	Unknown	Ansell et al. (1988)
Unknown	Beach	Selsey Peninsula, West Sussex, England	Stones	From offshore	Joliffe and Wallace (1973)
Fucus vesiculosus, *F. serratus*	Beach and nearshore	Western Baltic Sea	Pebbles	Unknown	Kudrass (1974)
Unknown	Beach	Weymouth, England	Typically 2.5 tons of shingle transported to Weymouth foreshore in one storm	From offshore	Joliffe (1983)
E.g. *Chorda filum*	Offshore	Unknown	Pebbles, sand, shell fragments	Unknown	Norton and Mathieson (1983)
Macrocystis pyrifera	Offshore	Unknown	Can lift huge boulders from the seafloor and suspend them in mid-water	Unknown	Norton and Mathieson (1983)
Fucus vesiculosus	Intertidal flat	Baffin Island, Canada	Up to c. 90 mm stones weighing up to 1268 g	Unknown	Gilbert (1984)
Sargassum spp.	Beach	Bermuda	Up to 8213 g m^2 y^{-1} carbonate (mainly bryozoans) delivered	Offshore to beach	Pestana (1985)
Hormosira banksii	Shallow sand flat to beach	Princess Royal Harbour, Albany, Western Australia	Infaunal bivalve shells occasionally dislodged and transported ashore	Up to 400 m	Black and Peterson (1987)
Sargassum muticum	Unknown	Southwest Netherlands	May carry off attached oysters	Unknown	Critchley et al. (1987)
Unknown	Seafloor	Northwest of Cape Columbine, South Africa	Rounded exotic pebbles up to 10 cm in diameter and shells	120 km, 350 m depth	Woodborne et al. (1989)
'At least 8 species of alga'	Beach	Dornoch, east Scotland; Wales	Large numbers of bivalve *Donax vittatus* dislodged due to drag and flotation by epiphytic algae	Unknown	Ansell et al. (1988)