Short communication

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The unusual occurrence of green algal balls of *Chaetomorpha linum* on a beach in Sydney, Australia

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Abstract: In spring 2014, thousands of green algal balls were washed up at Dee Why Beach, Sydney, New South Wales, Australia. Reports of algal balls are uncommon in marine systems, and mass strandings on beaches are even more rare, sparking both public and scientific interest. We identified the algal masses as *Chaetomorpha linum* by using light microscopy and DNA sequencing. We characterize the size and composition of the balls from Dee Why Beach and compare them to previous records of marine algal balls. We describe the environmental conditions that could explain their appearance, given the ecophysiology of *C. linum*.

Keywords: aegagropilious; algal balls; *Chaetomorpha linum*; Cladophoraceae.

Thousands of algal balls washed up on the popular swimming beach at Dee Why in Sydney, New South Wales, Australia (33.753609°S, 151.297114°E), on the morning of 16 September 2014 (Figure 1A). Mass strandings of large, near-spherical balls of algae on beaches are a rare occurrence that capture the attention of scientists and the public alike (see Newton 1950, Mathieson and Dawes 2002). Indeed, there do not appear to be any previous records of living algal balls in Sydney, explaining the global scientific and media interest (see Crew 2014, Nuwer 2014, Poore 2014). The majority of balls were washed back into the sea over the next few days, and the balls that persisted on the beach visibly deteriorated (Figure 1B). Small numbers of balls continued to wash up intermittently throughout September and October 2014 (Julia Cooke pers comm). There were no reports of algal balls washing up on any of the adjacent beaches.

Free-floating algae occur worldwide in both freshwater and marine systems and form habitats that support diverse life-forms (Norton and Mathieson 1983). They can act as ecosystem engineers by significantly changing the light and nutrient levels, and provide habitat for diverse communities of associated animals (Acton 1916, Ballantine et al. 1994, Thiel and Gutow 2005).

Ball formation occurs by the mechanical action of free-floating thalli being rolled against a substratum, either by gentle rocking on a lake bottom or more vigorous wave action in shallow marine environments (van den Hoek 1963). Harder substrates generate rounder balls (Mathieson and Dawes 2002). Algae that form free-floating balls are described by the term aegagropilious (Linnaeus 1753), which refers to their resemblance to bezoar, the masses found in gastrointestinal tracts of goats, *Capra aegagrus* (Erxleben). The most famous algal balls are the moss balls or marimo in Lake Akan in Japan, which are designated as a national treasure and celebrated in an annual festival (Kurogi 1980, Wakana et al. 2005). Marimo are formed by *Aegagropila linnaei* (Kützing), and are found in lakes throughout the northern hemisphere (Boedeker et al. 2010). They grow to 40 cm in diameter and are hollow (Kurogi 1980). Formation of aegagropilious algae is well documented in some freshwater/brackish lakes in the northern hemisphere (Boedeker et al. 2010), but marine records remain rare.

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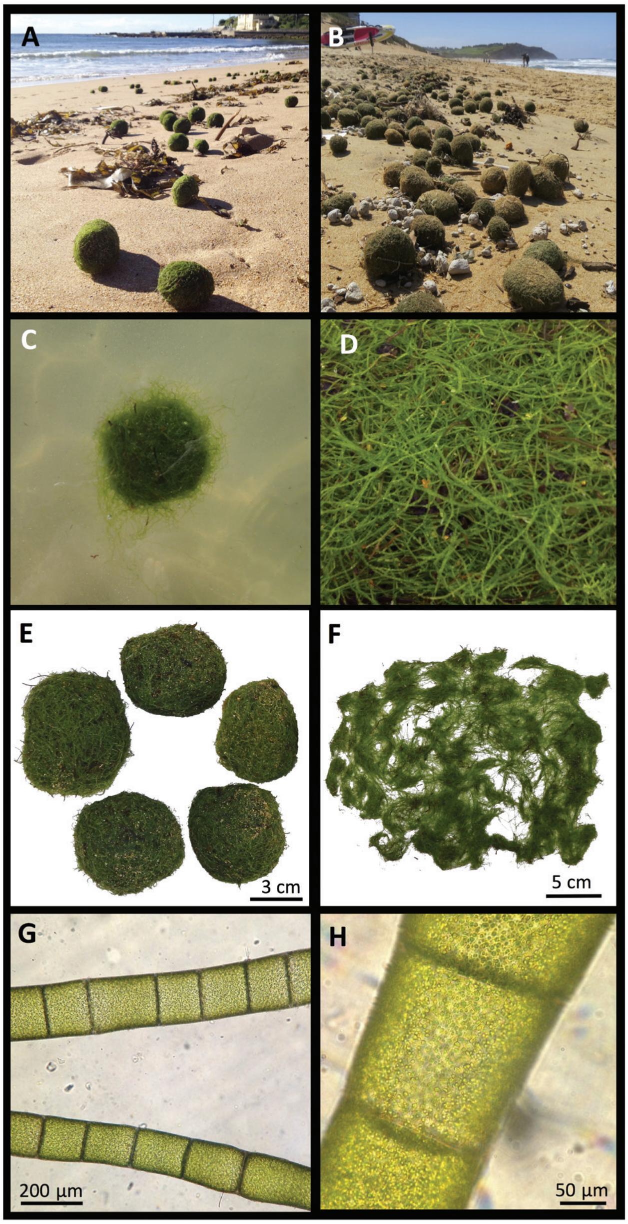

Figure 1: Images of algal balls *in situ* and close up. We collected two fresh balls that had washed up on 28 September (used for DNA sequencing and morphological examination), and an additional 15 newly arrived balls on 1 October. We photographed submerged balls *in situ*, up to 0.5 m below the surface of the water on 12 October 2014. (A) Algal Balls washed up on Dee Why Beach, Sydney; (B) balls beginning to dry out on 22 September; (C) a ball floating in the water column; (D) the algal balls were predominantly composed of filaments of *Chaetomorpha linum*, but also red algal fragments; (E) a range of algal ball shapes and sizes; (F) one algal ball pulled apart; (G) microscopic view of algae showing unbranched filaments of cylindrical cells; and (H) microscopic view of numerous chloroplasts. Several balls are preserved in the Downing Herbarium (Accession numbers MQU 74000170-MQU 74000174) and National Herbarium of New South Wales, Royal Botanic Gardens, Sydney (Accession numbers NSW982603, NSW982609, NSW982263).

Using morphological characteristics and published keys (May 1938, Millar and Kraft 1994, Womersley 1984), we identified the dominant green alga forming the balls from Dee Why as *Chaetomorpha linum* (O.F.Müller) Kützing (Cladophorales; Cladophoraceae). Each strand was one cell thick and approximately 200 µm in diameter and 0.75–1.5 times diameter long (Figure 1G). Cell lengths ranged from 150 to 300 µm (Figure 1G). The cells were cylindrical with many chloroplasts clearly visible (Figure 1H). Subsequent sequencing of the material confirmed the algal species as *C. linum* (Figure 2).

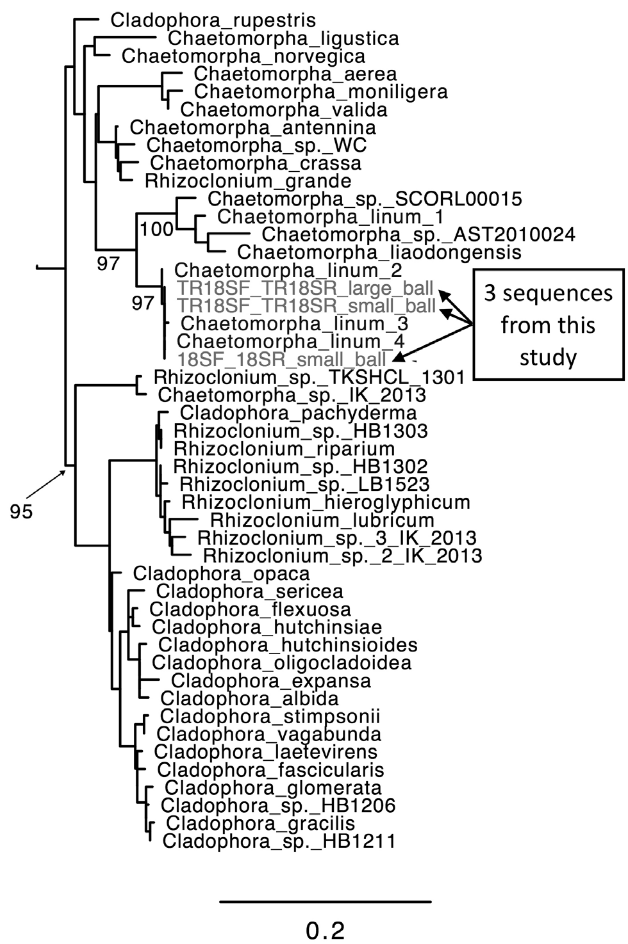

Figure 2: Phylogenetic tree of 18S sequences of Cladophorales obtained from GenBank (http://www.ncbi.nlm.nih.gov/genbank/), and 3 new sequences from two of the algal balls described in this article. Bootstrap support for key nodes is given below the branches, which show that the sequences of the algal balls from Dee Why unambiguously group with those from *Chaetomorpha linum* (97% bootstrap support). The new sequences have been lodged in Genbank (accession numbers: KT593551, KT593550, KT593552, top-bottom). In addition a full description of the sequencing, phylogenetic analysis, and a larger tree reconstruction is given in Gillings et al. (2014).

Table 1: Records of marine algal balls. The literature was searched using terms including: algal balls, aegagropilious, moss balls, lake balls, *Chaetomorpha* balls, and *Cladophora* balls.

Year	Month (Season)	Location	Dominant species	Size (diameter)	Site description	Reference
2014	October (Spring)	Dee Why, NSW, Australia (33.75360°S, 151.297114°E)	*Chaetomorpha linum,* Cladophorales	6.6±0.7 cm	Bay. On beach	This study
2012	Feb–July (Spring/Summer)	Charco de San Gines, Arrecife (Canary Islands). (28.961355°N, 13.546640°W)	*Valonia aegagropila,* Cladophorales	4–8 cm	Inlet. On seafloor	Gil-Rodríguez et al. 2012
2011	August (Summer)	Ria de A. Coruna, Galicia, Spain (43.34326°N, 8.365523°W)	*C. linum,* Cladophorales	2–5 cm	Inlet. On seafloor	Bárbara 2012
2002	July (Summer)	New Hampshire coast, USA (42.94702°N, 70.7865°W)	*Chaetomorpha picquotiana,* Cladophorales	5.9±0.3 cm	Bay. On beach	Mathieson and Dawes 2002
1994	Permanent	Isla Dos Mosquises Sur, Los Roques archipelago, Caribbean Sea (11.834428°N, 66.908219°W)	*Halimeda opuntia,* Bryopsidales; *Dictyota cervicornis,* Dictyotales; *Gelidiopsis variabilis,* Rhodymeniales	3–6 cm, 0.5–10.5 cm	Sheltered bay. On seafloor	Ballantine et al. 1994
1980	May (Autumn)	Gippsland Lakes, swamp in Coastal Park near Ocean Grange (37.98°S, 147.75°E)	*Wittrockiella salina,* Cladophorales	nd	Brackish lake. On lakebed	Herbarium Record, AD-A 53315
1979	August (Winter)	Peel-Harvey Inlet (32.525297°S, 115.710884°E)	*Cladophora montagneana,* Cladophorales	1–3 cm	Inlet. On seafloor	Herbarium record, PERTH 7063628, Gordon et al. 1985
1979	Year round, predominantly washed up in summer	Nahant near Boston, Massachusetts (approximately 42.454573°N, 70.929122°W)	*Pilayella littoralis,* Ectocarpales	2.8 cm	Bay. On seafloor and beach	Wilce et al. 1982
1976	May (but records suggest permanent)	'Moss Ball Pool' Mullachie Swamp, Lakes Entrance, Victoria (37.880612°S, 147.762973°E)	*W. salina,* Cladophorales	nd	Brackish lake. On lakebed	Herbarium Record, MELU, 22328
Approx 1971		La Parguera, Puerto Rico (17.971472°N, 67.038425°W)	*Caulerpa racemosa*, Caulerpales; *Bryothamnion seaforthii*, Ceramiales	nd	In water – mangrove and coral canals	Almodovar and Rehm 1971
1964	May (but records suggest permanent)	'Moss Ball Pool' Mullachie Swamp, Lakes Entrance, Victoria (37.880612°S, 147.762973°E)	*W. salina,* Cladophorales	nd	Brackish Lake. On lakebed	Herbarium record ADU A52350
1950	Jan (Summer)	Bay of Shoals, Kangaroo Island, South Australia (35.615405°S, 137.617785°E)	*Cladophora aegagropiloidea,* Cladophorales	nd		Herbarium record AD-A 12607
1949	October (Autumn)	Torbay, England (approximately 50.441470°N, 3.555517°W)	*Cladophora repens,* Cladophorales	2.5 cm (average, but up to 5 cm across)	On beach	Newton 1950
1931	April (Autumn)	Kingston, Tasmania (42.980080°S, 147.326495°E)	*Halopteris funicularis,* Sphacelariales	2.5–5.5 cm	On beach. Balls formed of both plant and inorganic matter	Dickinson 1933

Typically, species of green algae from the Cladophorales, including *Chaetomorpha* spp., occur as felt-like mats where the water is a few metres deep (van den Hoek 1963). *Chaetomorpha linum* is a globally distributed alga, most commonly found as long, attached filaments, but at times forming detached mats in the water column (Guiry 2014). It proliferates in response to increased nitrogen and phosphorus concentrations in the water, reducing the amount of nutrients available to other benthic life (Menéndez et al. 2002, Krause-Jensen et al. 1996). This species is tolerant of high light levels, including UVB, through increased resistance to oxidative stress (Bischof et al. 2006). In Australia, *C. linum* has been best studied at Peel Inlet, Western Australia, where algal growth has become a problem following eutrophication of the inlet. In that estuary, the high abundance of *C. linum* was attributed to its capacity to overwinter, thereby storing nitrogen and allowing higher growth in summer and faster uptake of nutrients in comparison to co-occurring dominant algal species (Lavery and McComb 1991).

The balls from Dee Why were on average (±SE) 6.56±0.74 cm in diameter (n=7, Figure 1E) and ranged from roughly spherical to a prolate spheroid. The fresh balls, after draining, weighed 36.38±19.32 g (n=4) and when air-dried, 6.06±4.38 g (n=4). Dissection of the balls revealed a solid, dense mass of entwined filaments, almost entirely of *C. linum* (Figure 1D,F), but also containing fragments of degraded, incomplete and usually bleached plant material (0.3–7.0 cm in length, maximum 2 mm wide). The fragments included *Sphacelaria cirrosa* (Roth) C.Agardh, *Acrosorium ciliolatum* (Harvey) Kylin, *Laurencia clavata* Sonder, *Pterosiphonia* sp., *Heterosiphonia* sp., *Polysiphonia* sp., and unidentified species of Rhodomelaceae, bryozoans and angiosperms (of marine or terrestrial origin). In some balls, the only non-organic matter was sand on the outside of the balls, presumably from the beach. In other balls, a layer of sand within the ball suggested they were washed up for the second time having accumulated a sand layer from an earlier beaching. Two balls were kept in an aquarium and numerous small invertebrates were seen emerging from and retreating into the balls (M. Gillings, pers comm).

Despite the limited number of records, it is possible to compare reports of this phenomenon. From a search of the literature and herbarium records, we found 14 records of marine aegagropilious algae (including the recent event at Dee Why, Table 1). Of these, only four were records of specimens washed up on beaches, with the remainder found in shallow waters of open lagoons, inlets or rarely offshore from beaches. Ten of these records involved green algae from the Cladophorales, with other records involving green algae from the Bryopsidales and Caulerpales, brown algae from the Dictyotales, Ectocarpales and Sphacelariales, and red algae from the Ceramiales and Rhodymeniales (Table 1). The balls from Dee Why are most similar to the two most recent records listed in Table 1. In 2011, balls were found in Galicia, Spain that were also predominantly composed of *C. linum* (Bárbara 2012). This species was also found in 79% of the 100,000s of balls dominated by *C. picquotiana* that washed up on the New Hampshire Coast, USA in 2002 (Mathieson and Dawes 2002).

Due to their novelty, occurrences of algal balls are reported in the literature, but data describing the conditions that could contribute to their formation and beaching are generally missing and poorly understood. Widespread, large mats of *Chaetomorpha piquotiana* (Montagne) were reported prior to balls of this species washing up on beaches in NH, USA (Mathieson and Dawes 2002). These authors suggested that increased temperature rather than nutrients was responsible for build-up of the algae due to the preceding atypically warm weather. We have no evidence of enhanced temperatures prior to the appearance of the algal balls at Dee Why, with maximum daily temperatures of predominantly 16–19°C being the same or lower as long-term averages for these months of 18–22°C (Australian Bureau of Meteorology 2015a). Across all known records, the majority (10 of 13) were collected in warmer months of the year.

At Dee Why Beach, while temperatures prior to the mass stranding of algal balls were not unusual, rainfall was unusually high with monthly falls of 215 mm and 100 mm in August and September 2014, respectively, compared to long-term means of 63 and 71 mm (Australian Bureau of Meteorology 2015b). High rainfall in Sydney causes increased nutrient levels in water bodies through suburban run-off and sewage outlet overflow (Thomas 1997). Problematic levels of *C. linum* have been previously recorded in Dee Why Lagoon (which lies

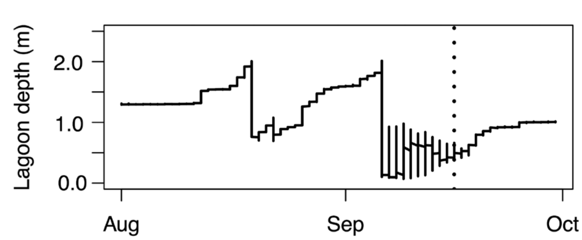

Figure 3: Water depth in Dee Why Lagoon for August and September 2014 with the arrival of the first algal balls on September 16 shown (dotted line). The lagoon depth data were supplied by NSW Public Works' Manly Hydraulics Laboratory.

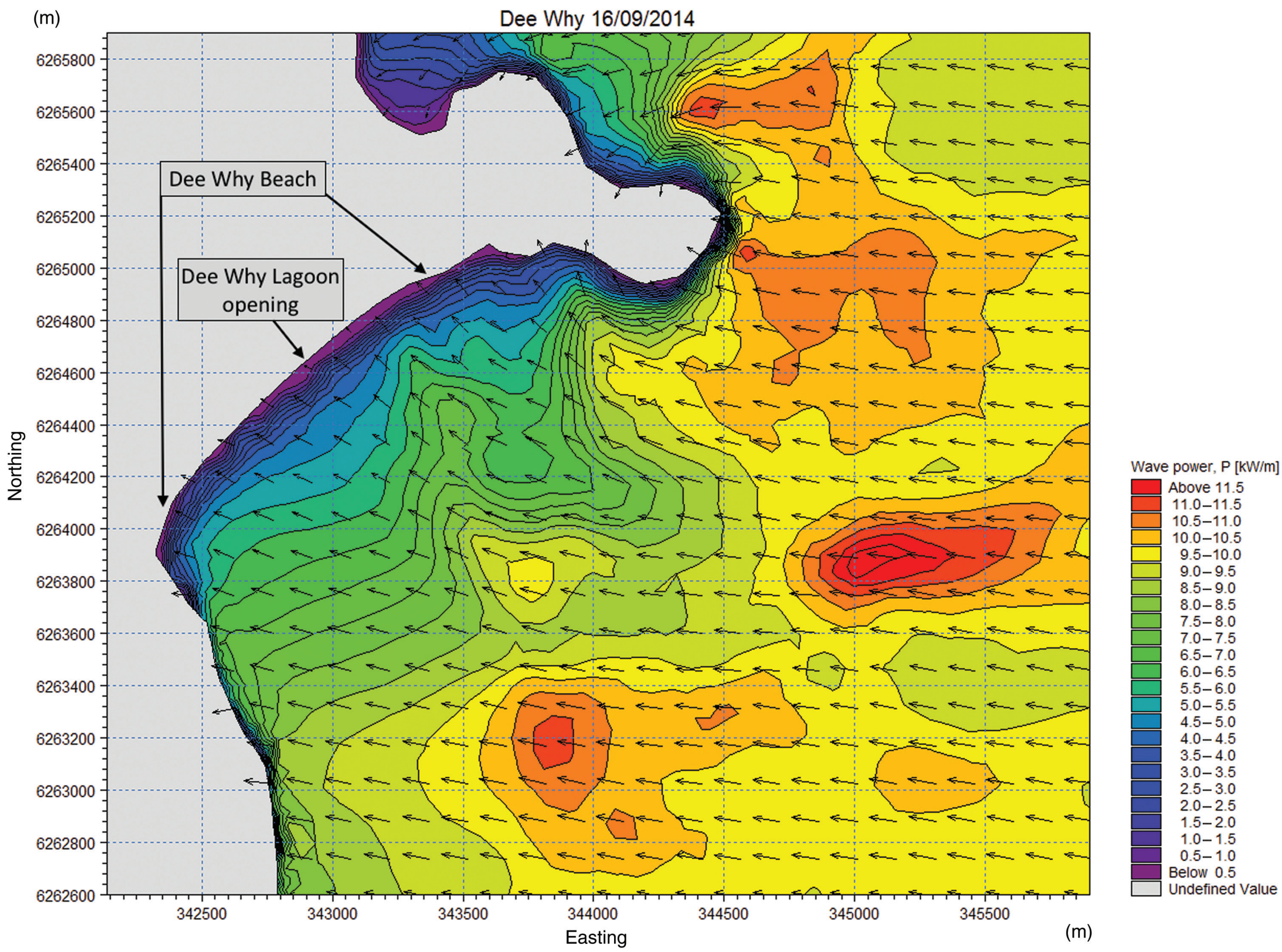

Figure 4: Directional wave power at Dee Why Beach on the day the balls appeared. The wave power and direction was modelled using WaveRider buoy data from the mid shelf off Long Reef (~80 m water depth, data supplied by NSW Public Works' Manly Hydraulics Laboratory) and modelled with the Danish Hydraulics Institute MIKE21 spectral wave model. The preceding ten days showed similar conditions, but with more south-easterly direction. The wave directional shift from persistent SE conditions to E is consistent with the transport of the algal mats and balls southwards from the lagoon entrance to eventual deposition on Dee Why Beach.

behind Dee Why Beach and opens intermittently) following nutrient enrichment (Chen 1981, Rutten et al. 2006). We postulate that an increase in nutrients from the high rainfall could have led to the proliferation of *C. linum*, either in the lagoon, or in surrounding subtidal environments following nutrient release with lagoon opening.

Water level records show Dee Why Lagoon opened to the sea on 20 August 2014, and again on 6 September after which water levels fluctuated (Figure 3), suggesting that tidal activity caused significant regular water flows into and out of the now shallower lagoon entrance and delta until the date the balls first arrived on the beach. In 2014, wave climate along the south-east coast of Australia was dominated by persistent south to southeasterly swell which produced high incident wave power along Dee Why Beach. The fate of algal mats discharged to the surf zone from the Dee Why Lagoon would have been transport by orbital wave energy in the inner and outer surf zone at Dee Why Beach (Figure 4). This orbital motion from swell waves is a plausible mechanism to fragment algal mats and agitate the fragments to form the observed algal balls.

To the best of our knowledge, green algal balls, or indeed any aegagropilious algae, have not been recorded on Sydney beaches. We suggest the phenomenon was due to atypically high rainfall causing higher nutrient levels that resulted in a proliferation of *C. linum*. South-easterly swells seem likely to have contributed to the formation of the balls and ultimately to have washed them up onto Dee Why Beach.

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Bionotes

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