Aquatic Botany, 47 (1994) 53–60
0304-3770/94/$07.00

Colonization by the alien marine alga *Hypnea musciformis* (Wulfen) J. Ag. (Rhodophyta: Gigartinales) in the Hawaiian Islands and its utilization by the green turtle, *Chelonia mydas* L.

Dennis J. Russell*[,a], George H. Balazs[b]

[a]*Biology Department, Everett Community College, Everett, WA 98201, USA*
[b]*Honolulu Laboratory, Southwest Fisheries Science Center, National Marine Fisheries Service, NOAA, Honolulu, HI 96822-2396, USA*

(Accepted 31 August 1993)

Abstract

In Hawaii, the alien red alga, *Hypnea musciformis* (Wulfen) J. Ag., was originally planted on reefs in Kaneohe Bay, Oahu, in January 1974, but has since spread to many other locations on Oahu and to other Hawaiian islands. This alga, along with the previously introduced alien seaweed, *Acanthophora spicifera* (Vahl) Boerg., is now being prominently used as a food source by the green turtle (*Chelonia mydas* L.) in the Hawaiian Islands. This is the first known documentation of introduced algae being incorporated into the diet of the green turtle, a species considered endangered world-wide.

Introduction

Over the past 42 years, 18 species of marine macro-algae have been introduced to the island of Oahu in Hawaii (Russell, 1992). Two have been highly successful, fast-spreading species; *Acanthophora spicifera* (Vahl) Boerg., which probably came from Guam in the 1950s (Doty, 1961), and *Hypnea musciformis* (Wulfen) J. Ag., introduced to Hawaii from Florida in January 1974 (Abbott, 1987). Seven of the remaining species failed to become established, while nine others are marginally successful. The case of *H. musciformis* is unique among alien marine algae since we know the time, source, and location of the introduction (Kaneohe Bay, Oahu), thus eliminating lengthy debate as to its alien status, place of origin, and so on.

During the early 1970s, several seaweed species from the South Pacific, Philippines and Florida were introduced to Oahu for commercial and exper-

*Corresponding author.

imental purposes (Doty, 1988; Glenn and Doty, 1990). *Hypnea musciformis* came with a shipment of two morphs of *Eucheuma isiforme* (C. Ag.) J. Ag. (Dawes, 1990) which were air freighted to Hawaii from southern Florida in January 1974. It was at that time *H. musciformis* and *E. isiforme* were planted on several reefs in Kaneohe Bay (Russell, 1992). These species are valued for their agar or carrageenan production and are farmed in other parts of the world (Guist et al., 1982; Abbott and Norris, 1985; Dawes, 1987; Abbott, 1988). *Hypnea musciformis* was a particularly good candidate for farming in Hawaii because of its production of kappa carrageenan, its rapid growth rate, its ability to colonize new areas easily and its tolerance to a variety of growing conditions (Friedlander and Lipkin, 1982; Friedlander and Zelikovitch, 1984). After *H. musciformis* became abundant in Kaneohe Bay, it began growing among *Eucheuma* thalli and contaminated shipments of *Eucheuma* exported alive to other countries in the Pacific (Doty, 1977; Russell, 1982, 1983). As a result, this alga has spread rapidly from its place of introduction to other locations in Hawaii and the tropical Pacific.

In 1973, a broad-based study of the green turtle (*Chelonia mydas* L.), a herbivorous species considered endangered world-wide, was initiated in the Hawaiian Islands (Balazs, 1980). This program included the salvaging and necropsy of dead, stranded turtles to identify their food sources. During this study, samples taken from sea turtles in Kaneohe Bay on 28 October 1977 contained *H. musciformis*, just 3 years after the alga had been introduced. This paper describes the spread of *H. musciformis* in Hawaii and its utilization by sea turtles, based on sea turtle stomach samples, herbarium specimens, personal observations, and other data.

Methods

Most of the seaweed samples were taken from the stomachs of turtles that had died from human-related impacts, such as illegal hunting, boat collisions and gill-net entanglement. Others may have succumbed from being afflicted with fibropapillomatosis, a disease of turtles that occurs in Hawaii and elsewhere (Balazs and Pooley, 1991). Food items were preserved in 10% formalin and identified to the lowest taxon possible. Diet samples were also obtained from live turtles via insertion of a plastic tube through the esophagus. Seawater was then introduced at low pressure to gently flush out food particles. In addition, if unswallowed particles of food were present in the turtle's mouth they were removed for identification. Fecal pellets and scrapings of algae from turtle shells were sampled, and seaweed was gathered from the reefs where sea turtles were seen feeding (Balazs et al., 1987). Records of *H. musciformis* collections were also obtained from the Bishop Museum, University of Hawaii herbaria, and our own personal data.

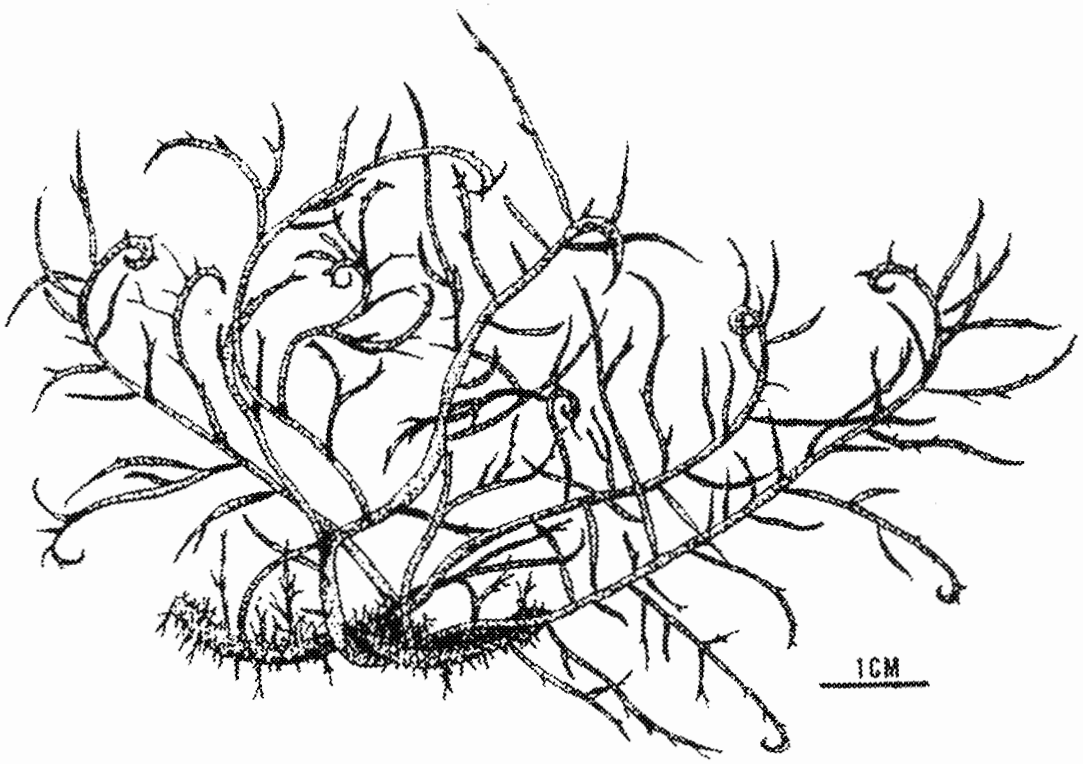

Fig. 1. Typical *H. musciformis* thallus with many distinct swollen hooks at the tips of the branches.

Description

Hypnea musciformis is a member of the phylum Rhodophyta, family Hypneaceae. It is native to the Atlantic Ocean, from Massachusetts south to tropical South American waters, from West Africa to the Bay of Biscaye and is also commonly found in the Indian Ocean, from East Africa to India. It is a fine, highly branched alga, usually red, but can be yellow in nutrient-poor or colder waters. It is now found on Hawaii's shallow reefs, usually as an epiphyte on other algae, especially *Sargassum echinocarpum* J. Ag., *Sargassum polyphyllum* J. Ag., and *A. spicifera*, or in windrows of algal drift along the beach. *Hypnea musciformis* is easily distinguished from other *Hypnea* species by the presence of often numerous swollen hooks that originate from the tips of its branches (Fig. 1). Positive identification of *H. musciformis* from turtle samples was made only when these distinct hooks were present.

Results and discussion

Introduction and spread of Hypnea musciformis *in Hawaii*

Three years after *H. musciformis* was planted on reefs in Kaneohe Bay in January 1974, it had become abundant. During that same year, it was found

in a green turtle sample, also taken from Kaneohe Bay, where it represented 80% of the wet mass of algae in that stomach sample, an indication that the seaweed was abundant, palatable, and presumably suitable for the green turtles' nutrition. Nearly 2 years later (September 1979), *H. musciformis* had spread to Bellows Beach Park and Kaaawa (Fig. 2). Its rate of spread along the shores of Oahu was about 3.8 km year^{-1}. The disjunct appearance of *H. musciformis* at Ewa Beach Park in November 1979 indicates a secondary point of inoculation (Fig. 2).

In 1984, *H. musciformis* appeared and spread explosively on the island of Maui, about 160 km to the east of Oahu (Fig. 2), where it was forming win-

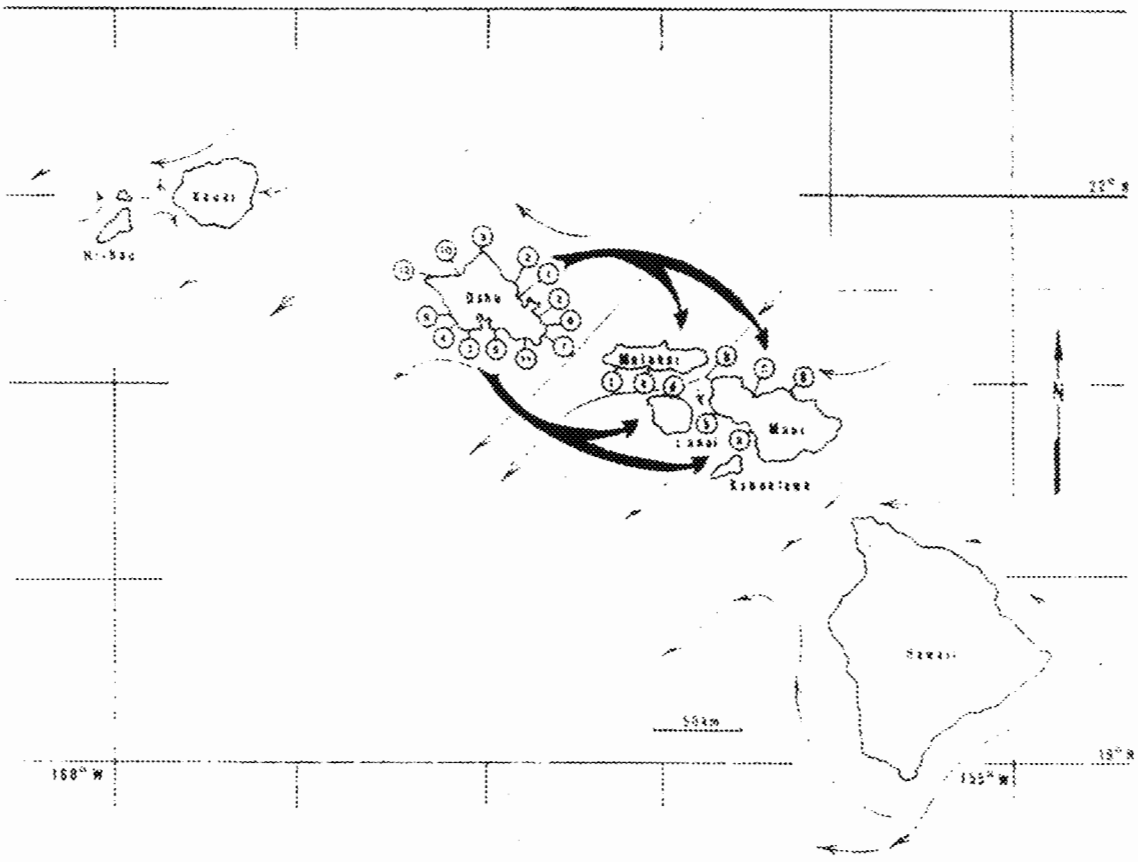

Fig. 2. Main islands of the Hawaiian Archipelago. Prevailing North Pacific Equatorial Current (thin arrows) as it flows westward through the Hawaiian Islands. The thicker arrows indicate the direction *H. musciformis* travelled. The numbers and letters mark where *H. musciformis* was first found at those locations: (1) Kaneohe Bay, March 1977; (2) Kaaawa and Bellows Beach, September 1979; (3) Ewa Beach Park, November 1979; (4) Nimitz Recreational Beach, September 1981; (5) Honolulu Airport Pond, March 1982; (6) Makapuu, March 1983; (7) Sandy Beach, April 1983; (8) Waianae Boat Harbor, April 1983; (9) Kawela Bay, March 1985; (10) Haleiwa Harbor, March 1986; (11) Maunalua Bay, June 1987; (12) Mokuleia, September 1987; (a) Kihei, July 1984; (b) Launiupoko Beach Park, December 1984; (c) Kahului Harbor, May 1985; (d) Kuahua, August 1985; (e) Molokai, November 1985; (f) Palaau, July 1988; (g) Baldwin State Park, December 1990; (h) Honokowai, September 1991.

drows of drift both on Launiupoko beach and in Kihei. By December 1990, it was well-established on Maui and is now commonly found at many other locations along the northern and southern shores of the island.

In 1985, *H. musciformis* appeared on the islands of Lanai and Molokai (Fig. 2). The Lanai sample was flushed from the stomach of a live, healthy turtle, while the Molokai sample was taken directly from the reef. *Hypnea musciformis* has not yet appeared in sea turtle samples or reef collections from the islands of Kauai or Hawaii.

The rapid dispersal of *H. musciformis* from its inoculation points to adjacent reefs on Oahu is probably a result of its high growth rate, abundant production of tetraspores and its ability to epiphytize other algae. The growth rate of *H. musciformis* in Kaneohe Bay was recorded in one experiment (inside a protective cage) to be 10–12% day^{-1} (based on wet weight; Russell, 1992). Thus, it was doubling its mass every 10 days. Its growth rate is probably higher in other some locations in Hawaii, based on growth rates reported elsewhere (American Virgin Islands, 50% day^{-1}, Humm and Kreutzer, 1975; Florida, 20% day^{-1}, Dawes, 1987).

Several problems occur when trying to measure the growth rate of *H. musciformis* in the field: fragmentation, recruitment, and predation. *Hypnea* thalli lose their branches easily, but at the same time drifting *Hypnea* pieces can enter the experimental thalli, attach firmly, and add weight. In addition, both crustaceans and fish graze on the thalli. *Hypnea musciformis* is quite palatable to fish and can grow at a faster rate than it is consumed, especially if it is growing among unpalatable seaweeds (Duffy and Hay, 1990). The same may hold true for *H. musciformis* grazed by the green turtle.

Hypnea's rapid growth rate is also important in offsetting losses owing to fragmentation. Its drifting fragments reattach to other algae, such as *Sargassum* spp., which become detached during storms and, because of their numerous pneumatocysts, can float long distances in the drift. We have observed *Sargassum* rafting *H. musciformis* from one location to another in Hawaii.

The prevailing surface currents in the Hawaiian Islands are complex, but usually the North Pacific Equatorial Current flows westward (Fig. 2). On occasion, the flow is reversed to a basically northeast direction by southerly wind-driven currents, but these are rare and of short duration (Haraguchi, 1979). Consequently, if *Hypnea* were spreading with the currents, we would expect *H. musciformis* to colonize Kauai before Molokai, Lanai or Maui, but the colonization occurred upstream and the first occurrences were either in or near harbors. Therefore, *Hypnea* probably colonized boats and was transported from island to island in much the same way *A. spicifera* was spread after its introduction to Hawaii (Russell, 1992). Lateral spread from the inoculation points then continued in nearshore currents by fragmentation and spore production.

Certain algae also colonize the carapaces of sea turtles and then could be

transported by turtles migrating between the Hawaiian Islands against the prevailing currents (Balazs, 1976). However, none of the 20 algal species we found on the skin and shells of sea turtles were alien algae.

It is unlikely that sea turtles are ejecting *H. musciformis* in buoyant fecal pellets which could float to new locations. Paya and Santelices (1989) cultured fecal droppings from fish species and found that a small number of algae survive digestion and could be transported by fish. However, our preliminary work involving the culturing of green turtle fecal pellets have found no algal growth.

Long-term tagging studies of immature and some adult turtles in foraging pastures suggest that very few turtles ever move between the main Hawaiian

Table 1
Occurrence of alien and native seaweeds in the combined data from Hawaiian green turtle mouth, stomach, feces samples and tabulated from only those 192 samples in which at least one alien algal species was present

Species	Average % wet sample	No. of samples sp. present	% samples sp. present
Alien species[1]			
Acanthophora spicifera (Vahl) Boerg.	34.3	151	78.7
Hypnea musciformis (Wulfen) J. Ag.	27.2	83	43.0
Gracilaria salicornia (C. Ag.) Dawson	20.0	4	2.1
Gracilaria tikvahiae McLachlan	50.0	2	1.0
Eucheuma denticulatum (Burm.) Col. & Herv.	< 1.0	1	< 1.0
Kappaphycus alvarezii (Doty) Doty	20.0	1	< 1.0
Kappaphycus striatum (Schmitz) Doty	15.0	1	< 1.0
Native species			
Codium edule Silva	8.3	51	26.6
Amansia glomerata C. Ag.	6.7	45	23.4
Codium arabicum Kützing	2.8	30	15.6
Laurencia nidifica J. Ag.	< 1.0	28	14.6
Halophila hawaiiensis Doty & Stone[2]	20.6	27	14.1
Hypnea cervicornis J. Ag.	1.2	26	13.5
Sargassum spp.	< 1.0	26	13.5
Pterocladia capillacea (Gmelin) Bornet	13.8	22	11.5
Spyridia filamentosa (Wulfen) Harvey	1.9	21	10.9
Dictyota spp.	< 1.0	19	10.0
Dictyosphaeria spp.	< 1.0	16	8.3
Ulva fasciata Delile	7.8	15	7.8
Gelidium pusillum (Stackhouse) LeJolis	2.7	13	6.8
Gracilaria coronopifolia J. Ag.	1.1	13	6.8
Halimeda discoidea Decaisne	< 1.0	13	6.8
Ulva reticulata Forsskal	1.6	12	6.3

Plus 21 species that occurred in fewer than 5% of the samples.

[1] At least one alien species was present in 32.2% of the total 755 samples collected from 1978 to 1992.
[2] Seagrass.

Islands. Their pasture of residency on a particular island appears to be generally fixed, until it is time for reproductive migration to French Frigate Shoals (Northwestern Hawaiian Islands) as adults. It is possible that they do graze at other pastures on the way back from French Frigate Shoals, against the current, but we have no evidence that this happens.

Ecological consequences of *H. musciformis* in Hawaii

When *H. musciformis* entered Hawaiian reefs, it invaded the niche occupied by the native *Hypnea cervicornis* J. Ag., which is often an epiphyte on *A. spicifera* (Russell, 1992). This kind of association has also been reported from the Atlantic (Shenkman, 1989). Although there is some inhibition of growth (competition) between *H. musciformis* and two native species (*H. cervicornis* and *Laurencia nidifica* J. Ag.), both aliens (*H. musciformis* and *A. spicifera*) apparently have added to the total productivity of certain reefs in Hawaii (Russell, 1992). These two alien species are now available to green turtles for food and sometimes represent 99–100% of the seaweed mass found in stomachs sampled. We found *A. spicifera* in 20% and *H. musciformis* in 11% of the total 754 samples collected from the mouths, stomachs, or fecal pellets of green turtles and when one of them was present in the sample, it was usually the most massive portion of the total food present (24–35%), compared with less than or equal to 9% for most of the individual native species (Table 1). These two alien algae now make up a significant part of the green turtle's diet in about a quarter of the individuals. Likewise, in Florida, where *H. musciformis* is native, more than 90% of the gut contents of some stranded green turtles is made up of *H. musciformis*, although they apparently prefer *Gelidium crinale* (Turner) Lamour. when available (B. Wershoven, personal communication, 1991; Wershoven and Wershoven, 1992).

References

Abbott, I.A., 1987. There are aliens among the algae, too – or limu malihini. Newsl. Hawaii. Bot. Soc., 26: 60–63.

Abbott, I.A. (Editor), 1988. Taxonomy of Economic Seaweeds. Vol. II. California Sea Grant College Program Report No. T-CSGCP-018, i–xv, 264 pp.

Abbott, I.A. and Norris, J.N. (Editors), 1985. Taxonomy of Economic Seaweeds. Vol. I. California Sea Grant College Program Report No. T-CSGCP-011, i–xv, 167 pp.

Balazs, G.H., 1976. Green Turtle migrations in the Hawaiian Archipelago. Biol. Conserv., 9: 125–140.

Balazs, G.H. 1980. Synopsis of biological data on the Green Turtle in the Hawaiian Islands. U.S. Department of Commerce, NOAA Technical Memorandum NMFS, Southwest Fisheries Center, NOAA-TM-NMFS-SWFC-7, i–ix, 141 pp.

Balazs, G.H. and Pooley, S.G., 1991. Research plan for marine turtle fibropapilloma. U.S. De-

partment of Commerce, NOAA Technical Memorandum, NMFS, NOAA-TM-NMFS-SWFSC-156, 113 pp.

Balazs, G.H., Forsyth, R.G. and Kam, A.K.H., 1987. Preliminary assessment of habitat utilization by Hawaiian green turtles in their resident foraging pastures. U.S. Department of Commerce, NOAA Technical Memorandum NMFS, Southwest Fisheries Center, NOAA-TM-NMFS-SWFC-71, i–iv, 107 pp.

Dawes, C.J., 1987. The biology of commercially important tropical marine algae. In: K.T. Bird and P.H. Benson (Editors), Seaweed Cultivation for Renewable Resources. Elsevier, New York, pp. 155–190.

Dawes, C.J., 1990. Observations on the physiological ecology of *Eucheuma isiforme* from the Western Atlantic: a review. In: C. Yarish, C.A. Penniman and P. Van Patten (Editors), Economically Important Marine Plants of the Atlantic: Their Biology and Cultivation. Connecticut Sea Grant College Program, Groton, CT-SG-89-07, pp. 27–35.

Doty, M.S., 1961. *Acanthophora*, a possible invader of the marine flora of Hawaii. Pac. Sci., 15: 547–552.

Doty, M.S., 1977. *Eucheuma* – current marine agronomy. In: R. W. Krauss (Editor), The Marine Plant Biomass of the Pacific Northwest Coast. Oregon State University Press, Corvallis, OR, pp. 203–214.

Doty, M.S., 1988. Prodromus ad Systematica Eucheumatoideorum: a tribe of commercial seaweeds related to *Eucheuma* (Solieriaceae, Gigartinales). In: I.A. Abbott (Editor), Taxonomy of Economic Seaweeds. Vol. II. California Sea Grant College Program Report No. T-CSGCP-018, pp. 159–208.

Duffy, J.E. and Hay, M.E., 1990. Seaweed adaptations to herbivory. BioScience, 40: 368–375.

Friedlander, M. and Lipkin, Y., 1982. Rearing of agarophytes and carrageenophytes under field conditions in the eastern Mediterranean. Bot. Mar., 25: 101–105.

Friedlander, M. and Zelikovitch, N., 1984. Growth rates, phycocolloid yield and quality of the red seaweeds, *Gracilaria* sp., *Pterocladia capillacea*, *Hypnea musciformis*, and *Hypnea cornuta* in field studies in Israel. Aquaculture, 40: 57–66.

Glenn, E.P. and Doty, M.S., 1990. Growth of the seaweeds *Kappaphycus alvarezii*, *K. striatum* and *Eucheuma denticulatum* as affected by environment in Hawaii. Aquaculture, 84: 245–255.

Guist, Jr., G.G., Dawes, C.J. and Castle, J.R., 1982. Mariculture of the red seaweed, *H. musciformis*. Aquaculture, 28: 375–384.

Haraguchi, P., 1979. Weather in Hawaiian Waters. Pacific Weather, Inc., Honolulu, i–x, 99 pp.

Humm, H.J. and Kreuzer, J., 1975. On the growth rate of the red alga, *H. musciformis*, in the Caribbean Sea. Caribb. J. Sci., 15: 1–3.

Paya, I. and Santelices, B., 1989. Macroalgae survive digestion by fishes. J. Phycol., 25: 186–188.

Russell, D.J., 1982. Introduction of *Eucheuma* to Fanning Atoll, Kiribati, for the purpose of mariculture. Micronesica, 18: 35–44.

Russell, D.J., 1983. Ecology of the imported red seaweed *Eucheuma striatum* Schmitz on Coconut Island, Oahu, Hawaii. Pac. Sci., 37: 87–107.

Russell, D.J., 1992. The ecological invasion of Hawaiian reefs by two marine red algae, *Acanthophora spicifera* (Vahl) Boerg. and *Hypnea musciformis* (Wulfen) J. Ag. and their association with two native species *Laurencia nidifica* J. Ag. and *Hypnea cervicornis* J. Ag. ICES Mar. Sci. Symp., 194: 110–125.

Schenkman, R.P.F., 1989. *Hypnea musciformis* (Rhodophyta): Ecological influence on growth. J. Phycol., 25: 192–196.

Wershoven, R.W. and Wershoven, J.L., 1992. Stomach content analysis of stranded juvenile and adult Green Turtles in Broward and Palm Beach counties, Florida. In: M. Salmon and J. Wyneken (Editors), Proceedings of the 11th Annual Workshop Sea Turtle Biology Conservation. NOAA Technical Memorandum NMFS-SEFSC-302, pp. 124–126.