***Fucus serratus*, serrated wrack, *Fucus vesiculosus*, bladder wrack or rockweed, and *Ascophyllum nodosum*, knotted wrack or rockweed (Order Fucales)**

Background

These are species of brown algae inhabiting temperate to arctic rocky intertidal zones of estuaries, harbours, and open coasts. *Fucus serratus*, likely introduced from Europe (Schneider 2002 and references therein), ranges from Chaleur Bay and the tip of Cape Breton to Bar Harbor, Maine. *Fucus vesiculosus* extends from Ellesmere Island to North Carolina (Sears 2002, Taylor 1957). *Ascophyllum nodosum* ranges from Baffin Island to New Jersey (Taylor 1957). In the Canadian Atlantic *F. vesiculosus* typically is abundant and the dominant species of the genus. *Fucus serratus* grows in high densities on European shores. However, *Ascophyllum nodosum* is the dominant brown alga throughout the littoral zone, favouring the mid- to low region, where it forms extensive beds, especially in protected sites (http://www.acadianseaplants.com; Sears 2002). *Fucus serratus* occupies the lowest area of the shore zone, with *F. vesiculosus* just above it. In all species each individual plant attaches to the rocky substrate via a holdfast. *Fucus vesiculosus* can withstand significant exposure to wind and wave action, while many *Fucus serratus* plants may be lost to winter storms. In areas of frequent ice scour *F. vesiculosus* dominates; *A. nodosum* is dominant in areas without or with infrequent ice scour. In the most exposed or ice scoured areas *A. nodosum* is replaced by *Fucus* (Sharp 1987). In these species the sexes are separate. Each species has one protracted reproductive season per year. In European waters *Fucus vesiculosus* reproduces from winter to summer (http://www.arkive.org/), and *Fucus serratus* from late spring/early summer to late summer/autumn, peaking in August to October (http://www.marlin.ac.uk/). *Ascophyllum nodosum* reproduces from April to June (Sharp 1987; http://www.seaweed.ie/descriptions/Ascnod.html). Generally these species exhibit low dispersal. In *Fucus* each fertilized zygote settles within a few meters of the female parent (Coyer *et al*. 2006 and references therein), and dispersal in *Ascophyllum nodosum* is very localized (Dudgeon *et al*. 2001). Zygotes grow into mature individuals where they settle. However, detached *F. vesiculosus* and *A. nodosum* float by means of their air bladders and are capable of long distance dispersal (van den Hoek 1987).

Fucus serratus is not harvested in North America but is taken elsewhere for the production of cosmetics and for thalassotherapy. *Fucus vesiculosus* is harvested commercially in the Maritime provinces and Maine for various medicinal and nutritional purposes. *Ascophyllum nodosum* is the principal seaweed harvested in waters from Newfoundland to Maine for use in agricultural products, livestock feeds, and as a stabilizer and conditioner in paints, cosmetics, and foods.

Temperature limits, critical thresholds, vulnerability, and barriers to adaptation

Sea surface temperatures in the current distribution of *Fucus serratus* range from a February minimum of -1.8^{o}C to an August maximum of 18.8^{o}C. Respective values for *F. vesiculosus* are -2.1^{o}C and 27.8^{o}C, and for *Ascophyllum nodosum* -2.1^{o}C and 22.8^{o}C.

These brown algae generally are cold water species as evidenced by their northern distributions and the SSTs they experience. Adults of these species grow best between 10°C and 21°C (Chock and Mathieson 1979, Strömgren 1977, 1983). Fertilization is optimal between 8°C and 20°C (Brawley *et al*. 1999). After fertilization growth of young *Fucus serratus* is best up to 15°C (Bird *et al*. 1979), and from 4°C to 20°C in *A. nodosum* (Sheader and Moss 1975). The upper limit for adult growth in all species is approximately 30°C (Strömgren 1977), and about 23°C in young *A. nodosum* (Sheader and Moss 1975).

These species, in fact all plants examined, ranked the most sensitive of all species in this study. This was due principally to their lack of mobility at all life stages, limiting dispersal as a means of adapting to changing temperatures. Dispersal by detached floating plants was not considered in this analysis. Eurythermal capacity contributed to low sensitivity only in *F. serratus*, and was due to its restricted distribution. In its native eastern North Atlantic this species ranges from the Arctic to northern Spain, and in North American waters suitable thermal habitat extends to the north and south of its present range (see below). Therefore, the eurythermal capacity score derived from the present distribution of this introduced species may be artificially low. Thermally the most critical stages of these brown algae appear to be at fertilization and as young plants for which temperatures up to approximately 20°C are optimal.

Impacts

A 4°C rise in global temperature will impact the future distribution of these brown algae in the western North Atlantic to differing degrees. The North American introduction of *Fucus serratus* was in Nova Scotian waters in 1887 (Coyer *et al*. 2003). Its distribution has spread to New Brunswick and Maine, but there are thermally suitable waters well to the north of the current range (blue region in figure). The southern limit for this species is Bar Harbor in southern Maine. All models and scenarios indicate that waters south of Bar Harbor will be thermally unsuitable for *Fucus serratus* with climate change. All models and scenarios but CCSR A2 show that remaining Maine coastal waters and those in the Bay of Fundy will remain favourable to *F. serratus*. Most or all thermal habitat in Nova Scotia and the southern Gulf of St. Lawrence will be lost. Likely there will be habitat loss in parts of the northern Gulf and western and southern Newfoundland, as well. Remaining Newfoundland waters should remain favourable to *F. serratus*. In Labrador waters our models and scenarios are quite evenly split between habitat loss and gain. There will be no negative economic impact from these changes in distribution since this species in not harvested commercially.

For *Fucus vesiculosus* we predict loss of habitat in the southern part of its range, from North Carolina northward to perhaps New Jersey. Only model CCSR predicts loss elsewhere, in Labrador waters. No northward gain of habitat is predicted in our study, which does not extend to the northern limit of *F. vesiculosus*. All other waters generally will remain suitable for this species. There will be no economic consequence to this habitat loss as seaweeds are not harvested in the affected states (http://www.st.nmfs.gov/st1/commercial/landings/ds_8850_bystate.html).

Waters will become thermally unsuitable for *Ascophyllum nodosum* in the southern part of its range, approximately from New Jersey to Cape Cod or northward into Massachusetts. Further north there may be habitat loss in the southern Gulf of St. Lawrence and perhaps in northern Nova Scotia waters. Model CCSR predicts loss on the Labrador coast, surprisingly with more loss in the better Scenario B2. These losses may affect negatively the commercial harvest in the southern Gulf of St. Lawrence.

These brown algae lack mobility at all life stages, limiting dispersal as a means of adapting to changing temperatures. This is not critical for the species as their distributions extend (or for *F. serratus* could extend) into northern waters where conditions will remain thermally suitable. But for individual plants thermal conditions in the waters discussed above will become unsuitable, resulting in mortality. Where water temperatures remain suitable it seems likely that elevated temperatures will induce greater growth since this occurs under experimental conditions (Stromgren 1977, 1983). The present adverse impact of high air temperatures during neap tides on *A. nodosum*, (Schonbeck and Norton 1978) presumably will be aggravated by increasing air temperatures resulting from climate change. Though this situation presently does not exist for *F. serratus* or *F. vesiculosus*, higher air temperatures in the future may negatively impact these species, as well. Experimental evidence indicates that loss of the algal canopy provided by these species, particularly in the upper intertidal zone of rocky shores, will increase substantially substrate temperatures and evaporative water loss, and negatively impact recruitment, growth, and survival of understory organisms (Bertness *et al*. 1999). This thermal stress may lead to variable changes in ecological dynamics of predators, prey, and the algal canopy, such as a lowering of the vertical intertidal limit of barnacles resulting from canopy loss (Leonard 2000).

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