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Sustainable seaweed cutting? The rockweed (*Ascophyllum nodosum*) industry of Maine and the Maritime Provinces

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Burgeoning global demand for products derived from seaweeds is driving the increased removal of wild coastal seaweed biomass, an emerging low trophic level industry. These products are marketed as organic and "sustainable." Brown macroalgae, such as kelps (Laminariales) and rockweeds (Fucales), are foundational species that form underwater forests and thus support a diverse vertebrate, invertebrate, and algal community—including important commercial species—and deliver organic matter to coastal ecosystems. The measure of sustainability used by the rockweed (*Ascophyllum nodosum* (L.) LeJolis) industry, maximum sustainable yield, accounts for neither rockweed's role as habitat for 150+ species, including species of commercial or conservation significance, nor its role in coastal and estuarine ecosystems. To determine whether rockweed cutting is "sustainable" will require data on the long-term and ecosystem-wide impacts of cutting rockweed. Once a sustainable level of cutting is determined, strict regulation by resource managers will be required to protect rockweed habitat. Until sustainable levels of cutting and appropriate regulations are identified, commercial-scale rockweed cutting presents a risk to coastal ecosystems and the human communities that depend on those ecosystems.

Keywords: *Ascophyllum nodosum*; rockweed; sustainability; marine macroalgae; seaweed harvest

Introduction

Benthic marine macroalgae, or seaweeds, are critical components of coastal ecosystems. As primary producers they contribute to nutrient cycling, sequester nitrogen and carbon,[1] contribute energy to food webs,[2–4] and provide three-dimensional structure and habitat for fish,[5–7] waterfowl,[8,9] algae,[10] shellfish,[11] shellfish spat,[10,12] and other invertebrates.[11,13]

The rate of wild seaweed extraction is increasing globally[14] as human populations find more and more uses for marine plant-based products in agriculture, animal production, pet foods, cosmetics, and human food.[15] The intensity of seaweed extraction ranges from small operations for individual use, to artisanal collection of seaweeds as food, to commercial harvests of hundreds to thousands of tons daily.[16] The volume of seaweed processed for human uses across the globe is outpacing the ability of wild seaweed populations to supply the demand.[14] Yet the removal of wild seaweed species at the commercial level, marketed as organic and sustainable, continues and intensifies, leading to conservation concerns: should wild seaweeds be harvested at all?[17] Management of commercial seaweed operations globally has not been sufficient to prevent overharvest of some of these species.[18] Is the cutting of wild seaweeds on a commercial scale ecologically sustainable?

The brown macroalgal species in the families Laminariales (kelps) and Fucales (fucoids or rockweeds) are foundational species that form underwater forests that provide numerous ecological services to coastal ecosystems: food, habitat, and shelter for a diverse invertebrate and vertebrate community, as well as essential nutrients to productive coastal ecosystems.[13,19] *Ascophyllum nodosum*, a brown fucoid seaweed (also known as rockweed, bladderwrack, Norwegian kelp, or simply "kelp"), inhabits coastal shorelines from the Canadian Arctic, Greenland, Iceland, and Norway to Portugal and

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Figure 1. The rockweed zone exposed at midtide, Friendship Long Island, Maine.

the east coast of the United States south to New Jersey. *Ascophyllum*'s dominance in the intertidal zone creates an eponymous band in the intertidal zone, the "rockweed zone."[20]

At low tide, dense layers of *Ascophyllum* fronds lie prostrate on the substratum (rocky shore; Fig. 1), creating a protective blanket for other species fixed to the rocks below, living in sediments underneath, or residing in its canopy. The prostrate fronds rise on the incoming tide and form a rockweed forest[21] (Fig. 2). *Ascophyllum* provides habitat to 34 species of fish[22–25] (Table 1) and 100+ invertebrate taxa,[11] which are a food source for fish[26] and birds.[8,27,28] A complete rockweed zone food web was documented by Gollléty *et al.*[29]

Ascophyllum is characterized by a slow growth rate[30] and long life span (holdfasts, which attach the alga to the substrate, may be up to 400 years old[31]). The great height (length[32–35]), high fecundity, high within-population genetic diversity, and weak large-scale population phenotypic differentiation[30] mean that *Ascophyllum* plants are analogous to trees,[30,36] and rockweed beds are the underwater equivalent of old-growth forests.[30] Because of the diversity and significance of its ecological services, rockweed is valued as a "high-priority" species (ranking fourth out of 161 monitored marine species) for protection in the United States and Canada,[37] a "priority species" in Northern Ireland,[38] and a "high-sensitivity species" in the UK.[39] Rockweed harvesting has been ranked one of the top human impacts across coastal habitat types in the Gulf of Maine.[40]

Ecological services

Biomass and net primary production

The best ecosystem-level study of rockweed is found in the work by Vadas *et al.*,[3] who studied its biomass and productivity. They reported wet-weight biomass of 11.4–28.9 kg/m^2 at five sites in Cobscook Bay. Separately, Trott and Larsen[41] reported mean wet-weight biomass of 10–17 kg/m^2 in Cobscook Bay, Sutherland[42] reports mean biomass ranging from 6.7 to 12.9 kg/m^2 in Southern New Brunswick, and Keser *et al.*[43] reported a range of 5.0–17.5 kg/m^2 in Nova Scotia.

As seen in ecosystem studies of grasslands, estimates of net primary productivity (NPP) for rockweed are complicated by its multiple points of growth, continuous loss of biomass to herbivory and breakage, and high local, spatial variation in its occurrence. Vadas *et al.*[3] estimated NPP of rockweed in Cobscook Bay at 8.15–11.65 kg wet weight/m^2/yr, giving an annual turnover of 40–70%/yr for rockweed biomass (equivalent to a mean-residence time of 1.4–2.5 years). Schmidt *et al.*[13] estimated primary production at 1.3 kg wet weight/m^2/yr in Nova Scotia. For nine sites in Nova Scotia, Cousens[44] reported mean net primary production of 0.820–2.120 kg/m^2/yr (dry weight) and a mean turnover of 44%/yr. The highest values for net primary production in Cobscook Bay equate to 0.894 kg C/m^2/yr,[4] which is equivalent to net primary production in the world's most productive terrestrial forests.[45]

Most of the carbon in rockweed biomass enters detrital pools. In Great Bay, New Hampshire, 4.62 mt of nitrogen (N) and 0.31 mt of phosphorus (P)

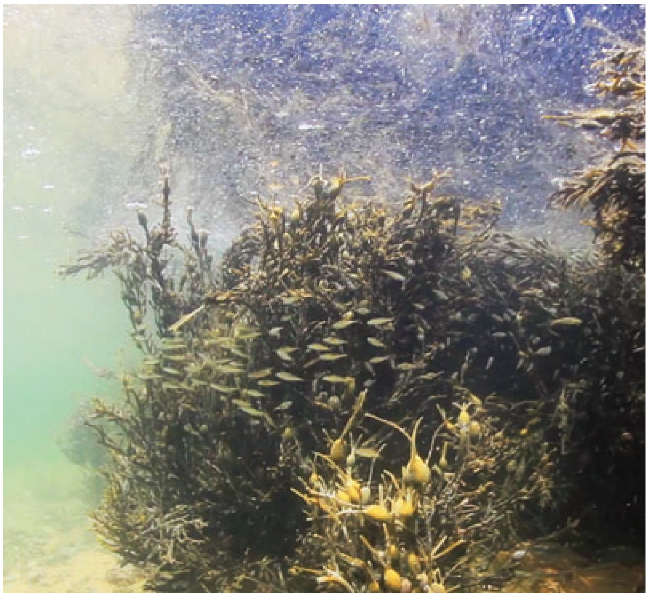

Figure 2. Stickleback fish in a rockweed forest at high tide, Hallowell Island, Moosehorn National Wildlife Refuge, Edmunds, Maine.

are estimated as available to the detrital pool from shed *Ascophyllum* receptacles.[46] After benthic diatoms and phytoplankton, rockweeds are the third most productive component of the Cobscook Bay ecosystem.[4] The productivity of fucoids, primarily *Ascophyllum*, may underlie the productivity of scallops and soft-shell clams and the high diversity of the filter-feeding invertebrate community in Cobscook Bay.[3] Sea scallops (*Placopecten magellanicus*) feed on brown algal detritus when phytoplankton populations are reduced,[47] and Cobscook Bay harbors the most productive scallop beds in Maine[48] (worth $1.0 million in 2004–2005[49]). The work of Vadas *et al.*[3] suggests that *Ascophyllum* plays a significant role in the productivity of those beds as well as the productivity of other commercially important shellfish species. Up to 82% of macrophyte (primarily *Ascophyllum*) production leaves the intertidal zone in Passamaquoddy Bay (NB Canada) during the summer months and is assumed available for decomposition into the bay.[50] Decaying macroalgae in the strand line of Passamaquoddy Bay is released to the sea during spring tides and represents ~7.3% of the primary productivity of the bay.[50]

Habitat

In Maine, coastal wetlands (including the rockweed-covered shore) and significant wildlife habitat are protected under the Natural Resources Protection Act (NRPA).[51] "Seaweed communities" were included as part of Significant Wildlife Habitat for tidal waterfowl/wading birds.[52]

Ascophyllum creates complex habitat in three forms: "wrack" (fronds that are unattached and stranded by tidal action in the high intertidal zone), unattached macroalgal mats drifting near the coast, and plants attached by a holdfast to hard substratum in the intertidal zone.

Macroalgae generally, and *Ascophyllum* wrack in Maine and the Maritimes, decomposes and creates habitat for small invertebrates, especially insects and amphipods[50] that are prey for migrating shorebirds.[53,54] Rockweed rafts floating at sea increase habitat complexity there,[55] providing habitat for isopods, amphipods, and fishes.[56,57]

Over 100 taxa of invertebrates,[11] including lobster, clams, and snails; 34 species of fish, including pollock, herring, flounder, and cod (Table 1); shorebirds, seabirds, and waterfowl (Table 1); and several other algal species[10] use attached *Ascophyllum* habitat. Epifaunal density is correlated with rockweed biomass.[58] "Some species are attracted to rockweed to graze upon it or its associated epiphytes,[59] while others benefit from the physical structure it provides. At low tide, rockweed thalli protect against

Table 1. Conservation status in the United States and Canada of fish and bird species that use rockweed habitat

Species	Common name	Conservation status United States	Conservation status Canada
Fish			
Alosa pseudoharengus[22,25]	Alewife	2011 candidate for ESA listing;[69] USFWS priority species[70]	COSEWIC candidate Group 2[71]
Ammodytes americanus[22]	American sand lance		
Anguilla rostrata[22,25]	American eel	USFWS priority species;[70] MCWCS: SGCN 1;[72] IFW special concern[73]	
Apeltes quadracus[22]	Fourspine stickleback		
Clupea harengus[22,24]	Atlantic herring		
Cyclopterus lumpus[22,24]	Lumpfish		
Fundulus heteroclitis[22,25]	Mummichog		
Gadus morhua[22]	Atlantic cod		
Gasterosteus wheatlandi[22]	Blackspotted stickleback		
Gasterosteus aculeatus[22,24]	Threespine stickleback		
Hemitripterus americanus[22,24,25]	Sea raven		
Liparis atlanticus[22,23]	Atlantic seasnail		
Macrozoarces americanus[22]	Ocean pout		
Menidia menidia[22]	Atlantic silverside		
Merluccius bilinearis[22,24]	Silver hake		
Microgadus tomcod[22,25]	Atlantic tomcod		
Myoxocephalus aenaeus[22,23,25]	Grubby		
Myoxocephalus octodecem-spinosus[22,24,25]	Longhorn sculpin		
Myoxocephalus scorpius[22–25]	Shorthorn sculpin		
Osmerus mordax[22,24,25]	American smelt	MCWCS: SGCN 2;[72] NMFS species of concern[74]	
Pholis fasciata[24]	Rock gunnel		
Pholis gunnellus[22,23]	Rock gunnel		
Pollachius virens[22,24,25]	Pollock		COSEWIC candidate Group 2[71]
Pleuronectes (=Pseudopleuronectes) americanus[22,24,25]	Winter flounder	USFWS priority species[70]	
Pungitius pungitius[22]	Ninespine stickleback		
Raja radiata[22]	Thorny skate		
Salmo salar[22,24]	Atlantic salmon	Endangered species status;[75] USFWS priority species;[70] MCWCS: SGCN 1[72]	Endangered (COSEWIC and SARA)[76]
Scomber scombrus[22,25]	Atlantic mackeral		
Squalus acanthias[24]	Dogfish		
Syngnathus fuscus[22]	Northern pipefish		

Continued

Table 1. *Continued*

Species	Common name	Conservation status United States	Conservation status Canada
Tautogolabrus adspersus[22,25]	Cunner		
Tautoga onitus[25]	Tautog		
Ulvaria subbifurcata[22]	Radiated shanny		
Urophycis tenuis[22,25]	White hake		
Birds[27]			
Somateria mollissima	Common eider	MCWCS: SGCN 2[72]	
Anas rubripes	American black duck	USFWS priority species;[70] MCWCS: SGCN 2[72]	
Anas platyrhynchos	Mallard duck		
Calidris maritima	Purple sandpiper	USFWS priority species;[70] MCWCS: SGCN 2;[72] U.S. Shorebird Plan Cat. 2 [77]	Canadian Shorebird Plan, Cat. 2[78]
Phalacrocorax auritus	Double-crested cormorant		
Pandion haliaetus	Osprey	USFWS priority species[70]	
Gavia immer	Common loon	USFWS priority species;[70] MCWCS: SGCN 2[72]	
Ardea herodias	Great blue heron	IFW: special concern;[73] MCWCS: SGCN 2[72]	
Larus philadephia	Bonaparte's gull	IFW special concern (breeding pop only)[73]	
Sterna hirundo	Terns, including common tern	IFW special concern;[73] USFWS priority species;[70] MCWCS: SGCN 2[72]	
Bucephala albeola	Bufflehead		
Melanitta spp.	Scoters		
Scolopacidae, including *Calidris pusilla*	Including semipalmated sandpiper	(*Calidris pusilla*) IFW special concern;[73] USFWS priority species;[70] MCWCS: SGCN 2;[72] U.S. Shorebird Plan cat. 3[77]	Canadian Shorebird Plan cat. 3[78]
Charadriidae, including *Charadrius semipalmatus*	Including semipalmated plover	(*C. semipalmatus*) U.S. Shorebird Plan cat. 2[77]	U.S./Canadian Shorebird Plan cat. 2[78]
	Kingfishers		
	Mergansers		
	Grebes		

heat, light, desiccation, and predation, allowing for enhanced intertidal survival of invertebrate fauna, especially at the higher tidal levels."[60] At high tide, the expanded floating plant canopy serves as a predation refuge for juvenile fishes and a feeding site for birds.[6,8] Furthermore, the reduced water velocity within rockweed beds facilitates the settlement and attachment of pelagic larvae of species such as barnacles and mussels.[11] Commercially important invertebrates such as lobster (*Homarus americanus*) (Cowan, 2011, personal communication to R.H. Seeley),[13,24,61,62] common periwinkles,[11] blue mussels,[11] soft-shell clams,[11] and bivalve spat[12] all use the shelter of rockweed stands. Noncommercial, but ecologically important, members of the rocky intertidal community include amphipods (food for shorebirds, ducks; and fish, such as pollock and herring[26]), mysid shrimp (food for commercially important fish, such as herring and cod[26] and longhorn sculpin[63]), native periwinkles (*Littorina obtusata* [grazer]), and dog winkles (*Nucella lapillus* [predator]).[11] *L. obtusata* also deposits egg masses on *Ascophyllum* fronds.

Lobsters (*H. americanus*) have been found in rockweed in the Maritimes[13,24,61] and in Maine (Cowan, 2011, personal communication to R.H. Seeley).[62] Lobsters in rockweed are noted in a Gulf of Maine Council on the Marine Environment report.[64] Although the reported density of lobsters found in rockweed is low,[13,24,61] the commercial importance of lobster to Maine's coastal economy,[65] and the observation that much of the habitat for juvenile lobsters is *Ascophyllum*-covered rocks (Cowan, 2011, personal communication to R.H. Seeley),[62] suggest that more research attention should be paid to day-and-night use of *Ascophyllum* beds by lobsters.

Few invertebrates in the NW Atlantic rocky intertidal zone consume live rockweed, because it is chemically well defended by polyphenols,[66] but in the NE Atlantic, *Ascophyllum* subsidizes growth of a key intertidal grazer, the limpet *Patella vulgata*.[67]

Thirty-four species of fish are found in *Ascophyllum* habitat (Table 1). Pollock are a particularly good example of a fish species using rockweed habitat. Pollock moved up to 200 m inshore with the tide for feeding and likely predator avoidance.[6,7] Juveniles appeared in the intertidal zone in early May.[7] Juvenile pollock prefer open intertidal habitat, where they school on falling tides, but prefer dense algal intertidal habitat, where they are solitary or in small shoals, on high-rising tides.[7] Juvenile pollock also feed in rockweed habitat, preying on invertebrates associated with rockweed: crustaceans (copepods, isopods, and amphipods) and small gastropods (*L. obtusata*) are the most widely consumed prey types.[6]

Many bird species, including those of conservation concern, use the rockweed zone as a habitat for feeding, reproduction, or sheltering (Table 1). The rockweed canopy is particularly important for Common Eider ducklings, who lack the ability to dive for food for about three weeks after hatching, and thus forage for amphipods in the canopy floating at the surface.[8,9,27] The *Ascophyllum* zone food web is stable, and it is likely that its complexity, with multiple trophic pathways, is responsible for this stability.[29] The rockweed canopy supports numerous trophic pathways and thus the stable functioning of the mid intertidal zone.[29] After simulated species removals (25%) from the rockweed community in Maritime Canada, food webs collapsed.[13] The rockweed food web was less robust than the food web in eelgrass.[13] In Iceland, Sarà *et al.* found that organic matter from *Ascophyllum* flows through the food web to top predators via predation or scavenging.[68]

Biogeochemistry

Most N enters Cobscook Bay during tidal exchange with the Gulf of Maine. Runoff from fertilizer, sewage disposal, and salmon aquaculture add a small amount of available N to the ambient concentrations.[79] Unfortunately, in recent years, red tides have resulted in closure of shellfish fisheries during the summer months, their occurrence largely blamed on excessive N concentrations in the estuary.[80] If its tissue N content averages about 1% (0.8%;[13] 1.15%[81]), the total production of rockweed in Cobscook Bay (6.3 × 109 gC/yr)[2] sequesters about 60 t/yr of N from the estuarine waters. Alternatively, Garside and Garside estimate the total tidal inflow of N at 70 t/day in Cobscook Bay.[79] Thus, the growth of rockweed can be expected to remove $<1\%$ of the N delivered to Cobscook Bay each year, converting it to organic forms. Nevertheless, the N content in rockweed beds is an important resource for higher trophic levels.[13]

Commercial-scale cutting of *Ascophyllum*

Despite its critical ecological role in coastal ecosystems, *Ascophyllum* is a target of a growing rockweed-processing industry. Rockweed beds are cut with hand-held cutter rakes, sickles, or mechanical cutter devices on boats and processed into fertilizers and agricultural growth stimulants (also dog food, cosmetics, and meat preservative) in Norway, Ireland, Scotland, France, Canada, and the United States (Maine). As a result of global demand for rockweed products, which are marketed as organic and "sustainable," the intensity of *Ascophyllum* (rockweed) cutting in the NW Atlantic (United States and Canada) has risen dramatically since 1986 (Maine Department of Marine Resources, personal communication to R.H. Seeley).[82] In Maine, rockweed landings have nearly doubled in the past five years, from 7.1 (2006) (Maine Department of Marine Resources, personal communication to R.H. Seeley) to 12.7 (2010) million pounds.[83] In the Maritimes, landings of rockweed have increased from ∼9.9 (1984–1985, Ref. 82) to ∼88.1 million pounds in 2010.[82] Rockweed cut in NB is capped by the Canadian government at ∼26 million pounds (11,000 mt; Table 2).

The industrial-scale removal and processing of low trophic level species such as coastal seaweeds is an illustration of "fishing down the food web."[87] In fact, seaweed cutting is often conducted by fishers who are switching from other higher trophic level fisheries that have been depleted, such as groundfish, sea urchins, clams, and scallops.[85] Targeting low trophic level species, such as marine plants, risks impacting high trophic level species and could lead not only to widespread changes in ecosystems, but also to the collapse of traditional fisheries.[88]

History of rockweed harvesting

Ascophyllum has been used for fertilizer and other agricultural uses by coastal farmers and gardeners in New England (United States) at least since the 18th century.[89] *Ascophyllum* was so valuable to farmers that rights to rockweed on the shore were specifically mentioned in legal documents.[90]

The modern era of industrial-scale rockweed cutting began in 1959 in Nova Scotia[91] when the provincial government began area management. In the 1950s, *Ascophyllum* was used primarily as raw material for sodium alginate and "kelp" meal. After introduction of the highly efficient suction mechanical seaweed harvester in 1985,[92,93] rockweed landings jumped from 9,448 t in 1985 to 29,598 t in 1989.[92] Exploitation rates reached 95% of biomass,[94] resulting in overharvested areas.[95] Starting in 1988, areas of overharvest in SW Nova Scotia (Annapolis Basin, St Mary's Bay, Lobster Bay)[95] were closed. There was a mix of open areas (no limitations), exclusively licensed areas with true area management, and other areas that were not monitored.[96] Mechanical harvesting of rockweed was discontinued in Nova Scotia after the overharvest but is currently (2011) returning to Nova Scotia in the form of an experimental mechanical harvesting lease (Nova Scotia Department Fisheries and Agriculture, 2011, personal communication to R.H. Seeley). As recently as 2006, some areas of SW Nova Scotia were still being overharvested.[95]

In the early 1990s, even more rockweed was needed to meet demand, and in New Brunswick there were virgin stands of *Ascophyllum*.[86] New Brunswick was opened to *Ascophyllum* cutting for the first time in 1995,[96] but not without protest from fishing and conservation communities.[97] As the pilot harvest was starting in the island community of Grand Manan, the Grand Manan Fisherman's Association, Chamber of Commerce, Municipal Council, and representatives of traditional dulse and periwinkle harvesters formed the Island Rockweed Committee to protect Grand Manan's rockweed, asserting that "rockweed is as essential to their fisheries as topsoil is to farmers."[98] The citizens of Grand Manan viewed the rockweed cutting as a threat to their economic sustainability.[97] As a result of conservation concerns, a strict set of regulations was enacted in New Brunswick, including a cap on landings (originally 10,000 mt, but after industry reassessed total biomass, the cap was raised to 11,800 mt).[42] Mechanical harvesting is not currently permitted in NB (Table 2). According to the rockweed industry, NS harvest areas have now reached "maximum annual sustainable production."[82]

In Maine, commercial rockweed harvesting apparently started in 1950, when fishermen in Harpswell cut and shipped rockweed from Bailey Island.[99] A large Canadian company, Acadian Seaplants Ltd. (ASL), which is responsible for ∼92% of the harvesting in the Maritimes,[82] expanded its cutting area from Canada into eastern Maine in the 1990s. ASL announced its intention to expand the rockweed harvest from eastern Maine to the rest of the Maine coast.[100] A 2009 Maine state law established the first and only rockweed management area in Maine (Cobscook Bay Rockweed Management Area).[84]

Regulation of rockweed harvesting

Rockweed cutting in New Brunswick and Nova Scotia (Canada) is managed more strictly than in Maine (Table 2). The most important points of difference are area management (leases and sectors), limits on take, closed conservation areas, and reporting (pre- and postharvest plan).

Outside the Cobscook Bay Rockweed Management Area, there is no area management (any person

Table 2. Rockweed harvest management in Maine (United States) and the Maritime Provinces (Canada)

	United States[84] ME outside CBRMA	United States [84] ME within CBRMA	Canada (Conservation Council of New Brunswick, Fundy Baykeeper and K. Watson, personal communication to R.H. Seeley) NB	Canada[85] NS
Harvest				
Management authority	State	State	Province and federal	Province and federal
Harvest method	Any	Any	Hand only	Hand only (one experimental mechanical harvest license)
Limit (tons)	None	Annual limit: 17% of available tons per sector	11,000 mt[42]	None
Area management in place?	No	Yes	Yes, lease areas	Yes, lease areas
Area management scheme	None	Sectors assigned to companies	Yes	Exclusive areas and open areas
Cutting height mandated	16″	16″	5″	5” in lease areas and nonleased areas
Required holdfast incidence in landings, by weight	Cutting height is 16” above holdfast	Cutting height is 16” above holdfast	<10%[86]	≤15%
Data and reporting				
Biomass study required prior to cut	No	Yes	Yes	Yes
Required biomass study conducted by?	Industry	Industry	Industry	
Conservation areas closed to cutting	Federal properties only: NPS, USFWS	Yes	Yes	None (the minister has the authority to designate conservation areas)
Formal opportunity for objections to cutting in a sector/lease area	No	No	Yes	Yes
Licenses and fees				
Harvester license required	Yes	Yes	Yes	Yes
Harvester license fee	US $58	US $58	$50 Can. personal fishers reg, $50 Can. for vessel license number	Federal (DFO); $100 Can.
Nonresident harvester license	Yes, allowed	Yes, allowed	No	No
Nonresident license fee	US $230	US $230	N/A	N/A
Lease fee required			No	Yes
Lease fee amount			NA	$608.24 Can.
Seaweed buyer fee	Yes	Yes	N/A	Yes
Nonresident buyers	Yes	Yes	No	No
Nonresident buyer fee	US $500	US $500	N/A	N/A
Royalty fees required	Yes	Yes	Yes	Yes
Royalty fees	US $1.50/wet ton	US $1.50/wet ton	Confidential	$2.25 Can/wet ton
Harvester reporting				
Management plan required prior to harvest	No	Yes	Yes	Yes
Postharvest report required	No	No	Yes	No
Postharvest business report required	No	No	No	Yes

Continued

Table 2. *Continued*

	United States[84] ME outside CBRMA	United States [84] ME within CBRMA	Canada (Conservation Council of New Brunswick, Fundy Baykeeper and K. Watson, personal communication to R.H. Seeley) NB	Canada[85] NS
Third-party verification of landings?	No	Required	Dockside monitoring program: tonnage. Third party certified by DFO monitors 10% of landings	No
Landings data reported by harvester	Yes	Yes	Yes	No
Landings data reported by company/leaseholder	No	No	Yes	Yes
Deadline for landings reporting	December of following year (e.g., 2010 take data must be reported by December 2011)	December of following year (e.g., 2010 take data must be reported by December 2011)	Feb. 2012 for 2011 season	January 15 of following year
Penalties for noncompliance	Summons and fine	Summons and fine	Ranges from verbal warning to company license revocation	License revocation

CBRMA, Cobscook Bay Rockweed Management Area.

licensed by the state can cut anywhere), non-Maine residents and non-U.S. citizens may obtain licenses, and a cutting height of 16″ is mandated but not effectively enforced (e.g., holdfasts in Maine landings[32] represent a 0″, not a 16″, cut height). Closed conservation or research areas are limited to federal property (USFWS and USNPS lands in Maine have been closed to commercial rockweed cutting since ∼2000). Within the Cobscook Bay Rockweed Management Area,[84] there is an annual limit (17%) on take (based on the available rockweed biomass, which is estimated by industry and reported verbally to Department of Marine Resources staff [Maine Department of Marine Resources, personal communication to R.H. Seeley]), area management through assigned sectors, and state and private conservation areas closed to rockweed cutting. Unlike Canada, Maine allows mechanical harvesting anywhere in the state. Complicating rockweed management in Maine is private ownership of intertidal areas. This has led to a debate over whether or not there is a public trust right to remove seaweed from private shores. The Maine Department of Marine Resources issues permits for seaweed harvesting while not taking a position on the question of rockweed ownership.[83]

Impacts of rockweed cutting

Impacts of rockweed harvests on the rockweed community are indirect (e.g., through changing habitat architecture, food, or cover availability) or direct (removal of species in bycatch). Rockweed harvest also impacts the rockweed itself (Table 3).

Indirect impacts of rockweed harvesting on common eider (*Somateria mollissima*) ducklings stem from duckling feeding behavior. For about three weeks, ducklings are unable to dive for mussels and must forage in the floating rockweed canopy (for small prey such as amphipods[8]). During this time, ducklings are vulnerable to predation by bald eagles and great black backed gulls.[118,119] Rockweed cutting activity can disturb eider crèches at a critical time and removes rockweed canopy where the ducklings feed,[8] as a result of harvesters targeting the largest and heaviest clumps with most rockweed biomass in the upper canopy.[111,112] For this reason, researchers in New Brunswick recommended that the start of rockweed harvesting be delayed until early to mid-July.[8,27,120] Hamilton[8] also warned that rockweed cutting should not be conducted in a way that changes height and structure of the rockweed canopy, but both eider ducklings and harvesters target the canopy. The longest *Ascophyllum* plants, with

Table 3. **Documented impacts after rockweed harvest to vertebrate, invertebrate, and algal species and to the rockweed community**

Group 1	Group 2	Level of impact	Common name	Species	Impact
Vertebrate	Bird	Species	Common eider	*Somateria mollissima*	Duckling numbers decreased,[9] reduced feeding of ducks[28]
Vertebrate	Fish	Species	Cunner	*Tautogolabrus adspersus*	Reduced feeding[25]
Vertebrate	Fish	Community	Fishes: Atlantic tomcod, cunner, pollock, grubby, short-horned sculpin, long-horned sculpin, Atlantic sea raven, winter flounder	*Microgadus tomcod, Tautogolabrus adspersus, Pollachius virens, Myoxocephalus aeneus, Myoxocephalus scorpius, Myoxocephalus octodecemspinosus, Hemitripterus americanus, Pseudopleuronectes americanus*	Biomass reduced[25]
Invertebrate	Coelenterate	Species	Hydroid	*Dynamena pumila*	Reduced abundance[10]
Invertebrate	Crustacean	Species	Isopods	*Jaera marina, Idotea balthica*	Removed in bycatch[101,102]
Invertebrate	Crustacean	Species	Amphipods	*Gammarus, Marinogammarus*	Removed in bycatch[101,102]
Invertebrate	Crustacean	Species	Green crab	*Carcinus maenas*	Reduced abundance,[10] removed in bycatch[101,102]
Invertebrate	Crustacean	Species	Barnacle	*barnacle (larvae)*	Removed in bycatch[101,102]
Invertebrate	Crustacean	Species	Barnacle	*Balanus*	Reduced abundance[103]
Invertebrate	Crustacean	Taxonomic group	Crustaceans	*Planktonic crustaceans*	Site-specific: reduced abundance[25]
Invertebrate	Crustacean	Taxonomic group	Sediment meiofauna	*crustaceans*	Reduced abundance[103]
Invertebrate	Mollusk	Species	Blue mussel	*Mytilus edulis*	Removed in bycatch[101,102]
Invertebrate	Mollusk	Species	Bivalves	*Mya arenaria, Hiatella arctica*	Removed in bycatch[101,102]
Invertebrate	Mollusk	Species	Macoma clams	*Macoma*	Removed in bycatch[101,102]
Invertebrate	Mollusk	Species	Snails	*Littorina saxatilis, Lacuna vincta, Nucella lapillus*	Removed in bycatch[101,102]
Invertebrate	Mollusk	Species	Rough periwinkle	*Littorina saxatilis*[a]	Removed in bycatch[32]
Invertebrate	Mollusk	Species	Smooth periwinkle	*Littorina obtusata*	Removed in bycatch;[101,102] reduced abundance in winter[104]
Invertebrate	Mollusk	Species	Common periwinkle, wrinkle	*Littorina littorea*	Removed in bycatch[32,101,102,105]
Invertebrate	Mollusk	Species	Bivalve spat		Removed in bycatch[12,106]
Invertebrate	Sponge	Species	Sponge	*Hymeniacodon/Hymeniacidon*	Reduced abundance[103]
Invertebrate	Sponge	Species	Sponge	*Halichondria*	Reduced abundance[103]
Invertebrate	Worm	Taxonomic group	Bristle worms	*polychaetes*	Removed in bycatch[101,102]
Invertebrate	Worm	Taxonomic group	Aquatic earthworms	*oligochaetes*	Removed in bycatch[101,102]
Alga	Alga	Species	Encrusting algae	*Phymatolithon lenormandii*	Reduced abundance (% cover) or death[10]
Alga	Alga	Species	Encrusting algae	*Hildenbrundia rubra*	Reduced abundance[10]
Alga	Alga	Species	Wrack	*Fucus vesiculosus*	Removed in bycatch;[107] reduced abundance[10,103]
Alga	Alga	Species	Ephemeral algae	*Enteromorpha, Ulva*, unspecified	Increased abundance[108,103,104]
Alga	Alga	Species	Green alga	*Cladophora*	Increased abundance[103]
Alga	Alga	Species	Rockweed plant morphology	*Ascophyllum nodosum*	Shorter plants[10,42,109,28]
Alga	Alga	Species	Rockweed plant morphology	*Ascophyllum nodosum*	Increased number of laterals on stipe[10,34,103,110]
Alga	Alga	Species	Rockweed plant morphology	*Ascophyllum nodosum*	Decrease in proportion of reproductive laterals[44]

Continued

Table 3. ***Continued***

Group 1	Group 2	Level of impact	Common name	Species	Impact
Alga	Alga	Species	Rockweed plant morphology	*Ascophyllum nodosum*	Holdfast loss[32,93,111,112,102,113,114]
Alga	Alga	Species	Rockweed	*Ascophyllum nodosum*	Reduced abundance (% cover)[10,103,104]
Alga	Alga	Population	Rockweed	*Ascophyllum nodosum*	Reduced biomass, length;[109] reduced % cover[10]
Alga	Alga	Population	Rockweed plant morphology	*Ascophyllum nodosum*	"Long-term changes" noted in harvesting areas[115]
Alga	Alga	Population	Rockweed beds	*Ascophyllum nodosum*	Decrease in biomass[116]
Alga	Alga	Population	Rockweed beds	*Ascophyllum nodosum*	Reduced structural complexity[10]
Alga	Alga	Population	Rockweed population structure	*Ascophyllum nodosum*	Population structure altered by long-term harvesting[115]
Alga	Alga	Population	Rockweed population structure	*Ascophyllum nodosum*	Population structure altered by mechanical harvesting[93]
Community	Community	Community	Rockweed community	*sessile invertebrates*	Site-specific: reduced abundance[25]
Community	Community	Community	Rockweed community	*invertebrates and algae*	Boulders: animal cover decreased 66%;[103] mean number of species reduced by 33%[103]
Community	Community	Community	Rockweed community	*invertebrates and algae*	Species richness reduced[10]
Physical environment			Sediment size		Sediment coarser[103]

[a]Questionable species identification based on reported numbers and sizes of *L. saxatilis*. High-spired *L. obtusata*[117] may have been misidentified as *L. saxatilis*. No voucher specimens from the study were retained.

a high canopy available to ducklings, are also the largest (most of the biomass in plants over 80 cm in length [height] are distal[111,112]) and thus more attractive to rockweed harvesters paid by the pound. Rockweed clumps over 130 cm that are cut are typically reduced up to 55% of length (height) and 78% of biomass.[109] Rockweed areas where common eiders breed are protected in some areas of New Brunswick and on some conservation lands in Maine (within the Cobscook Bay Rockweed Management Area, federal wildlife refuges, and Acadia National Park).

Allen notes that several factors, including rockweed harvesting, are likely acting in concert to limit eider populations in the Gulf of Maine.[118] Allen *et al.* note that Quahog Bay, Maine, which has suitable eider habitat, has no eiders.[119] Rockweed has been harvested in Quahog Bay for many years.[34]

Other indirect impacts on fish that use the rockweed zone have been detected. Black and Miller[25] found that a fish species abundant in rockweed, cunner (*Tautogolabrus adspersus*), consumed less food in intertidal areas where *Ascophyllum* was cut than in areas where *Ascophyllum* was intact. Total abundance of fish (numbers) in cut and intact rockweed areas did not differ, but fish biomass in areas from which rockweed was removed was significantly reduced.[25]

Impacts on the rockweed community as a result of simulated rockweed cutting were investigated in Maine by Fegley:[10] overall species richness declined and did not recover during the two-year study. In light of these results, it is noteworthy that the rockweed community in Brittany, France, a region with a long rockweed harvesting history, has reduced species diversity (50 taxa)[121] relative to the high species diversity reported for rockweed communities in Maine (100+ taxa).[11]

Rockweed cutting also significantly affected abundance of common intertidal species: green crabs (*Carcinus meanas*), common periwinkles (*L. littorea*), blue mussels (*Mytilus edulis*), limpets (*Tectura testudinalis*), a colonial hydroid (*Dynamena pumila*), blue mussel spat (*M. edulis* recruits), and barnacles (*Semibalanus balanoides*).[10]

Data on direct impacts of rockweed harvesting to the rockweed community are found in studies of bycatch conducted by government[101,102] and industry.[32] Species directly impacted through bycatch removal include *L. littorea*, *L. obtusata*, *L. saxatilis*, *C. maenas, M. edulis, D. pumila, Gammarus* spp., *Marinogammarus* sp., *oligochaetes, polychaetes, Lacuna vincta, N. lapillus, Macoma, Mya arenaria, Hiatella arctica, Jaera marina, Idotea balthica*, barnacle larvae, and *Fucus vesiculosus* (Table 3). Bycatch of algal species in rockweed harvest has not been addressed[120] by Maine DMR resource managers, but reports of unwanted *Fucus* in the harvest landings have been published by industry,[107,122] indicating there is algal bycatch.

Rockweed harvesting has direct impacts on plant morphology (individual), rockweed clump, and rockweed bed structure (population). Before cutting, rockweed plants form an underwater forest (Fig. 2) up to 200 cm tall;[32,33] after cutting, plants are shorter (e.g., Maine's 16″ [40 cm] regulation; Table 2) and produce numerous lateral branches,[34,35] creating a much shorter rockweed "bush." Many have noted short- to medium-term effects on the plant itself of cutting rockweed, including reductions in rockweed length, an increase in the number of lateral branches, and the proportion of laterals that are reproductive (Table 3). Fegley noted that full recovery of *Ascophyllum* had not occurred even two years after cutting: cut rockweed was significantly shorter.[10] Rockweed harvesting can also result in a loss of habitat complexity, since the most complex part of the clump in the canopy is removed. Holdfast loss occurs when the cutter rake has a dull blade[93] and when harvesters cut in areas where rockweed is easily dislodged.[120,123] Long-term effects noted in Canada include an altered population structure[115] and effects on habitat (Table 3 and references therein).

The "17% of biomass" guideline has been adopted in rockweed harvest management in NB as a "precautionary" level of harvest.[124] In the Cobscook Bay Rockweed Management Area (ME), 17% of available biomass in each bay sector may be removed.[84] What is the source of this number, and should it continue to be used as a "precautionary" management tool? The 17% figure is derived from a Canadian estimate that 50% of biomass could be removed every three years, although the state of Maine reports that rockweed biomass recovers from harvest in 3–11 years.[83] Rockweed is cut annually, and assuming 50% regrowth in three years, ~17% could be removed per year.[125] In the late 1990s, government managers of the rockweed harvest in New Brunswick questioned whether the biomass removed should be 17% everywhere in Canada,[12] recognizing that 17% may not be the right amount for particular areas, "including beds that, because of the substrate, would be vulnerable to holdfast removal during harvest. . .[and] beds known to be used by young eider ducklings, and beds adjacent to designated protected areas. . .These areas. . .might be harvested at a different exploitation rate, following a schedule which takes into consideration use by various species, or might be excluded from the management plan entirely."[12] We agree, and note in addition to these concerns, that 17% (which is ~34% of net primary production [NPP]) is too high to sustain NPP levels (this paper; see below).

To evaluate sustainability, many variables need to be considered. Data on rates of regrowth of rockweed are one. The list of factors affecting rockweed growth rates is long, and includes plant age,[126] size,[31] wave exposure,[43,44] solar irradiance,[44,127] temperature,[127,128] position in the intertidal zone,[127,129] season of the year (related to seasonal variation in temperature and light[127,130]), and site.[129] The large number of factors affecting regrowth rates is one reason that rockweed management on wide geographic scale (e.g., the state of Maine) is problematic.

Holdfasts are the primary source of frond recruitment to the population each year,[111] since recruitment via sexual reproduction is limited.[131] The estimate of "% holdfasts" (% of wet weight of clumps with holdfasts attached[112]) has been assumed to represent rockweed plant mortality.[112] Mortality has been estimated at 4–15% for cutter rake harvests[111] and 20–36% for mechanical harvests.[111] Recent work indicates that hand cutter rakes actually remove 17% of the holdfast tissue area when rockweed plants with attached holdfasts are removed,[112] suggesting that rather than clump mortality, "% holdfast material" represents plant injury, since some holdfast tissue remains. However, the ability of the holdfast to regenerate lost tissue is unknown.[112] Industry points to the observation that naturally storm-cast rockweed in the strand line also contains holdfasts as indicative that the impact of rockweed harvests is small compared to natural events. However, naturally storm-cast rockweed collected on the shore had significantly smaller area of holdfast material attached compared to the harvested clumps.[112] Furthermore, the naturally cast clumps with holdfasts decompose in the wrack and provide a source of nutrients to the ecosystem and food for crustaceans and insects[50] and birds,[54] whereas harvested rockweed clumps are lost from the marine ecosystem.

It is not simple to compare the impact of hand cutter rake and mechanical harvesting. Holdfast mortality from cutter rake harvests depends on individual harvester maintenance of the rake.[132] Mechanical harvesters shift the structure of the rockweed population from bimodal to unimodal, an effect that appears to last for approximately three years.[93] In general, mechanical harvesting removes more holdfasts than hand harvesting,[111] and mechanical harvesters are capable of taking more rockweed biomass per tide (hand: 2–3 t per boat; mechanical: 50 t/day).[133]

Is rockweed cutting "sustainable?"

The challenge of determining sustainable rockweed harvests has been taken up by industry representatives, resource managers, and conservationists in countries along the North Atlantic for at least the past decade (United States[125] and Canada,[97,134] Scotland,[15] Northern Ireland,[135,136] Ireland,[16,116] and Iceland[137]). Governments grapple with the question of how much rockweed can be "sustainably" removed in a harvest, yet they lack the information needed to determine these limits. For example, as the rockweed cutting industry moved into Grand Manan Island, NB, the Canadian government set the goal of ensuring that "harvesting and processing are undertaken in an environmentally acceptable manner;"[97] however, it did not establish criteria for determining the acceptability or sustainability of harvests. Consequently, it had no way to assess whether harvests were sustainable or not.[97]

What variables should be included in a definition of sustainable rockweed harvests? We can start to answer this question by looking at the relationship between NPP and the consumption of biomass by native herbivores in terrestrial ecosystems. McNaughton *et al.* found that about 15% of aboveground primary productivity is typically consumed by herbivores in grasslands.[138] Similarly, Cebrian reported that about 10% of NPP is consumed in marine macroalgal communities, drawing on data from 28 studies, one of which examined fucoid algae in Canada.[139] Given these estimates, a commercial harvest in which 17% of rockweed biomass is removed (e.g., NB and Cobscook Bay Rockweed Management Area, ME) is excessive. This is because removing 17% of biomass removes 34% of NPP, given that the biomass turnover rate is typically about 0.5. This points out the serious shortcomings of using biomass recovery at a 17%/yr removal rate or using maximum sustainable yield (MSY) as a measure of sustainable harvests.[82,140–142]

Besides setting the removal rate at the right level, other critical parameters that need to be considered in defining an ecologically sustainable harvest include recovery of preharvest rockweed morphology, rockweed bed structure, rockweed community structure and function, and ecosystem function. There is agreement in the scientific community that identifying ecologically sustainable harvests will require impact studies that include cumulative impacts of annual harvests and impacts on a landscape scale.[88] Fegley hinted that the effects of repeated cutting on a large scale are likely to be larger than the effects documented in her smaller-scale experimental study and recommended landscape-scale studies to understand the full impact of commercial rockweed harvesting.[10] A cumulative impact assessment is necessary to achieve ecologically sustainable harvests,[143] but cumulative impacts are still unknown.[83,88]

In addition to problems defining a ecologically sustainable level of rockweed harvest and the challenge of understanding cumulative impacts on a landscape scale, there are three further difficulties in assessing an ecologically sustainable level of harvest: a complex web of interactions in a diverse rockweed community[29] creates challenges for direct harvest impact assessments;[22] the rockweed community (vertebrates, invertebrates, algae) varies in space and time,[10,22,144] creating site- and time-specific impacts,[10,25] and high-power statistical tests of impact will require large sample sizes or long-term studies,[22] or both.

The challenges described above result in a lack of adequate measures of the full impact of rockweed harvesting. The dearth of impact assessment, combined with the tendency of state and provincial governments to allow rockweed harvests unless and until negative impact information is available, has produced a situation in which rockweed harvests are intensifying even though critical scientific information is lacking. In contrast, participants at the 1999 rockweed workshop in St. Andrews, New Brunswick, suggested that independent studies demonstrating no long-term impacts should be required prior to the start of rockweed harvesting, rather the procedure usually in place in which scientists bear the burden of demonstrating negative impacts before large-scale harvests are curtailed.[27]

Sustainability concerns in the NE Atlantic

The Scottish Environmental Protection Agency (SEPA) has stated that "SEPA's primary concern would be to see that any harvesting is undertaken in a manner that is sustainable and does not therefore harm the ecosystem" (Baird).[15] Scottish National Heritage concluded that assessments of sustainable rockweed harvest show "ecosystem as well as *Ascophyllum* recovery. . .such studies would have needed a much longer term study."[15] In Northern Ireland, the Environment and Heritage Service (EHS, currently the Department of Environment) refused to support mechanical harvesting "unless it can be demonstrated that it will not have an adverse impact on the environment."[135] The EHS proposed an Environmentally Sustainable Seaweed Harvesting Code of Conduct,[135] including consent from landowners, preharvesting plan, rotation cycles, harvesting methods, environmental protection measures, and harvest records. The Code of Conduct was proposed to industry but never adopted. With respect to sustainability, the final EHS report concluded that "there is a lack of specific information on the carrying capacity of marine ecosystems to support seaweed harvesting."[136] In Ireland, there is concern about the impact of repeat harvesting and a recommendation that mechanical harvesting be prohibited.[16]

Once a sustainable level of harvest is determined for an area, strict enforcement of regulations is necessary, because the cutter with the rake will be biased toward immediate benefit rather than long-term health of the rockweed.[113,145]

Is Ascophyllum *a species under threat?*

The old-growth rockweed forest is already at risk from warming ocean temperatures[122] and pollution, which has led to the loss of *Ascophyllum* in the Baltic.[146,108] There is evidence that *Ascophyllum* is slowly being replaced by *Fucus*[107] in the NW Atlantic, as *Chondrus* was replaced by *Furcellaria* in the Maritime provinces.[147] *Chondrus* raking was also once a thriving industry in Maritime Canada and the Gulf of Maine, but as a percentage of total seaweed landed, *Chondrus* is now near zero.[147] *Ascophyllum* stands may, in fact, be relicts, established prior to the arrival of the common periwinkle, *L. littorea*.[148]

Landed Maine seaweed, primarily rockweed (~92–96% of landings since 2006 [Maine Department of Marine Resources, personal communication to R.H. Seeley]), is valued at two cents a pound, ranked last (by value) in the list of commercial harvests listed by the ME DMR.[149] Millions of pounds of rockweed are removed annually from the Maine coast. Without ecologically appropriate sustainability data, the level of rockweed harvests placing at risk species much higher on Maine's commercial value ranking—including lobster, scallop, clam, periwinkle, and groundfish (pollock, herring, flounder)—is unknown. Maine's management of rockweed harvesting, outside of the Cobscook Bay Rockweed Management Area, seems particularly weak compared to Canada's much stricter requirements. The rockweed industry in most areas of Maine is left to manage itself.

There is huge potential for mismanagement of rockweed harvesting, with significant ecosystem consequences. We are pessimistic about any improvement in Maine's management of rockweed harvests as they intensify, given declining state resources. For this reason, it would be prudent to curtail rockweed harvests until appropriate resources are found to devote to rockweed management, including landscape-scaled and long-term studies of community impacts of cutting rockweed and corresponding design and enforcement of regulations that protect rockweed habitat. Despite its protected status under Maine's NRPA, "Significant Wildlife Habitat" (including "seaweed communities") of special value to wading birds, shorebirds, and ducks is harvested for rockweed, as is areas of "High Value Habitat for Priority Trust Species" (e.g., the Jonesport/Beals area[52]).

There is no evidence that rockweed cutting in Maine and the Maritime provinces is ecologically sustainable, but there is a long history in fisheries management of allowing resource extraction when scientific information is missing until a crisis of overharvest occurs.[150] Should resource extractors be required to show evidence of ecological sustainability before commercial extraction of low trophic level, habitat-forming seaweeds is permitted? Or is it acceptable and wise to permit the extraction despite missing scientific information?[150]

Conclusions

(1) Rockweed has critical value as habitat, as food, and as a nutrient source supporting a community of over 150 other organisms in Maine and the Maritime Provinces (Ref. 11; Table 1).
(2) Cutting rockweed has documented impacts on the alga itself and on the rockweed community as a whole (Table 3).
(3) The current metric for "sustainable" harvests—MSY—is inappropriately narrow. A metric for an ecologically sustainable harvest must be based on the data from large-scale, long-term studies of postharvest recovery of rockweed morphology, of rockweed community structure and function, and of ecosystem impacts. Until this metric is developed and enforceable regulations based on it are developed, commercial-scale rockweed cutting should not be permitted.

As Smith *et al.*[151] have recently reported in a study of global fisheries, removing low-trophic level species that constitute a high proportion of the biomass in the ecosystem or are highly connected in the food web at standard levels of MSY can have large impacts on the rest of the ecosystem, including commercially valuable fish. *Ascophyllum* fits all three criteria (low-trophic level, high proportion of biomass,[3] highly connected in the food web[13,29]). Therefore, Smith *et al.*'s[151] findings serve as a warning about the dangers of failing to manage rockweed and other wild seaweeds sustainably.

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Conflicts of interest

The authors declare no conflicts of interest.

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