Invasive Species of the Pacific Northwest:

Wakame, *Unidaria pinnatifida,* Sea mustard, Japanese Kelp

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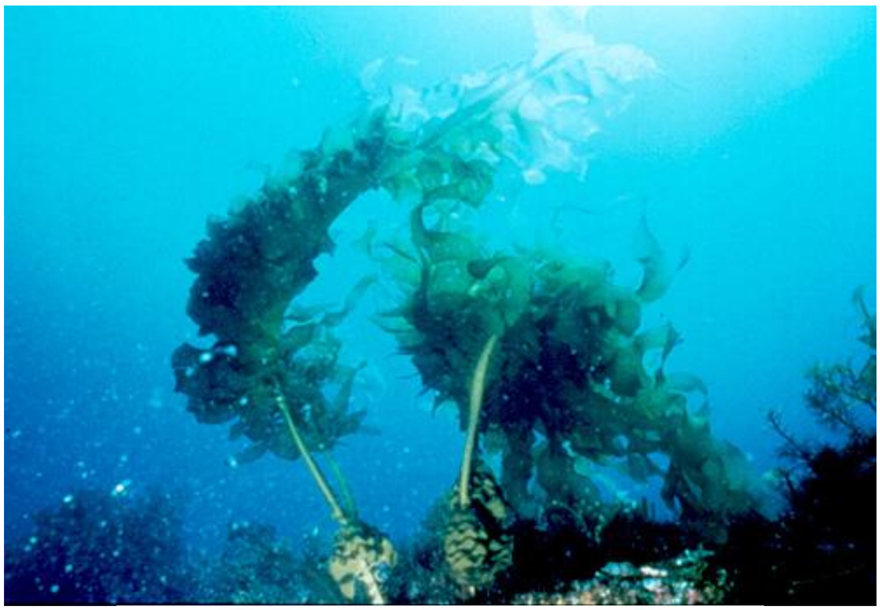

Fig.1 shows *Unidiara Pinnfida* in its Native range of the coast of Japan Photo beneath shows Wakame hat is found in stores used in cooking. Photos from: http://www.ala.org.au/blogs-news/have-you-seen-this-seaweed-in-victoria/ and http://static.caloriecount.about.com/images/medium/wel-pac-fueru-wakame-4585.jpg

Diagnostic Information

Taxonomy:

Order: *Laminaries*
Family: *Alariaceae*
Genus: *Unidaria*
Species: *U.pinnatifida*

Identification Key

Wakame is a type of brown algae found in the cold temperate areas of the Northwest Pacific ocean. In particular it is native to coastal areas of Japan, China, Korea and Russia. Wakame is known to grow up to 1-3 m in length and has long been cultivated as a food source. It has a golden brown color and occurs in dense stands. *Unidaria* occupy the canopy of the intertidal zone. (MarLin: The marine Life Information Network) Near the base of the plant is a branched holdfast. The hold fast is a root like structure that the algae use to anchor on to the sea bed. (NNSS:GB non-native species secretariat) Coming of the hold fast are reproductive frills along both sides of the stipe. The stipe is elongated growing up the middle of the fond. The blade is lanceolate and broad with shallow pinnae. The blade is spotted with white cryptostomata and dark gland cells. It can be sometimes misidentified as other algae such as the furbelows(*Saccorhiza polyschides)* or sea belt(*Laminaria saccharina.* The distinctive mid-rib is what sets the *Unidaria Pinnatifida* apart from other marine aquatic plants. (MarLin: The marine Life Information Network)

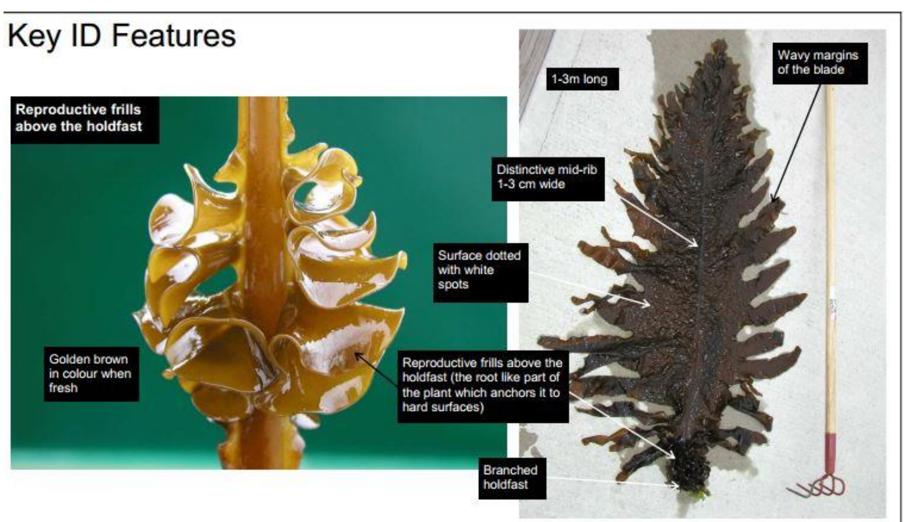

Fig. 2 shows the unique characteristics found on *U. pinnatifida* (NNSS:GB)

Life-history And Basic Ecology

Life Cycle

U. pinnatifida has a typical heteromorphic life cycle. Wakame has two main life stages, sporophyte and microscopic gametophytes. The adult stage is known as a sporophyte. The life cycle begins in autumn; when water temperatures are cooling down to allow the recruitment of sporophytes. Once the water cooled to optimal growth temperature, typically in the winter time the sporophytes begin to develop spores. These haploid spores are formed after meiotic division of the diploid nuclei in the unilocular sporangia that are grouped in fertile areas called the sori. These spores are released and can swim up to 5-6 hours before settling on a firm substrate. This typically happens around spring. Upon settlement, they develop directly into male and females gametophytes. Biflagellate male gametes are released and fertilized the female eggs of the female gametophytes. Once fertilized, this develops *in* situ into an embryonic sporophyte.(Silva, P.et al. 2002) These gametophytes take the summer season to develop into a mature sporophyte and the cycle starts again. In New Zealand, maturation is complete only after 50-70 days. (Wotton, D et al. 2004) In its native range, gametophore release is observed from March to July. In New Zealand and Australia, where this species has colonized, there have been two or more generations per year. There is a year round presence of sporophytes and spore release happens nearly year round. The fecundity of gametophytes and sporophytes are high, but percentage of establishment and survival are low. (Schaffelke, B et al. 2005) Due to the similarity in waters if wakame be introduced to the Pacific Northwest, it would most likely adapt a life cycle similar to the one of its native range. However, there is no telling for certain how the life cycle will be for an environment in the Pacific Northwest. Researchers hypothesize that water may be cold enough year round that there may be a possibility of over lapping generations a year, due to the fact that growth happens when the sea surface temperatures are the coldest. This bi-phasic life history has been key component in its facilitation of global spread. (Thornber,C et. Al 2004)

Environmental optima and tolerances

One of the main contributing factors to its geographic distribution is wakame's ability to survive in a wide range of sea water temperatures. For gametophytes, the optimal growth temperature is 20°C with an upper critical temperature of 28°C. For maturation into sporophytes an optimal temperature between 10°C-15°C is needed. (Teruwo M. et all 2003)Although water temperature is important for survival and determines key timing events in its life history it has little effect on growth. Wakame is the only laminaries that is a winter annual. This means that maximal growth happens when light levels are lowest and sea water nitrate concentrations are high. (Dean, P et. al, 2007) A study of seasonal growth showed a negative correlation with solar iridescence and sea surface temperature. There was positive correlation between sea water nitrate concentration and growth. This is why growth is often seen in winter time months because light is low and nutrient concentrations are high. Its competitive ability has seen in decrease in spring when the Nitrate concentrations are the lowest. Unlike, other algae wakame does not store large nitrate pools and has the ability to assimilate nitrate for photosynthesis quite rapidly. The maximum soluble tissue content is 27umol/gw is lower than most perennial laminarmins. The North West is a region of strong upwelling. Upwelled water brings cold and nutrient rich water to the surface. A species like wakame would thrive in a region such as the Puget Sound where water is being upwelled in the winter months. Wakame is usually found in coastal regions around 4m in sub littoral zone. (Dean, P et. al, 2007)*Unidaria* usually prefers a habitat in allows a greater chance of survival for the gametophtes once they are released from the sporophyte. Despite its preference for low wave action areas it is able to establish in locations which are exposed to chronic and significant wave action. Areas of shallow water up to 2-8 meters in depth that are in the intertidal zone have been sites to have known *Unidaria* populations. The most plastic quality is the sporophyte's ability to attach to almost any surface when it is dislodged or settled to being its maturation. Sporophytes can grow on any available surface from natural substrata (rocks and shells) to artificial (docks, metal, concrete, plastic, glass). (Russell, L, et. al, 2008) Dispersal is found to be greatest in harbors with high water exchange with surrounding coastal waters. Prevailing currents also allow for the movement of spores that release the gametophores. Establishment is achieved by mature sporophytes washing up in rocky intertidal zones such as rock pools. The greatest observed populations are found on jetties and artificial substrata such as sea walls, buoys and docks.

Biotic Associations(pathogens, parasites, and commensals)

Out of all the members of the *Laminariales*, *Unidaria has* the most pests associated with it. There are several known types of bacteria, animals, fungi associated with *Unidaria*. Firstly, there are no known viruses associated with these algae. There are two types of disease called "spot-rotting" disease and "shot hole disease" associated with *Unidaria*.

Host	Viruses	Bacteria	Animals	Fungi	Other algae	Total
Alaria esculenta			2	1	1	4
Alaria marginata					1	1
Alaria sp.					1	1
Alaria tenuifolia					1	1
Chorda filum				1	10	11
Costaria sp.					3	3
Cymathaere triplicata					1	1
Dictyoneurum californicum					1	1
Ecklonia maxima					1	1
Ecklonia radiata	3		1		4	8
Egregia laevigata		1				1
Egregia menziesii				2	4	6
Eisenia arborea			2			2
Hedophyllum sp.					1	1
Laminaria andersonii					1	1
Laminaria digitata		1		5	12	18
Laminaria hyperborea					8	8
Laminaria ochroleuca				1		1
Laminaria setchellii			3			3
Laminaria sinclairii					1	1
Laminaria sp.		1		7	5	13
Lessonia tholiformis					1	1
Lessoniopsis littoralis					4	4
Macrocystis integrifolia					3	3
Macrocystis pyrifera		1	1		8	10
Nereocystis luetkeana		1			4	5
Pelagophycus porra		1				1
Pleurophycus gardneri					1	1
Pterygophora californica			1			1
Saccharina dentigera			3		2	5
Saccharina groenlandica					1	1
Saccharina japonica		34	1	1	2	38
Saccharina latissima				10	23	33
Saccharina longicruris				2	3	5
Saccharina ochotensis		5				5
Saccharina sessilis					1	1
Undaria pinnatifida		16	14	3	8	41
Total	3	61	28	33	117	242

Aermonas, *flavoebacterium* and *Vibrio* are just

Table 1: Is a summary of the number of recors of pest type for every member of the *Laminariales* (Ministry of Agriculure and Forestry of New Zealand)

some of the gram-negative bacteria associated with these diseases. *Vibro* affects young sporophytes. The “shot hole disase” is characterized by an infection that causes brown spots to appear on the thallus blade near the mid rib. The “green spot rot” is caused by an unknown bacteria in Japan and South Korea. The first symptom is green spots that rot the plan’s tissue. This results in small holes with green margins and the internal parts of the frond is exposed which further accelerates the decay. The *Unidaria* in Japan are also infected by a unspecified that causes “yellow hole disease” In infections such as these bacteria enters the thallus of U.pinnatifida through dead mucilage changes and digest cells and cells wall in the medulla. Cells in the cortex and merisotoderm show sturctral damage. When the host finally dies the disease symptoms can be seen visually. There are a small number of crustaceans that are associated with diseases in *Unidara*. The “pin hole disease” is caused by a frond-mining of harpacticoid copepod from Japan and in South Korea. There is another animal that is associated with the *Unidaria* that bores a tunnel that causes separation of the entire from the midrib. This animal is a gammeride amphipod native to South Korea. Further damage can be inflicted on the plant where the holdfast may be detached from the substrate.
Finally, there is fungal infection that occurs in this species called “chytrid blight.” This disease is caused by an oomycete under the genus of *Olipidopsis*. The fungus affects sporophytes by growing inside it and slowly killing it. The algae eventually lose its color and will disintegrate. (Ministry of Agriculture and Forestry of New Zealand 2009)

Current Geographic Distribution

Wakame is naturally found in abundance on the rocky coasts of the Sea of Japan. Wakame has been found outside of its native range in the Mediterranean off the coast of France. It then spread to other parts of Europe: Belgium, the United Kingdom and the Netherlands. (Schaffelke, B. et. al, 2005) Wakame has also been found in New Zealand and Australia. Recently, California and the Pacific East Coast of Mexico have had known populations. Currently there are no known cases of U. pinnatifida established in the Pacific Northwest. However, marine debris from the Japanese tsunami of 2011, ballast water, and hull fouling all threaten to introduce this species to the Northwest.

Fig. 3 Top: Native Range Bottowm:Shows Wakame’s global distribution (SIMoN Sancuatry)

History of Invasiveness

Wakame has been cultivated from nature and preserved to use be used in cooking by the Japanese for many centuries. A well-known dish that uses *U. pinnatifda* is miso soup served with tofu and pieces of wakame added for flavor and texture to the dish. In Eastern medicine it has been used as an ailment for detoxifying blood, easing digestive distress and improving reproductive health. (Wellness today) My mother used to tell me to eat my wakame if I wanted long and healthy hair. This alga has long standing in Japanese culture. To improve productivity and prevent exhaustions many methods of cultivation have been developed in 1952. One of the more common practices is having aquaculture facilities in the Open Ocean in which wakame is grown hanging off ropes that have been casted out. In recent times, it has been marketed as a superfood due to its many health benefits and low caloric intake. In 1971 a lagoon on the Mediterranean coast, Etang de Thau, wakame was first discovered outside its native range. It was thought to have been accidental imported with Pacific Oyster that is harvested in the waters of that region. (Silva, P.et al. 2002) Soon it spread down the south coast of France to two sites in Italy. In the Atlantic coast there have been several different sites from Spain to the Netherlands and to Southern England where *Undaria* has been introduced. In 1987 it was first discovered in New Zealand and has spread to nearby Stewart Islands. It was classified as and "unwanted organism" there under the Biosecurity Act of 1993. This classification is bestowed to organisms capable of causing unwanted harm to any natural resource or human health. (Russell, L, et. al, 2008) Australia first recorded wakame in 1988, on the east coast of Tasmania. By 1996, just 15 years later it has spread 150 km north and 80km south of the initial invasion site. A secondary site was identified that in 1996, off the coast of Victoria. In 1992, the species was found in a site in Argentina. On the west coast of the United States, *Undaria* was found in Los Angeles Harbor on March 2000 on a floating pier and boom. By June there was an abundance of mature sporophytes and actively moved up the west coast. It has been found in Long Beach Inner Harbor in May, a month later is was found in Channel Islands Harbor. In April 2001, there was a robust population found on the Santa Barbara Harbor on floating piers and concrete pilings that are home to transient boats. 190kg (wet weight) of *Undaria* were removed from that harbor in May 2001. Finally it has been found on Catalina Island and Monterrey Harbor. Although there have been no established populations found north of Monterrey Harbor. *Unidaria* has a high chance of establishing in the Northwest. Water temperatures from Baja California to British Columbia are favorable for the establishment of this population. Vectors such as ballast water, hull fouling and debris could move this organism further up the west coast. On June 4, 2012 a floating dock washed ashore on Agate Beach, Oregon. This dock has been named Misawa "1" dock and was dislodged by the 2011 Tōhoku Earthquake and Tsunami. There were over 130 different species found living on this dock after months of floating in the open ocean. There were 30 living species of *Unidaria* found on this single dock alone. This raised much concern to the ecologist of Oregon State University.(Species Found on Floating dock OSU Data) Since over 40 other skiffs and a number of other debris materials such as cars have washed up on the coasts of Washington and Oregon. Not all of these items have positively identified *Unidaria* on them; however some have been known to be carrying it. Without rapid response and proper disposal it can easily establish due to the favorable conditions of the sea water.

Fig. 4 *U.Pinnatifida found attached to the dock*
https://www.flickr.com/photos/80098236@N07/

Fig. 5 Photo of the boat found in Agate Beach.

https://www.flickr.com/photos/80098236@N07/7158793927/

Invasion Process

Wakame has been able to spread globally through transport associated with international shipping. These vectors include ballast water and hull fouling. The life stages of *Unidaira* reinforce its dispersal. The gametophyte stage is microscopic, making it nearly impossible to detect. It most likely is taken up by ballast water. In order to maintain proper stability and to minimize drag, ships will often take up water from their port of origin and travel to its destination. Upon arrival, ships will unload hundreds of gallons of water. When this water is disposed many of the organisms that were taken up are dumped in a new location. As previously mentioned, *Unidaria* prefers to establish in ecosystems in which it is protected from wave actions. Harbors are provided a number of substrates that it can attach on such as docks and buoys. Harbors also provide protection from waves that lower survivorship of the propagule. The ability for a sporophyte to grow on any substrate also provides another vector: hull fouling. This species is able to attach to any part of a boat and travel across the ocean to a new environment. Things such as anti-fouling paints have helped in reducing the number of organisms that can hitchhike their way to a new site. In places such as harbors where there is high boat traffic increases the propagule number. With high initial populations at the time of introduction paired with frequent boat traffic the probability of establishment become high. Wakame has also been established in both hemispheres, where the seasonal changes that affect the life cycle happen at different times. This can lead to a higher probability of mature sporophytes reaching a different location. Finally, the debris of the tsunami and earthquake are reaching the shores of the Pacific Northwest. Many of these docks and boats that e washing up have propagules of good ndition and are arriving with parts of the onor region that help them survive. urthermore the donor region has key aracteristics in helping *Unidaria* survive. With l three vectors combined this creates a greater opagule pressure. Domestic translocation of is species is often attributed to fishing, boating and aquaculture activities. *Unidaria* has been introduced in some instances by accident with its close association to the Pacific oyster, or has been intentionally introduced for food cultivation. In many areas of the world Wakame is harvested in the wild or cultivated for production. Often time these intentional introductions have unintended consequences as the case was in France. (Silva, P.et al. 2002)Finally, natural dispersal can occur through the dislodgement of fragments or whole sporophytes can drift from a range of 100 meters to a few kilometers. Spore dispersal happens on a much smaller scale of less than 100m. (Russell, L, et. al, 2008) *Unidaria* uses more of an optimistic approach to establishing a population rather than one of being an aggressive competitor. It has been shown that native algae in both Australia and California have shown resistance and have facilitated the establishment of *Unidaria*. In places where there had been a disturbance event such a canopy removal have allowed for wakame to come in and dominate the landscape. Many of these disturbance regimes are cause by sea urchin "barrens" in which sea urchins have grazed most of the native algae leaving an open canopy. (Valentine, J. et. al, 2009)

Most of the economic impacts of this species have been efforts put into its removal. In New Zealand, it cost NZ$ 380,000 for a cleaning of a 40m long trawler that had sunk and another NZ 45,000 for monthly diver inspections from May 2001 to 2003. This project was successful in eradicating *Unidaria*. (Valentine, J. et. al, 2009) Ongoing removal efforts that are taking place in New Zealand are costing about NZ$500,000/yr for areas of high value and most concern. Areas such as these contain endemic species or species of high endangerment risks. (Lonhart, S, 2009) Wakame has also threatened the fisheries and matriculture industry. There have been increased costs of handling and selling of fouled shellfish.

There also may be indirect influence on commercially important species. (NNSS:GB non-native species secretariat)Tsunami debris cleanup is associated with the prevention of establishment with this species. The estimated cost of Japanese tsunami debris removal between 2012-2015 in just the Oregon Parks and Recreation Dept. alone will range from $1.55-$5.65 million dollars. This cost does not include costs by other organizations for risk analysis and human and safety concerns and aquatic invasive species associated with tsunami debris. (Species Found on Floating dock OSU Data) A positive economic impact of the growth of wakame is its value as a food source. In Japan, 239 tons of wakame grown in nature was harvested. Bringing 8.3 million dollars in to its economy an additional 70,760 tons are produced in aquaculture facilities. This amount is said to be worth 132.5 million dollars. (Silva, P.et al. 2002)

There is a lot of unknown ecological impact establishment has on native communities and has been a topic for further investigation. However it is a known fact that disturbance of native algae species leads to a higher chance of invasion probably as previously mentioned. The only place to have studied and seen a measureable ecological impact has been in Golfo Nuevo, Argentina. The presence of *Unidaria* has been associated with increased species richness and diversity as shown by Irigoyen, A and others. Most of the native algae in this area do not grow as long as *Unidari.* As consequence, there has been a measureable abundance of benthic macro fauna species. This could potentially produce a bottom- up effect in the local food chain. Increasing the amount of species on lower trophic levels means more prey viable for a wide range of predators. It also has habitat forming effect so organisms such as small fish are able to find protection. *Udiara* has the possibility to enhance the consumer populations of the green sea urchin and the snail tegula. There are many harmful impacts the establishment of this invasive species, however there is a silver lining.

Management strategies and Control Methods

Unidaria's ability to release millions of spores and drift long distances as an adult sporophyte once it has been establishes it is nearly impossible to completely eradicate the species. The key to managing this species is early detection and rapid response. There have been several methods that have been used to try managing this species. The first is the manual remove of the species in rationalized concentrations. Of the three class sizes of this species, any sizes over 55 cm were targeted for

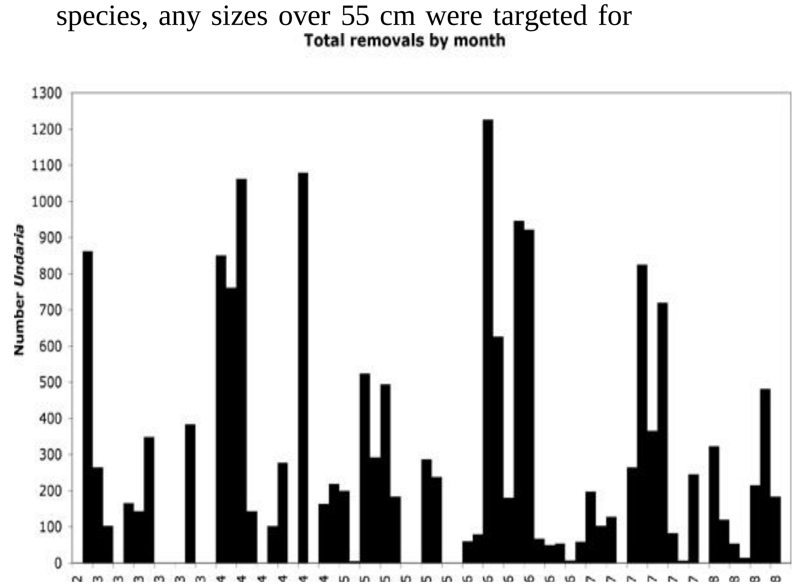

Fig. 5 Starting Dec. 2002 Volunteers and San tuary Sraff of Monterey Harbor have removed and measure 17,000 indviduals. This figure shows the numver removed per month. Months with no data were not surveyed (SIMoN Sanctuary)

removal. Larger sporophytes produce the greatest proportion of zoospores. It has been suggested in Schaffelke, that there should be 5 dive days each month for an area of 800m^sup2^ every 1-2 weeks to control and area in Tasmania. In Montery Harbor, there have been many volunteer programs coincided with governmental organizations of physically removing *Unidaria.* Many of these eradication efforts go unsuccessful due the sheer number of species in a given population. (Schaffelke, B et al. 2005)

Heat treatment methods have also been used in removing *Unidaria*. Heat treatments have been seen as practical, cost effective and environmentally sound compared to other methods. This method was used on a sunken trawler in Chatman Islands, New Zealand. In this method targeted areas were exposed to temperatures around 60°C. This kills the *Unidaria* because it is a temperature well beyond its upper critical point. Heat was applied with two different methods. One was to use plywood boxes with elements to heat the hull of the boat and to kill the gametophytes. The second method entailed a diver using a Petrogen flame torch to treat areas of the hull, in which the boxes were not practical. As previously mentioned this procedure has an initial investment of NZ$380000(~30000 USD) and additional NZ$ 45,000 (~35000 USD), but it was a successful eradication.

In other places of the world, such intensive removal is not needed. In California native herbivores can be capable of effectively controlling the spread of wakame. A native kelp crab *Pugettia porducta* have been preventing the winter recruitment pulse. Lab experiments have shown that *Pugettia* consumes wakame as it consumes the native kelp and it Udaria was significantly more palatable. In addition, many of the native algal species facilitate the growth of *Unidaria.* The west coast of North America holds the most diversity for native kelp species in the world. Most of these species are perennial with occurrence of annual species facilitated by disturbance. (Thornber, C. et. al, 2004) Wakame may impact these communities if they are more persistent than seasonal. This may be a possible threat as the waters of the Pacific Northwest are much colder. This could possibly promote year-round populations with overlapping generations. Constant monitoring and control efforts should be put in place to prevent invasion to places that are susceptible to these optimal conditions for *Unidaria.*

Current Research and Management Efforts

There has been ongoing research to assess the ecological impacts of *Unidaria* on the ecosystem it establishes in. These studies are being done on a spatial scale. In places such as California and New Zealand this work is currently being done. This takes time and careful monitoring, which can sometimes be costly. Recently there has been work done to use algae such as *Unidaria* as a biofuel. Algae biofuel production would be a cost effective, renewable and abundant energy source. In places where *Unidaria* poses a threat to the ecosystem, this application would manage population sizes and create a new sector of the economy. In order to create biofuel the algae is put through a careful process, first starting with a pretreatment. Then the pathway breaks off into enzyme production that feeds in back into the cycle of saccharification and fermentation. Both of these steps are done simultaneously and move on to recovery and distillation where ethanol is produced. At this step solids are separated and burned to create steam and power generation. This steam can be processed to create electricity. (Li, K. et al. 2014)

Table II. Carbohydrate content of algae cell (% of dry matter).

Algae	Biomass	Carbohydrate	Reference
Microalgae	*Chlorococcum infusionum*	32	[16]
	Chlamydomonas reinhardtii	59.7	[17]
	Porphyridium cruentum	40–57	[18]
Macroalgae	*Undaria pinnatifida* (brown seaweed)	48.5	[19]
	Sargassum spp. (brown seaweed)	41.81	[20]
	Kappaphycus alvarezii (red seaweed)	64	[21]
	Gelidium amansii (red seaweed)	67.3	[22]
	Ulva lactuca (green seaweed)	54.3	[23]

Management efforts should be put towards controlling existing populations and maintain populations of native algae in grazers. *Unidaria* is not known to be an aggressive competitor, but rather fill niches in an environment in which there is no canopy. To prevent establishment, managers should focus more on maintaining a viable native algae population so that there is less of an opportunity for *Unidaraia* invasion. Similarly, native grazers like the *Pugettia* pordcuta and species such as native urchin should be protected. Well established populations of grazers will keep the natural order of the habitat and checking the growth of Unidaria. The most effective management tool is early detection and rapid response. This action plan should be taken with the tsunami debris washing ashore on the coasts of Washington and Oregon. The sooner these things are removed the less time *Unidaria* has to establish in the area where the debris was washed up. Finally, the public should be informed about what this plant looks like and who to contact if there is a place in which it is spotted. The public should also be informed of its health benefits. In places like New Zealand *Unidaria* is cultivated and sold to local restaurants and businesses.

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Other Key Sources of Information

Species Found on Floating dock:
http://blogs.oregonstate.edu/floatingdock/

Global Invasive Species Database:
http://www.issg.org/database/species/impact_info.asp?si=68&fr=1&sts=&lang=EN

SIMoN Program on Monterey Bay National Marine Sancuary:
http://sanctuarysimon.org/projects/project_info.php?projectID=100184

NNSS:GB non-native species secretariat:
http://www.nonnativespecies.org/factsheet/factsheet.cfm?speciesId=3643

MarLin: The marine Life Information Network:
http://www.marlin.ac.uk/speciesinformation.php?speciesID=4547

Wellness Today:
http://www.wellnesstoday.com/nutrition/wakame-the-sea-vegetable-you-should-be-eating

Regional Contacts:

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Report Marine debris

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