Invasive species of the Pacific Northwest:

Didymo: *Didymosphenia geminata*.

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FISH 423: Olden

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Fig. 1 Man holding up rocks covered in didymo with stream rocks covered as well in background. Photo courtesy of http://cisr.ucr.edu/didymo_rock_snot.html

Diagnostic Information

Classification

Order: Cymbellales

Family: Gomphonemataceae

Genus: *Didymosphenia*

Species: *geminate*

Common names: Didymo Rock snot

Identification key

Didymo is a freshwater benthic diatom (Fig. 2) that typically survives in cold, clear water in streams, rivers, and lakes. These single celled organisms have silica cell walls that are around 100 micrometers long, and contain a raphe (allowing them to move on surfaces) and a apical porefield(which the mucopolysaccharide stalk is secreted)(Fig. 2) (Minnesota Seagrant 2014).Once attached to a solid surface, typically a rock, using its polysaccharide stalks (Bothwell, Lynch, Wright, & Deniseger 2009) it will then grow via its bifurcating division pattern of cells and stalks. Eventually this will form multiple branching stalks. This results in thick hemispherical clumps which can grow to be around 2-3 feet in length (Minnesota Sea Grant 2014) (Fig.3) which, under favorable growth conditions, leads to an expansion of individual groups of Didymo into large mats formed by their stalks (Fig. 1).

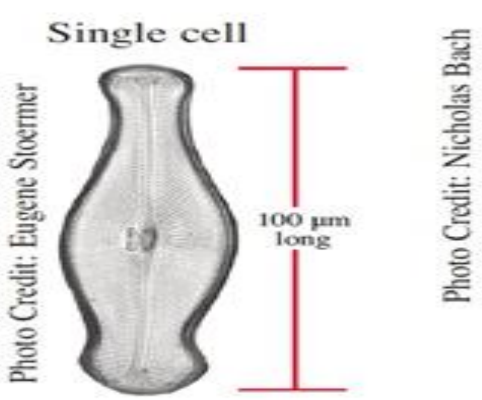

Fig. 2 Photo identification of the single celled Didymo. Photo courtesy of http://www.seagrant.umn.edu/ais/didymo

These large mats are typically 1-5 mm thick (Gretz 2007) and several feet in length. They can be tan, brown, or yellow in color with white ends that float downstream, appearing similar to wet toilet paper (PA Fish & Boat Commission 2014, Yosemite National Park 2010, NY Department of Environmental Conservation 2014). Contrary to its common name as “rock snot”, it is not slimy but has been described with a texture akin to wet wool or cotton fabric (Yosemite National Park 2010).

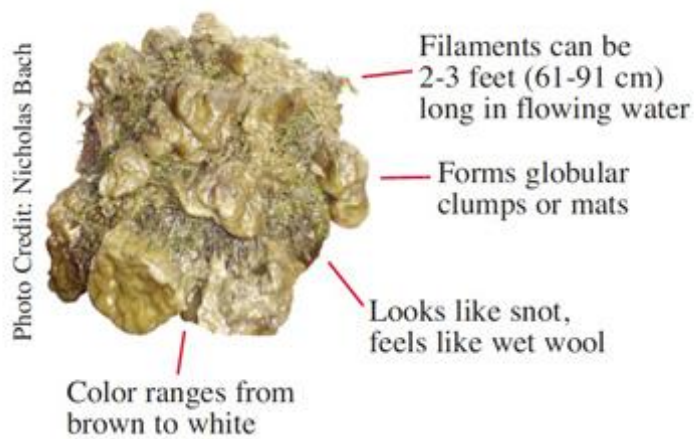

Fig. 3 Rock snot formation before they turn into mats. Photo courtesy of http://www.seagrant.umn.edu/ais/didymo

Life history and basic ecology

Reproduction

Didymo have been shown to reproduce both asexually and sexually, but typically by asexual cell division. Sexually, auxopore formation (when the diatom cell is spherical in shape and lacks a silica cell wall) of Didymo, as observed by Meyer (1929) in Lake Baikal, showed that two cells paired within a mucilage tube before “mating”; with cells always pairing head to tail (Canter-Lund & Lund 1995). Post auxophore forms looked morphologically different from typical cells found within the vicinity. However, it should be noted that sexual reproduction for Didymo has not been recently documented (Bothwell et al. 2007) though has been observed in relatives to Didymo such as *D. lineata* (Skabichevsky 1983).

Environmental optima and tolerances

After research was conducted to study the impact of environmental factors (namely light and nutrient concentrations of nitrogen and phosphorus) leading to Didymo propagation in New Zealand, three papers were published which are known as the "Didymo Trilogy" each of which contain information on how each of these environmental factors effect Didymo.

Light is a factor that impacts Didymo blooms, though eventually leads to photo-inhibition. Measuring Didymo cell attachments and stalk lengths under different light treatments, Kilroy and Bothwell (2014) found that an increase in light influenced Didymo positively (with an increase in attachment densities and stalk length) but eventually showed a decrease after exposed to very high intensities. Didymo's positive response to an increase in light, resulting in Didymo blooms, has been found in other studies (Kilroy & Bothwell 2011, Gillis et al 2010)

Contrary to most other algal blooms, Didymo actually bloom in water that has low nitrogen and phosphorus content (nutrient poor waters) the main elements of influence. Within the previous study, it was found that Didymo stalk length exposed to nitrogen elevated up to 115 mg m-3 growth were negatively affected but the treatment did not affect cell attachment to substrate (Kilroy & Bothwell 2014).

Within the three environmental factors, the main impact upon Didymo blooms is phosphorus content. Low phosphorus content has been linked to Didymo blooms within multiple studies. When exposed to high concentrations of phosphate, cells will divide rapidly for a short period of time but then colony biomass will eventually decrease (Bothwell & Kilroy 2011).

However, with exposure to low phosphorus amounts (lower than 2 parts per billion (ppb)) Didymo will show a rapid increase in diatom specific growth (Bothwell, Taylor, & Kilroy 2014). Looking at the South Island of New Zealand, Kilroy and Bothwell (2012) found that Didymo was mostly concentrated at sites that had mean dissolved reactive phosphorus of less than the 2 mg m^{-3}.

This was further studied by exposing Didymo sites to water enriched with phosphate for 4 weeks and then nutrient levels were allowed to drop back down. Didymo communities showed that the average stalk length increased 250% after just two weeks post nutrient enrichment exposure with the actual color changing from a dark brown to pale (a typical color for Didymo blooms).

The main reason for why low phosphorus concentrations relate positively to Didymo growth is that they are inversely related to cell division rates. As in the previous study, cell division rates declined by 60% post nutrient enrichment exposure. Physical processes proposed for this are outlined in Bothwell, Taylor, and Kilroys study (2014), 1) atmospheric deposition of reactive nitrogen from fossil fuel use and urbanization 2) climate regime shifts due to timing of snowmelt that decreases phosphorus input in rivers 3) nitrogen enrichment via agricultural practices resulting in an increase of terrestrial retention of phosphorus and 4) decline of marine derived nutrients from spawning salmon.

Other environmental factors also can impact Didymo. Though they can survive a wide range of hydraulic conditions, this can depend on the area that the Didymo inhabit. It was found that within New Zealand, North America, and Europe Didymo blooms were greatest at water exposed to regulated river flows rather than unregulated (Whitton & Ellwood 2007 & Kawecka & Sanecki 2003). This would mean that areas below impoundments, such as dams are more likely to be effected by Didymo blooms.

Didymo also prefer a wide range of temperatures from 4 degrees Celsius to 27 (Spaulding & Elwell 2007) yet have a more constricted range due to pH, needing waters that are at or above 7. Didymo are also only known to bloom in streams and rivers, even though they inhabit more than these types of bodies of water such as lakes.

Current Geographic Distribution and History of Invasiveness

Native area

Didymo is native to the north most parts of North America and Europe (Blanco & Ector 2009, Spaulding & Elwell 2007), with historical records dating back to around the 1890s, were it was observed on Vancouver Island, British Columbia. Within Europe, Didymo blooms are considered normal in northern and western rivers of the United Kingdom.

North America: Canada

Distribution of Didymo in the North American continent spans its native habitat on Vancouver Island, British Columbia in many of its central rivers (Bothwell, Lynch, Wright, & Deniseger 2009, MDDEP-MRNF 2007), and areas where it has been established. However, even in its native range Didymo blooms, which were first observed in 1989, are considered somewhat new to Vancouver Island, and are thought to be correlated to the distribution of the species via fisherman’s felt soled boots (Bothwell, Lynch, Wright, & Deniseger 2009).

In areas of Canada where it is not considered native, it has been reported in the Bulkley, South Thompson, Kettle, Columbia, and Kootenay Rivers in British Columbia, along with the Red Deer, Old Man river basins in Alberta (MDDEP-MRNF 2007). Within Quebec it is found in the Matapedia River of the Lower St, Lawrence region where it was first observed in 2006.

North America: United States of America

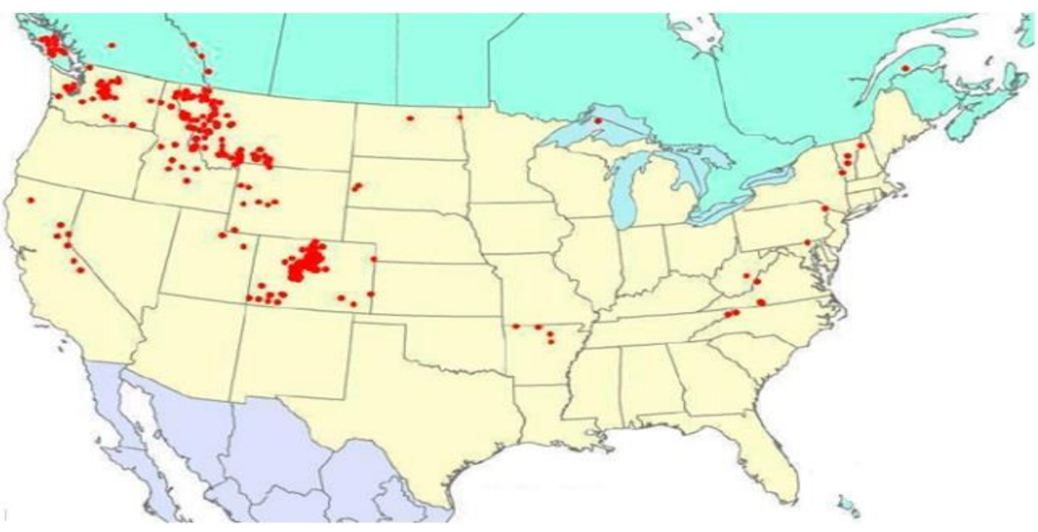

Fig. 4 Map of US showing distribution of Didymo from 2008. Photo courtesy of http://nyis.info/index.php?action=invasive_detail&id=40

Didymo has become established in these states: WA, CA, ID, MT, ND, SD, WY, UT, CO, AR, VA, WV, NC, NH, and PA (Fig. 4). It was discovered first in Tennessee in 2005 east of the Mississippi River (Bergey et al 2009, Schroeder 2005). Though the exact causes for distribution are unknown, a highly likely vector for this species is the use contaminated fishing gear (especially felt boots) (National Invasives Species Center 2014).

Within Washington, it is typically found within alpine lakes but has been shown to expand to lowland rivers. Though considered not problematic for Washington state as of yet (WALPA 2012), it is known to form Didymo blooms in low nutrient streams. Areas of extreme concern for invasive species establishment, such as Didymo, include the Snake River, part of the Columbia River below the confluence of the Snake River, Burnt Bridge Creek and Vancouver Lake, Thornton Creek, McAleer Creek, and Kelsey Creek (all of whom flow into Lake Washington, and many others as seen in Fig. 5 (Department of Ecology 2014). Didymo establishment is also a potential problem in moderate concern areas as Didymo can get worked into felt soled boots and be introduced to these areas. However, as seen by fig. 4, areas where Didymo has already been sighted include most of the western side and fewer sightings far south and far east.

Other countries of invasion

Though Didymo is not specified as a harmful invasive within these countries, Didymo has spread to Chile, China, Hungary, Iceland, Ireland, Kazakhstan, Kyrgzystan, Norway, Pakistan, Poland, Romania, Russian Federation, Svalbard and Jan Mayen Islands, Sweden, Turkey, and Ukraine.

Yet a recent study done by Taylor and Bothwell (2014) could suggest that Didymo might not even be invasive in many of the cases where it is considered to be. Recent fossil and historical evidence points to that Didymo has existed on every continent, except for Africa, naturally, and has only recently come to light as a possible invasion as there has been recent

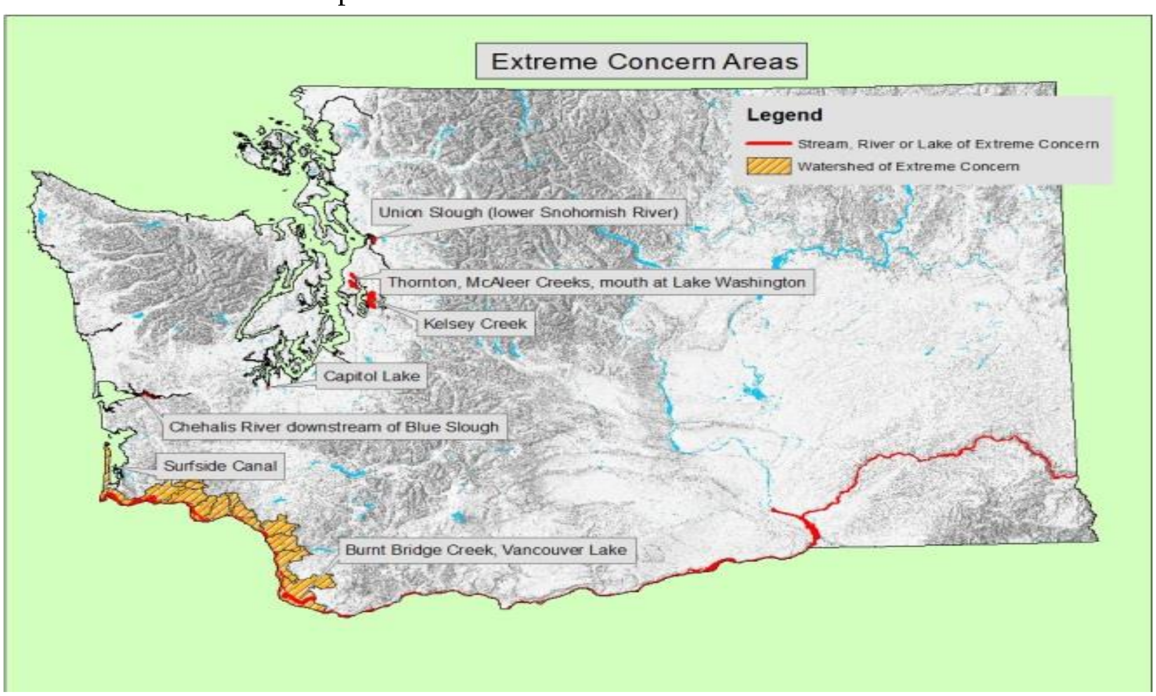

Fig. 5 Map of Washington showing areas of extreme concern for invasive species establishment like Didymo. Photo courtesy of http://www.ecy.wa.gov/programs/eap/InvasiveSpecies/AIS-PublicVersion.html

proliferations, i.e. blooms, that have been brought to attention. Fossilized forms of Didymo have been found on at least 11 countries in Europe, North America, Asia, and South America. It is possible that its native range expands far wider than what was previously thought, and rather it is due to changing environmental regimes that have caused Didymo to become more of a nuisance.

New Zealand

There is one country on which Didymo is definitely considered an invasive and that is New Zealand. First found in 2004 on the Lower Waiau and Mararoa Rivers of Southland (Kilroy 2004), it has expanded since then to 44 new locations with notably the Tasman district (the upper reaches of the Buller River specifically), Otago regions (Hawea, Upper Clutha, and Von Rivers), the Canterbury region (Waitaki and Ahuriri Rivers) and additional rivers in the Southland (Oreti, Aparima, and Upper Waiau) as observed established areas of Didymo (GISD 2006).

Invasion process

Pathways, vectors, and routes of introduction

The main pathway for Didymo distribution is recreational fishing, with the vector being transportation of gear that contains Didymo. This microscopic diatom is transported on fishing equipment, previously on the felt soled boots (Fig.7) of fisherman, and then spread when proper cleaning of gear is not utilized (Root & O'Reilly 2012). This vector is probably how Didymo came to be established and spread between nearby countries (such as Canada and the US) and between states. For areas such as New Zealand, it has also been thought that Didymo came over from North America and Europe from fishing equipment that was not cleaned properly. There are however certain types of gear associated with fishing that impact how far Didymo can spread, such as the vector impact felt soled boots will have (more easily transferrable between countries) versus a car (harder to take between countries or at least those that are overseas) (Fig. 6)

Fishing equipment when not cleaned well enough can still be damp after months from when it was first used, such as neoprene waders and felt soled boots, carrying surviving Didymo cells into new countries. Didymo cells can survive even with very little moisture and light for at least two months at cool (Lagerstedt 2007) and the increase in Didymo spread has been correlated to the previous use of felt soled boots that were sold starting in the late 1980s (Bothwell, Lynch, Wright, & Deniseger 2009). However, Didymo survival time is variable, making it harder to

Vectors		Modes		
	Water (abundant cells)	Small clumps	Few individual cells	Area of dispersal
River clothing	Low	Medium	High	Catchment, National, International
River footwear	Low	Medium	High	Catchment, National, International
Fishing lines	Low	Medium	Medium	Catchment, National, International
Kayaks	High	High	Low	Catchment, National
Cars	Medium	High	High	Catchment, National
Animals	Low	Low	Medium	Catchment

Fig. 6 Table showing areas of possible dispersion related to different recreational river gear.

predict its ease at establishing into newly introduced areas.

Factors influencing establishment and spread

As said earlier, environmental controls highly impact whether or not Didymo will be able to establish, especially nutrient content. Streams and rivers that were more regulated via impoundments are also very suitable for Didymo; however this species can occur in an optimal range of environments and are known to survive for long periods of time in marginal conditions.

Fig.7 Comparison of felt soled boots (left) and rubber soled boots (right) photo courtesy of http://fishbio.com/field-notes/wildlifeecology/fisherman%E2%80%99s-%E2%80%9Csole%E2%80%9D

Potential ecological impacts

Didymo has shown no significant impacts on many species of fish. After looking at historical records of returns and productivity for three of Pacific salmonids (Coho, Chum, and Steelhead Trout) found in the rivers where there were no Didymo or were Didymo, on Vancouver Island, it was found that all species showed that no significant impact on productivity or showed an actual positive effect (Bothwell and Spaulding 2008). There has also been no evidence shown for negative impact of Didymo on diadromous fishes. However, it has been shown that abundances of adult brown trout populations for Rapid Creek, South Dakota have declined coinciding with Didymo blooms, though there is no evidence for this in other areas (Shearer and Erickson 2006, Larson and Carreiro 2007)

Impact upon Didymo really depends on the species unique life history, what it eats, and other interactions with species. Possible reasons for why Didymo actually show none or positive significant impact on the three above mentioned salmonid species and the decline of the brown trout population in South Dakota is due to how Didymo impacts the macrobenthic community.

Studies both in New Zealand and Canada show that there was a change in the benthic communities where Didymo are established. Looking at three independent studies from different rivers on South Island, New Zealand where Didymo was first observed, Kilroy, Larned and Biggs (2009) discovered that there were shifts in the benthic community composition with increases in Oligochaeta, Chironomidae, Cladocera, and Nematoda. Though there was an increase in spatial invertebrate community homogeneity with high Didymo biomass, there were no signs of declines in taxon richness or diversity.

Researchers in Canada also found similar results with Macrobenthic samples that were obtained in 2006, upstream of blooms discovered in the Matapedia River, Québec and at the sampling sites a year later (Gillis & Chalifour 2010). Results showed that there was a significant increase in the Chironomidae proportions and the benthic macroinvertebrate densities.

These changes in benthic communities could be why there were no significant changes or positive changes to the three salmonids studied by Bothwell and Spaulding, as a shift in macroinvertebrates might have changed the diet of these salmonids for the better.

In regards to Rapid Creek and the decline in resident adult brown trout, it was found through analysis of the invertebrate community that a feeding bottle-neck could have resulted in the decline of adult brown trout. The study also showed an increase in abundance of up to age 1 fish. A decline in Ephemeroptera, Plecoptera, and Trichoptera populations which were previously the food source of adult trout (Larson & Carrerio 2007) would explain the decline in adult brown trout populations and the increase in of younger trout due to the shift in the macrobenthic community.

Potential economic impacts

Though there are no direct effects to humans, concerns about how it directly impacts the aesthetic qualities of areas that are valued for recreational use could lead to declines in tourism and freshwater angling. This is particularly important to areas that are prized for this such as previously pristine areas used by recreational anglers and other water recreational enthusiasts. Didymo blooms are especially concerning as they can cover an entire stream bed, which can not only look un-aesthetically pleasing, but has led to concerns about sanitation and sewer malfunctions as its long white strands ted to be mistaken as toilet paper (Kilroy 2004).

New Zealand, which boasts many pristine recreational trout fishing areas, has thousands of anglers visiting the country every year for the purpose of fishing for wild trout and other sport fish in a pristine environment. Many anglers hire guides for a significant amount, especially those who rent out helicopters to gain access to remote locations. Both tourist and local anglers bring in a significant amount of money for new Zealand with recreational anglers fishing in excess of one million angler days per annum (Unwin 2009).

Already Didymo has taken a toll on the economy of New Zealand, with an estimated total impact (accounting for all industries that will be affected) of $127.8 million between 2006 and 2010. Furthermore, estimates for the annual impact that Didymo will have from 2011 to 2020 vary from $36 million (in regards to a low impact scenario) to $152.9 million (under a high impact scenario) with a total impact between $210.6 and $854.8 million (Ministry of Agriculture and Forestry 2011).

Popular water recreational areas in the US are also being affected by Didymo blooms, with potential impacts on the fly fishing industry effecting around 5.6 million people. Not only would it impact those directly related to the recreational angling industry but those that benefit from the people it brings in to local communities, as fly fisherman are calculated to spend an average of 22 days fishing per year, half of which are overnight trips which provide additional benefits to the local economies (Outdoor Industry Association 2013).

Water intakes could also be impacted as Didymo can build up and restrict the flow of water in water intake systems. The maintenance costs for this process will depend on the type of intake system but can affect multiple businesses that rely on these systems. Drinking water could also be affected, as water sourced from Didymo infested rivers could have an abnormal taste or smell which would need to be treated.

Management Strategies and Control Methods

Possible management strategies include prevention of Didymo from establishing elsewhere by making sure certain products, such as the felt soled boots, are prohibited in certain bodies of water that Didymo could establish in.

Outreach to the public, especially certain groups such as those in the recreational angler community, is important so early detection and rapid response can happen so as to remove offending Didymo from established areas. Furthermore, outreach and education about practices to prevent the spread, such as cleaning fishing gear, of Didymo are important as some are unaware of how to best control Didymo distribution and either inadequately clean their gear or do not clean at all.

However, it should be noted that many areas that Didymo are currently in, could possibly be native areas as current research is starting to show more evidence that Didymo has been there all along. The only reason for concern now is due to the changing environmental regimes that are leading to these blooms.

Current research and management efforts

Management Efforts

Previously the Department of Environmental and Natural Resources and places in New Zealand placed Wader Washer Stations (Fig.8) in some areas but further concern of Didymo invasion led to more aggressive action. Knowing that the main vector for Didymo expansion was through felt soled boots, many states in the US and Canada have started to ban these products including Alaska, Maryland, Missouri, Nebraska, New Jersey, Rhode Island, South Dakota, and Vermont all of whom have statewide bans on felt soled boots in an effort to curb the Didymo invasion.

After listing Didymo as an unwanted non-native under the Biosecurity Act of 1993, in New Zealand it is now considered an offence to knowingly spread Didymo leading to charges of 5 years of imprisonment, and/or a fine up to $100,000 (GISD 2006). This act also requires aquatic recreational equipment to be 1) Check equipment before leaving the river and remove any obvious clumps of algae and also look for hidden clumps. If clumps are found after leaving the river, dry them and dispose into the trash. 2) Clean equipment by soaking and scrubbing all items for at least one minute in hot (over 60 degrees Celsius) water or in a 2% solution of house grade bleach or 5% solution of

Fig.8 Didymo Cleaning Station found in New Zealand. Photo courtesy of http://s138.photobucket.com/user/troutsafarisnz/media/didymostnpic.jpg.html

dish washing detergent or antiseptic hand cleaner. 3) Dry equipment and then wait 48 hours before use in a different waterway (Fig.9) (GISD 2006).

Fig.9 Poster used to educate the public on how to prevent Didymo from distributing in New Zealand as issued by Biosecurity. Photo courtesy of http://www.nsmcentre.org.uk/node/522/pv.

Current Research

Current research has mainly been focused on the environmental impacts on Didymo that cause the algae blooms and historical evidence of its native distribution. As said before, it is thought that low phosphorus is the main environmental factor attributing to Didymo blooms (Kilroy and Bothwell 2014). Other main factors have also been found to cause Didymo blooms, making up the Didymo Trilogy: light, nitrogen, and phosphorus. Increase in light, whether due to less riparian shade cover or areas that are shallow, shows that Didymo reacts positively (with an increase in attachment densities and stalk length) but eventually showed a decrease after exposed to very high intensities (Kilroy and Bothwell 2014).

Though native areas are currently considered to be parts of Europe and the northernmost parts of North America (Blanco & Ector 2009, Spaulding & Elwell 2007), recent research has shown that areas that might be considered non-native to Didymo could possibly be actual native habitat. Historical records have shown that previously thought areas of invasive Didymo establishment are actually native territory, but in the past Didymo was just less abundant than it is now (Taylor and Bothwell 2014)

Current research on the economic impact has shown that Didymo could really negatively impact the recreational water industry, especially recreational angling as once pristine stream bed habitat could be completely covered in Didymo if blooms were to occur, thus impacting the aesthetic quality of the stream. There are also those that are studying the possible positive economic impacts that Didymo could have such as Didymo being used for biofuel (Ziska & Dukes 2014).

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National Invasive Species Information Center

http://www.invasivespeciesinfo.gov/aquatics/didymo.shtml

National Park Service: Yosemite National Park

http://www.nps.gov/yose/naturescience/upload/Didymo-fact-sheet-04-10.pdf

Global Invasives Species Database

http://www.issg.org/database/species/ecology.asp?si=775&fr=1&sts=&lang=EN

BioSecurity: Ministry for Primary Industries New Zealand

http://www.biosecurity.govt.nz/didymo

Regional Contacts

Washington State Toxic Algae: reporting blooms

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