Effect of discharge and habitat type on the occurrence and severity of *Didymosphenia geminata* mats in the Restigouche River, eastern Canada

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Abstract

Since 2006, the Restigouche River watershed, eastern Canada, has been affected by nuisance growths of the mat-forming diatom, *Didymosphenia geminata*. In 2010, in view of the potential impacts of this alga on the local Atlantic salmon fishery, we created a volunteer monitoring network to assess *D. geminata* mat severity within the watershed. Over the course of six monitoring summers, more than 1200 observations of *D. geminata* mat severity were reported in 20 sub-watersheds of the Restigouche River basin. Observations were mapped to illustrate the yearly severity of *D. geminata* mats throughout the watershed. Metrics were then extracted from this dataset to assess the spatial and temporal variability of mat severity. At the reach scale, *D. geminata* occurrence was predominantly found in riffles compared to any other river habitat type. At the watershed scale, a two-sample KS-test highlighted a significant effect of maximum spring discharge on mean annual *D. geminata* mat severity, indicating that when maximum spring discharge is high, severity of *D. geminata* mats in the following months is significantly lower. Additionally, maximum spring discharge explained 71% of the variability in annual mat severity. This study contributes to the understanding of mat severity dynamics and illustrates the value of volunteer monitoring networks for studying complex ecosystem dynamics.

Introduction

In July 2006, unprecedented algal growths were reported in the Matapedia River, a major tributary of Restigouche River, one of the most important Atlantic salmon rivers of the Gaspe Peninsula in eastern Canada. The growths were identified as *Didymosphenia geminata* (Lyngbye) M. Schmidt, a mat-forming diatom frequently associated with the clear and cold waters of pristine rivers. This was the first incidence of this species reported at nuisance levels in eastern North America. *D. geminata* can produce thick growths of dense fibrous stalk material covering the entire streambed surface and persist for several months (Biggs, 1996; Larned et al. 2007, Spaulding & Elwell 2007) (Figure 1). It is therefore not surprising that it has been reported to modify the aquatic food base, alter ecosystem structure and function (Larned et al. 2007, Gillis & Chalifour, 2010) and decrease the aesthetic value of affected rivers (Spaulding & Elwell 2007, Beville 2012). Soon after its appearance in 2006, *D. geminata* became conspicuous in many other rivers of the Gaspe Peninsula and New Brunswick, Canada. However, several rivers remained unaffected, raising questions as to why mat formation would occur in some rivers and not others. In their conceptual model for the blooming behavior and persistence of *D. geminata*, Cullis et al. (2012) emphasized the role of water chemistry, river morphology and flow thresholds in defining the habitat window of this alga. According to this model, cold, clear and shallow water are required to provide the amount of light necessary for the growth of *D. geminata*, while high flow events generate the critical shear stress and bed material transport causing the removal of the algae. Although the conceptual model is based on numerous field observations, the authors concluded that the validation of its components would require field data offering both good spatial coverage and longer time series observations. In fact, most of the existing studies on the variability of *D. geminata* encompass, on average, a two-year period.

In eastern Canada, although some regional scale observations provided insights on the distributional range of *D. geminata*, presence-absence data were scarce and too infrequent to allow a comprehensive analysis of the factors determining its distribution. In addition, observation methods were not standardized across stakeholders and agencies, therefore limiting comparability of mat severity between watersheds. Thus, a more systematic monitoring program was required. To achieve the collection of a long-term dataset while constrained by limited financial resources, there was therefore a need to create a *D. geminata* monitoring network following a citizen science approach. Several examples have shown the ability of citizen science to gather valuable scientific data while involving citizens in a true collaborative partnership with academia (Chopyak & Levesque 2002, Crall et al. 2010). Such an approach has, for example, contributed to the early detection and monitoring of emerging nuisance species across local and regional scales (Lodge et al. 2006, Crall et al. 2010).

In the case of the Restigouche River, the first objective was therefore to identify habitat types most favorable to the *D. geminata* mat formation and persistence. This was accomplished by collecting a comprehensive dataset describing the longitudinal distribution of river habitat types and *D. geminata* mat occurrence along a 65 km-long section of the Matapedia River in 2007. The second objective was to involve volunteers from several key organizations to generate a long-term dataset from standardized visual monitoring of *D. geminata* describing this alga's spatial and temporal variation throughout the watershed for at least six years, beginning in 2010. Lastly, the final objective was to analyze the dataset generated from the monitoring network to determine the effect of discharge on the inter-annual variability of *D. geminata* mat severity.

Methods

Study Area

Located in eastern Canada, the Restigouche River drains an interprovincial watershed (Quebec and New Brunswick) of more than 12 000 km^2 and has five major tributaries: the Matapedia River, Patapedia River, Kedgwick River, Little Main River and Upsalquitch River. The study area is unregulated and has a snow-melt dominated hydrological regime. These rivers have had occasional to persistent growth episodes of *D. geminata* since 2006 (Gillis and Chalifour 2010).

Reach scale mapping of habitat type and D. geminata mat occurrence *along the Matapedia River*

Between August 5th and 28th 2007, during stable low flow conditions, the Matapedia River was surveyed to assess presence-absence of *D. geminata* mats along a 65 km-long section of the river. Along the longitudinal transect, each channel unit was classified into homogeneous mesohabitat types according to bed topography and low water surface flow facies as defined in Frissell et al. (1986). Habitat types were categorized in terms of depth, substrate and velocity, as either rapids, runs, pools or riffles (Table 2). Within each unit, we assessed substrate composition, channel width and depth as well the occurrence of *D. geminata* mats. Visual surveys of *D. geminata* mat presence-absence were conducted with a viewfinder from a canoe.

Didymo Monitoring Network (DoMiNo) development and quality control

To develop an effective monitoring network, we approached key organizations involved in Atlantic salmon fisheries that were keen to understand how this nuisance alga affected fish habitat and potentially the local economy. Recruitment of these partners (e.g. fishing/hunting outfitters, fishing camps, watershed organizations, canoers, kayakers, anglers and field technicians, see Table 1) helped define monitoring site locations. While aiming for a well distributed sampling effort, care was taken to make it possible for volunteers to include data collection in their daily routine. This approach yielded a high participation rate amongst targeted groups and promoted volunteer retention through the duration of the study. Within the Restigouche River watershed, the network currently involves 70 volunteers from 22 different key organizations with an interest in Atlantic salmon conservation.

DoMiNo Volunteer Booklet

To assist volunteers in the proper collection of data, an English and French educational booklet was developed. First, the text addressed the importance of the monitoring network and reminded volunteers of the importance of this effort towards the advancement of *D. geminata* research. It also provided information on the general biology and ecology of the diatom and described how their efforts would be integrated in research questions and objectives. The data collection protocol was presented into detail to remind participants how observations should be collected. The protocol involved a visual classification of *D. geminata* presence into five different categories of percentage of bed coverage by *D. geminata* in increments of 20%. To limit biased estimates of mat coverage, photographs, representative of each category, were provided in the photo-guide section of the booklet. One representative measurement of mat thickness was then determined with a ruler. Pre-formatted waterproof data sheets (figure 2) were provided to ensure that all relevant information was collected (i.e. name of the observer, date, location, percent cover category, thickness and type of coverage (mats or tufts) and allowed for consistency in data collection among volunteers.

Training

At the beginning of each monitoring summer, participants of each organization took part in an interactive training session where they were taught how to identify *D. geminata* adequately, how to use the monitoring network booklet and collect data. When possible, volunteers were also accompanied in the field by the authors to conduct live search and identification of *D. geminata*. As recommended by Bonter & Cooper (2012), frequent follow-ups (i.e. communication and field visits) were conducted throughout the sampling period to ensure proper monitoring, data quality and limit inter-operator variability (Kilroy et al. 2013).

Data collection

Between 2010 and 2015, volunteers gathered weekly observations of *D. geminata* mat coverage and thickness data with their DoMiNo booklet in their assigned sites between mid-May and late October of each year. Each organization then forwarded the information on a fortnight basis for data quality control and compilation. Thus, data reported by volunteers was frequently validated by field visits and/or by corroborating estimations with supplemental photos. Moreover, all newly reported affected reaches (first positive report for a given watercourse) were visited by the authors. Per year, we visited, on average, 25% of the monitored sites for in-field validation of *D. geminata* percent cover and thickness. All validated observations were geo-referenced. Over the course of six monitoring periods (2010-2015), volunteers gathered 1228 validated observations of *D. geminata* mat severity throughout the Restigouche River.

Data analysis

Reach scale occurrence of D. geminata mats

A contingency table of the frequency of occurrence of *D. geminata* mats within each habitat type was developed for the 2007 survey data. Pearson's chi-square test was applied to the frequency data of *D. geminata* mats in relation to habitat type and substrate and used to highlight habitat preferences for mat formation.

Mat severity: Standing Crop Index

When each visual observational data was compiled into the regional database, a Standing Crop Index (SCI) value was calculated by multiplying the thickness of the *D. geminata* mat by its percent areal coverage. This method was initially developed by Kilroy (2006) and enables the production of a standardized metric that can be compared across local, regional, national and international scales (Kilroy and Bothwell 2012). In this manuscript, we use the Standing Crop Index as a proxy defining *D. geminata* mat severity.

Mapping

Standing Crop Index (SCI) observations spanning six monitoring periods (2010-2015) were used to map *D. geminata* inter-annual variability throughout the watershed. For each year, maps were created by interpolating the SCI values, constrained to areas for which observations existed, along the river network. Sites comprising multiple values per monitoring period were averaged to provide mean SCI throughout the monitoring period. Inverse distance weighting (IDW) was applied in a stream-wise direction using a kernel of radius 2.5 km to ensure that interpolated values did not substantially stray outside the limits of the observed data points. Interpolated SCI values were classified according to nuisance periphyton criteria (Kilroy & Wech, 2012), where *green* denotes 'good' status (SCI below 200), *amber* denotes 'alert' status (SCI between 200 and 600) and *red* (SCI above 600) denotes that a management response is required. This method was used as an effective management tool on the Lower Waiau River in New Zealand by characterizing occurrence and severity of *D. geminata* mats (Kilroy & Wech, 2012). Inter-annual variation and spatial distribution of *D. geminata* mat severity was subsequently quantified by calculating the percentage composition of mat coverage in terms of these three severity classes as well as by computing the mean SCI across the entire watershed for each summer monitoring period.

Analysis-of-variance (ANOVA) was used to determine whether SCI values varied significantly between streams of different Strahler order.

Hydrological data

Annual discharge conditions within the Restigouche watershed were examined to identify potential mechanisms responsible for inter-annual variability in *D. geminata* mat coverage falling into each of the three severity classes (green-yellow-red). Daily discharge data were assembled by combining records from two gauging stations located towards the confluences of the Matapedia and Restigouche sub-basins (Environment Canada ID 01BD009 and 01BJ007 respectively). A series of simple regression analyses (linear, exponential, power) was used to explore correlations between *D. geminata* mat severity and a range of hydrological metrics. These metrics comprised mean, minimum and maximum annual discharge, peak spring discharge (defined as maximum daily discharge between February 1st and May 31st), number of high discharge events (defined as the number of days where discharge exceeded a predefined threshold of 65 m^3s^{-1}) and number of days since flood. If regression analysis indicated the existence of a correlation between *D. geminata* severity and a given hydrological metrics, a two sample Kolmogorov-Smirnov test was used to compare distributions of hydrological parameters and SCI.

Results

Reach scale variability of D. geminata mat occurrence

Frequency of *D. geminata* mat occurrence was determined visually for each habitat type (Figure 5) in 2007. Visual presence-absence data showed that the occurrence of mats was dependent on the various habitat types (i.e. rapids, runs, pools and riffles) indicating a strong habitat preference for riffles ($\chi2$ (3, N= 276), $p < 0.05$). Conversely, *D. geminata* presence was not dependent on substrate type within riffles ($\chi2$ (3, N= 123), $p > 0.05$).

Inter-annual variability of D. geminata mat severity

Data collated between 2010 and 2015 was analyzed and severity maps were created to highlight the yearly spatial variability of *D. geminata* mat severity throughout the Restigouche River watershed (Fig. 3). Table 3 presents the yearly proportion of *D. geminata* mat severity per class. *D. geminata* mat severity was highly spatially variable between monitoring periods. *D. geminata* mats were most severe in 2013 (14.7% of sites under red status). Conversely, *D. geminata* mats were less severe in 2010, 2011, 2014 and 2015, where the percentage of sites under green status was the highest throughout the time series. This trend was observed throughout the watershed across all monitored reaches (Strahler's stream order varying from 4 to 8). One-way analysis of variance (ANOVA) showed that mean SCI values did not vary significantly between stream order.

Of the various hydrological metrics, maximum spring discharge was the only one that exhibited a significant correlation ($p < 0.05$) with SCI (i.e. *D. geminata* mat severity) under any of our regression analyses (linear, exponential, power). Using a power regression model (fig 4), maximum spring discharge (Q_{max}) explained 71% of the observed variability in SCI ($R^2 = 0.71$, $p < 0.05$). Furthermore, the distributions of mean SCI and maximum spring discharge differed significantly (two-sample KS test: $p < 0.05$) indicating that when maximum spring discharge is high, severity of *D. geminata* mats in the following months will be significantly lower.

Data quality

Over the course of six monitoring periods, less than 2% of the data needed to be corrected due to over or underestimation of *D. geminata* mat severity following field visits and/or photo validation. Furthermore, *D. geminata* was misidentified on only three occasions where another stalk-forming diatom, i.e., *Cymbella sp.* was mistaken for *D. geminata*.

Discussion

In this study, the creation of a didymo monitoring network allowed for the development of a comprehensive dataset describing the spatial and temporal distribution of *D. geminata* in the Restigouche River watershed between 2010 and 2015. The time and effort spent training volunteers resulted in an extensive dataset of reliable observations that could not have been obtained otherwise through a conventional monitoring program, which clearly demonstrates that citizen science can help further the understanding of this nuisance species.

Factors driving D. geminata mat occurrence and severity

At the reach scale, our results indicate that the spatial variability in *D. geminata* mat coverage was explained by habitat characteristics. *D. geminata* mats were occasionally found in runs and pools, but were most prevalent in riffles. They were however almost completely absent from rapids. Rapids may render unsuitable conditions due to high shear stress and higher frequency of bed load transport causing mat scouring whereas light availability is limited in deeper pools. This result supports previous observations that geomorphological units define physical habitat suitability for mat colonization and growth (Cullis et al. 2015; Miller et al. 2009). Runs and riffles offer optimal conditions for *D. geminata* colonization, mat development and persistence due to their shallow depths, high light availability and stable substrate between high discharge events.

At the watershed scale, analysis of the correlation between the mean annual SCI against multiple hydrological metrics showed that maximum spring discharge best explained inter-annual variability in SCI. As a corollary, high maximum spring discharge was associated with a lower proportion of “red” or “orange” status for 2011, 2014 and 2015. For example, 2011 was characterized as a “wet” year and *D. geminata* was found to be limited within the basin. In comparison, 2010, 2012 and 2013 were dryer years in eastern Canada with fewer high-flow events that may have limited *D. geminata* growth and mat establishment. Our findings are in accordance with Richardson *et al.* (2014) who found that inter-annual variability of the hydrological regime and higher peak flows limited *D. geminata* density. In our study, maximum spring discharge was the only hydrological factor to have a significant effect on *D. geminata* mat severity. Conversely, in New Zealand, Kilroy & Wech (2012) found that the number and duration of floods above 65 m^3s^{-1} were significantly correlated with the percentage of time that surveys yielded a green status due to reach-scale scouring. They also showed that the number of days since a flood occurred best explained the amount of time under red status. Recent work by George & Baldigo (2015) found that the frequency of high-flow events significantly decreased stalk biomass.

Data reliability and limitations

The quality of data collected by citizen science initiatives is often criticized. However, good quality data can be ensured by proper sampling design, standardized methods and appropriate training (Yoccoz *et al.,* 2003, Delaney *et al.,* 2007, Schmeller *et al.,* 2009). Kilroy *et al.* (2013) found that assessments of visual periphyton surveys by multiple participants was not a challenging issue if given proper training. A review by Crall *et al.*, (2010) also highlighted that appropriate training can provide ample scientific skills for neophyte volunteers to collect required data. As in Dickinson *et al.* (2012), the availability of an educational tool (here the monitoring network booklet) promoted and facilitated the collection of appropriate data while maintaining awareness and reminding users of the importance and relevance of their efforts.

Quality control of citizen science data is however a necessary step to validate data consistency and reliability (Bonter & Cooper 2012).

Citizen science datasets are defined by sampling efforts and by the spatial distribution of monitored sites. Thus, resulting distribution patterns are substantiated by the fact that "absence of evidence is not evidence of absence" (Altman & Bland 1995), and suggest a probable underestimation of the documented phenomenon. It is therefore considered that the visual monitoring efforts carried out by volunteers do not discount watercourses of absolute *D. geminata* presence. Nevertheless, this effort offers good insights on the broad scale occurrence of *D. geminata* across landscapes and the authors are confident that the data obtained ensured an efficient monitoring of *D. geminata* mats. In parallel, this type of extensive monitoring data can help define regional trends in occurrence and severity by comparing existing ancillary physical and chemical data of affected and non-affected reaches.

Conclusion

The Didymo Monitoring Network was the first network to be developed to monitor the occurrence and severity of *D. geminata* mats. Following this initiative, other organizations are now effectively monitoring *D. geminata* by training and involving volunteers (e.g. The New Hampshire Rivers Council's *River Runners*; the Three Rivers Community College's *Citizen's River Monitoring Program*; the Trout Unlimited *Discovering Didymo Distribution* using the iNaturalist app piloted by the University of Calgary and the University of North Carolina). These project schemes offer potential for partnership and future collaborative efforts will be pursued to enhance our current liked-minded projects across landscapes, state and international boundaries. Yielding a higher standardized sampling effort at greater geographical scales will contribute to the production of a robust dataset enabling ecological modelling of *D. geminata*. Cell vouchers may also be useful in monitoring programs towards increasing quality control and validation of recorded observation data by microscopic identification of cells.

Mapping the severity and distribution of nuisance growths throughout the Restigouche River watershed helped managers and local stakeholders comprehend factors explaining the observed yearly variability. Although hydrological metrics alone cannot define *D. geminata'*s habitat window (Cullis *et al.*, 2012) nor entirely account for observed seasonality and yearly variability (Kilroy & Wech, 2012; Kirkwood *et al.*, 2007), this study highlights trends in inter-annual SCI variability driven by the hydrological regime. A more comprehensive look at *D. geminata* seasonality is needed to highlight the importance of hydrological metrics driving site-specific changes in SCI values. Furthermore, an assessment of the relative importance of other intrinsically related variables to discharge such as temperature and light availability is needed to better define yearly and seasonal trends as well as defining *D. geminata'*s habitat window for colonization, growth and persistence of nuisance growths in eastern Canada. Future research efforts should focus on developing tools for assessing the severity of *D. geminata* nuisance growths by incorporating the timing, duration and proportion of affected vs. non-affected habitats. This biomass assessment may then be incorporated in *D. geminata* ecosystem impact studies.

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References

Altman DG & Bland JM (1995) Absence of evidence is not evidence of absence. *British Medical Journal* 311(7003):485.

Beville ST, Kerr GN & Hughey KFD (2012) Valuing impacts of the invasive alga Didymosphenia geminata on recreational angling. *Ecological Economics* 82(0):1-10.

Biggs BJF (1996) Patterns in benthic algae of streams. Stevenson RJ, Bothwell ML & Lowe RL (Eds.) *Algal Ecology*, Academic Press, San Diego, CA.

Bonter DN & Cooper CB (2012) Data validation in citizen science: a case study from Project FeederWatch. *Frontiers in Ecology and the Environment* 10(6): 305-307.

Chopyak J & Levesque PN (2002) Community-Based Research and Changes in the Research Landscape. *Bulletin of Science, Technology & Society* 22(3): 203-209.

Crall A, Newman G, Jarnevich C, Stohlgren TJ, Waller DM & Graham J (2010) Improving and integrating data on invasive species collected by citizen scientists. *Biological Invasions* 12(10): 3419-3428.

Cullis JDS, Gillis C-A, Bothwell ML, Kilroy C, Packman A & Hassan M (2012) A conceptual model for the blooming behavior and persistence of the benthic mat-forming diatom Didymosphenia geminata in oligotrophic streams. *Journal of Geophysical Research.* 117(G2):G00N03.

Cullis JDS, Spaulding SA & McKnight DM (2015) Hydrodynamic Control of Benthic mats of Didymosphenia Geminata at the Reach Scale. *Canadian Journal of Fisheries and Aquatic Sciences* 72(6):902-914.

Delaney D, Sperling CD, Adams CS & Leung B (2008) Marine invasive species: validation of citizen science and implications for national monitoring networks. *Biological Invasions* 10(1): 117-128.

Dickinson JL, Shirk J, Bonter D, Bonney R, Crain RL, Martin J, Phillips T & Purcell K (2012) The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* 10(6): 291-297.

Frissell CA, Liss WJ, Warren CE & Hurley MD (1986) A Hierarchical Framework for Stream Habitat Classification: Viewing Streams in a Watershed Context. *Environmental Management* 10(2):199-214.

George SD & Baldigo BP (2015) Didymosphenia geminata in the Upper Esopus Creek: Current Status, Variability, and Controlling Factors. *PLoS ONE* 10(7):e0130558.

Gillis C-A & Chalifour M (2010) Changes in the macrobenthic community structure following the introduction of the invasive algae *Didymosphenia geminata* in the Matapedia River (Quebec, Canada). *Hydrobiologia* 647(1):63-70.

Harding JS, Clapcott JE, Quinn JM, Hayes JW, Joy MK, Storey RG, Greig HS, Hay J, James T, Beech MA, Ozane R, Meredith AS & Boothroyd IKD (2009) Stream habitat assessment protocols for wadeable rivers and streams of New Zealand. University of Canterbury Press, Christchurch.

Kilroy C (2006) *Ecological studies on Didymosphenia geminata*. NIWA Client Report CHC2005-123, 79 p.

Kilroy C & Wech J (2012) Managing nuisance periphyton in the Lower Waiau River: update for 2011-2012. NIWA Client Report CHC2012-064.

Kilroy C & Bothwell ML (2012) *Didymosphenia geminata* growth rates and bloom formation in relation to ambient dissolved phosphorus concentration. *Freshwater Biology* 57(4):641–653.

Kilroy C, Booker D, Drummond L, Wech JA & Snelder TH (2013) Estimating periphyton standing crop in streams: a comparison of chlorophyll a sampling and visual assessments. *New Zealand Journal of Marine and Freshwater Research* 47(2): 208-224.

Kirkwood AE, Shea T, Jackson L & McCcauley E (2007) Didymosphenia geminata in two Alberta headwater rivers: an emerging invasive species that challenges conventional views on algal bloom development. *Canadian Journal of Fisheries and Aquatic Sciences* 64(12):1703-1709.

Larned ST, Arscott D, Blair N, Jarvie B, Jellyman D, Lister K, Schallenberg M, Sutherland S, Vopel K & Wilcock B (2007) *Ecological studies of Didymosphenia geminata in New Zealand, 2006-2007*. NIWA Client Report CHC2007-070, 127 p.

Lodge DM, Williams S, MacIsaac HJ, Hayes KR, Leung B, Reichard S, Mack RN, Moyle PB, Smith M, Andow DA, Carlton JT & McMichael A (2006) Biological invasions: recommendations for US policy and management. *Ecological Applications* 16(6):2035–2054

Miller MP, McKnight DM, Cullis JDS, Greene A, Vietti K & Liptzin D (2009) Factors controlling streambed coverage of Didymosphenia geminata in two regulated streams in the Colorado Front Range. *Hydrobiologia* 630(1):207-218.

Richardson D, Oleksy I, Hoellein T, Arscott D, Gibson C & Roots S (2014) Habitat characteristics, temporal variability, and macroinvertebrate communities associated with a mat-forming nuisance diatom (Didymosphenia geminata) in Catskill mountain streams, New York. *Aquatic Sciences* 76(4):553-564. doi: 10.1007/s00027-014-0354-7

Schmeller DS, Henry P-Y, Julliard R, Gruber B, Clobert J, Ziock F, Lengyel S, Nowicki P, Déri E, Budrys E, Kull T, Tali K, Bauch B, Settele J, Van Swaay C, Kobler A, Babij V, Papastergiadou EVA & Henle K (2009) Advantages of Volunteer-Based Biodiversity Monitoring in Europe Ventajas del Monitoreo de Biodiversidad Basado en Voluntarios en Europa. *Conservation Biology* 23(2): 307-316.

Spaulding SA & Elwell L (2007) Increase in nuisance blooms and geographic expansion of the freshwater diatom Didymosphenia geminata. *Open-file report 2007-1425* (U.S. Geological Survey,, Reston, Va.), p iv, 38 p.

Yoccoz NG, Nichols JD & Boulinier T (2003) Monitoring of biological diversity - a response to Danielsen et al. *Oryx* 37(4):410.

Table 1. Overview of organizations monitoring the occurrence and severity of *D. geminata* mats throughout the Restigouche River watershed

Organization	Type	Nb. trained volunteers	Nb. monitored rivers
Fed. Quebecoise Saumon Atlantique	Anglers	2	6
Matapedia-Restigouche Watershed	River management	4	10+
Restigouche River Watershed Management Council	River management	3	7
Listuguj Rangers	Conservation	2	1
Arpin Canoe Restigouche	Ecotourism	4	5
Nature Aventure	Ecotourism	3	9
ZEC Casault	Outfitter	1	1
CGRMP	Outfitter	12	14
Auberge de la Riviere Matapedia	Outfitter	1	2
Fishing Camps	Private	31	9
Dept. of Fisheries & Oceans	Science	4	20+
Centre Interuniversitaire de la recherche sur le saumon atlantique	Science	3	2

Table 2. Definitions and features of categorized habitat types. Adapted from Harding *et al.* (2009)

Habitat type	Depth	Flow	Surface flow pattern
Rapid	Shallow to moderate	Swift and strong currents	Surface broken with white water
Riffle	Shallow	Moderate to fast with mixed currents	Surface rippled but unbroken
Pool	Deep	Slow	Smooth
Run	Shallow to moderate	Slow to moderate, uniform	Surface unbroken, smooth

Table 3. Proportion of *D. geminata* mat severity comprising each class per monitoring period in relation to maximum spring discharge

	Percent proportion of SCI levels					
	2010	**2011**	**2012**	**2013**	**2014**	**2015**
Low (<200)	80,1	81,9	65,6	66,0	84,3	89,8
Medium (200 - 600)	15,5	9,9	25,9	19,3	8,8	4,1
High (>600)	4,4	8,2	8,5	14,7	7,0	6,0
Max spring discharge (m^3s^{-1})	1718,8	2452,1	1556,2	1165,1	2553,8	2314,5

Figure 1. Large growths of *D. geminata* mats in the Duval River, a tributary of the Bonaventure River, Gaspesie, Quebec, Canada

DATE:	LIEU/LOCATION:			GPS:		
TYPE DE PROLIFERATION / TYPE OF COVER :	TAPIS / MAT ☐			SPHÈRES / TUFTS ☐		
OBSERVATIONS:	POURCENTAGE DE RECOUVREMENT / PERCENT COVER					
ÉPAISSEUR / THICKNESS:	AUCUN NONE 0%	TRÈS FAIBLE VERY LOW 0% - 20%	FAIBLE LOW 20% - 40%	MOYEN MEDIUM 40% - 60%	ÉLEVÉ HIGH 60% - 80%	TRÈS ÉLEVÉ VERY HIGH 80% - 100%
NOM / NAME :	☐	☐	☐	☐	☐	☐

Figure 2. Data collection sheet used by the volunteers to monitor *D. geminata* percent cover and mat thickness.

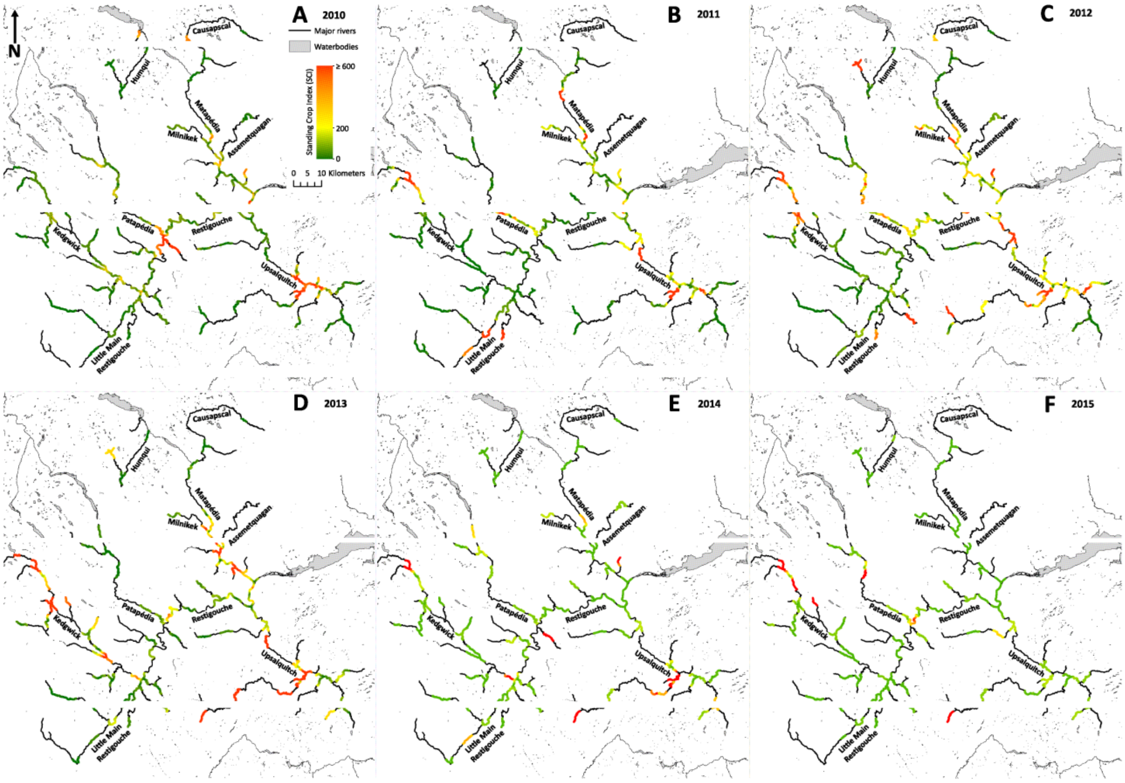

Figure 3. Maps of interpolated *D. geminata* mat severity throughout six monitoring periods between 2010 (A) and 2015 (F). Severity scale is presented in map A and color classification is based on Kilroy & Wech (2012); Table 3.

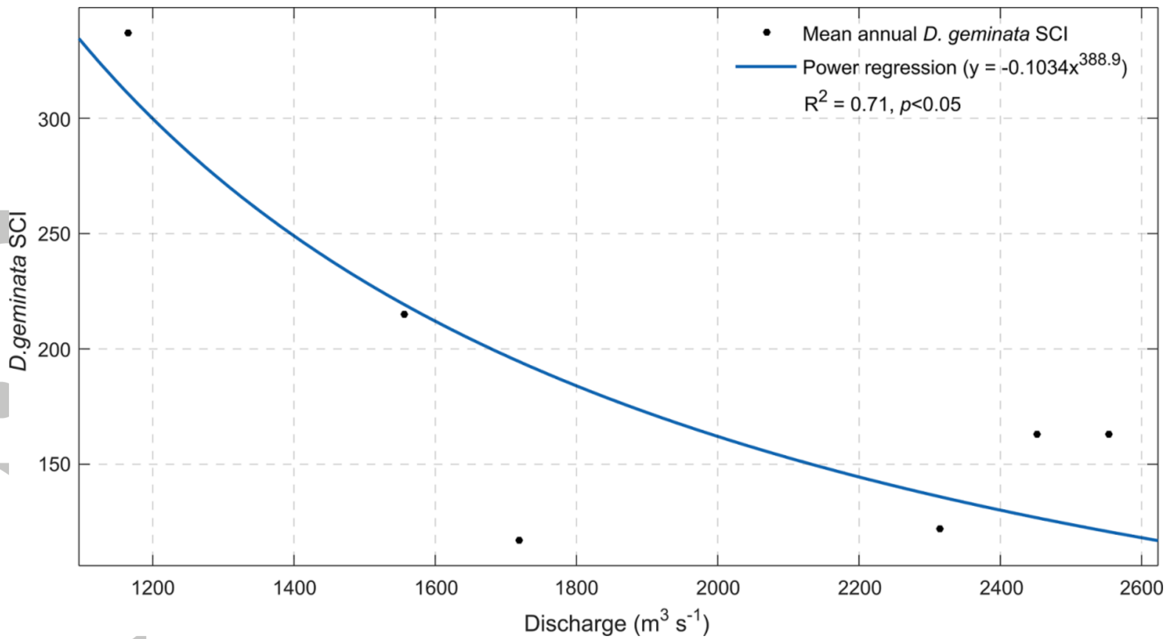

Figure 4. Power regression model of mean annual *D. geminata* SCI in relation to maximum spring discharge (m^3s^{-1}).

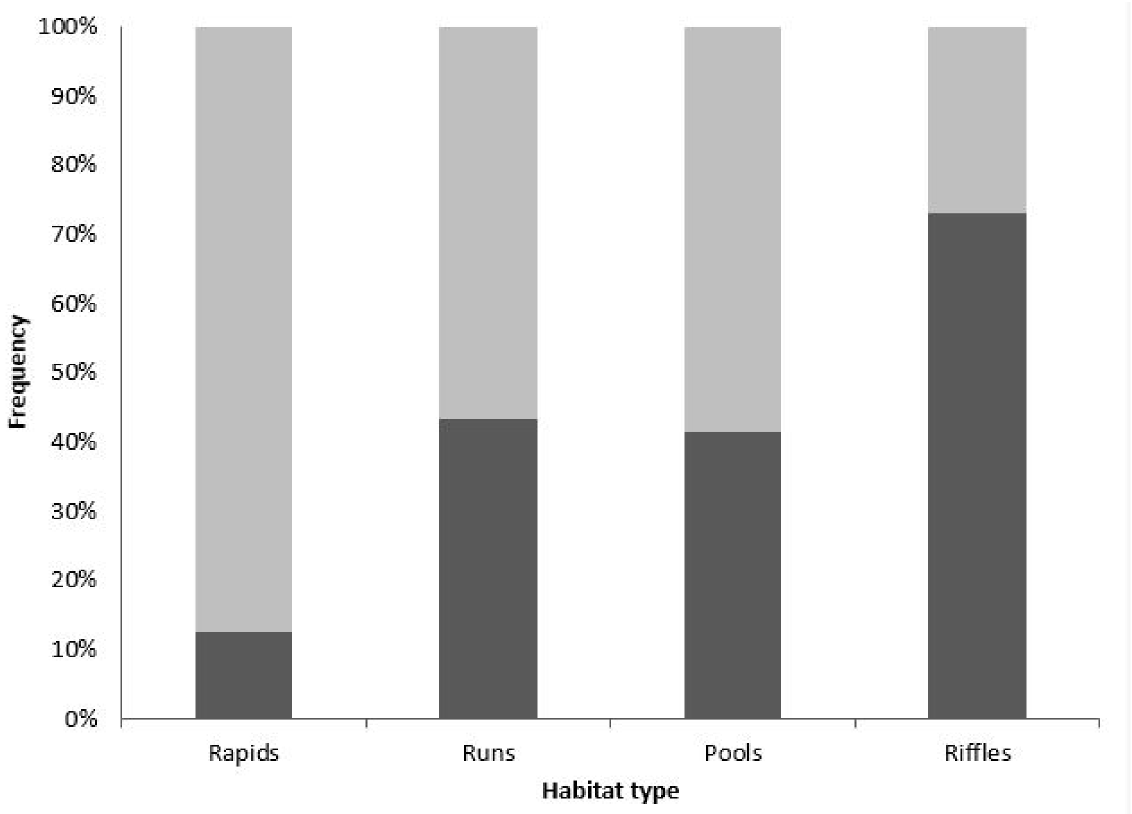

Figure 5. Frequency of *D. geminata* mat presence (dark grey) and absence (light grey) in various habitat types of the Matapedia River