CASCADE

States of Jersey, Department for Infrastructure

St Aubin's Bay
Ulva Studies 2014-2015

March 2016

In association with:

Nurture ecology

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Client: **States of Jersey, Department for Infrastructure**

Title: **St Aubin's Bay**
***Ulva* Studies 2014-2015**

Project No: **CC1109**

Date of Issue: **March 2016**

Status: **Final**

Version No: **1.0**

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NON-TECHNICAL SUMMARY

Large blooms of seaweed are formed by opportunistic, short-lived algae, which are a natural component of shallow-water marine communities. However, humans are believed to have increased the magnitude, extent, frequency, and duration of their proliferation by increasing nutrient inputs to coastal waters. Anecdotal evidence indicates that 'green tides', nuisance blooms of *Ulva* (sealettuce) have become more frequent in St Aubin's Bay over recent years. Brittany has also experienced serious problems with green tides over the past few decades, causing serious issues for the tourism industry. Problems with *Ulva* blooms are reported elsewhere in Europe (e.g Italy and Ireland), as well as further a field in China and New Zealand.

St Aubin's Bay is a large tidal bay located on the south coast of Jersey which receives water quality inputs from a number of sources, most notably several streams which drain a large proportion of the island of Jersey and the treated effluent from Bellozanne Sewage Treatment Works, the main waste water treatment facility on Jersey. In addition to the land based water quality inputs, the Bay is heavily influenced by water quality in the wider marine oceanic environment (the Bay of St Malo). The wide shallow nature of the Bay provides for a low energy wave environment, which favours growth of species such as *Ulva*.

Green tides can have serious ecological consequences, changing ecosystem structure and reducing species diversity. Release of hydrogen sulphide during the breakdown of large volumes of sea lettuce has also been associated with health issues. The ongoing appearance of *Ulva* blooms in St Aubin's Bay do not appear to be resulting in adverse ecological consequences at this point. The seagrass and other marine communities in the Bay are currently assessed as in good health (as defined by the Department of Environment monitoring as part of their WFD programme). The *Ulva* blooms do however pose a considerable amenity issue.

In 2013 the States of Jersey commissioned Cascade Consulting to undertake a literature review to identify factors controlling the growth of *Ulva* and the conditions that lead to the formation of blooms. Following on from that work, States of Jersey Department for Infrastructure (DfI) commissioned Cascade Consulting to undertake a site visit in July 2014. These observations revealed that the species of *Ulva* growing attached to rocky substrate in the Bay was different to the species that was accumulating on the beach. The species attached to rock had a 'tubular' structure and the species washing up on the beach had a 'sheet-like' structure. The initial observations of *Ulva* growth in St Aubin's Bay made on the site visit provided the basis for the design of a series of studies, which were then commissioned by the DfI.

The aim of the 2014 summer surveys was to provide an understanding of the volume of *Ulva* transported into and out of the Bay via tidal movement. In conjunction a survey to estimate the volume of drift *Ulva* stranded on the beach and floating in the water column was undertaken. Cascade undertook these studies, in collaboration with Nurture Ecology and the Société Jersiaise, in the late summer of 2014 to provide a snap shot of the biomass distribution of *Ulva* in the Bay and to investigate the source of the bloom biomass.

These studies revealed that the total mass of *Ulva* moving in and out of the Bay on each tide was in the range 0.6-70 tonnes wet weight. The mass of *Ulva* across the intertidal area of the Bay was estimated at 8774 tonnes wet weight. Surveys of offshore reefs, which were identified as possible source habitat for the bloom (Grunes aux dardes, Sillette, Grande Vaudin), revealed very little *Ulva* present.

These studies were continued in 2015 to provide an understanding of the bloom species distribution and seasonal patterns in the distribution of the bloom in the eastern portion of the Bay. This was the area of the Bay that the 2014 studies found the highest volume of *Ulva*. The 2015 growth season study coincided with a large bloom that lasted well into the autumn. The study yielded a number of key pieces of information, including the identification of the *U.rigida* as the species that is related to the largest component of the *Ulva* bloom.

A clear seasonal pattern in the development of the bloom was also observed, with density and coverage of *Ulva* highest in July. The largest mass of *Ulva* was found when seawater temperatures are around 15C and higher (the period June-August). The volume of *Ulva* declined by October, however the coverage remained high, with the seaweed spread more thinly over the beach at that time.

Other studies have also found that temperature (and light) are closely linked to the ability of *Ulva* to grow rapidly. These studies show remarkable agreement, despite the range of *Ulva* species investigated, and point to an optimum temperature range of 15-20°C for growth. The 30 year average summer seawater temperature measured in St Helier Harbour is 16.5°C, and this average has been increasing.

When light and temperature are suitable for growth the influence of other factors become important. The key remaining influence on *Ulva* growth is availability of a nitrogen source. Nitrogen concentrations are heavily influenced by human activities, as is the case in St Aubin's Bay. A control in the nitrogen contribution from the human population is potentially the most plausible method for controlling the extent and frequency of *Ulva* blooms.

Several studies are recommended to provide an understanding of the sources of nutrients used by the *Ulva* in St Aubin's Bay, including those from the wider marine environment. Studies are also recommended to enable the 'seed stock' of the *Ulva* blooms to be understood. This information would be required to identify if any effective management strategies could be implemented. The future management of the blooms needs to consider not only the role of nitrogen sources, but the influence of climate change on seawater temperatures which may also exacerbate the problem.

Contents

Non-Technical Summary

1 INTRODUCTION

Large blooms of macroalgae are formed by opportunistic, ephemeral algae, which are a natural component of shallow-water marine communities. However, humans are believed to have increased the magnitude, extent, frequency, and duration of their proliferation by increasing nutrient loads in coastal waters. Anecdotal evidence indicates that 'green tides', nuisance blooms of *Ulva* have become more frequent in St Aubin's Bay over recent years. Brittany has experienced serious problems with green tides over the past few decades, causing serious issues for the tourism industry. Problems with *Ulva* blooms are reported elsewhere in Europe (e.g Italy and Ireland), as well as further afield in China and New Zealand.

St Aubin's Bay is a large tidal bay located on the south coast of Jersey (**Figure 1**) which receives water quality inputs from a number of sources, most notably several streams which drain a large proportion of the island of Jersey and the treated effluent from Bellozanne Sewage Treatment Works (STW), the main waste water treatment facility on Jersey. The Bay has one of the largest tidal ranges in the world, with 12m between high and low water during spring tides. Hence the volumes of water in motion during tidal variation are considerable. In addition to the land based water quality inputs the Bay is also heavily influenced by water quality in the wider marine oceanic environment (the Bay of St Malo). The wide shallow nature of the Bay provides for a low energy wave environment, which favours growth of species such as *Ulva*.

Green tides can have serious ecological consequences, changing ecosystem structure and reducing species diversity[1,2]. Whilst impacts on seagrass are the most widely documented[3,4], the anoxic break down of green tides and the attenuation of light levels by the floating mass of algae can impact a range of marine flora and fauna[5,6] including perennial macroalgae and fish. Ecosystem services such as navigation, fisheries, aquaculture, sailing and tourism can also be impacted, with adverse economic consequences[7]. Release of hydrogen sulphide during the breakdown of large volumes of sea lettuce has also been associated with health issues[8].

The ecological status of St Aubin's Bay has been monitored over the last few years following the Water Framework Directive standards. Results show that the status is 'good' or better for

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[1] Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., Foreman, K. (1997).Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences, *Limnology and Oceanography* 42, 1105-1118.

[2] Liu, D., Keesing, J.K., He,P., Wang, Z., Shi, Y. (2013) The world's largest macroalgal bloom in the Yellow Sea, China: Formation and implications, *Estuarine, Coastal and Shelf Science* 129: 2-10.

[3] Dolbeth, M., Cardoso, P., Pardal, M.A. (2011) Impact of Eutrophication on the Seagrass Assemblages of the Mondego Estuary (Portugal), In: A.A. Ansari et al. (eds.), *Eutrophication: Causes, Consequences and Control*, Springer Science.

[4] McGlatherty, K. (2001) Macroalgal blooms contribute to the decline of seagrass in nutrient-enriched coastal waters, *Journal of Phycology* 37:453–456

[5] Bohórquez, J., Papaspyrou, S., Yúfera, M., van Bergeijk, S.A, García-Robledo, E. Jiménez-Arias, J.L., Bright, M., Corzo, A. (2013) Effects of green macroalgal blooms on the meiofauna community structure in the Bay of Cádiz, *Marine Pollution Bulletin* 70: 10–17.

[6] Dolbeth, M., Cardoso, P.G., Ferreir,a S.M., Verdelhos, T., Raffaelli, D., Pardal, M.A. (2007) Anthropogenic and natural disturbance effects on a macrobenthic estuarine community over a 10-year period, *Marine Pollution Bulletin* 54:576–585.

[7] Cellina, F., De Leo, G.A., Rizzoli, A.E., Viaroli, P., Bartoli, M. (2003) Economic modelling as a tool to support macroalgal bloom management: a case study (Sacca di Goro, Po river delta) *Oceanologica Acta* 26:139–147.

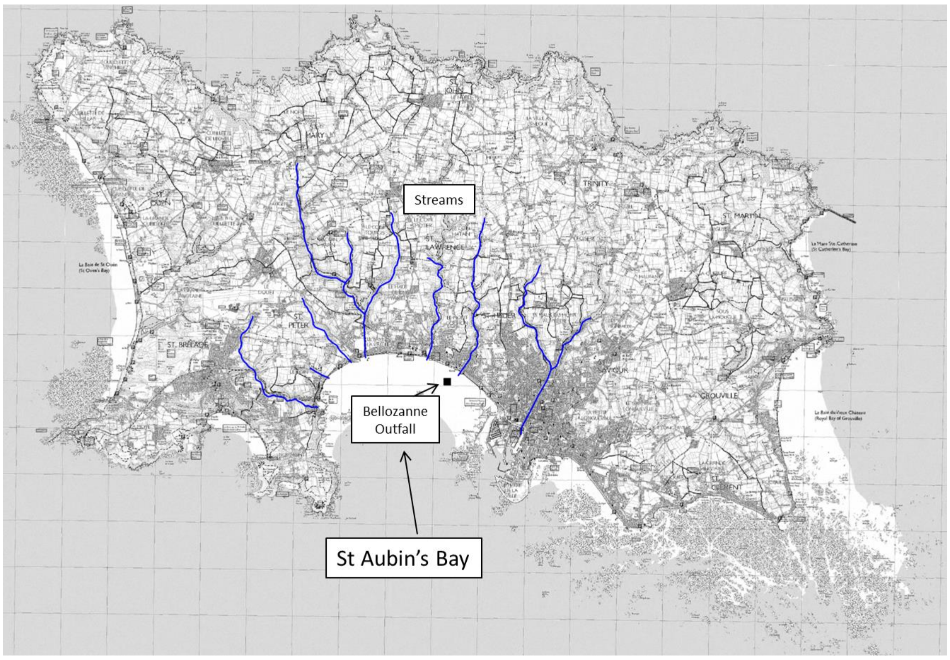
[8] BBC (2009*) Seaweed suspected in French death*, 07/09/09, http://news.bbc.co.uk/1/hi/8242649.stm

most elements, including seagrass which is considered to be at 'High' status. The 'opportunistic algae' status (which includes *Ulva*) is 'moderate', which reflects the prevalence of *Ulva* blooms. .

In 2013 the States of Jersey commissioned Cascade Consulting to undertake a literature review to identify factors controlling the growth of *Ulva* and the conditions that lead to the formation of blooms[9]. Following on from that work, States of Jersey Department for Infrastructure (DfI; formerly Transport and Technical Services Department) commissioned Cascade Consulting to undertake a site visit in July 2014. The initial observations of *Ulva* growth in St Aubin's Bay made on the site visit provided the basis for the design of a series of studies, which were then commissioned by the DfI. Cascade undertook these studies, in collaboration with Nurture Ecology and the Société Jersiaise, in the late summer of 2014 to provide a snap shot of the biomass distribution of *Ulva* in the Bay and to investigate the source of the bloom biomass. These studies were continued in 2015 to provide an understanding of the bloom species distribution and seasonal patterns in biomass distribution in the eastern portion of the Bay.

This report sets out the findings of the above studies, and provides a synthesis with reference to recent literature on the topic.

Figure 1. Location of St Aubin's Bay



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[9] Cascade Consulting (2013) *St Aubin's Bay Sea Lettuce Literature Review*, Report prepared for the States of Jersey.

2 SUMMER 2014 STUDIES

2.1 SITE VISIT 2014

The findings of the site visit were detailed in a briefing note to improve understanding of *Ulva* growth in St Aubin's Bay[10]. The site visit in July 2014 provided the following key findings:

- Rocky substrate within the Bay (at Elizabeth Castle and St Aubin's Fort) provides habitat for tubular species of *Ulva* (e.g. *U.intestinalis* and *U.compressa*);
- Pebbles and small boulders located in areas of low water motion also provide habitat for tubular species (e.g. next to the Elizabeth Castle causeway);
- Very few sheet-like individuals (*U.lactuca or U.rigida*) were found attached to substrate at either Elizabeth Castle or St Aubin's Fort. No attached sheet-like *Ulva* was found in any quadrat but small areas were observed beyond quadrats;
- Unattached, drift sheet-like *Ulva* was abundant in the middle of the Bay;
- Smaller quantities of sheet-like *Ulva* were found in the upper intertidal at Elizabeth Castle and St Aubin's Fort; and
- Only small volumes of *Ulva* were observed in the water column.

Whilst these findings were based on preliminary surveys they provided evidence that the volume of drift *Ulva* observed on the beach in St Aubin's Bay far exceeds the quantity growing attached to substrate within the Bay. The species growing attached to substrate within the Bay (tubular species) differed from the drift *Ulva* species on the strand line (clearly a sheet-like species). The source of the drift *Ulva* was considered unlikely to be macroalgae resident on rocky substrate within the Bay.

On the basis of the site visit observations it was considered therefore that the source of the drift algae may be external to the Bay. There are two possible scenarios that would see quantities of drift *Ulva* washed onto the beach in the St Aubin's Bay; 1) the drift *Ulva* volume is entirely sourced from outside the Bay, and 2) smaller quantities of biomass enter the Bay then increases in volume once within the Bay.

Understanding the source of the bloom biomass is necessary to be able to develop a range of management responses. A series of screening studies were carried out in late summer 2014 in order to provide insight into the source of the bloom biomass.

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[10] Cascade Consulting (2014) *St Aubin's Bay Ulva Site Visit*, Briefing Note prepared for TTS, States of Jersey.

2.2 BLOOM BIOMASS SURVEYS

The aim of the 2014 surveys was to provide an understanding of the volume of *Ulva* biomass transported into and out of the Bay via tidal movement. In conjunction with a survey to estimate the volume of drift *Ulva* biomass both stranded on the beach and resident in the water column, these surveys provided data for an initial estimated mass balance model of *Ulva* biomass in St Aubin's Bay.

The methodology and results are presented in full in **Appendix A**, and are summarised below.

2.2.1 Establishing the Volume of Drift *Ulva* Entering / Leaving the Bay

This component of the study aimed to provide an estimate of *Ulva* biomass entering and leaving the Bay on a spring tide in August 2014. A bespoke biomass capture unit was deployed on the sediment surface in the path of the flooding spring tide, and then reversed to capture biomass moving out on the retreating tide (see **Figure A1.2** in **Appendix A**). The location for deployment was selected based on knowledge of the hydrodynamics of the Bay, allowing capture from both flooding and retreating tidal currents (see **Figures A1.1** and **A1.3** in **Appendix A**. The survey was repeated over three consecutive tidal cycles.

The results provided an initial estimation of the mass of *Ulva* moving throughout St Aubin's Bay on a tidal cycle in late summer. The survey coincided with the end of an *Ulva* bloom of, in comparison with recent blooms, mild proportions. Capture of *Ulva* biomass moving on three consecutive tides revealed a high degree of variability between days and tidal flow direction. Preliminary estimates of the total mass of *Ulva* moving in and out of the Bay on each tide are in the range 0.6-70 tonnes wet weight per tide.

The variability encountered during this pilot study indicates that multiple units would need to be deployed across the Bay in order to provide a more accurate estimation of the volume of *Ulva* moving into and out of the Bay.

2.2.2 Establishing the Biomass of Drift *Ulva* Present in the Bay

Drift *Ulva*

The collection of drift *Ulva* stranded on the beach in St Aubin's Bay coincided with the tidal capture survey above. The survey involved the collection at low tide of all *Ulva* biomass within four 1m^2 quadrats along each of nine transects spanning the width of the bay (see **Figure A1.5** in **Appendix A**).

The density of stranded *Ulva* averaged 0.137 (± 0.209) kg dry weight/m^2 (equivalent to 0.49 kg wet weight/m^2). The total biomass across the 586 ha Bay area during the survey was estimated at 2431 tonnes dry weight (equivalent to 8774 tonnes wet weight).

Surf Zone Water Column *Ulva*

In addition to the drift *Ulva* stranded on the beach a collection of the biomass floating in the nearshore 'surf zone' was also made.

A trawl of 25m length extending outwards from the lowest point of each beach biomass transect was made using a fishing net.

Biomass collected in these trawls averaged at 0.013 kg dry weight/m^3. Using assumptions on the depth and width of the surf zone, the total volume of the surf zone equated to approximately 256500m^3. *Ulva* biomass in the surf zone totalled at 3.2 tonnes dry weight (11.6 tonnes wet weight).

2.2.3 Establishing the Source Habitat of the Drift *Ulva*

Tidal movement can transport drift macroalage significant distances, so the source habitat for the drift *Ulva* in St Aubin's Bay could be some distance away. An initial search of the nearest rocky habitat was made as a first step towards determining the source habitat.

A diving survey of three near shore reefs (Grunes aux dardes, Sillette, Grande Vaudin) located in the path of the flood tide (see **Figure A1.6** in **Appendix A**) was conducted in mid September 2014.

Very little *Ulva* was present on any of the reefs. Of the six transects completed only one had more that 5% cover of *Ulva* in any quadrat. The majority of quadrats had either no *Ulva* present or less that 1% cover. The very low cover of *Ulva* on the reefs make it unlikely they provide the 'seed' for blooms within the Bay.

2.3 2014 SUMMARY

The 2014 studies carried out in St Aubin's Bay captured information during a summer which ultimately saw only a 'mild' bloom, with volumes, coverage of the Bay and persistence of the bloom all much reduced compared to the following year. Nevertheless the data collected provided useful information on a series of points. These include:

Ulva species growing attached to substrate in the Bay

- Rocky substrate within the Bay (at Elizabeth Castle and St Aubin's Fort) provides habitat for tubular species of *Ulva* (e.g. *U.intestinalis* and *U.compressa*);
- Pebbles and small boulders located in areas of low water motion also provide habitat for tubular species (e.g. next to the Elizabeth Castle causeway);
- Very few sheet-like individuals (*U.lactuca* or *U.rigida*) were found attached to substrate at either Elizabeth Castle or St Aubin's Fort;

Bloom species

- Unattached sheet-like *Ulva* (*U.lactuca* or *U.rigida*) was abundant as 'drift' on the beach in the Bay;

Movement of *Ulva* throughout tidal cycle

- Capture of *Ulva* biomass moving on three consecutive tides revealed a high degree of variability between days;
- Estimates of the total mass of *Ulva* moving in and out of the Bay on each tide are in the range 0.6-70 tonnes wet weight;

Biomass of 'drift' *Ulva* on beach

- The density of stranded *Ulva* averaged 0.40 kg wet weight/m^2;
- The total biomass across the 586 ha Bay area is estimated at 8774 tonnes wet weight;

Biomass of *Ulva* in 'surfzone'

- Biomass collected in trawls through the surfzone averaged at 0.46 kg wet weight /m^3;
- *Ulva* biomass in the entire surf zone estimated at 11.6 tonnes wet weight;

Ulva on offshore reefs

- Survey's of offshore reefs revealed very little *Ulva* present.

3 2015 GROWTH SEASON STUDY

3.1 OVERVIEW

The studies in summer 2014 provided a useful snapshot of *Ulva* biomass during the Bay in late summer of that year, and indicated that the 'drift' bloom species differed from the *Ulva* species resident on rocky substrate in the Bay. These studies were not able to provide an indication of the seasonal changes in biomass, which is crucial to understanding the bloom dynamics. Any future management strategy for *Ulva* blooms would need to be based on a thorough understanding of the triggers for, and timing of, excessive *Ulva* growth. This requires a seasonal approach to the observation of biomass and species composition, as well as recruitment processes.

As a first step towards this understanding, the Société Jersiaise conducted biomass sampling throughout the growth season (April-October), concentrating on transects along the eastern section of the Bay (Victoria Pool, Outfall East and Outfall West). These transects were identified as being the area of highest biomass in the 2014 study. In addition, sampling was carried out during two lunar cycles (July & August) to provide information on short-term variation in biomass and influence of tidal movement.

3.2 METHODOLOGY

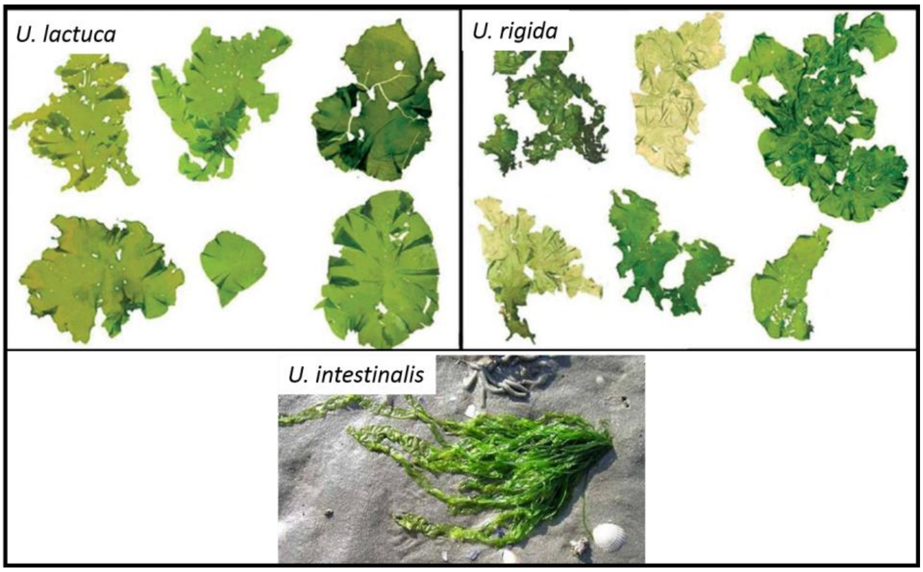
Three locations were identified along each transect, representing the upper, middle and low intertidal positions (see **Figure 2**). Three representative quadrats were sampled at each location. Quadrats were photographed for later analysis using Image J software (to provide percentage cover data) and then all biomass within the quadrat was collected, shaken to remove sand, wrung out in a net and weighed using a field scale. A subsample of each quadrat was retained for later identification of species. Each quadrat was then classified by the dominant species found. Many *Ulva* species look morphologically alike (see **Plate 1**) so identification requires microscopy to differentiate species using cellular structure. Both *U.rigida* and *U.lactuca* have a 'sheet like appearance whereas *U.intestinalis* has a tubular morphology.

Samples of sediment were also retained to quantify the density of *Ulva* propagules or spores resident in the sediment. Unfortunately this proved unsuccessful with the equipment available, so no data was collected.

A 'sea lettuce cam' was also installed which captured images at 3 hourly intervals throughout the season. Every image taken that coincided with low tide, as well as daylight hours, was combined to form a slideshow of the growth season (see separate file 'St Aubin's *Ulva* 2015.mpv'). No quantitative data can be extracted from the slideshow, however it provides a useful qualitative record of the variation in biomass throughout the year.

Figure 2. 2015 Biomass Collection Transects and Quadrats

Plate 1. Variation in *Ulva* Morphology (Source, Hofmann *et al* 2010[11])



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[11] Hofmann, L.C. , Nettleton, J.C. , Neefus, C.D., Mathieson, A.C. (2010) Cryptic diversity of *Ulva* (Ulvales, Chlorophyta) in the Great Bay Estuarine System (Atlantic USA): introduced and indigenous distromatic species, *European Journal of Phycology,* 45:3, 230-239

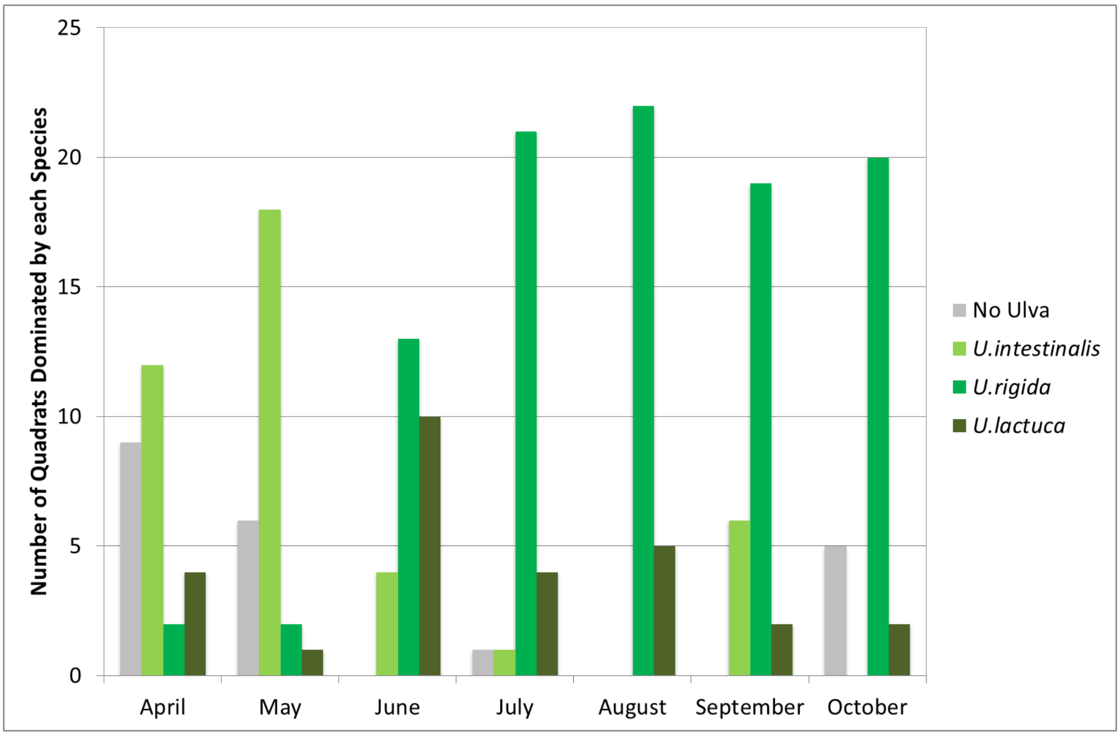
3.3 RESULTS

3.3.1 Bloom Species Richness and Seasonal Dominance

A seasonal variation in the pattern of species richness and in the species dominating the bloom biomass was found. **Figure 3** illustrates the number of quadrats dominated by each species (or 'no growth') across the period April-October. Results have been summed across transects, and therefore represent the results for a total of 27 quadrats.

Early in the season (April) a third of quadrats contained no *Ulva* at all. Those quadrats with *Ulva* present were dominated by *U.intestinalis*, with only small numbers dominated by *U.lactuca* (four quadrats) or *U.rigida* (two quadrats). The dominance of *U.intestinalis* increased into May, with 18 quadrats dominated by this species at that time. By June all quadrats had *Ulva* present and the dominance of *U.intestinalis* had declined, with *U.lactuca* dominating 10 quadrats and *U.rigida* dominating 13 quadrats. Over the next four months (July- October) the bloom biomass was clearly dominated by *U.rigida*, which dominated 18-22 quadrats over that period.

Figure 3. Species Biomass Dominance Patterns During 2015 Bloom Surveys



3.3.2 Seasonal Patterns in Biomass

The biomass levels in **Figure 4** and **Table 1** illustrate the mean biomass across all quadrats / transects for each month. The variability within each month was high in the overall means, and also in the means across each transect (see **Figure 5** and **Table 2**). However, a clear seasonal pattern in the development of the bloom biomass was observed, with mean density of *Ulva* highest in July at 0.81 kg wet weight.m^{-2}. The distribution of the *Ulva* bloom across the intertidal area was still very variable in July, with the density ranging from 0-5.45 kg wet weight.m^{-2} within quadrats sampled that month.

Table 1. Mean Biomass and Percentage Cover Each Month

Month	Mean Wet Weight (g/m²)	SD	Mean %Cover	SD
April	16.3	3.1	0.5	0.6
May	171.4	37.4	4.9	6.1
June	575.0	433.9	20.5	22.0
July	812.4	1231.5	35.2	33.7
August	517.3	649.6	41.2	27.4
September	334.0	565.6	34.9	29.0
October	132.0	167.7	26.9	26.6

The average seawater temperatures for St Helier Harbour[12] are also plotted on **Figure 4**. The largest biomass is found when seawater temperatures are around 15°C and higher. The data provided by Jersey Met included 30 year period averages, which indicates the average summer sea water temperature has increased through the last few decades; period 1961-1990 summer average 16.1°C; 1971-2000 summer average 16.2°C; and 1981-2010 summer average 16.5°C.

Dissolved inorganic nitrogen levels in the middle of the Bay (measured through the States of Jersey Department of Environment WFD monitoring program) are also plotted on **Figure 4**, and show a spike in concentration in June. An additional data set provided by the Department of Environment records the total inorganic nitrogen concentration in the nearshore zone of St Aubin's Bay through weekly monitoring. The data is presented in **Table 3**, and indicates that the concentration of nitrogen in the water is much higher prior to dispersal of land-based discharges into the wider Bay.

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[12] Data provided by Jersey Met Office.

Figure 4. Seasonal Variation in Mean Biomass, Seawater Temperature and Dissolved Inorganic Nitrogen Concentration

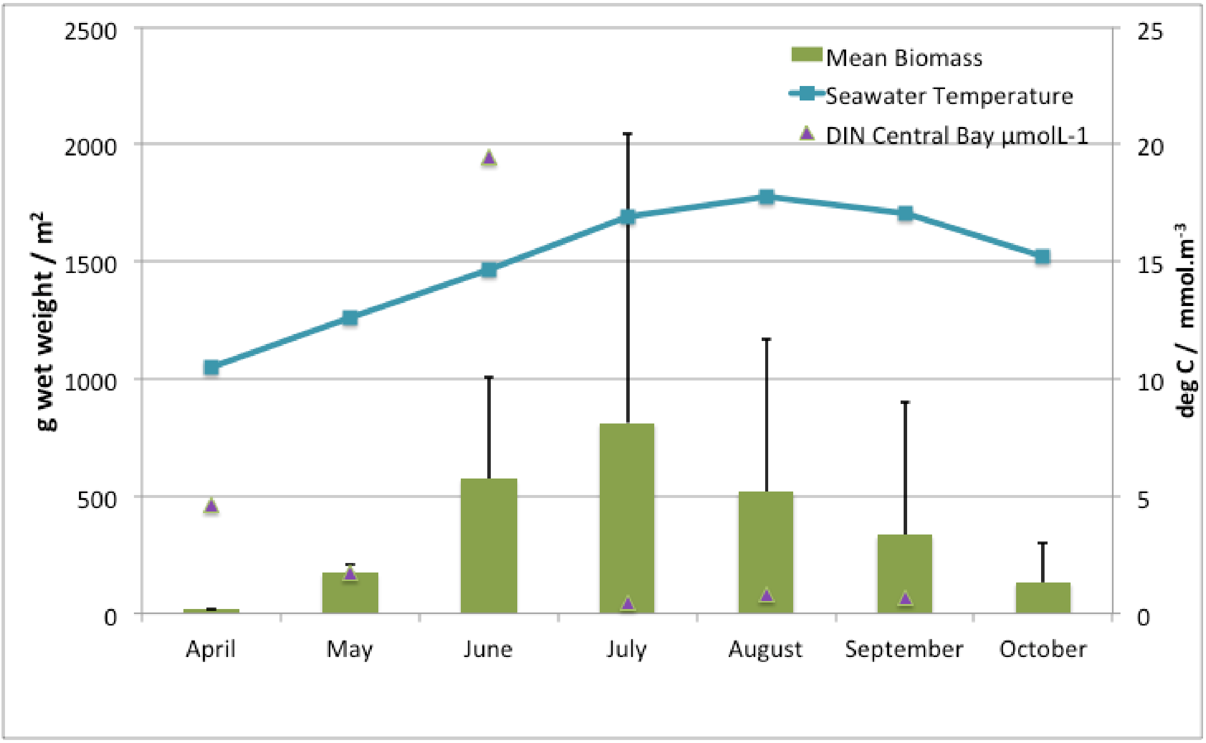


Figure 5. Seasonal Variation in Mean Biomass Along Each Transect

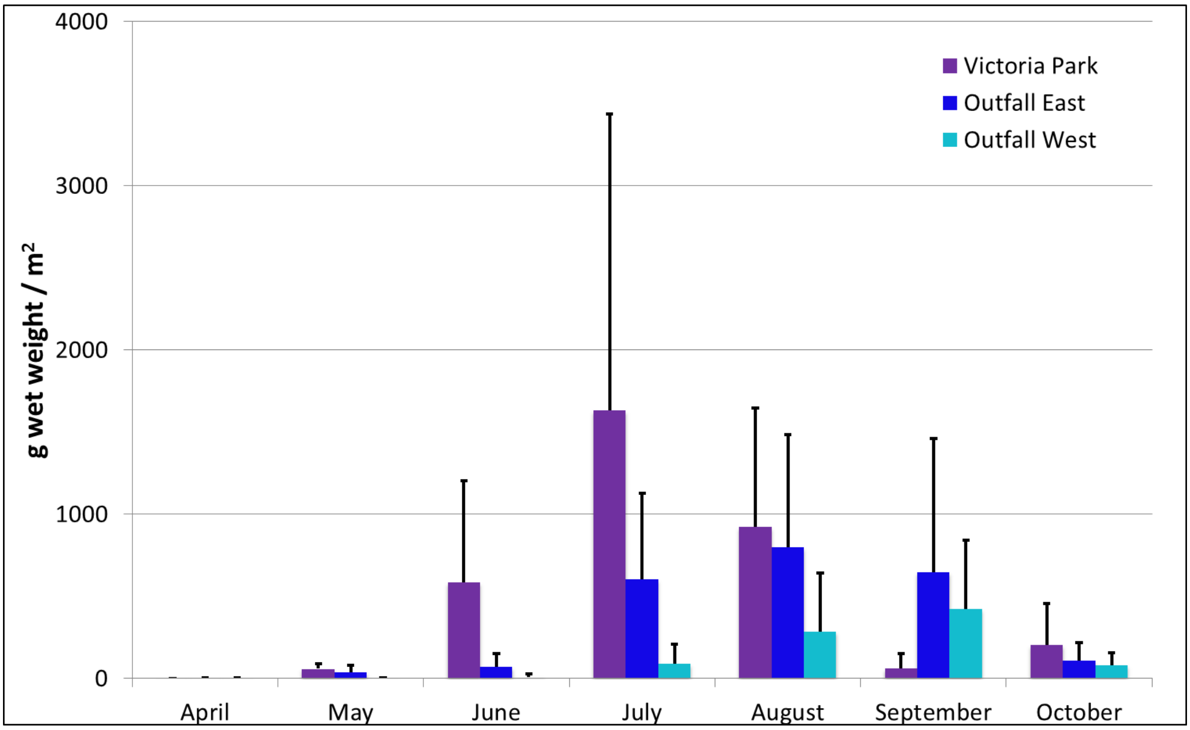


Figure 6. Seasonal Variation in Mean Biomass and Mean monthly Hours of Sunlight

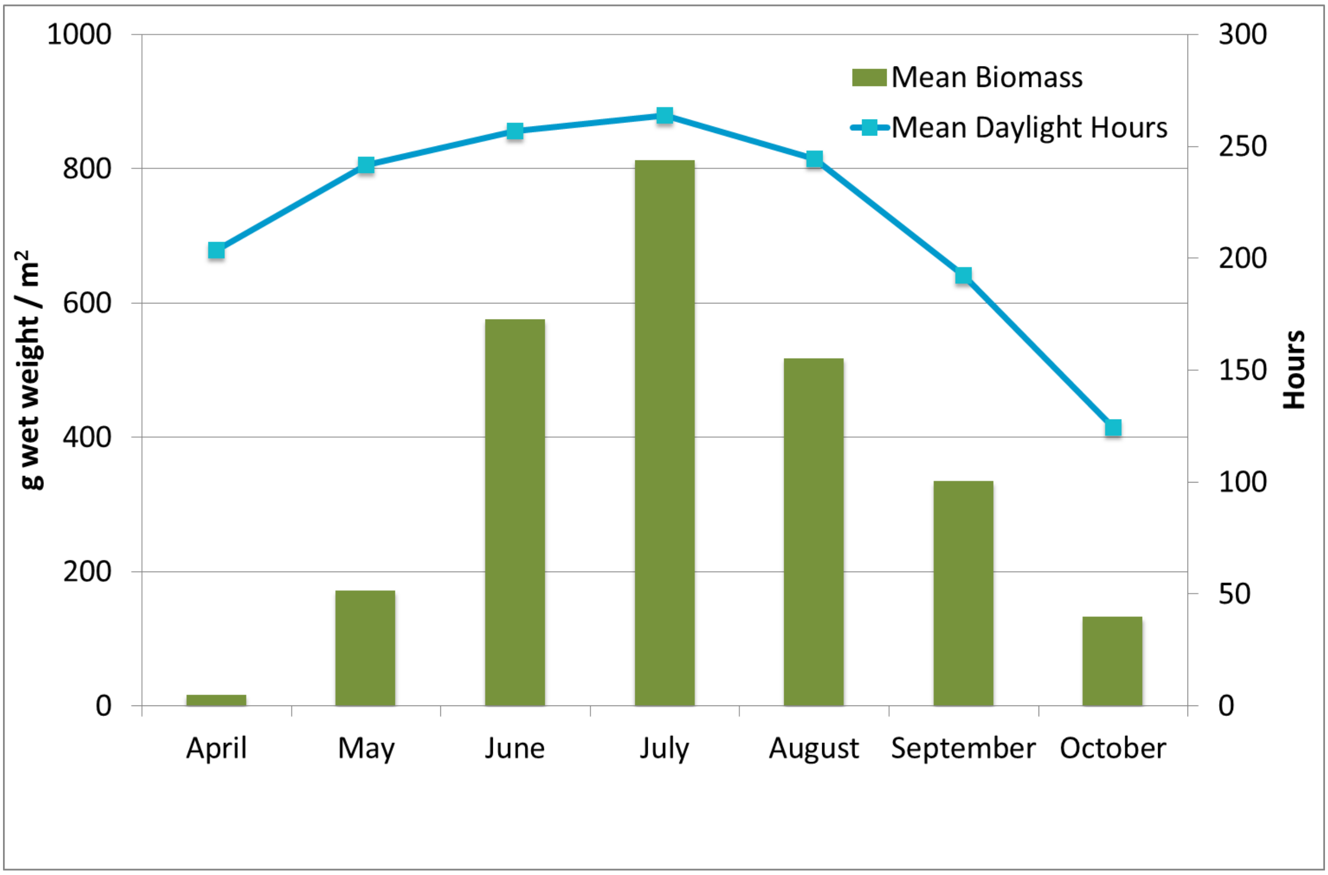


Table 2. Mean Biomass and Percentage Cover Along Each Transect

	Victoria Park				Outfall East				Outfall West			
Month	**Mean Biomass (g wet weight / m^2)**	**SD**	**Mean % Cover**	**SD**	**Mean Biomass (g wet weight / m^2)**	**SD**	**Mean % Cover**	**SD**	**Mean Biomass (g wet weight / m^2)**	**SD**	**Mean % Cover**	**SD**
April	0.9	0.9	0.4	0.4	2.5	4.2	0.4	0.6	2.4	3.3	0.6	0.7
May	59.4	32.9	7.5	4.3	38.4	40.3	6.6	8.4	2.7	2.2	0.6	0.6
June	585.2	617.4	37.6	23.1	71.3	80.0	20.7	18.9	11.3	15.1	3.2	4.0
July	1632.3	1803.9	52.5	40.6	604.6	522.9	39.6	28.4	90.0	118.0	13.4	18.5
August	922.6	722.3	50.5	36.3	798.9	684.8	47.6	19.5	286.9	353.5	25.6	18.2
September	60.9	93.4	11.6	19.1	647.3	812.2	49.0	31.6	424.4	417.4	44.2	21.1
October	203.3	254.2	31.0	37.8	110.3	110.7	25.7	22.4	82.3	74.2	23.9	18.6

Figure 7. Relationship Between Mean Biomass and Seawater Temperature and Daylight Hours

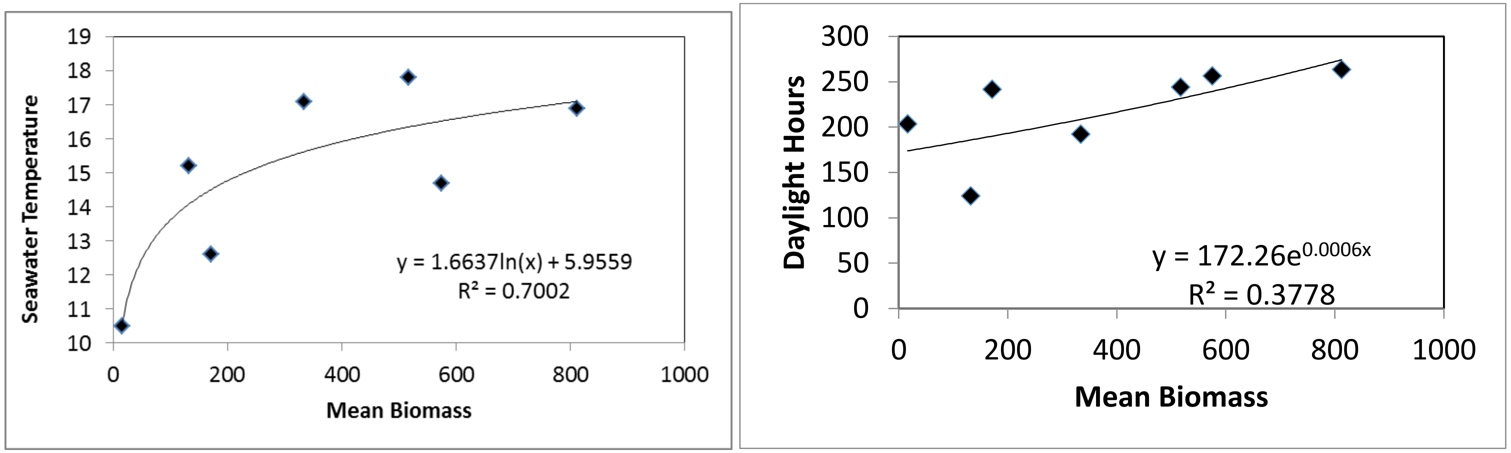


Table 3. Average Total Inorganic Nitrogen Concentration in St Aubin's Bay Nearshore Zone

Month	Average Total Inorganic Nitrogen (mmol/m^3)
April	112
May	89
June	82
July	53
August	74
September	18
October	200

The average monthly hours of sunshine at Fort Regent Signal Station (overlooking St Helier) are plotted with mean monthly biomass in **Figure 6**. The relationship between mean biomass and mean seawater temperature is plotted on **Figure** 7, and as would be expected, a positive relationship exists between these two variables. The decline in biomass in autumn follows the trend in decline in sunlight hours, however the relationship is not significant (see **Figure** 7). This lack of correlation will be due to the difference between indicant sunlight and availability of irradiance to macroalgae, which will be influenced by day length as well as turbidity levels in the water column.

The August mean in 2015 (0.51 kg.m^{-2}) is remarkably consistent with the mean value in the August 2014 study (0.49 kg wet weight.m$^{-2;}$ see Section 2.2.2).

3.3.3 Biomass Variation with Tidal Height

The variability in biomass levels make it difficult to pull out any clear difference in biomass levels at the different tidal heights (see **Table 4**). Levels of biomass declined more slowly at the two lower tidal heights, whereas levels were still high in September at the High tidal height and these then declined to zero by October.

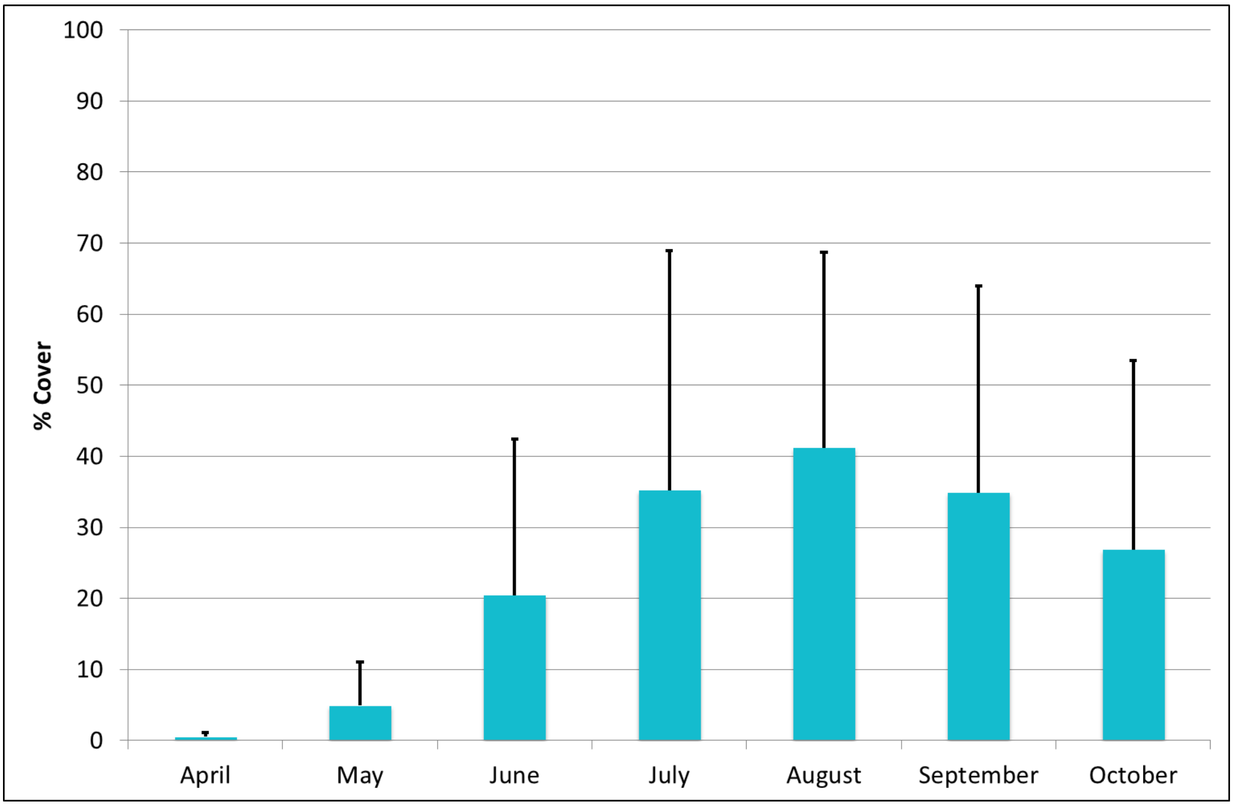
Table 4. Mean Biomass and Percentage Cover at each Tidal Height

Month	Tidal Height	Mean Biomass (g wet weight / m²)	SD	Mean % Cover	SD
April	High	0.0	0.0	0.0	0.0
	Mid	3.8	4.5	0.7	0.6
	Low	2.1	1.7	0.8	0.5
May	High	16.6	30.4	1.0	1.9
	Mid	36.7	38.0	4.3	4.1
	Low	47.1	40.5	9.4	7.8
June	High	396.0	682.7	20.7	29.1
	Mid	160.3	285.3	21.0	22.1
	Low	111.6	110.4	19.6	15.2
July	High	600.0	550.5	28.2	24.2
	Mid	1060.8	2001.5	28.7	41.3
	Low	666.0	692.9	48.7	33.2
August	High	681.4	792.5	31.6	26.8
	Mid	778.9	657.3	44.4	25.0
	Low	548.0	529.9	47.7	30.8
September	High	813.0	820.2	44.2	36.7
	Mid	181.2	185.5	28.8	26.9
	Low	138.4	107.9	31.6	22.7
October	High	8.4	14.7	0.7	1.1
	Mid	118.5	61.2	26.7	14.5
	Low	269.0	221.2	53.2	23.3

3.3.4 Seasonal Patterns in Percent Cover

Similarly to the biomass data, the mean monthly percentage cover displays a high degree of variability (see **Table 1**). A seasonal pattern is evident however, with the peak coverage in August (**Figure 8**). Cover of *Ulva* reduced by October, however not to the same proportion that the biomass levels declined at that time. Percentage cover in October remained higher on average than that observed in June. The percentage cover of *Ulva* at the low tidal height in October was equal to the July and August coverage (see **Table 4**).

Figure 8. Seasonal Variation in Percentage Cover of *Ulva*

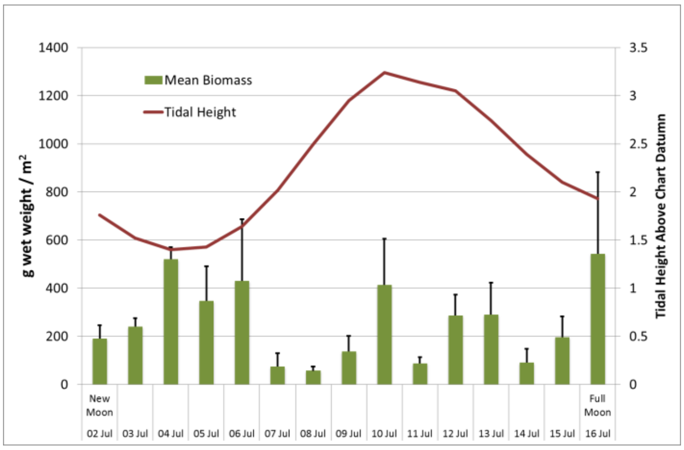


3.3.5 Lunar Cycle Sampling

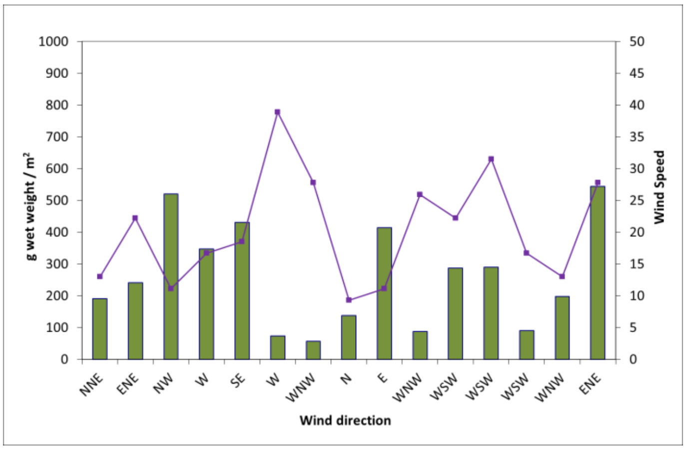
Daily sampling progressed across two lunar cycles, one each in July and August, at three quadrats at the mid tidal height site on the Outfall East transect (OE2; see **Figure 2**). The daily variation in biomass was high in the July sampling, with no clear pattern apparent with tidal height (**Figure 9a**) or wind direction or speed (**Figure 9b**). High variability was also found in the August sampling (**Figure 10a**), however a general trend of increasing biomass towards the middle of the lunar cycle was apparent. No relationship with wind direction or speed was found (**Figure 10b**). Percentage cover varied in similar ways to biomass in both July and August. (**Figure 9c** and **10c**).

Figure 9. Biomass Collected at Outfall East Transect (OE2) over a Lunar Cycle in July

a)



b)



c)

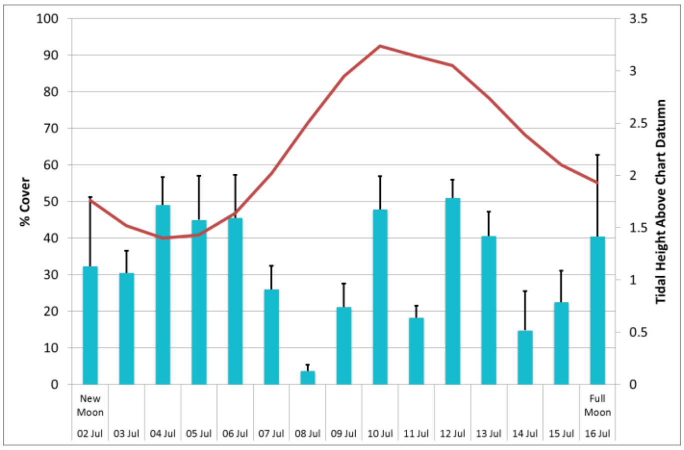
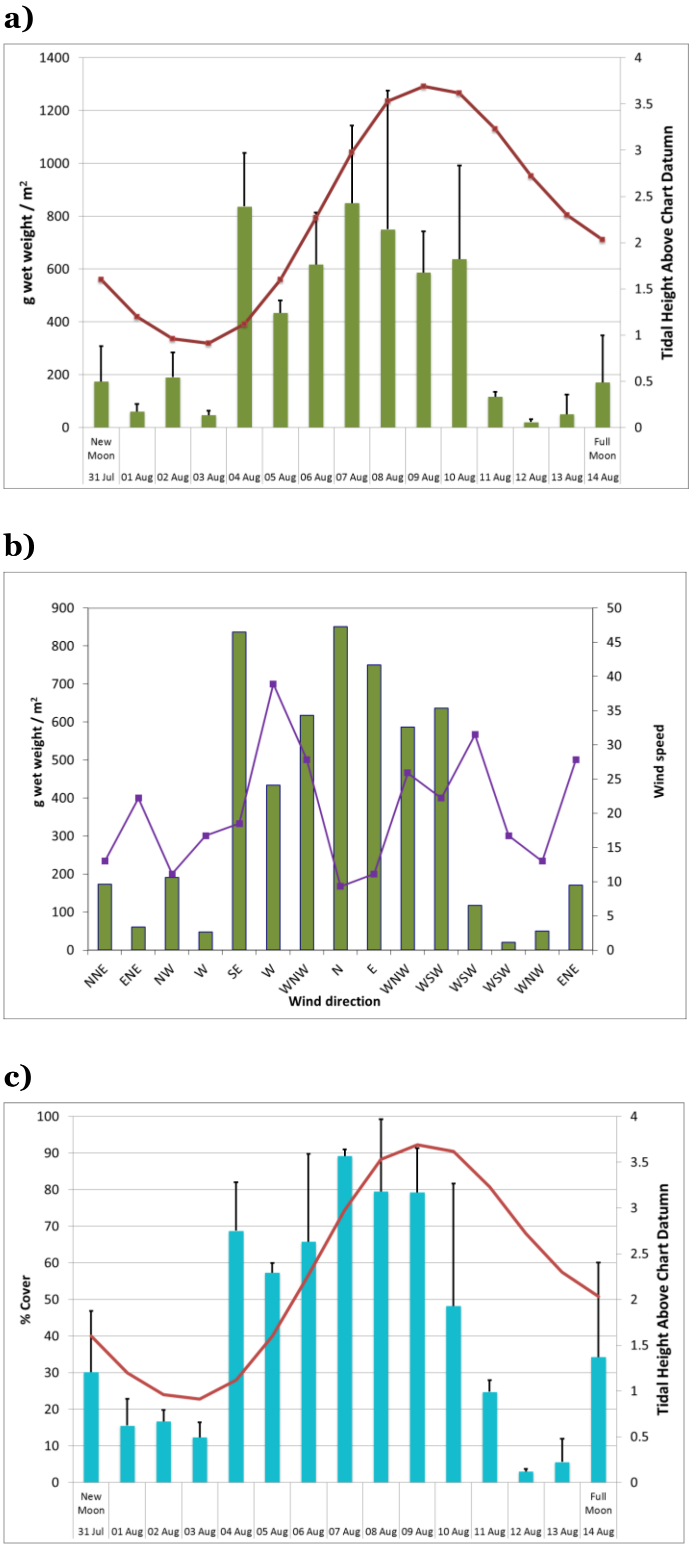


Figure 10. Biomass Collected at Outfall East Transect (OE2) over a Lunar Cycle in August



3.3.6 Department for Infrastructure *Ulva* Removal Activities

The pattern of biomass observed throughout the 2015 season will have been influenced to some degree by the removal of stranded *Ulva* by DfI contractors for amenity reasons. This activity concentrated on areas used for the Island Games in July / August, however as illustrated in **Table 5**, the removal of significant tonnages continued all summer[13]. The method of collection results in a large proportion of sand in the collected matter so the recorded tonnages do not reflect removal of *Ulva* only. The algae was deposited in the low tide region, and was thus not removed from the Bay, but this will have influenced the distribution both across the Bay and along the tidal gradient.

Table 5. Approximate tonnage of *Ulva* removed from Victoria Pool area and deposited to low tide

Date	Approximate Tonnage of Sand and Algae Removed
Sunday 28th June	140
Monday 29th June	154
Tuesday 30th June	392
Wednesday 1st July	308
Thursday 2nd July	392
Friday 3rd July	308
Saturday 4th July	56
Sunday 5th July	84
Monday 27th July	24
Tuesday 28th July	35
Wednesday 29th July	36
Thursday 30th July	275
Friday 31st July	26
Monday 17th August	84
Wednesday 19th August	322
Thursday 20th August	266
Wednesday 2nd September	224
Thursday 3rd September	210
Friday 4th September	154
Tuesday 1st September	22
Wednesday 2nd September	25
Thursday 3rd September	17
Friday 4th September	15
Saturday 6th September	110
Thursday 15th October	281
Friday 16th October	305
Wednesday 4th November	410
Thursday 5th November	308

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[13] DfI Cleaning Services (2015) *West Park Lake – Green Sea Lettuce Removal*

3.4 2015 SUMMARY

The 2015 growth season study coincided with a large bloom which lasted well into the autumn. The study yielded a number of key pieces of information, including:

Bloom species

- Early in the season (April and May) *U.intestinalis* dominated the samples, however *U.rigidia* dominated samples from June to October. The dominance of *U.rigidia* coincide with the highest biomass levels (see below) and can be considered the key species causing nuisance levels of biomass in St Aubin's Bay;

Seasonal variation in biomass

- A clear seasonal pattern in the development of the bloom biomass was observed, with density of *Ulva* highest in July at 0.81 kg wet weight.m^{-2}. Variability in biomass levels were high, however, with the density ranging from 0-5.45 kg wet weight.m^{-2} in July;

- The largest biomass is found when seawater temperatures are around 15C and higher (the period June-August);

- By October *Ulva* was still present but in lower levels (mean 0.13 kg wet weight.m^{-2});

- Patterns in biomass across two lunar cycles were highly variable and did not relate to wind direction or speed.

- Biomass patterns were influenced by an unknown degree from algal clearance activities, which saw the removal of *Ulva* in the Victoria Pool area throughout the summer with the biomass then deposited at low tide.

Percentage Cover

- The seasonal variation in percentage cover mirrored that of the biomass levels, however the decline in cover by October was not as apparent. Percentage cover in October remained higher on average than that observed in June, which indicates the biomass was more extensively distributed at that time.

4 SYNTHESIS

The mechanisms for macroalgal bloom formation are complex and not fully understood by the scientific community. The importance of light, temperature, nutrient levels, and salinity (in estuarine systems), is well documented. However the response by different *Ulva* species to these factors, and the response of populations growing in different locations, has been shown to vary, and therefore the triggers apparent for rapid growth elsewhere will not necessarily remain relevant in waters around Jersey. The studies conducted over the last two years have for the first time provided quantitative information on the *Ulva* blooms in St Aubin's Bay.

Importantly these blooms can now for the first time be attributed to *U.rigidia*. Several other members of the *Ulva* genus also exist in St Aubin's Bay, including *U.lactuca* and *U.intestinalis*. However the high levels of biomass appear to be associated with the growth of *U.rigidia*. This information will allow future studies to focus on understanding the growth of this species as a priority to understanding the dynamics of *Ulva* blooms in St Aubin's Bay, as each species will respond differently to environmental variables. It also allows useful comparisons with studies elsewhere on *U.rigidia*, which will provide more relevant information than studies on other species.

4.1 BLOOM INITIATION – PROPAGULE SURVIVAL AND REPRODUCTIVE STRATEGIES

Initial surveys in 2014 found that the *Ulva* species resident on rocky substrate in the Bay do not include *U.rigida*. The identification of *U.rigida* as the primary component of the bloom biomass means efforts must focus on establishing the initial 'seed' source of this population. The rapid growth rate of *Ulva* means a substantial 'seed bank' would allow rapid expansion of the population.

A number of recent studies have focussed on the ability of *Ulva* to 'overwinter' as propagules (spores or juvenile individuals) or tissue fragments which enable rapid population growth when conditions become favourable in the spring. Extensive efforts in particular have focused on the widespread blooms in China, which are related to growth of *U.prolifera*. Further information is available on other aspects of reproduction, such as germination rates. In summary these studies found:

- Propagules, vegetative fragments and thalli buried in the sediments can survive cold winter conditions, including those of *U.rigida*[14,15,16,17]. Research had previously established that *Ulva* is capable of producing new individuals from fragments[18];

- *Ulva* may rely on vegetative reproduction in the early stages of the bloom, however sexual reproduction as the bloom develops provides a mechanism for widespread colonisation and rapid proliferation of the population[19,20,21] ;
- Numbers of spores / gametes in 1g of *U.prolifera* tissue were in the order 3 x 10^8 to 3 x 10^9;
- Propagules have low motility so high concentrations in the water column will be found only near the source stock (floating / attached *Ulva*) or in the path of direct currents [22,23];
- Spore production and germination[24] is facilitated by higher temperature (and to a lesser extent light) conditions, and rates were found to be increased in the later stages of the green tide[25];
- Fragmentation can accelerate the rate of spore production and release[26], and damage to *U.prolifera* tissue resulted in production of spores after 2-3 days;
- Desiccation provides a cue for spore release[27];

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[14] Zhang, X, Wang, H., Mao, Y. ,Liang, C. , Zhuang, Z., Zang, Q., Ye, N. (2010) Somatic cells serve as a potential propagule bank of *Enteromorpha prolifera* forming a green tide in the Yellow Sea, China. *Journal of Applied Phycology* 22:173-180.

[15] Zhang JH, Huo YZ, Zhang ZL, Yu KF, He Q, Zhang LH, Yang LL, Xu R, He PM (2013) Variations of morphology and photosynthetic performances of *Ulva prolifera* during the whole green tide blooming process in the Yellow Sea. *Marine Environmental Research* 92:35-42.

[16] Geng, H., Yan, T., Zhou, M., Liu, Q. (2015) Comparative study of the germination of *Ulva prolifera* gametes on various substrates. Estuarine, Coastal and Shelf Science 163: 89-95.

[17] Rinehart, S., Guidone, M., Ziegler, A., Schollmeier, T., Thornber, C. (2014). Overwintering strategies of bloom-forming *Ulva* species in Narragansett Bay, Rhode Island, USA. Botanica Marina. 57(4): 337-341.

[18] Santelices, B., Paya, I. Digestion Survival of Algae: Some Ecological Comparisons between free spores and propagules in fecal pellets. *Journal of Phycology* 25:693-699

[19] Zhang JH, Huo YZ, Zhang ZL, Yu KF, He Q, Zhang LH, Yang LL, Xu R, He PM (2013) Variations of morphology and photosynthetic performances of *Ulva prolifera* during the whole green tide blooming process in the Yellow Sea. *Marine Environmental Research* 92:35-42.

[20] Song, W., Li, Y., Fang, S, Wang, Z., Xiao, J., Li, R., Fu, M., Zhu, M., Zhang, H. (2015) Temporal and spatial distributions of green algae micro-propagules in the coastal waters of the Subei Shoal, China. *Estuarine, Coastal and Shelf Science* 163:29-35.

[21] Huo, Y., Hua, L. , Wu, H., Zhang, J., Cui, J., Huang, X., Yu, K., Shi, H., He, P., Ding, D. (2014) Abundance and distribution of *Ulva* microscopic propagules associated with a green tide in the southern coast of the Yellow Sea. Harmful Algae 39:357-364.

[22] Song, W., Li, Y., Fang, S, Wang, Z., Xiao, J., Li, R., Fu, M., Zhu, M., Zhang, H. (2015) Temporal and spatial distributions of green algae micro-propagules in the coastal waters of the Subei Shoal, China. *Estuarine, Coastal and Shelf Science* 163:29-35.

[23] Li, Y., Song, W., Xiao, J., Wang, Z.L., Fu, M.Z., Zhu, M.Y., Li, R.X., Zhang, X.L., Wang, X.N., (2014). Tempo-spatial distribution and species diversity of green algae micro-propagules in the Yellow Sea during the large-scale green tide development. *Harmful Algae* 39: 40-47.

[24] Lotze, H.K., Worm, B., Sommer, U. (2000) Propagule banks, herbivory and nutrient supply control population development and dominance patterns in macroalgal blooms. Oikos 89: 46-58.

[25] Zhang JH, Huo YZ, Zhang ZL, Yu KF, He Q, Zhang LH, Yang LL, Xu R, He PM (2013) Variations of morphology and photosynthetic performances of *Ulva prolifera* during the whole green tide blooming process in the Yellow Sea. *Marine Environmental Research* 92:35-42.

[26] Zhang JH, Huo YZ, Zhang ZL, Yu KF, He Q, Zhang LH, Yang LL, Xu R, He PM (2013) Variations of morphology and photosynthetic performances of *Ulva prolifera* during the whole green tide blooming process in the Yellow Sea. *Marine Environmental Research* 92:35-42.

[27] Zhu, M., Liu, Z.P., Xu, J.T., Mao, Y.X., Yao, D.R., 2011. The release, adhesion and germination of spores of *Enteromorpha prolifera* and its adaptation to different desiccation conditions. *Acta Oceanologica Sinica* 35 (7), 1–6 (in Chinese with English abstract).

- The development of green tides in China were facilitated by the settlement of *Ulva* spores on *Porphyra* aquaculture ropes[28]. Rates of settlement were similar on all substrates but germination success was significantly higher on plastic ropes (2680 germlings developed per cm^2) than on rock (56 germlings developed per cm^2) or sand (0.5 germlings developed per cm^2). Blades within the established bloom were considered able to provide possible substrate for germination, however germination success on this substrate was considered to be 'poor';

- Herbivory is an important mechanism controlling the size of the *Ulva* population at the juvenile stage[29].

The above studies indicate it is possible that the 'seed stock' for *U.rigida* blooms in St Aubin's Bay may remain resident in the middle of the Bay throughout winter, existing as vegetative fragments or propagules in the sediment. Alternatively, a population resident offshore may provide a propagule / fragment source which, following proliferation within the favourable conditions in the Bay, would be capable of forming the bloom biomass. The initial surveys in 2014 found very little evidence of *Ulva* growing attached to the three offshore reefs surveyed, however this only represents a small portion of the available habitat outside the Bay. These two scenarios would have fairly similar consequences for any management strategies, as the trigger for germination is predominantly seawater temperature which cannot be controlled. A rise in average summer sea water temperature (as recorded in St Helier Harbour; see Section 3.3.2) indicates that global climate change is likely to have an influence on the timing of growth initiation.

An understanding of the reserves of *Ulva* within the Bay (or in habitat elsewhere and the flux into the Bay) would be central to provide an understanding of the initial phase of the bloom development and the rate of expansion of the population. A scenario which sees the bloom develop from a small reserve of propagules / fragments would potentially provide greater opportunity for intervention (for example a strict control of nutrient levels to limit bloom development over a defined critical period, to avoid a 'critical mass' of *Ulva* developing in spring), in comparison to a scenario in which the 'seed bank' is large and only a short period of time is required to reach bloom dimensions.

4.2 RAPID POPULATION EXPANSION

4.2.1 Light and Temperature

Following on from the establishment of the seed stock, the next phase of bloom development requires a period of rapid growth. The *U.rigida* population in the 2015 bloom reached high

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[28] Qing Liu, Q., Yu, R., Yan, T., Zhang, Q., Zhou, M. (2015) Laboratory study on the life history of bloom-forming *Ulva prolifera* in the Yellow Sea *Estuarine, Coastal and Shelf Science* 163: 82-88.

[29] Lotze, H.K., Worm, B., Sommer, U. (2000) Propagule banks, herbivory and nutrient supply control population development and dominance patterns in macroalgal blooms. *Oikos* 89: 46-58.

levels when seawater temperatures reached around 15°C.

Previous studies have shown the expansion of the population will only occur when temperature and light are not limiting, regardless of other factors such as nutrient concentrations[30]. The rise in seawater temperature to beyond a critical level is believed to have facilitated the development of the widespread 2012 bloom in the Yellow Sea[31]. When light is non-limiting, temperature is reported in multiple studies as being the most important factor, influencing both growth rates and nutrient uptake rates[32,33,34] .

Numerous studies have either directly or indirectly investigated the temperature range in which *Ulva* species grow in temperate regions[35,36,37,38,39]. These studies show remarkable agreement, despite the range of *Ulva* species investigated, and point to an optimum temperature range of 15-20°C for growth. The maximal growth of *U.rigidia* was found to occur at 17°C at sites in France and Italy[40] and at 15°C in Langstone Harbour, southern England[41]. The 30 year average summer seawater temperature measured in St Helier Harbour is 16.5°C.

4.2.2 Nitrogen

When light and temperature are suitable for growth the influence of other variables become important. The key remaining influence on *Ulva* blooms is availability of a nitrogen source. Nitrogen concentrations are heavily influenced by human activities, and a control in the anthropogenic nitrogen contribution is possibly the most plausible method for controlling the extent and frequency of *Ulva* blooms.

The nutrient uptake rate and the photosynthetic efficiency of *Ulva* increases in response to

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[30] Liu, X., Li, Y., Wang, Y., Zhang, Q., Cai, X. (2015) Cruise observation of *Ulva prolifera* bloom in the southern Yellow Sea, China. *Estuarine, Coastal and Shelf Science* 163: 17-22.

[31] Huo, Y., Han, H., Shi, H., Wu, H., Zhang, J., Yu, K., Xu, R., Liu, C., Liu, K He, P., Ding, D. (2015) Changes to the biomass and species composition of *Ulva* sp. on *Porphyra* aquaculture rafts, along the coastal radial sandbank of the Southern Yellow Sea. *Marine Pollution Bulletin* 93:210-216.

[32] Duke, C.S., Litiker, W., Ramus, J. (1980) Effect of temperature on nitrogen limited growth rate and chemical composition of *Ulva curvata* (Ulvales:Chlorophyta). *Marine Biology* 100:143-150.

[33] Huo, Y., Han, H., Shi, H., Wu, H., Zhang, J., Yu, K., Xu, R., Liu, C., Liu, K He, P., Ding, D. (2015) Changes to the biomass and species composition of *Ulva* sp. on Porphyra aquaculture rafts, along the coastal radial sandbank of the Southern Yellow Sea. *Marine Pollution Bulletin* 93:210-216.

[34] Fan et al 2015

[35] Bruhn, A., Dahl, J., Nielsen, H.B., Nikolaisen, L., Rasmussen, M.B., Markager, S., Olesen, B., Jensen, P.D. (2011) Bioenergy potential of *Ulva lactuca*: Biomass yield, methane production and combustion, *Bioresource Technology* 102: 2595–2604.

[36] Guidone, M., Thornber, C.S., Vincent, E. (2012) Snail grazing facilitates growth of two morphologically similar bloom-forming *Ulva* species through different mechanisms, *Journal of Ecology*, 100: 1105–1112.

[37] Kalita, T.L., Titlyanov, E.A. (2013) Influence of temperature on the infradian growth rhythm in *Ulva lactuca* (Chlorophyta), *European Journal of Phycology*, 48:210-220

[38] Luo, M.B., Liu, F., Xu, Z.L. (2012) Growth and nutrient uptake capacity of two co-occurring species, *Ulva prolifera* and *Ulva linza Aquatic Botany* 100 (2012) 18– 24.

[39] Viaroli, P., Bartoli, M. Azzoni, R., Giordani, G., Mucchino, C., Naldi, M., Nizzoli, D., Taje, L. (2005) Nutrient and iron limitation to *Ulva* blooms in a eutrophic coastal lagoon (Sacca di Goro, Italy), *Hydrobiologia* 550:57–71

[40] de Casibianca

[41] Taylor, R., Fletcher, R.L., Raven, J.A. (2001) Preliminary Studies on the Growth of Selected 'Green Tide' Algae in Laboratory Culture: Effects of Irradiance, Temperature, Salinity and Nutrients on Growth Rate. Botanica Marina 44:327-336.

increased nutrient supplies[42]. This makes the alga highly capable of rapid expansion in growth in high nutrient conditions, and this competitive advantage allows the population to reach bloom levels[43]. *Ulva* also has the ability to engage in 'luxury consumption' of nutrients at nutrient concentrations beyond which productivity rates are saturated[44],[45],[46]. This enables the alga to store nutrients for use when levels are lowered, thereby maintaining high growth rates for up to several weeks following a reduction in nutrient supply. Nitrate is stored in vacuoles, the capacity to store other nutrients is more limited.

Relationship with Growth Rates

The influence that nitrate concentration have on growth rates of *U.rigida* has been investigated experimentally[47]. At 10 mmol/m^3 growth increased at a rate of 2% per day; at 50 mmol/m^3 growth increased at a rate of 6% per day; at 200 mmol/m^3 growth increased at a rate of 8% per day. Over a wide geographic area in Europe the growth rates and uptake rates of *Ulva* increased as ambient levels of nitrogen increased[48] .

Whilst the relationship between the growth rate of *Ulva* and nitrogen is well established[49,50] , the actual concentrations required for the rapid growth rates required to cause a bloom (i.e. to enable *Ulva* to outcompete all other species) are less well understood. The recent literature also makes clear that the relationship is heavily influenced by the historic nitrogen levels to which an alga has been exposed. The relative response of *Ulva* to nitrogen enrichment is negatively correlated to the ambient dissolved inorganic nitrogen concentration[51]. In addition the maximum rate of nitrate uptake is higher in *Ulva* with a lower nitrogen storage pool[52].

A positive relationship between relative growth rate and annual mean dissolved inorganic

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[42] Dailer, M.L., Smith, J.E., Smith, C.M. (2012) Responses of bloom forming and non-bloom forming macroalgae to nutrient enrichment in Hawai'i, USA, *Harmful Algae* 17:111–125.

[43] Luo 2012

[44] Buapet, P., Hiranpan, R., Ritchie, J., Prathep, A. (2008) Effect of nutrient inputs on growth, chlorophyll, and tissue nutrient concentration of *Ulva reticulata* from a tropical habitat, *ScienceAsia* 34 (2008): 245–252.

[45] Lapointe, B.E. (1997) Nutrient Thresholds for Bottom-Up Control of Macroalgal Blooms on Coral Reefs in Jamaica and Southeast Florida, *Limnology and Oceanography* 42:1119-1131.

[46] Pedersen, M.F., Borum, J. (2006) Nutrient control of algal growth in estuarine waters. Nutrient limitation and the importance of nitrogen requirements and nitrogen storage among phytoplankton and species of macroalgae, *Marine Ecology Progress Series*, 142: 261-272.

[47] Taylor, R., Fletcher, R.L., Raven, J.A. (2001) Preliminary Studies on the Growth of Selected 'Green Tide' Algae in Laboratory Culture: Effects of Irradiance, Temperature, Salinity and Nutrients on Growth Rate. *Botanica Marina* 44:327-336.

[48] Teichberg, M., S.E. Fox, Y.S. Olsen, I. Valiela, P. Martinetto, O. Iribarne, E.Y. Muto, M.A.V. Petti, T.N. Corbisier, M. Soto-Jimenez, F. Paez-Osuna, P. Castro, H. Freitas, A. Zitelli, M. Cardinaletti, and D. Tagliapietra. 2010. Eutrophication and macroalgal blooms in temperate and tropical coastal waters: nutrient enrichment experiments with *Ulva* spp. *Global Change Biology* 16: 2624-2637.

[49] Dailer, M.L., Smith, J.E., Smith, C.M. (2012) Responses of bloom forming and non-bloom forming macroalgae to nutrient enrichment in Hawai'i, USA, *Harmful Algae* 17:111–125.

[50] Wallace, R.B., Gobler, C.J. (2015) Factors Controlling Blooms of Microalgae and Macroalgae (*Ulva rigida*) in a Eutrophic, Urban Estuary: Jamaica Bay, NY, USA. *Estuaries and Coasts* 38:519–533

[51] Teichberg, M., S.E. Fox, Y.S. Olsen, I. Valiela, P. Martinetto, O. Iribarne, E.Y. Muto, M.A.V. Petti, T.N. Corbisier, M. Soto-Jimenez, F. Paez-Osuna, P. Castro, H. Freitas, A. Zitelli, M. Cardinaletti, and D. Tagliapietra. 2010. Eutrophication and macroalgal blooms in temperate and tropical coastal waters: nutrient enrichment experiments with *Ulva* spp. *Global Change Biology* 16: 2624-2637.

[52] Sun, K., Li, R., Li, Y., Xin, M., Xiao, J., Wang, Z., Tang, X., Pang, M. (2015) Responses of *Ulva prolifera* to short-term nutrient enrichment under light and dark conditions. Estuarine, Coastal and Shelf Science 163: 56-62

nitrogen concentrations has also been established[53]. This relationship is likely to relate to the ability to moderate uptake rates (see above) and to store nitrogen. In a study of *Ulva* at different sites in France, all with differing dissolved inorganic nitrogen concentrations, the average tissue nitrogen content was similar across all sites[54]. If nitrogen concentration fluctuates in a waterbody, a program of frequent, long term monitoring of nitrogen levels may be required to understand the concentration levels driving higher growth.

Concentrations for Excessive Growth

Regardless of the complexity of the relationship between growth rate and nitrogen concentration, it is clear that nitrogen enrichment enhances the growth rate of *Ulva*. The ability to control *Ulva* blooms in a large part revolves around controlling the nutrient environment. However the extent to which intervention is required relates to the site and the species-specific relationship between growth rate and nitrogen concentration. The excessive growth of *U.prolifera* in China was supported by dissolved inorganic nitrogen concentrations of 7.8 to 13.5 mmol/m^3[55,56]. These conditions enabled the biomass to increase by 165 times in one month.

The temperatures were higher than in St Aubin's Bay (reaching 21°C) and the results relate to a different species, however these levels are potentially indicative of concentrations required to support bloom growth. These concentrations fit within the range established from a previous review of the literature[57]. The data available for 2015 shows the concentrations in St Aubin's Bay to be well below these levels with the exception of a higher concentration in June (see Section 3.3.2).

The nitrogen tissue content is likely to provide a more relevant 'trigger' level for excessive growth, as a critical content is required for growth. This tissue content is around 20-25 mg N / g dry weight in *U.rigida*[58]. If this content can be maintained for much of the growth season, through use of ambient nitrogen sources / storage of nitrogen during pulse events, then assuming other conditions are favourable the resulting rapid growth rate will provide for the potential for bloom levels of biomass.

Noting the importance of the long-term nutrient environment on *Ulva* growth, a more intensive water-sampling program (ideally continuous monitoring) would be required to

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[53] Teichberg, M., S.E. Fox, Y.S. Olsen, I. Valiela, P. Martinetto, O. Iribarne, E.Y. Muto, M.A.V. Petti, T.N. Corbisier, M. Soto-Jimenez, F. Paez-Osuna, P. Castro, H. Freitas, A. Zitelli, M. Cardinaletti, and D. Tagliapietra. 2010. Eutrophication and macroalgal blooms in temperate and tropical coastal waters: nutrient enrichment experiments with *Ulva* spp. *Global Change Biology* 16: 2624-2637.

54 Merceron, M., Antoine, V., Auby, I., Morand, P. (2007) *In situ* growth potential of the subtidal part of green tide forming *Ulva* spp. stocks, *Science of The Total Environment* 384: 293-305.

[55] Shi, X., Qi, M., Tang, H., Han, X. (2015) Spatial and temporal nutrient variations in the Yellow Sea and their effects on *Ulva prolifera* blooms. *Estuarine, Coastal and Shelf Science* 163: 56-62

[56] Liu, X., Li, Y., Wang, Y., Zhang, Q., Cai, X. (2015) Cruise observation of *Ulva prolifera* bloom in the southern Yellow Sea, China. *Estuarine, Coastal and Shelf Science* 163: 17-22.

[57] Cascade Consulting (2013) *St Aubin's Bay Sea Lettuce Literature Review*, Report prepared for the States of Jersey.

[58] Wallace, R.B., Gobler, C.J. (2015) Factors Controlling Blooms of Microalgae and Macroalgae (*Ulva rigida*) in a Eutrophic, Urban Estuary: Jamaica Bay, NY, USA. *Estuaries and Coasts* 38:519–533.

establish the 'trigger' concentration for growth in St Aubin's Bay. This would need to be conducted in conjunction with sampling to elucidate the seasonal variation in tissue nitrogen, and the relationship between ambient nitrogen sources in the water column with growth rate.

Nitrogen Form and Sources

The recent literature also indicates that *Ulva* may be able to utilise multiple forms of nitrogen[59], inferring the use of dissolved organic nitrogen as the nitrogen content measured in tissue exceeded, in experimental conditions, the available dissolved inorganic nitrogen. This work is consistent with older studies also inferring this possibility[60] .

Decaying *Ulva* biomass, and its influence on the retention of nitrogen in St Aubin's Bay, is likely to be an important factor in driving subsequent blooms. *Ulva* provides dissolved organic carbon to the surrounding water during active growth and provides particulate organic carbon during senescence, which is likely to decay within weeks[61]. Following decline of bloom biomass this is likely to be an important input to the nitrogen cycle in the Bay and the surrounding coastal waters. The supply of dissolved inorganic nitrogen from sediments has shown to support growth of a subtidal population of *Ulva* in Brittany[62].

A range of recent studies have investigated the use of stable isotope analysis in *Ulva* tissue as a method for monitoring eutrophication[63],[64],[65]. Nitrogen consists of two stable isotopes, ^{14}N and ^{15}N. The heavier of the two, ^{15}N tends to be retained by organisms during metabolic processes, so that organisms higher up in the food chain tend to accumulate ^{15}N. The ratio of ^{14}N and ^{15}N can be used as a 'signature' for identifying different nitrogen sources. This ratio is zero in atmospheric nitrogen, and rises to around 3‰ in fertiliser (derived from atmospheric nitrogen). Bacterial decomposition of sewage favours metabolism ^{14}N so the remaining nitrogen in effluent will contain more ^{15}N[66]. Macroalgae display little or no fractionation during nitrogen assimilation, so populations utilising sewage effluent as a nitrogen source will

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[59] Sun, K., Li, R., Li, Y., Xin, M., Xiao, J., Wang, Z., Tang, X., Pang, M. (2015) Responses of *Ulva prolifera* to short-term nutrient enrichment under light and dark conditions. *Estuarine, Coastal and Shelf Science* 163: 56-62.

[60] Tyler, A.C., K.J., Macko, S.A., 2005. Uptake of urea and amino acids by the macroalgae *Ulva lactuca* (Chlorophyta) and *Gracilaria vermiculophylla* (Rhodophyta). *Mar. Ecol. Prog. Ser.* 294, 161e172.

[61] Tyler, A.C., K.J., Macko, S.A., 2005. Uptake of urea and amino acids by the macroalgae *Ulva lactuca* (Chlorophyta) and *Gracilaria vermiculophylla* (Rhodophyta). *Mar. Ecol. Prog. Ser.* 294, 161e172.

[62] Merceron, M., Antoine, V., Auby, I., Morand, P. (2007) In situ growth potential of the subtidal part of green tide forming *Ulva* spp. stocks, *Science of The Total Environment* 384: 293-305.

[63] Orlandi, L., Bentivoglio, F., Carlino, P., Calizza, E., Rossi, D., Costantini, M., Rossi, L. (2014) d15N variation in *Ulva lactuca* as a proxy for anthropogenic nitrogen inputs in coastal areas of Gulf of Gaeta (Mediterranean Sea) *Marine Pollution Bulletin* 84:76-84

[64] Barr, G.N., Dudley, B.D., Rogers, K.M., Cornelisen, C.D., (2013). Broad-scale patterns of tissue-d15N and tissue-N indices in frondose *Ulva* spp.; developing a national baseline indicator of nitrogen-loading for coastal New Zealand. *Marine Pollution Bulletin* 67: 203–216.

[65] Connelly 2013

[66] Costanzo, S.D., Udy, J., Longstaff, B., Jones, A., (2005). Using nitrogen stable isotope ratios (d15N) of macroalgae to determine the effectiveness of sewage upgrades: changes in the extent of sewage plumes over 4 years in Moreton Bay, Australia. Marine Pollution Bulletin 51, 212–217.

display a higher $\delta^{15}N$ ratio representative of the effluent, in order of 6-30‰[67],[68],[69]. The fast growth, response to nitrogen pulses and rapid nitrogen turnover in *Ulva* species mean they provide an accurate representation of recent nitrogen sources present in a water body. Tissue values remain representative of seawater values over a range of nitrogen concentrations and physical conditions[70].

4.3 POPULATION DECLINE

The gradual decline in the bloom in 2015 coincided with decline in both light and temperature, which are likely to be the key factors resulting in a slowing growth rate. Increased turbidity with autumn storms is also likely to play a role in reducing the quantity of available light reaching algae suspended in the water column. The lowered light availability as a result of phytoplankton blooms in a eutrophic estuary were considered a key factor in control of *Ulva* blooms[71]. Autumn phytoplankton blooms in St Aubin's Bay could contribute to the decline in the bloom.

4.4 REGULATORY AND OPERATIONAL CONSEQUENCES OF BLOOMS

The proliferation of *Ulva* in St Aubin's Bay has resulted in a WFD status assessment of 'moderate' for opportunistic macroalgae. In addition to a 'moderate' status for dissolved inorganic nitrogen, this is driving a 'less than good' overall ecological status classification of St Aubin's Bay. The individual status classification for other elements, such as seagrass and rocky shore macroalgae, remain at 'high' or 'good', suggesting the blooms have not had an adverse effect on other communities. However impacts of *Ulva* blooms on other biota have been documented elsewhere. Whilst impacts on seagrass are the most widely documented[72,73,74,75,76,77], the anoxic break down of green tides and the attenuation of light

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[67] Wallace, R.B., Gobler, C.J. (2015) Factors Controlling Blooms of Microalgae and Macroalgae (*Ulva rigida*) in a Eutrophic, Urban Estuary: Jamaica Bay, NY, USA. *Estuaries and Coasts* 38:519–533

[68] Costanzo, S.D., Udy, J., Longstaff, B., Jones, A., (2005). Using nitrogen stable isotope ratios (d15N) of macroalgae to determine the effectiveness of sewage upgrades: changes in the extent of sewage plumes over 4 years in Moreton Bay, Australia. Marine Pollution Bulletin 51, 212–217.

[69] Barr, G.N., Dudley, B.D., Rogers, K.M., Cornelisen, C.D., (2013). Broad-scale patterns of tissue-d15N and tissue-N indices in frondose *Ulva* spp.; developing a national baseline indicator of nitrogen-loading for coastal New Zealand. Marine Pollution Bulletin 67: 203–216

[70] Barr, G.N., Dudley, B.D., Rogers, K.M., Cornelisen, C.D., (2013). Broad-scale patterns of tissue-d15N and tissue-N indices in frondose *Ulva* spp.; developing a national baseline indicator of nitrogen-loading for coastal New Zealand. Marine Pollution Bulletin 67: 203–216

[71] Wallace, R.B., Gobler, C.J. (2015) Factors Controlling Blooms of Microalgae and Macroalgae (*Ulva rigida*) in a Eutrophic, Urban Estuary: Jamaica Bay, NY, USA. Estuaries and Coasts 38:519–533

[72] Choi, T.S. Kang, E.J., Kim, J. & Kim, K.Y. (2010) Effect of salinity on growth and nutrient uptake of *Ulva pertusa* (Chlorophyta) from an eelgrass bed, *Algae* 25(1): 17-26.

[73] Dolbeth, M., Cardoso, P., Pardal, M.A. (2011) Impact of Eutrophication on the Seagrass Assemblages of the Mondego Estuary (Portugal), In: A.A. Ansari et al. (eds.), *Eutrophication: Causes, Consequences and Control*, Springer Science.

[74] Hessing-Lewis, M.L., Hacker, S.D., Menge, B.A., Rumrill, S.S. (2011) Context-Dependent Eelgrass–Macroalgae Interactions Along an Estuarine Gradient in the Pacific Northwest, USA, *Estuaries and Coasts* 34:1169–1181.

[75] McGlatherty, K. (2001) Macroalgal blooms contribute to the decline of seagrass in nutrient-enriched coastal waters, *Journal of Phycology* 37:453–456

[76] Rasmussen, J.R., Pedersen, M.F., Olesen, B., Nielsen, S.L., Pedersen, T.M. (2013) Temporal and spatial dynamics of ephemeral drift-algae in eelgrass, *Zostera marina*, beds, *Estuarine, Coastal and Shelf Science* 119: 167-175.

[77] Thomsen MS, Wernberg T, Engelen AH, Tuya F, Vanderklift MA, et al. (2012) A Meta-Analysis of Seaweed Impacts on Seagrasses: Generalities and Knowledge Gaps, *PLoS ONE* 7(1): e28595. doi:10.1371/journal.pone.0028595.

levels by the floating mass of algae can impact a range of marine flora and fauna[78,79,80,81,82,83,84] including perennial macroalgae and fish. The repeated occurrence of *Ulva* blooms may therefore have further impacts on the WFD status of St Aubin's Bay.

The *Ulva* blooms over the past few years have also resulted in operational consequences. The response to *Ulva* blooms in Jersey is to clear algal biomass from the beaches[85],[86]. The biomass is cleared from the upper areas of the beach and deposited at the low tide mark. Clearance of the sea lettuce blooms from the beaches is a significant cost to the States of Jersey. For several years approximately £25,000 -30,000 per year has been spent to remove *Ulva* blooms from selected beaches during the summer months by contractors. In 2015 the cost was at the top end of this range as the Island hosted the Island Games, which included the use of St Aubin's Bay as a venue for swimming events, and which coincided with significant early season *Ulva* deposits in the West Park area of St Aubin's Bay. This precipitated a larger effort to clear the beach during this period due to the high numbers of visitors to the Island.

These clearance efforts are expensive and ultimately less than fully effective as the biomass is not removed from the Bay. Investigations are underway by the DfI for future operational strategies[87]. These include consideration of machinery currently used in Brittany to clear beaches. The costs of this equipment would be considerable, estimated at a capital machinery cost in excess of £500,000 plus significant annual operating costs.

The ongoing appearance of *Ulva* blooms in St Aubin's Bay do not appear to be resulting in adverse ecological consequences at this point, however they do pose a considerable amenity issue. The recent decision to close the West Park Marine Lake for the 2016 season was attributed to the *Ulva* blooms. There also remains a risk of impacts on other marine communities (e.g. seagrass, macroinvertebrates) which will have regulatory consequences (e.g. a deterioration in WFD status). The influence of climate change on seawater temperatures may also exacerbate the problem. Therefore there is a clear need to understand the dynamics and causes of the *Ulva* blooms in St Aubin's Bay in order to establish effective management strategies and solutions to this problem.

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[78] Zhang, J. Huo, Y., Yu, K., Chen, Q., He, Q., Han, W., Chen, L., Cao, J., Shi, D., He, P. (2013) Growth characteristics and reproductive capability of green tide algae in Rudong coast, China, *Journal of Applied Phycology* 25:795–803.

[79] Bohórquez, J., Papaspyrou, S., Yúfera, M., van Bergeijk, S.A, García-Robledo, E. Jiménez-Arias, J.L., Bright, M., Corzo, A. (2013) Effects of green macroalgal blooms on the meiofauna community structure in the Bay of Cádiz, *Marine Pollution Bulletin* 70: 10–17.

[80] Corzo, A., van Bergeijk, S.A., García-Robledo, E. (2009 Effects of green macroalgal blooms on intertidal sediments: net metabolism and carbon andnitrogen contents, *Marine Ecology Progress Series*. 380: 81–93

[81] Dolbeth, M., Cardoso, P.G., Ferreir,a S.M., Verdelhos, T., Raffaelli, D., Pardal, M.A. (2007) Anthropogenic and natural disturbance effects on a macrobenthic estuarine community over a 10-year period, *Marine Pollution Bulletin* 54:576–585.

[82] Lapointe, B.E. (1997) Nutrient Thresholds for Bottom-Up Control of Macroalgal Blooms on Coral Reefs in Jamaica and Southeast Florida, *Limnology and Oceanography* 42:1119-1131.

[83] Sundbäck, K., Miles, A., Hulth, S., Pihl, L., Engström, P., Selander, E., Svenson, A. (2003 Importance of benthic nutrient regeneration during initiation of macroalgal blooms in shallow bays, *Marine Ecology Progress Series* 246: 115–126.

[84] Norkko, A. & Bonsdorff, E. Rapid zoobenthic community responses to accumulations of drifting algae, *Marine Ecology Progress Series* 131: 143–157.

85States of Jersey (2013) *Beach Seaweed Removal*, TTS Operational Services Directorate Cleaning Services, Technical Briefing Note, 11/07/13.

[86] TTS Cleaning Services (2015) *West Park Lake – Green Sea Lettuce Removal.*

[87] Jersey Evening Post (2016) *Sea lettuce solution?*, 16 February 2016.

5 FUTURE STUDIES

Future management strategies of blooms in St Aubin's Bay require a more thorough understanding of the bloom dynamics. Extensive studies in China have enabled a fairly clear picture of the bloom in the Yellow Sea, providing information on the seed source / substrate for propagule germination (*Porphyra* aquaculture ropes and mats), the triggers for growth (temperature and light conditions), nutrient concentrations required for excessive growth, nutrient sources to the waterbody and the mechanism for dispersal of the large mats of *U.prolifera* (tidal currents). However this information has been acquired through a large research effort, prompted by the extensive economic losses (aquaculture and tourism) which result from the green tides. The bloom in June 2008 extended over 30,000km^2 and the emergency clean-up of the Olympic sailing venue in Qingdao cost over US$100million.

The more limited resources in the Jersey context means that research effort needs to be directed to the topics which will yield the most useful information for bloom control. Following the information gathered from limited studies conducted over the last two years, and a review of the recent literature, the following studies are recommended:

<u>Bloom 'Seed Source'</u>

- A series of simple germination studies using samples from throughout the Bay (intertidal and sub tidal) of both sediment and hard substrate (logistics would require this to be restricted to small pebbles / small boulders) would enable quantification of the extent to which propagules and vegetative fragments 'overwinter' in the Bay. If extended over the spring period these studies would also provide valuable insight to the early dynamics of the bloom.

- Whilst the preliminary studies indicated that *U.rigida* does not grow in significant quantities on hard substrate in the Bay, this requires a series of basic macroalgal surveys to be conducted along set transects over the spring / summer period in order to rule out this potential source.

- The role of *Ulva* populations external to St Aubin's Bay in providing a seed source of both propagules and vegetative fragments should be investigated. The use of freely available Landsat 8 satellite imagery to identify areas of floating vegetation in the Bay of St Malo has been trialled by Cascade using a number of vegetation indices, notably the Normalised Difference Vegetation Index (NDVI), Floating Algae Index (FAI) and Surface Algal Bloom Index (SABI). These are recognised techniques in remote sensing for determining land-based and marine vegetation and have been used to identify *Ulva* and *Sargassum* (a species of brown macroalgae) in many previous studies. The technique is dependent on cloud free images being available for the period of interest (e.g. early summer) but the pilot study indicates that floating mats of algae can be identified in the wider marine environment. The use of this imagery could therefore reveal a relationship between a rapid increase in biomass in St Aubin's Bay with an input from external sources.

Growth rates of *U.rigida* in St Aubin's Bay

- A series of controlled experiments to establish the rate of growth of *U.rigida* at various nitrogen concentrations and temperatures, repeated throughout the growth season would provide an understanding of the ability of the *Ulva* population to expand, as well as the influence of the historic nutrient environment on these growth rates. This would need to be carried out in conjunction with either frequent sampling of the water quality in the Bay, or ideally with deployment of a water quality sonde which would enable an accurate picture of the nutrient environment to which the *Ulva* population had been exposed. Populations from other Bays around the Island should be used as control populations.

Nitrogen Sources

- A thorough understanding of the sources of nitrogen to the Bay is needed to provide the basis for selecting any future management strategies, in conjunction with the knowledge gained above from the relationship between nitrogen levels and growth rates. These nitrogen sources will include terrestrial inputs from streams and other point discharges (e.g. Bellozanne STW). The STW effluent is already measured, and the Department of Environment monitor nutrient concentration in some streams on a monthly basis. A wider monitoring program which also includes flow measurements would be needed to provide an accurate picture of the nutrient load entering the Bay from the wider catchment. This monitoring would need to be combined with data from the Bay water quality monitoring mentioned above.

- Marine water quality sampling has previously been undertaken along a 40km transect stretching approximately southwards from St Aubin's Bay. The dissolved inorganic nitrogen concentrations were measured along this transect and these were found to be relatively constant, indicating a strong influence of the Bay of St Malo on the water quality of St Aubin's Bay. A repeat of this transect with an extension further south towards St Malo would provide a useful dataset to enable external nitrogen sources to be better quantified.

- The role of nitrogen captured in the sediment and standing stock of biomass in the Bay should be investigated by sediment sampling throughout the year (to coincide with the sampling for propagules / fragments above) and analysis of nitrogen content. The analysis of tissue nitrogen content has already been specified above in the seasonal studies of *Ulva* growth rates.

- Determination of the sources assimilated by the *Ulva* tissue should be investigated using stable isotope analysis of *Ulva* tissue, representative inputs to the Bay (streams and STW effluent) and the water column in the Bay. An alternative method of source identification is the use of DNA tracers (e.g. EnviroGene) which can be released at each potential source and tracked once incorporated into algal tissue.

APPENDICES

[*see separate file*]