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# Observational Evidence of Regional Eutrophication in the Caribbean Sea and Potential Impacts on Coral Reef Ecosystems and their Management in Anguilla, BWI

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### ABSTRACT

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Local point source pollution and/or nutrient enrichment has been a recognised source of stress to coral reef habitats for a number of years. It has been documented to lead to increased algal growth and an overall reduction in habitat resilience. These local sources, although potentially contributing to regional eutrophication phenomenon, generally appear to only have effects on a local level. Of greater concern are larger regionally influential sources of nutrients from heavily populated areas of South America and the Gulf states. Recently there has been growing evidence of previously understudied nutrient sources emanating with seasonal river plumes from the Amazon, and to a lesser extent the Orinoco. These plumes, laden with nutrient rich water accentuated by deforestation and agricultural run-off, have recently been suggested as the cause of large algal blooms that spread over vast areas in the Caribbean in 2009 and 2010. Other studies have also documented these plumes as the source of unprecedented amounts of Sargassum that washed ashore fouling local beaches in 2011 and again in 2014/2015. Although the long-term ecological effects of these events are unknown, and the short term picture is that excessive nutrients are metabolised and ultimately sink to the sea floor, it does highlight for the first time this significant contributor to regional eutrophication that up until now was largely attributed to local sources. Furthermore, water current patterns appear to be at least partially recirculating nutrient rich water back into the Caribbean, or at times inhibiting its departure from the region. It is theorised that this may be causing an overall nutrient build up, explaining why the river plumes now produce an observable bloom, or 'green water event', that would previously have mixed with ocean waters and dissipated without causing such an event. The secondary effects of these nutrients are largely detrimental in nature and create tertiary stresses, some of which may interact synergistically with other multiple stressors, and lead to increased habitat degradation and contribute to the ultimate loss of a once diverse ecosystem. Although management of regional nutrient sources will involve multi-national intervention, mitigation measures on a local level can be introduced by managers, even in small island nations with limited financial and logistical resources.

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## INTRODUCTION

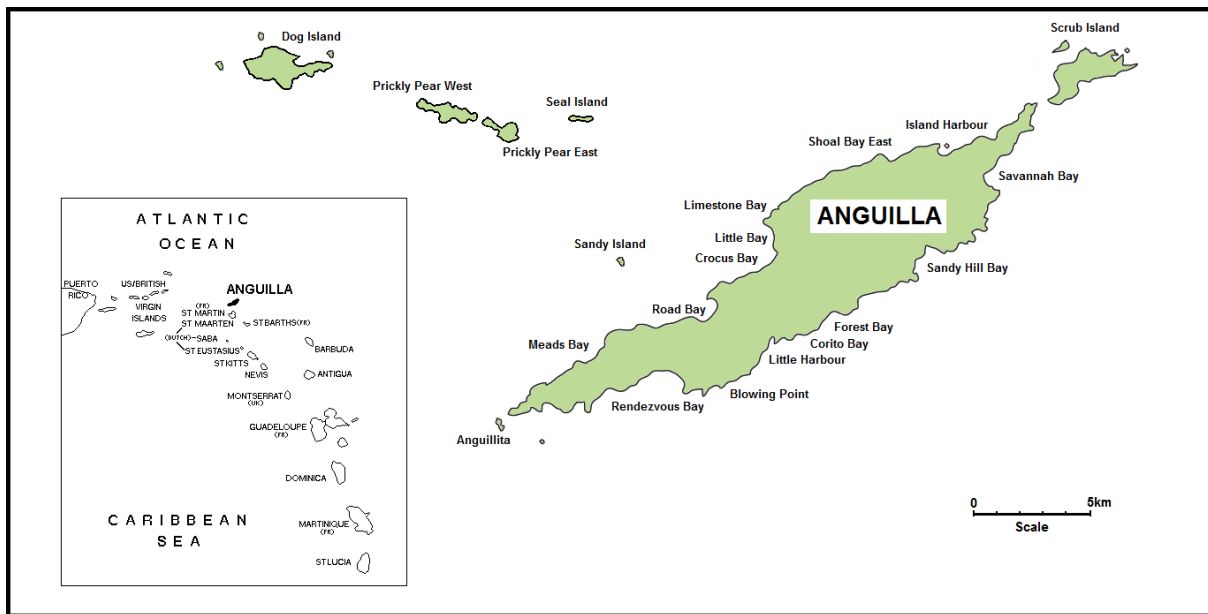
Habitat degradation in coral reef ecosystems has been well documented now for a number of decades (Goldberg & Wilkinson, 2004), with wide ranging causes that can all be traced back to an anthropogenic source. These causes (or stressors) are all ultimately derived from human population growth and the stress that trying to support such a population puts onto natural systems (Jameson, 2008). In terms of management, it is not possible in real time to address this ultimate cause, whether on regional or local levels, instead secondary or (more often) tertiary stressors are those that management must focus upon. Of these secondary stressors, eutrophication has been the subject of intense scientific debate over recent years (Szmant, 2002). Coral reefs are naturally oligotrophic systems, but when located near population centres or industry, nutrients invariably enter this system and cause nutrient enrichment (Angelo & Wiedenmann, 2014). It has been known for a number of years that this enrichment promotes algal growth, which itself can be viewed as one of the main tertiary stressors. It is at this level that multiple stressors may start interacting (for example: reduced numbers of herbivores) and all ultimately contribute, in this case, to coral reef habitat degradation (Hughes, 1994). The scientific debate has related to whether these nutrients also cause negative effects on coral physiology (Szmant, 2002). Recent evidence suggests that exposure of corals to increased levels of nutrients can induce a number of negative responses (Fabricius, 2005; Dunn *et al.*, 2012). Wiedenmann *et al.* (2013) suggest that past discrepancies are due to the negative physiological effects of increased nutrient levels on corals not always being witnessed by observers, as all essential nutrients were available at sufficient concentrations to ensure their chemically balanced growth; a situation that is rarely the case if an overall reduction in water quality occurs (i.e. nutrient levels not being the only variable in question). They also introduce the concept that nutrient starvation of zooxanthellae may result from accelerated growth at increased nitrogen levels.

In the past, effects from nutrients originating from local sources were usually only recorded in enclosed bays or river catchment areas (Donnelly *et al.*, 1998). Here, blooms of phytoplankton were often the result, although the fast removal of nutrients suggested effects on coral physiology were limited (Szmant, 2002). Recent findings suggest otherwise with studies that demonstrate nutrients in flood plumes can be transported distances greater than 50km (Angelo & Wiedenmann, 2014). Aside from direct physiological damage to coral however, the blooms themselves can travel large distances before reaching coral reefs, as was recorded in 2002 in the Florida Bight (Hu *et al.*, 2003; Hu *et al.*, 2004). Here, coral communities were impacted by the toxic decay products of the dinoflagellate *Karenia brevis* (during a so called ‘red tide’) and resulted in increased coral mortality during its two month duration. This coincided with a 40% loss of hermatypic coral species after a relatively stable percentage cover of between 15-20% for the five previous years.

Although coral mortality events cannot always be tied to phytoplankton blooms conclusively, the 2002 event in Florida does illustrate how an influx of nutrients can cause such a bloom, and how long this bloom is potentially able to last in the water column. Prior to this 2002 event, other less documented yet similar events occurred in the Caribbean region, although often their source was not established. Subsequently however two abnormally large blooms occurred in the eastern Caribbean during 2009 and 2010 that appeared to originate from the coast of South America’s Orinoco and Amazon river plumes, spreading across the entire Caribbean Sea to Puerto Rico (Johns *et al.*, 2014). No direct detrimental effects have been reported for these two blooms, or ‘green water’ events (due to the iridescent green colour water observed), although their occurrence is suggested to represent evidence of an overall increase in nutrient levels throughout parts of the Caribbean, backed up by increasing signs of tertiary effects in areas such as Anguilla that are devoid of high levels of local nutrient sources.

In the Caribbean region this debate is of particular interest as coral reef degradation has been occurring at an alarming rate (Gardner *et al.*, 2003), with a well-documented ‘phase-shift’ in the coral-algae balance witnessed in many areas (Hughes, 1994). This phase-shift is particularly easy to observe in areas with a local nutrient source (Lapointe *et al.*, 1997; Goreau, 2008), and accentuated where fishing pressure is high (Angelo & Wiedenmann, 2014), and other herbivores are lacking, for example the sea urchin *Diadema antillarum* (Lapointe, 1999). It is often observed that this phase shift is not as readily visible in areas at further distances from these local sources of nutrients and fishing pressure. Angelo & Wiedenmann (2014) point out this is due to nutrient dispersal and that healthy coral reefs can exist over a broad range of natural nutrient environments at the lower end of the concentration scale. This does not appear to be the case in Anguilla, the most northerly of the leeward islands in the Caribbean (figure 1); a small low lying coralline island with a relatively small population, no concentrated urban centres, and little industry.

Increasing levels of macroalgae have been recorded here since the 1990's (Oxenford & Hunte, 1990). Although some minor land-based nutrient sources are present, many of these are naturally occurring (i.e. salt ponds) and with very little farming taking place, overall nutrient input into the marine environment is considered minimal. Of the nutrient sources present, there is: a golf course whose incorporated salt pond has been connected to the sea; a landfill site that may leech into the ocean; and a small number of hotel developments and/or houses whose aging septic tanks may also leech into the sea. Coastal developments and removal of beach flora may also lead to increased run-off during times of heavy rain. High levels of macroalgae have not been recorded close to these sources, so it is concluded that prevailing currents carry nutrients away relatively rapidly (Wynne, 2016). Fishing is popular on the island and *D. antillarum* has still yet to fully recover from its die-off in the early 1980's (Lessios, 1988). These two factors, in combination with the (albeit limited) local nutrient sources, are those usually attributed as the cause of high level of macroalgae observed in the surrounding areas. However, the level of macroalgae found on most reef areas around Anguilla does not seem representative of local nutrient sources and instead suggests a general background level of eutrophication.



**Figure 1:** Map of Anguilla and its offshore cays, with its location in relation to other island illustrated in the inset situational map of the eastern Caribbean. Many of the locations referred to throughout this paper have also been labelled.

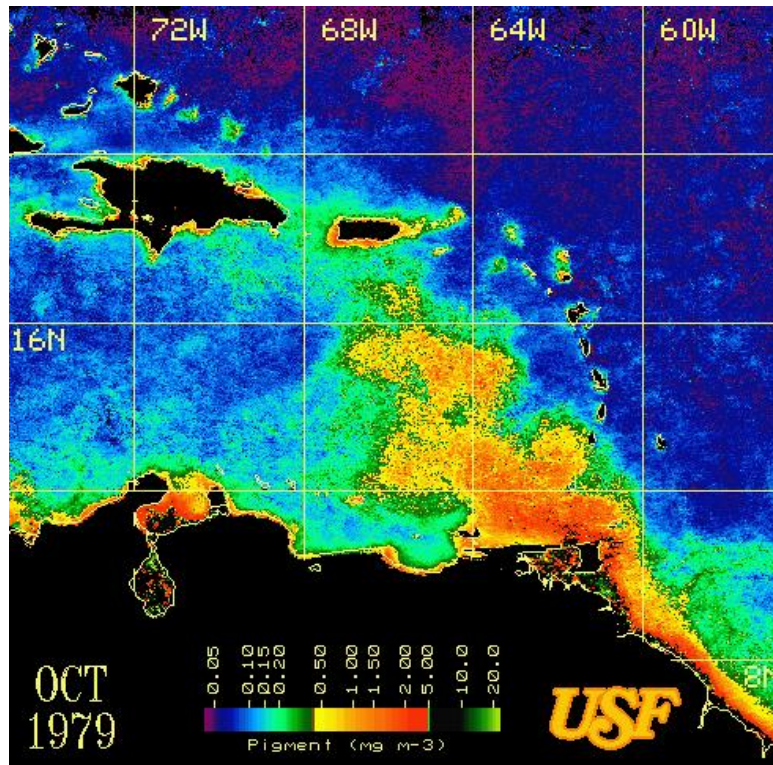
Through river plumes and run-off, sediments and land based nutrients have historically entered the Caribbean basin at unquantifiable historical baseline levels, but increasing loads since the early 1980's continue to impact coastal ecosystems (Restrepo *et al.*, 2006). Industrialisation, intensive farming and deforestation have led to an increase in nutrient inputs (Heileman, 2007), likely originating in the Gulf States, and passing through the Florida Straits out into the Atlantic. Indeed, it follows that this flow and nutrients emanating from sources such as the Mississippi supply nutrients to the Sargasso Sea and help sustain the growth of Sargassum in the area. Another source into the region is from the South American coast and associated river plumes. Since the 1970's changing land-use patterns in South America's Amazon region likely led to these river plumes having increased nutrient loads, with ocean currents pushing these nutrient rich waters into the Caribbean. Circulation patterns responsible for this are discussed later and include mechanisms that may trap nutrient rich water within the Caribbean basin, or recycle it back into the region from the Sargasso Sea. It is hypothesised that these mechanisms have led to a gradual increase in background nutrient levels in the Caribbean, and responsible for the tertiary effects observed in Anguilla. Even though inputs from the Amazon may no longer be increasing at the rate they did towards the end of last century, background levels may now be at a concentration that during times of high rainfall in the Amazon (i.e. during El Niño events), the mixing of the two water bodies can now produce these extended blooms (Johns *et al.*, 2014).

This paper presents evidence of this regional eutrophication theory and illustrates it with examples of the observable secondary effects, together with suggested mechanisms behind nutrient input and retention in the Caribbean. Using Anguilla as an example, evidence is also presented supporting the case that these regionally influential sources are, on a local level, likely more detrimental in the long-term to coral reef habitats than moderate to low local point sources. Management against these tertiary effects will also be discussed.

## REGIONAL EFFECTS OF EUTROPHICATION

### Green Water Events

*Early Reports:* Although the earliest reports of actual large scale phytoplankton blooms were not made until the mid-late 1990's, the satellite image presented in figure 2 illustrates the plume of induced high productivity nutrient rich water emanating from the Orinoco River and along Brazil's north-eastern coastline from the Amazon River in October 1979. During the rainy season the fresh water from these rivers are carried by the predominant currents into and extending over much of the Caribbean basin. These river catchments encompass most of Venezuela, Columbia and northern Brazil. The river outflow is enriched in nutrients, and being less dense than seawater it remains on the surface, gradually breaking up into lenses of less saline water.



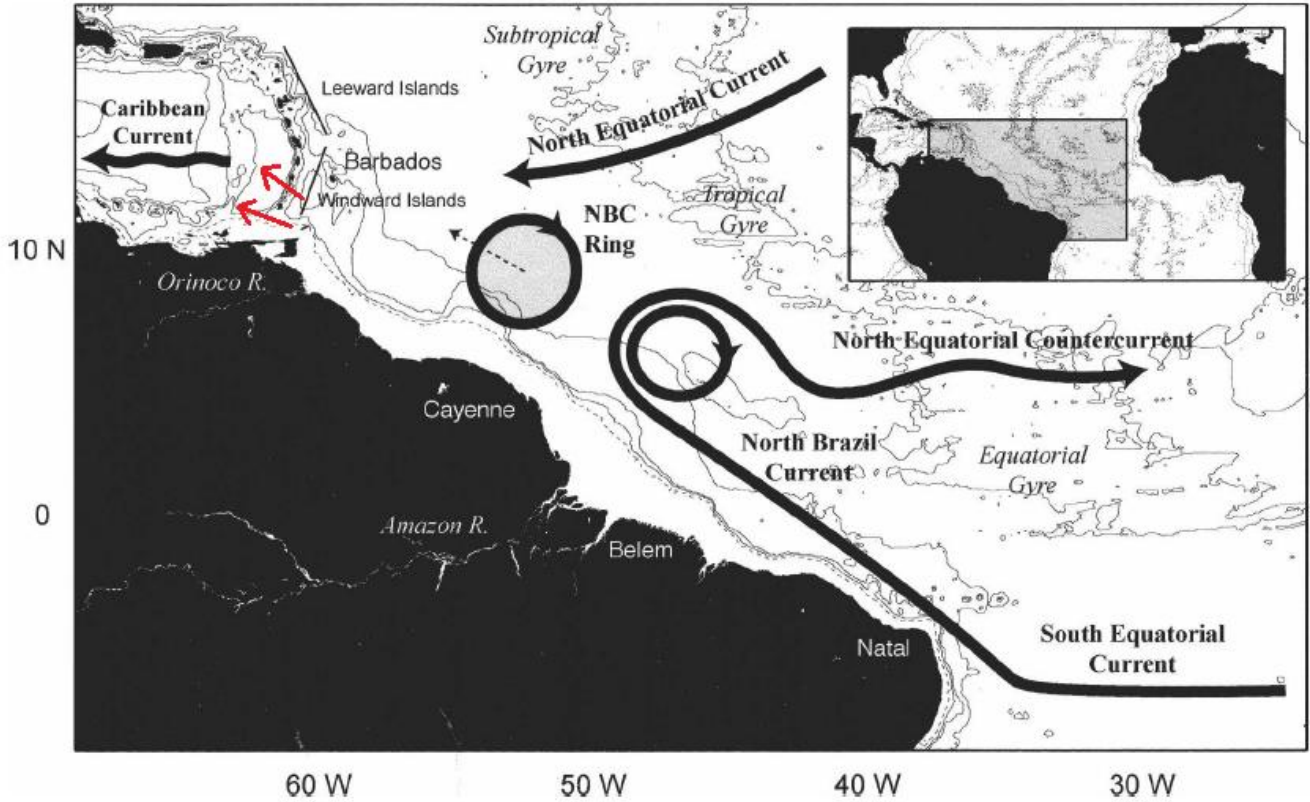
**Figure 2:** Composite image taken by the Coastal Zone Colour Scanner (CZCS) of the eastern Caribbean Sea for October 1979, showing the spatial extent of the Orinoco River plume of induced high productivity that occurs during the summer rainy season. (Image courtesy of Dr. Frank Muller-Karger, University of South Florida Remote Sensing Laboratory).

It would seem however that nutrient levels were not sufficient to induce algal blooms that could be sustained during the journey this plume makes across the Caribbean basin until recent years. Reports of green water events from the 1990's all stem from unknown or locally based nutrient sources. For example, one such event was documented to occur around the Florida Keys after the South Florida Water Management District released tons of dirty agricultural runoff from the Everglades agricultural area (Dr B.Lapointe, pers comm.). Although this event might essentially be considered as originating from a local point source, it was of sufficient scale to be considered of semi-regional significance. Other reports during 1991-1992 refer to sponge mortality during a cyanobacteria bloom caused by increased nutrient loading (Herrnkind *et al.*, 1995; Butler *et al.*, 2005; Stevenly *et al.*, 2010), with Peterson *et al.*, (2006) stating that these events have actually been occurring in Florida since 1987 and may be caused by lowering sponge populations and their filter feeding capacity similarly lowering. Peterson *et al.* states 'Some investigators have suggested that a new source of nitrogen or phosphorus is fuelling the elevated phytoplankton biomasses observed over the last decade in the north-central basins of Florida Bay. An alternative hypothesis is that the loss of the dominant suspension feeding sponges from this area of Florida Bay has rendered a system-wide trophic dysfunction, resulting in the initiation and great magnitude of the phytoplankton blooms. However, Boyer *et al.* (2006) presents evidence of dissolved organic matter being the source of these blooms in Florida, irrespective of whether a higher sponge population could mitigate against it. Similar localised events in Belize during 2011 reportedly killed off a significant portion of the sponge population. Wulff (2013) states 'The sponge mortality coincided with a clear environmental anomaly, an extremely dense phytoplankton bloom covering the entire southern portion of the Belize Barrier Reef for much of July–August 2011. Visibility at the census site was less than 30 cm for much of the monitoring.'

Most of these early and/or localised events usually fall into the broadly generalised category of a red-tide: blooms of often toxic dinoflagellates or other single celled algal species that discolour the water (Anderson, 1995). Actual 'green-water' events, where the water turns an iridescent green colour due to high levels of non-toxic phytoplankton were not reported until 2009, and again the following year in 2010.

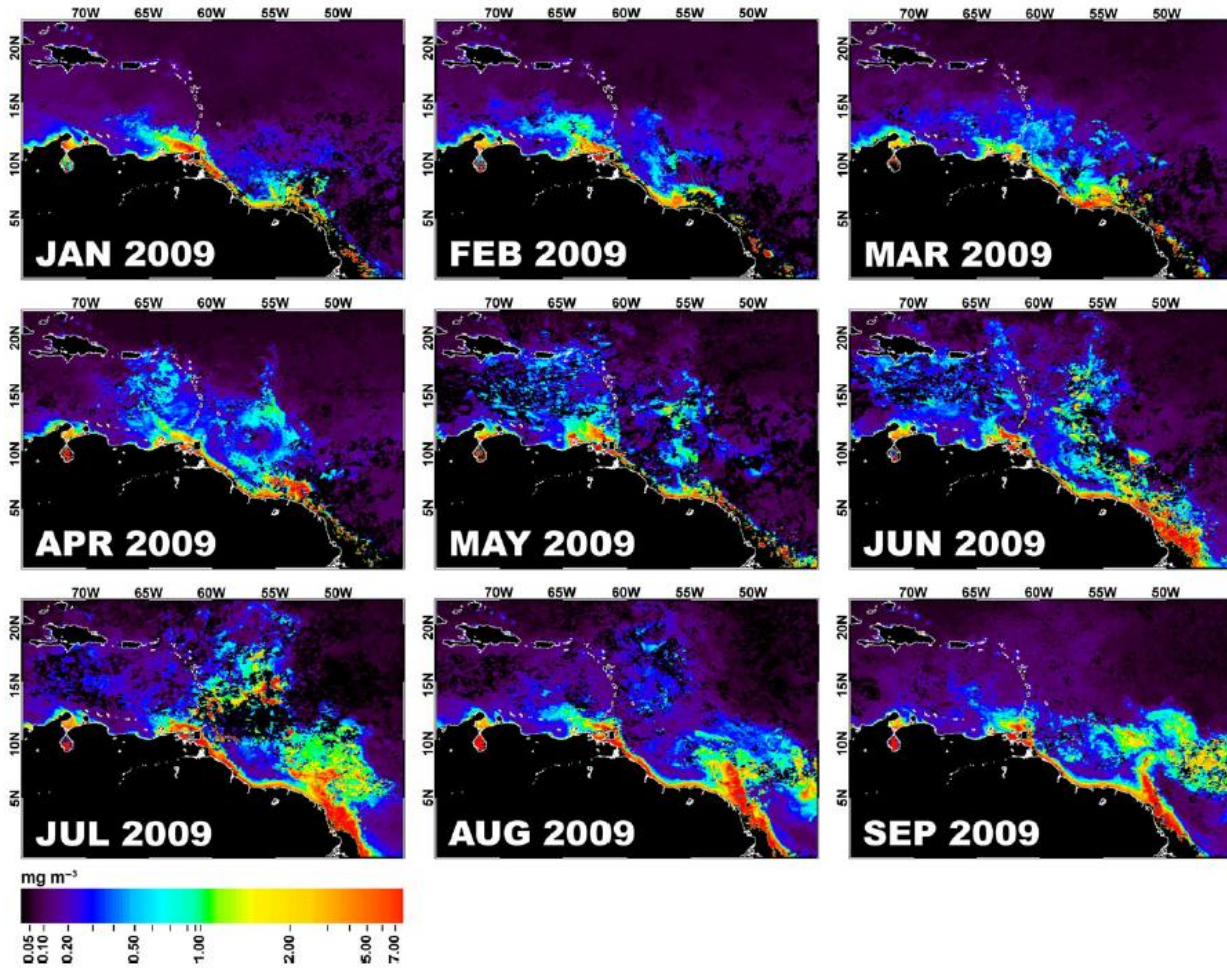
*The 2009 & 2010 events:* Satellite ocean colour images (figure 2) have illustrated since they were first produced in the early 1980's that productive water plumes deriving from the Amazon and Orinoco are delivered annually, on a strong seasonal cycle, to the western tropical Atlantic Ocean and eastern Caribbean Sea via prevailing currents. These plumes can be identified travelling across great distances, eventually dissipating as they mix with saline sea water. As described by Cherubin & Richardson (2007), and later Johns *et al.* (2014) after the peak of seasonal rain occurs during June/July in the north-eastern region of South America, freshwater plumes spread seasonally north-westwards across the Caribbean basin. These plumes are sustained by two main inflows from the North Brazil Current (NBC) and associated current rings (NBCR). The NBCR are created from the NBC as it turns offshore and flows east towards Africa, as the seasonal North Equatorial Counter-current is established (figure 3). Of the two main inflows, one enters the Caribbean Sea as it passes south of Grenada to become the main branch of the Caribbean Current in the southern Caribbean, while the second passes northwards of St Vincent towards the Leeward Islands. As the NBCR stall and decay east of the Lesser Antilles they release fresh water into the northern part of the eastern Caribbean Sea as it merges with the inflow from the North Equatorial Current (Fratantoni & Richardson, 2006).

The dispersal of the Amazon River plume is difficult to discern completely as it varies from year to year in both size and location, and the input of the Orinoco directly into the Caribbean Sea means that the effect of each individual plume is hard to trace (Johns *et al.*, 2014). Normally however, these plume waters enter the Caribbean to the south between May and September, and then disperse widely throughout the region, leading to slightly higher turbidity relative to the clearer oligotrophic waters naturally present in the area. However, in 2009 (and again in 2010) a major river plume event took place that was traced back predominantly to the Amazon, with addition of waters from the Orinoco, that caused extremely high levels of turbidity through heightened planktonic loads and associated chlorophyll-a concentrations (figure 4). Between April and June 2009 this water engulfed the Saba Bank, Virgin Islands and Anegada Passage, although it was not observed as far northeast as Anguilla (S.Wynne, pers. obs.). Based on the lack of previous reports it can be concluded that such a regionally dominating 'green-water' event had not occurred during the last 30 years. Johns *et al.*, (2014) who were conducting research in the area at the time studied this event and found that larval fish assemblages within the plume were significantly different from those of the surrounding waters, and from those encountered in the area in previous years.



**Figure 3:** Circulation in the western tropical Atlantic Ocean showing predominant currents and the formation of North Brazil Current Rings. The 200m (dashed), 1000m, 2000m, and 4000m depth contours are shown (Fratantoni & Richardson, 2006). Two small red arrows have been superimposed to represent the current inflows into the Caribbean basin.

Although the images in figure 4 could lead to the conclusion that the 2009 ‘Green Water Event’ (GWE) was part of the Orinoco plume, careful examination by Johns *et al.* (2014) of daily and weekly mean chl-a images from various sources painted a more complex picture. They put together a scenario showing that high chl-a water north of c.14°N immediately west of the Antilles is contained in boluses of Amazon water. These boluses moved across the island chain and started to travel rapidly north, with green water enveloping the Virgin Islands during the first week of April 2009. By May the plume had spread westward to 72°W and northward to 20°N into the Atlantic Ocean, although chl-a concentrations between 0.3 and 0.5 mg m<sup>-3</sup> and higher remained in the vicinity of the Virgin Islands through June 2009. It is thought that this event took place due to increased NBCR activity, as seen by a second mass of Amazon River water observed to the east of the central Caribbean island arc. The NBCR’s finally dissipated by the end of September. Under less active conditions it is thought that the NBCR’s would dissipate before reaching the northern islands. As such any GWE would take place in the central Caribbean region away from any land masses as seen in figure 2. Johns *et al.*, (2014) states that based on monthly climatological data between 1997 and 2010, the extent of chl-a ≥ 0.7 mg m<sup>-3</sup> does not normally exceed 14°N.

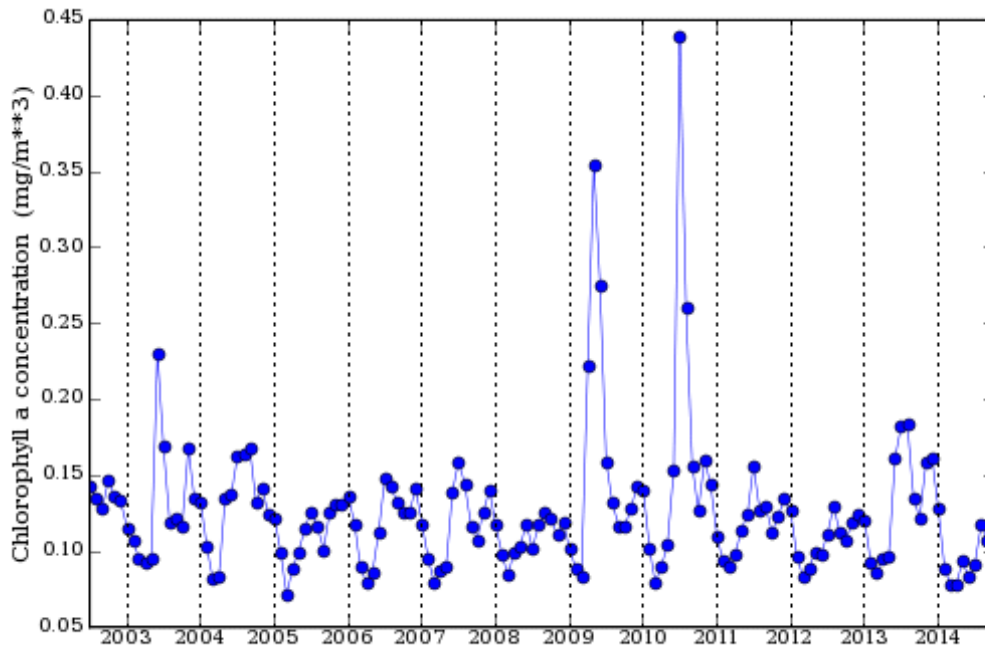


**Figure 4:** Monthly chlorophyll-a (chl-a) concentration (in  $\text{mg m}^{-3}$ ) composite images derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra satellite sensor, January to September 2009. Images produced by the University of South Florida (USF) Institute for Marine Remote Sensing (IMaRS). Johns *et al.*, (2014).

Despite the normal southern limits of highly productive waters reported, an extreme plume event leading to another GWE again took place in 2010 (figure 5). This event, although not as widely studied as that in 2009, is considered to have been more extensive as it reached further northwest, partially enveloping Anguilla by the 7<sup>th</sup> of July 2010 (Wynne, 2010). Reports stated that ‘the waters were incredibly turbid with visibility at times lower than one or two metres’. Unfortunately a full study of this event in Anguilla was not undertaken as it was very short lived and conditions returned to normal after a couple of days. Furthermore the GWE seemed only to affect the eastern end of Anguilla around Anguillita Island and its surrounding waters. Western areas were not reported to be affected, and so it follows that Anguilla represented the north-western extent of the GWE and associated plume.

*The Future:* Precise reasons for the 2009 and 2010 elevations and associated GWE remain unclear and need further study. No strong correlations were found between the results presented in figure 5 and the North Atlantic Oscillation, El Niño/La Niña or rainfall means in the Amazon basin. For example, Brito *et al.* (2014) describes La Niña episodes in 2008 and 2011 where rainfall extremes increased, and El Niño years of 2005, 2007 and 2010 where rainfall extremes over the Amazon basin were reduced. It is probable that rainfall levels, which are influenced by these oscillation events, play a role in the amount of terrestrial nutrient

runoff, but that this role is complex and in turn influenced by related factors such as increased freshwater dilution and climatic variations driving ocean currents and mixing. Nonetheless, based on older satellite imagery it is clear that these nutrient rich waters have been entering the region for many years (figure 2) but may have been overlooked as associated blooms might not have reached populated islands. Blooms of lesser extent than seen today would have been the dominating phenomenon due to the proposed ocean current recirculation mechanisms for regional eutrophication presented later in this paper.



**Figure 5:** MODIS area-averaged time series for Chlorophyll-a concentration in the Caribbean (region covering 67°W-62°W, 17°N-19°N) illustrating peaks in 2009 & 2010, combined with smaller yet notable elevation in 2003. Data taken from <http://modis.gsfc.nasa.gov>. Other visualisations produced via data from the SeaWiFS sensor produce elevated peaks, with an additional elevation recorded for 2000. In these projections the 2010 chl-a peak surpassed the 2009 readings by nearly a factor of two (Johns *et al.*, 2014).

It is also possible that, combined with this regional eutrophication, blooms are increasing in extent due to (for example), changing land use patterns or drainage policies in South America. Although it is documented that deforestation rates are decreasing in the Amazon basin, increases in agricultural dependency on fertiliser use or changes in farming intensity or commodity (livestock vs arable) needs consideration. To reliably project future scenarios these factors need further study and more detailed models produced.

### Sargassum Blooms

*The Sargassum Event of 2011:* Free floating species of Sargassum Seaweed have been studied for nearly 200 years, and form extensive aggregations trapped in the North Atlantic Ocean gyre. This area, known as the Sargasso Sea is fed significant amounts of Sargassum that originates from the Gulf of Mexico (Gower & King, 2011). Surveys conducted using the global MERIS dataset (Gower *et al.*, 2006), and combined with later work conducted by Gower & King (2011) have shown an annual cycle of Sargassum distribution in the Gulf of Mexico and North Atlantic, with considerable inter-annual variation. This variation however does not usually extend to the Caribbean Sea where only small amounts of pelagic Sargassum are usually found. This

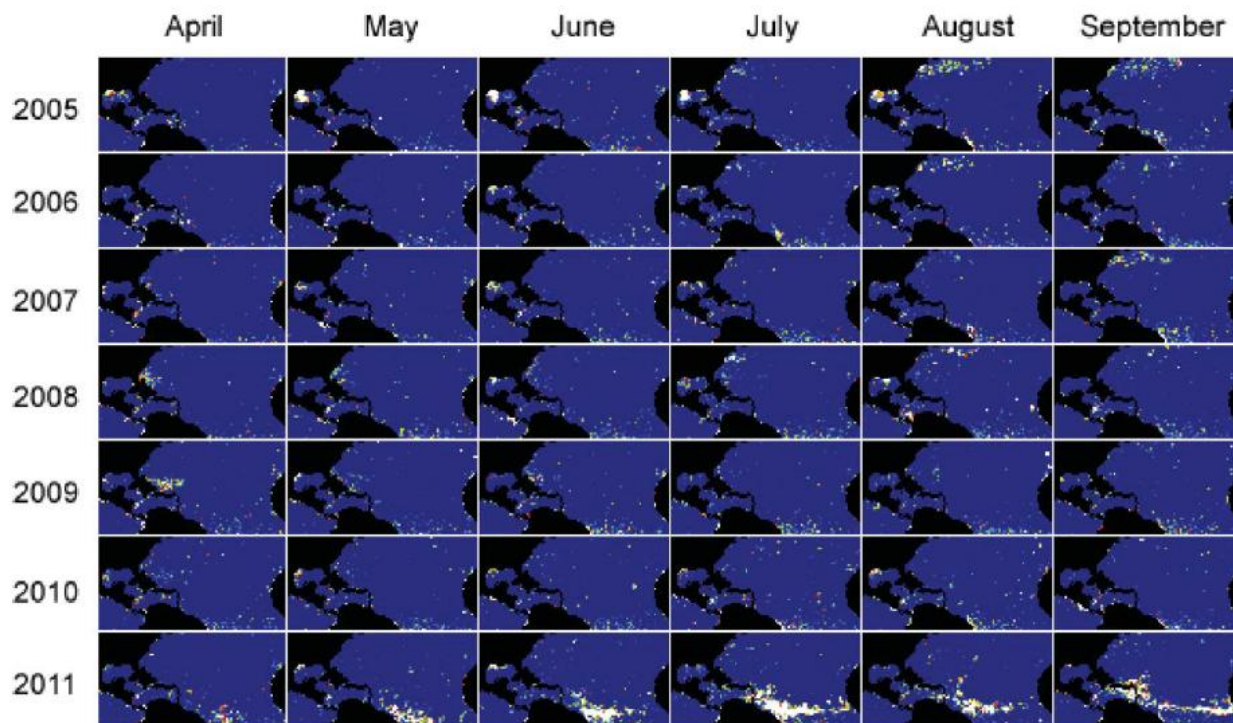
changed in 2011 when a major ‘Sargassum event’ occurred in the Caribbean Sea bringing huge amounts of seaweed onto the beaches of many of the islands in the region (Gower *et al.*, 2013). This event had a significant effect on local tourism while also clogging bay areas and adversely affecting boat usage and therefore fishing. When washed up the rotting seaweed produced a pungent sulphurous odour and entangled nesting turtles and other wildlife (figure 6).



**Figure 6:** Sargassum on the east coast of Barbados during the 2014/2015 inundation event. Photo courtesy of Hazel Oxenford, September 2014.

Based on historical records, initial suggestions as to the origin of the weed were the Sargasso Sea or the Gulf of Mexico, and the event attributed to changing currents and increasing variability of the Gulf of Mexico and North Atlantic annual cycle. The work conducted by Gower *et al.*, (2013) however suggests a new and alternative source. Through satellite observations this study presented evidence that the Sargassum event had its origin north of the mouth of the Amazon in an area not previously associated with Sargassum growth. Initially detected in April 2011 approximately 7°N and 45°W, by July it has spread to the coast of Africa in the east to the Lesser Antilles and the Caribbean in the west (figure 7). Gower went on to report that such large amounts of Sargassum were unprecedented even to the older inhabitants of the Lesser Antilles, who stated that it is common for small quantities to wash up now and again for relatively short periods but ‘we have never in recent memory had so much of it for so long and seen such huge mats or lines of it from the air’.

At the time the cause of this large shift in distribution was unclear, although Lapointe (1995) reported a possible connection between Sargassum blooms in the Gulf of Mexico and nutrient rich waters originating from the Mississippi plume. Gower *et al.*, (2013) suggest a similar link, with nutrient laden waters from the Amazon River plume and above normal run-off ascribed to anomalous rainfall associated with La Niña, becoming a significant source of nutrients to the equatorial Atlantic. The peak biomass that year was 200-fold higher than the previous eight years’ average biomass peak recorded in the Caribbean, and it was the first time that drifting Sargassum reached the coast of Africa (Smetacek & Zingone, 2013). By the end of the year however most of the Sargassum had dissipated and levels returned to normal after the nutrient reserves were presumably spent.



**Figure 7:** Monthly time series of MERIS between 2005 and 2011 of Sargassum detection counts for the area 0°– 45° N and 100°– 10° W covering the Gulf of Mexico, Caribbean and tropical Atlantic across to the west coast of Africa. Land is masked to black. The large area of high signal off northern Brazil shows white at the bottom of the lowest row and extends from the Caribbean to Africa in July and September 2011 (Gower *et al.*, 2013).

*The Sargassum Event of 2014/2015:* Following the 2011 Sargassum event, or ‘Golden Tide’ as it is sometimes referred to, sporadic reports came in of unusual amounts of Sargassum being deposited on beaches in the Caribbean Region (Moreira & Alfonso, 2013), although most were short lived and in areas where past deposits had been reported over recent decades. This changed during the latter half of 2014 however, when large amounts once again began washing up on beaches Caribbean wide, from Tobago to Antigua to San Andres Island (Gavio *et al.*, 2014). By the end of October that year seaweed drifts had built up as high as 3 to 4 feet, and once again began choking fishing ports and tourist beaches. The 2014 event did not dissipate towards the end of the year, with deposits continuing on into 2015. The latest reports, dating from early 2016 continue to describe large amounts of the weed washing up throughout the Caribbean. Most sources state that in their regions it has surpassed the severity of the 2011 event, most notably in peripheral regions that weren’t affected at all by the earlier event (Gavio *et al.*, 2014). Although climate change is likely to be playing a role in the growth and distribution of the Sargassum (increasing sea surface temperatures facilitating rapid growth for example), nutrient rich water from the Amazon River is now widely attributed as the main cause of the 2011 event (Johnson *et al.*, 2013; Lum, 2014), with research on the current event ongoing (Koffi *et al.*, 2016).

Similar anomalous deposits have been observed in Anguilla during 2015, with some of the most prized tourist beaches being affected. One effect that has also been noted is the fact that the rotting Sargassum on the beach, when washed by waves appears to leach nutrients back into the bay and cause localised GWE. This appears to be further accentuated by Sargassum that has been washed back into the bay and floats around slowly decomposing on the sea floor. Waters around the island that were previously pristinely clear become more turbid under these conditions. It remains to be seen if this has negative long term effects on surrounding ecosystems.

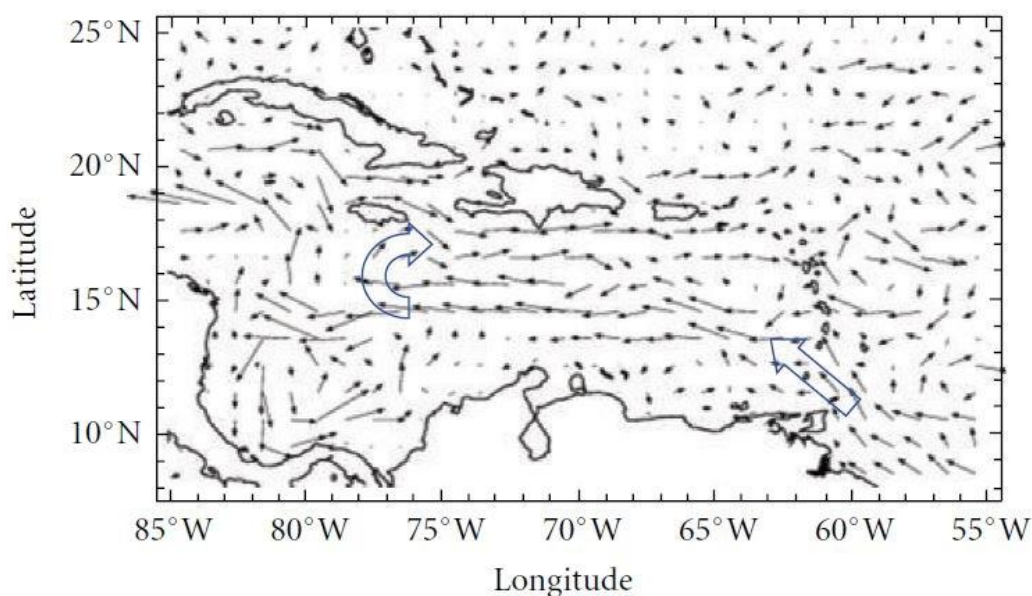
*The Future:* With the 2014 event persisting into 2015, the future remains unclear. Many scientists agree that it is a sign of ‘a deep problem at many levels’ (J.Franks, pers. comm.), and a sign that the eutrophication of the Caribbean region is still increasing, with the Amazon and Orinoco river plumes responsible for carrying nutrient-rich runoff from land newly deforested in the Amazon for farming (Biggs *et al.*, 2006; Neill *et al.*, 2011). Whether this is a preview of what the oceans in the 21st Century will look like after decades of pollution, overfishing and coastal development remains to be seen, but it certainly is an indicator of regional eutrophication and an example of one of the negative economic effects such changes can bring about. Ecological effects of the Sargassum itself are uncertain but it does appear to act as a vector for nutrient transport across large distances of ocean: The nutrients absorbed and used for growth close to the Amazon are locked away until their ultimate breakdown when the seaweed is washed ashore and decomposes, often being re-released back into the ocean. Although the removal of this material from the beach is controversial due to the loss of sand resources it can be advantageous as aside from entangling unsuspecting wildlife, stranding turtles, and offending local visitors it also has the potential to become a significant local point source of nutrients.

### **PROPOSED MECHANISM FOR REGIONAL EUTROPHICATION**

The evidence presented above illustrates a complex situation, but one where regional eutrophication sources appear to play a greater role in overall Caribbean nutrient load than smaller local sources. Historically land-based nutrient inputs would have been on a relatively small scale and dissipated naturally or been carried out of the Caribbean via prevailing currents. For example, the Mississippi plume and other sources from the Gulf States would be transported through the Florida Straits and out into the Atlantic. It is in fact likely that these waters would have fed the Sargassum growing in the Sargasso Sea and become trapped in the North Atlantic Gyre. Some recirculation from this gyre back into the Caribbean basin does take place, but nutrient levels within it at this point have dissipated to levels low enough to theoretically have minimal overall effect. As described earlier, waters from both the Amazon and Orinoco rivers enter the Caribbean via the North Brazilian Current on a seasonal cycle. Since deforestation and intensive farming in the 1970’s, the levels of nutrients in these incoming plumes have increased dramatically (Santos *et al.*, 2008). A slowing rate of deforestation over the last ten years mean the rate of increase may be lessening, although as deforested land is turned over to agriculture and intensity of both arable and livestock farming practices increases, the extent of this lessening is questionable.

These nutrient rich plumes have been entering the Caribbean for generations, although enrichment levels were not elevated enough to produce regionally significant algal blooms and so largely went unnoticed. Based on recognised prevailing currents, once the blooms have dissipated (or nutrients metabolised), these waters ultimately pass through the region and out into the Atlantic. However, recent studies have shown that anti-cyclonic recirculation of surface waters can occur during certain years that infuse the Caribbean with more nutrients from along the Venezuelan coast. This recirculation also produces gyres along the north edge of the Caribbean Current which inhibit the loss of productive waters to the Yucatan passage (Jury, 2011). Although this theory (Figure 8) requires further study as it may not occur on an annual basis, it does provide a potential mechanism where nutrients can be retained in the region and potentially build up over time.

This process would likely be gradual, as some of the nutrient laden waters would inevitably break off into prevailing currents and/or mix with nutrient poor water bodies. However, such a build-up would also explain why blooms may be becoming a more regular occurrence even if, for example, deforestation in the Amazon is slowing. A slowing rate of deforestation suggests a similar slowing rate of increase in nutrient input via agricultural runoff (although as suggested earlier an increased dependency of agriculture on fertilizer use has the potential to counteract this). If a gradual build-up is occurring, even lower levels of nutrient input may be substantial enough when mixed with already nutrified regional waters to initiate a bloom. As highlighted by the conclusions of Jury (2011), more work is needed in studying the phenomenon, including (but not limited to) a comparison of local versus regional nitrification processes.



**Figure 8:** Map of 0-200m vector currents identified by Jury (2011) showing potential water current mechanism behind a nutrient build-up in the Caribbean basin. Large blue arrows depict main flow into the region and later back-cycling.

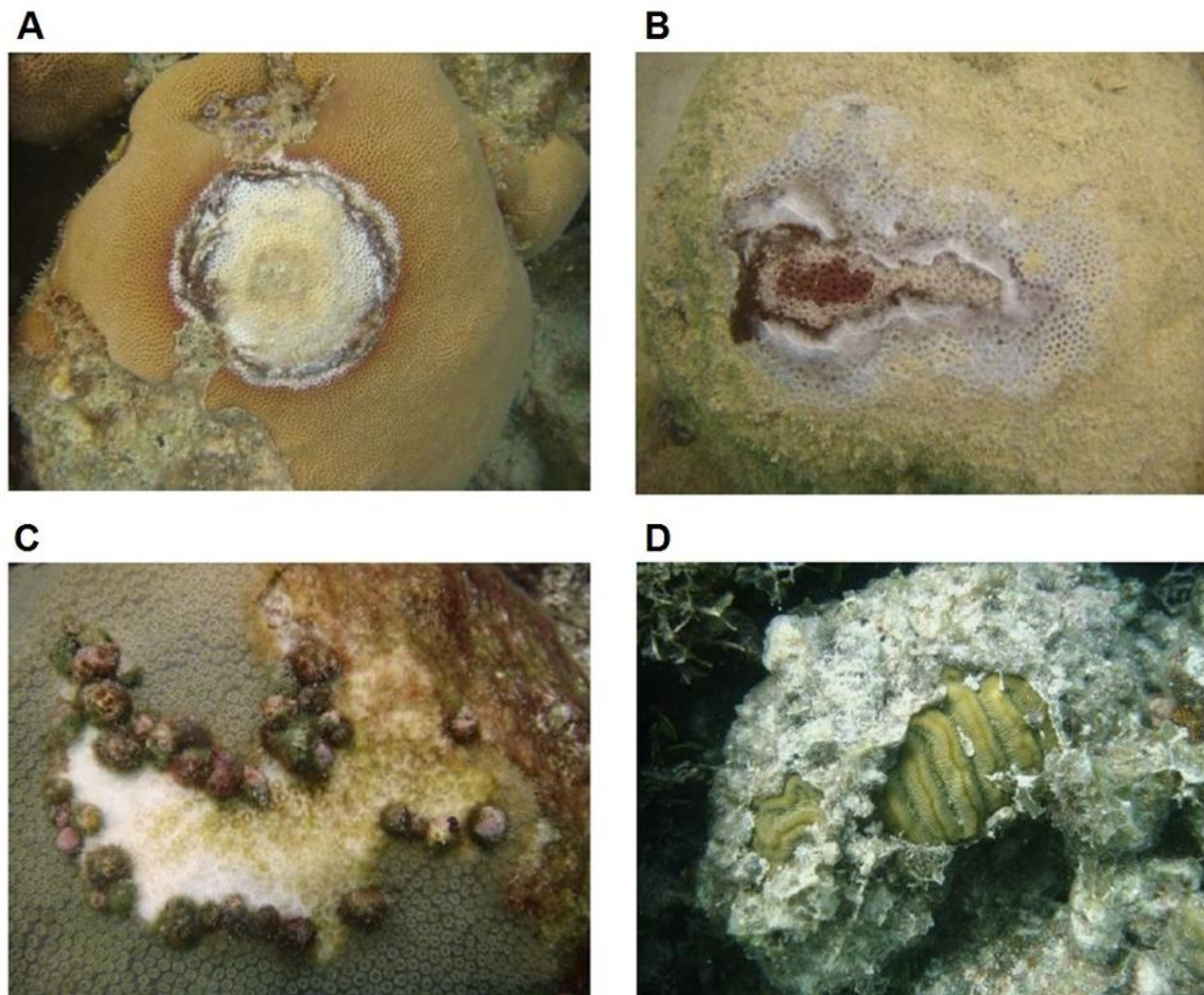
## LOCAL EFFECTS OF EUTROPHICATION

### Changes to Macro-Invertebrate Communities

Besides the controversy that surrounds the primary effects that nutrient enrichment has on invertebrate physiology (Szmant, 2002; Loya *et al.*, 2004; Fabricius, 2005; Dunn *et al.*, 2012) there are a number of reported effects at the community level. For example, the increased productivity caused by eutrophication might benefit certain coral species by increasing the availability of particulate matter that filter feeders rely on for food (Angelo & Wiedenmann, 2014). Such an effect has been suggested as the reason behind apparent increases in soft coral densities at a number of sites around Anguilla, British West Indies (S.Wynne, *pers. obs.*). These densities have reached such a level that in extreme cases they may shade and outcompete hard coral species.

Hard coral species can also be directly influenced by these primary effects either through smothering by sedimentation (Goldberg & Wilkinson, 2004), overgrowth by enhanced macroalgal vitality (Fabricius, 2005) or increased incidence or severity of disease (Bruno *et al.*, 2003). A number of hard coral diseases have been attributed to cyanobacteria growth which, as with macroalgae, is enhanced in eutrophic conditions. Incidences of coral diseases are high in Anguilla (Wynne, 2017), with the predominant cause observed to be through effects of cyanobacteria growth (figure 9).

As mentioned earlier, cyanobacteria growths have also been suggested to cause sponge mortality where widespread and persistent blooms coincided with the decimation of sponge communities over hundreds of square kilometres in Florida (Butler *et al.*, 1991, Herrnkind *et al.*, 1995, Stevenly *et al.*, 2010). This effect of the sometimes toxic 'red tides' can also effect higher community members (Trainer, 1999), not just macro invertebrates. However, as with the soft corals, most reports suggest that sponges benefit from other primary effects of eutrophication - non-toxic plankton and overall increased particulate matter – and, as suggested also for soft corals, may even help to reduce suspended particles and act as bio-controls for phytoplankton blooms (Peterson *et al.*, 2006, McMurry *et al.*, 2015).



**Figure 9:** Images of cyanobacteria growth on hard corals in Anguilla: A & B - *Siderastrea siderea*; C - *Orbicella faveolate* (with probable *Drupella sp.* infestation); D - *Colpophyllia natans* (photographs by S.Wynne).

### Changes to Vertebrate Communities

Aside from the toxic effects of red tides, the increased productivity that eutrophication brings has also been seen to effect fish abundances and species composition (Johns *et al.*, 2014). In the GWE of 2009 larval fish assemblages from the plume water were different from those in other water masses, where high abundances of pelagic and mesopelagic taxa were recorded. Reef and nearshore-associated taxa were lowest in the plume water, but it was suggested that they may have been displaced within the surface layers. Johns *et al.*, (2014) went on to conclude that if these events continue the ecological effects on the survival and recruitment of economically and ecologically important local reef fishes may be significant, although difficult to quantify at present.

The island of Barbados however, due to its closer proximity to the northern South America coast than the Lesser Antilles, is regularly surrounded by Amazonian plume water and so studied more extensively (Cowen, 2003). Observations showed that during some events larval fishes appeared to be rapidly advected away and resulted in a failure of larval settlement. Simultaneous changes were also observed in the vertical distribution of fish larvae. Larval fish encountering the plume waters were seen to

exhibit reduced growth rates and longer larval periods which was concluded to potentially reduce survival and ultimate recruitment success of coral reef fishes. It has yet to be established how much of these effects are caused by physical water properties versus the effects of the productivity within the waters. From other reports however, the effect of these productive waters is clear, as with the British Virgin Island reports from April 2009 (T.Baily, pers. comm.) where the GWE brought with it unusual fish assemblages, dolphins and large numbers of jellyfish.

Other more obscure effects that increased nutrient levels can have on vertebrates include potential increases in cases of ciguatera poisoning and an increase in cases of fibropapillomatosis in Green Turtles (*Chelonia mydas*). In terms of the latter, parts of Florida exhibiting habitat degradation and pollution have recorded a 200% increase in cases over recent decades (Foley *et al.*, 2005). Van Houtan *et al.*, (2010) reports elevated disease rates of *C. mydas* being clustered in watersheds with high nitrogen-footprints, both from natural and anthropogenic sources. It was concluded that this was due to invasive macroalgae and foraging ecology, where turtles now forage on invasive macroalgae that can dominate nutrient rich waters and affect production of the amino acid arginine. Arginine is known to regulate immune activity, promote herpes viruses, and contribute to tumor formation (Van Houtan *et al.*, 2014). These results have notable implications for understanding diseases in aquatic organisms under eutrophic conditions.

As for the biomagnification of the ciguatoxin produced by the dinoflagellate *Gambierdiscus toxicus*, a larger number of poisonings have been reported over the last five to ten years in Anguilla, with a wider range of species being linked to these poisonings (Sasso C, pers. comm.). Original reports of poisoning came from the consumption of barracuda (*Sphyraena barracuda*), but very quickly it became evident that it was also sensible to avoid larger species of jacks (i.e. *Caranx latus*), groupers (i.e. *Mycteroperca bonaci*) and snappers (i.e. *Lutjanus jocu*). Today, according to local reports, species of parrotfish (i.e. *Scarus sp.*) and surgeonfish (i.e. *Acanthurus coeruleus*) have also been responsible for incidents, which is especially interesting as these two families are herbivores so should be less susceptible to biomagnification processes. Although no direct link to eutrophication has been established, dinoflagellates, along with cyanobacteria, species of which can have toxic effects, thrive with increasing nutrients.

### Changes to Plant and Algal Communities

A Caribbean wide increase in macroalgae was initially attributed to the *Diadema antillarum* die-off in the early 1980's (Liddell, 1986; Lessios, 1988). It became problematic to corroborate this across the region as historical records are scattered, with only a handful of locations having data that reach back to the 1970's. After many years of study and deliberation it was ultimately concluded that *D. antillarum*, although a key grazing species, was only part of the picture (Lapointe *et al.*, 1997) and that other factors were also playing a key role in this 'phase shift'<sup>1</sup> (Mumby, 2009). These factors include over-fishing of herbivorous fish (Angelo & Wiedenmann, 2014), and local sources of nutrient rich run-off and/or effluence (Lapointe 1999). As in other parts of the Caribbean, high levels of macroalgae were recorded in Anguilla twenty five years ago by Oxenford & Hunte (1990), a situation which continued for the next twenty years (Wynne, 2010) and is still gradually increasing to this day (Wynne, 2017). Here, *D. antillarum* numbers appear to be recovering in certain areas, but no clear associations with overall macroalgae cover have been observed (Wynne, 2017). As discussed later, the situation is highly complex, with other research reporting herbivorous fish to not influence macroalgae growth (Suchley, 2016), and others questioning the overall role that nutrients play and the validity of experimental results (Littler *et al.*, 2006).

This phase shift is generally considered to be one of the major factors contributing to the region-wide habitat degradation recorded in Caribbean coral reefs (Gardner *et al.*, 2003). It consists of algae out-competing reef building hard corals, leading to an algae dominated habitat rather than one dominated by Scleractinia. This happens via two main pathways: either algae directly overgrows small to medium sized colonies gradually smothering them as it spreads; or dead/diseased corals/bare rock are

1. This term is popularly used to describe a shift in baseline conditions seen on Caribbean reef habitats, from one dominated by hermatypic coral species to that consisting predominantly of macroalgae. A discussion on the validity of this assumed phase shift can be found in Bruno *et al.*, (2014).

colonised by algae before the slower growing hard corals are able to establish. The latter is especially relevant to disturbance events which characterize coral reef ecosystems (i.e. storm damage etc); their resilience to these events and the ability they have to regenerate after disturbance is a crucial feature of coral reefs (Bellwood *et al.*, 2006). Aside from the dramatic disturbance events we see today this process is accentuated by increased incidence of coral diseases (as discussed earlier), and may be subject to synergistic interactions with other stressors (i.e. overfishing of herbivorous fish species) as will be discussed in the following subsection.

The effect eutrophication has on marine plants, unlike the rapid spread of macroalgae, is superficially considered positive. Seagrass for example, has been in decline not just in the Caribbean but world-wide (Waycott *et al.*, 2009) and increasing nutrient levels may in theory aid its growth. These plants are important food for manatees and turtles, habitat for juvenile fish and help stabilise the benthic substrate. This may be the case when nutrients are in relatively low concentrations, although what is being observed in Anguilla is decreased light penetration, increased epiphyte cover (most notably cyanobacteria) and the beginnings of a shift in community composition (Wynne, 2017): In some areas percentage cover of Fuzzy Finger Alga (*Dasycladus vermicularis*) has increased significantly, and the invasive seagrass species *Halophila stipulacea* has begun to dominate certain areas. However, *H. stipulacea* may in fact prove to be beneficial as it grows rapidly and can colonise areas where other seagrass species (i.e. *Thalassia testudinum* and *Syringodium filiforme*) failed to establish, aiding sand stabilisation. *H. stipulacea* is also associated with larger fish and a more species rich fish community than *S. filiforme* (Rogers *et al.*, 2014).

### Potential Synergistic Interactions

As mentioned in the previous subsection, complex interactions between multiple stressors have been theorised, and for more than a decade now have been the subject of considerable interest and study (Folt *et al.*, 1999). These interactions are generally placed into three categories: 'antagonistic', where the combined effect of stressors is less than the sum of their individual effects; 'additive', where the combined effect is equal to the sum of their individual effects; and 'synergistic', where the combined effect is greater than the sum of their individual effects (Nicholas *et al.*, 2014).

There is growing concern that these interactions will occur synergistically and produce ecological surprises that may be more common than simple additive effects (Darling & Côté, 2008). Indeed, evidence for the existence of ecological surprises, events where the behaviour of a natural system can dramatically deviate from that expected or historically observed, continues to mount (Lindenmayer *et al.*, 2010). However, meta-analytical studies over recent years have failed to find synergies between multiple stressors in coral reef ecosystems, even though there is evidence for them in freshwater and terrestrial systems (Darling & Côté, 2008; Nicholas *et al.*, 2014). Most synergies discovered have been during lab based experiments where variables can be tightly controlled (Crain *et al.*, 2008, Jessen *et al.*, 2014), although model based approaches have also been used in an attempt to uncover interactions that would be extremely difficult to study in the wild (Blackwood *et al.*, 2011). Direct field based experiments and analysis on coral reefs have yet to uncover synergies, and usually conclude effects are additive or antagonistic (Darling *et al.*, 2010). Recent studies have concluded that in systems as complex as coral reefs the lack of evidence for synergies is in part due to knowledge gaps for numerous stressor interactions and insufficient quantitative evidence (Nicholas *et al.*, 2014). It seems likely that such interactions exist, even on the simplest level where, for example insufficient top-down control may have catastrophic consequences for reef ecosystems as exemplified by the removal of grazers by overfishing or die-outs (Angelo & Wiedenmann, 2014). Despite this, such interactions are still a matter of great debate, with understudied complexities still confounding results (Suchley *et al.*, 2016), especially when discussing habitat destruction, overfishing, eutrophication and climate change (Momigliano *et al.*, 2015).

Even without direct evidence of synergies, it may be appropriate to assume it is only a matter of time until such evidence exists and thus proceed following the precautionary principle; managing systems in a way that attempts to mitigate against the most likely potential interactions. For example, it seems probable that eutrophication, overfishing and herbivore die-offs will have a greater than additive impact on overall habitat degradation when combined than when acting individually (Suchley *et al.*, 2016). In Anguilla much of the diverse coral reefs that once existed appear to be almost lost (Wynne, 2010) with most areas now

dominated by ‘survivor’ species with stress-tolerant and weedy life histories, as was also observed to occur after stress events in Kenya (Darling *et al.*, 2013). It is not clear as to whether these areas can or will recover in the future (especially in light of regional stressors), but without the strictest possible management interventions it is almost a certainty that they will not. At the present time, due to uncertainties and a continued lack of direct scientific evidence, the outcome of such interventions remains unclear. However, by trying to address these issues holistically after assessing the local situation, ecosystem stability and the potential for recovery will be given the best possible chances of success.

## LOCAL VS REGIONAL EUTROPHICATION & MANAGEMENT IMPLICATIONS

Following the *D. antillarum* die-off in the early 1980’s the role that eutrophication plays in macroalgae growth promotion, combined with other ecological and physiological factors, became more extensively studied. When discussing eutrophication most reports give examples where the nutrients are coming from local sources, usually terrestrial run-off (including river plumes) or sewage outflows. Examples of such studies are: Algal growth in the effluent receiving area from a turtle farm in the Cayman Island (Goreau, 2008); wastewater discharge increasing dissolved inorganic nitrogen in southeast Florida (Lapointe, 1997); and groundwater inputs and sewage pollution at Discovery Bay in Jamaica (Lapointe *et al.*, 1997). Although the relevance of these local sources of nutrients should not be understated as they can heavily influence the nearby area and also add to regional levels of eutrophication, it is the main hypothesis of this paper, that equally or more important for Caribbean marine habitats as a whole, are the larger sources of nutrients arriving from distant sources on ocean currents. As detailed earlier in this paper, the evidence for these sources as being a significant input of nutrients into the Caribbean has only recently begun to be collated, analysed and appreciated. These previously unappreciated sources of nutrients will have been adding to the local sources from before records began. This means that where local sources were once considered unimportant as they were assumed to be diluted at a rapid rate, a bigger picture can now be painted of thresholds quickly being reached with potentially catastrophic near future consequences. This is of particular importance in under populated areas that may have previously been considered safe from anthropogenic influence.

Anguilla is a case of such a relatively remote location with a comparatively small dispersed population. The lack of a large population centre or highly developed coastal areas means that the island does not fall into the usual model where significant pollution outflows exist. Furthermore, with little agriculture present, nutrient rich terrestrial runoff is unlikely, with most collecting in salt ponds rather than flowing directly into the sea. The only identified local nutrient and/or pollution sources are: old and poorly maintained leeching septic tanks; intentional or natural connections made from salt ponds to the ocean; pollution (grey water or otherwise) from boat traffic; and leeching from the Corito Bay landfill located only a relatively short distance from shore. Some effects of local eutrophication can be observed close to some of these potential sources: for example poor water quality and sporadic algal blooms in the port areas in Road Bay and Island Harbour. However, macroalgae levels around the mainland are high overall, and relatively uniform, showing no obvious link to these areas, and although offshore regions sometimes exhibit lower amounts of algal growth, generally levels are still high (Wynne, 2016). Furthermore, Wynne (2016) found eutrophic conditions both near to shore and offshore through water quality measures taken around the island. Although there is some discussion as to what ‘natural’ levels of macroalgae are, and suggestions that current observations are being biased by lack of a coral canopy that previously existed, hiding such growths from view (Bruno *et al.*, 2014), regional sources of nutrients must be assumed to play an important role in the present day ecology of the area. Even though further study is needed, for remaining relic coral populations in the Caribbean to be given the best chance of survival possible, this assumption is crucial. As management of regional nutrients is not possible without multi-national intervention, current efforts should be focused on mitigating against effects at a local level. Recognising and allowing for this regional stressor when making locally based management decisions will be essential if mitigation measures are to be given the best chance of success. Management options open to decision makers that may help mitigate against eutrophication from non-local sources (and the tertiary effects associated with this) include:

- Strict control and regulation of potential local sources of nutrients. In the case of Anguilla this is likely to be septic tank legislation, spot checks and enforcement; tight control of salt pond connections to the ocean; measures to control grey water dumping at sea (a marina with a waste water treatment facility would encourage this); assessment of Corito Bay landfill site and feasibility study to reduce potential leeching and/or relocate further inland.
- Protection of recovering key herbivores and/or relocation of threatened populations, for example *Diadema antillarum*.
- Protection of herbivorous fish species, with at least minimum size restrictions, in order to facilitate some level of top-down control.
- Restrictions to fishing methods used in protected areas and/or reef areas. Spearfishing targets species indiscriminately causing community structure collapse, especially when conducted in a completely unregulated manner as currently occurs in Anguilla. Trap fishing, the second most widely conducted fishing method in Anguilla is highly damaging when traps are placed directly on the reef, or lost at sea only to continue ghost fishing.

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