Determining the Origin and Ecology of a Macroalgae (*Ulva clathrata*) Bloom Along the Coast of Western Ghana and Cote d'Ivoire

A Summary Report of Field Observations and Sample Collection from Surveys Conducted in Dec 2010 and Dec 2011

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Cover Photo: Men hauling in a fishing boat, Western Region, Ghana

Cover Photo Credit: Stephen Granger

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Background

In November of 1993 communities along the coast from New Town to the Ankobra River, Ghana began reporting a green substance that would clog, or over-fill and split their fishing nets (EPA 1996). Approximately 25% of the coastal population participates in an artisanal fishery that deploys beach seines each day, providing up to 80% of the local diet. During the 1993 (and subsequent) events the sea appears green from copious amounts of small 4-6 cm green "tufts", hence the local reference to the bloom as "green-green".

In 1996 The Environmental Protection Agency (Ghana) provided the first official report describing socio-economic impacts of the bloom and identified the green substance as a naturally occurring macroalgae, *Enteromorpha* (Fig 2). *Entermorpha* is now included in the genus *Ulva*, so we adhere to this recent botanical reclassification and refer to the macroalgae as *Ulva* (Hayden et al. 2003). A recent genetic analysis at the Natural History Museum in London determined the species as *Entermorpha* (*Ulva*) *clathrata* (see Figure 1), a morphologically variable filamentous macroalgae that is very responsive to nitrogen enrichment. The EPA study also measured near/offshore water quality and conducted a demographic survey including questions on local knowledge of the bloom at five stations located from New Town and Cape Three Points (Fig 2).

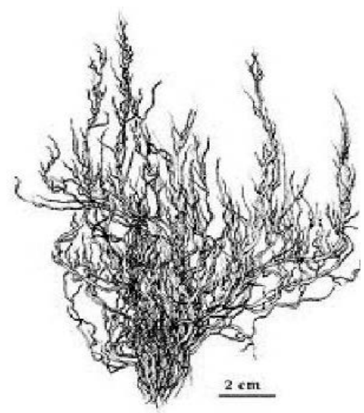

Figure 1: Ulva *clathrata*

In keeping with the oral tradition of Africa, most of what we currently know about the phenology of the bloom comes from interviews with fishermen, chiefs, and village elders. Despite variations due to geographic location, differences in personal opinions, and the vagueness of memory, several consistent themes emerged from the EPA and our own interviews. Field observations by Ghanaian fishermen indicate the macroalgae is brought to Ghana by wind or current coming from the east. It is moved to their location by the prevailing Guinea current, is found within two kilometers of shore, and is in greatest abundance in the New Town area (or moving westward from their village), and then diminishes in mass moving toward Cape Three Points. However, even with first-hand knowledge of the bloom, other specific aspects such as the time of onset, duration, and intensity varied greatly among communities.

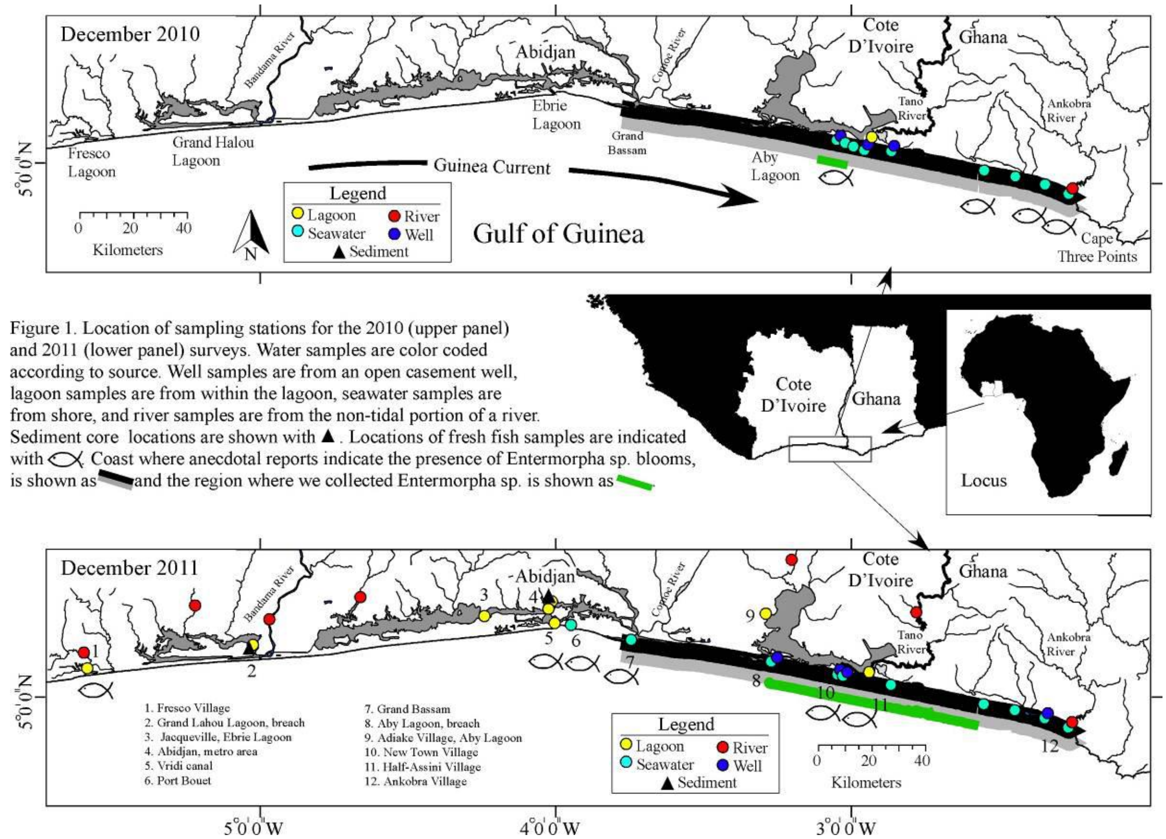

Figure 2: Map of sample sites

In April 1995, EPA documented a modest plankton bloom comprised of *Asterionella japonica*, a pennate diatom, which occurred simultaneously with the "green green" and reached cell counts of 6.1 * 10^6 per ml. Despite the simultaneous bloom, seawater nitrogen concentrations averaged around 3 micromolar (40 mg l^{-1}) and were higher than during the 2010 survey. In 2010 we found dissolved inorganic nitrogen and phosphorus concentrations in the sea were consistently low or undetectable at all stations during a time when Ulva was only found around New Town.

The EPA report concludes by stating the need to extend the study into Cote D'Ivoire for a more complete understanding of the forces supporting the bloom.

In 2010 the Ghanaian Ministry of the Environment worked with The Integrated Coastal and Fisheries Governance (ICFG) and CRC-Ghana to form a Task Force of collaborating institutions (see title page) to build on this earlier work by extending the survey into Cote D'Ivoire in order to more fully describe the ecology of the "green green" bloom and its underlying nutrient source(s).

Figure 3: Photographs of the *Ulva clathrata* bloom in New Town Dec 2011. The left panel shows 4-6 cm tufts of the seaweed near shore, while the right panel shows the deposition of *Ulva* on the shore at New Town Dec 10, 2011.

Field Surveys

This report summarizes our observations and sample collections during two field surveys designed to identify sources of nitrogen that enrich the coastal zone in Ghana and Côte d'Ivoire.

The first survey was on Dec 8th to the 11th, 2010 and focused on the Ghanaian coast from New Town to the Ankobra River (200 Km of coastline). The second survey on Dec 7th to the 22th, 2011 included from Fresco Lagoon in western Cote D'Ivoire to the Ankobra River, Ghana (375 Km of coastline) (Fig 2).

During the course of these surveys in both countries, representative samples of water, seaweed, sediment, and fish were collected for the determination of nitrogen (N) concentrations and stable isotope ratios ($\delta^{15}N$), (Fig 2). Stable nitrogen isotope ratios compare the common form of N, with an atomic mass of 14, to a heavier (and rare) version that has an atomic mass of 15. As the ratios of ^{15}N to ^{14}N vary with the source of the nitrogen and throughout a food web, measuring these ratios gives us further insight into the sources of N to the surveyed region. For a more complete discussion of nitrogen isotopes and ecosystem nutrient dynamics see Oczkowski et al. (2009). Nitrogen is the nutrient that limits plant growth in most coastal marine systems, therefore our field surveys were designed to locate and measure various sources of nitrogen that could support the bloom.

Nitrogen enters the study area in streams that empty either directly, or through a lagoon, into the sea. Less obvious (but potentially very important) sources include groundwater enriched by agricultural fertilizers, upwelling of deep ocean water, advection of seawater from the west by the Guinea current, and a number of smaller surface water inputs from land. Rain that falls in catch basins mobilizes and transports nitrogen to the sea in rivers and by infiltrating groundwater. Larger rivers were measured as closely as possible to their point of entry into a lagoon or the sea in order to determine (very roughly) relative watershed inputs of nitrogen (Fig 5). Likewise, coastal lagoons were sampled close to their connection with the sea to determine the availability of nitrogen within the lagoon. Village wells within 1000 meters of the seacoast are 3 to 6 meters deep and intercept the surface of the water table. Well water samples were taken to allow us to make a very approximate assessment of nitrogen concentrations in the groundwater aquifer as it enters the coastal zone. Finally, coastal stations were sampled to determine nitrogen concentrations in the sea. At each coastal and lagoon station we also collected samples of *Ulva clathrata* from the water if present, and several species of freshly caught fish if we had first-hand knowledge of where they were caught (Fig 2). Every effort was made to gather similar species of fish, and ongoing identification of the samples will allow for more detailed analysis of fish behavior and feed habits.

Phenology of an *Ulva clathrata* Bloom and Aby Lagoon

At the completion of the 2011 survey we developed a working hypothesis for the phenology of the bloom from our conversations with local fishermen, especially those from Aby Lagoon. Most reports of the bloom came from the immediate vicinity of a fishermen's village i.e. a single point of reference, so accounts of when the bloom first develops, the length of time a bloom persists, and the amount of seaweed biomass varied with location and between years.

The narrative of the bloom that follows links all the information we gathered from our interviews and resolves some apparent contradictions that arise when comparing local knowledge of the bloom among villages.

We learned from our many conversations with local residents that *Ulva clathrata* has been present in Aby lagoon since the 1980's. *Ulva* is a marine algae that enters the lagoon through tidal inlet and is able to survive in the lagoon as long as the salinity remains above 20 ppt. The algae growth first became problematic in 1991, when mats over 1.5 meters thick developed in the lagoon, killing large numbers of fish. Each year *Ulva* grows inside Aby lagoon during the dry season (Jan-Mar) and persists until the rainy season swells the Tano and Bia rivers (Fig. 5) which, in turn, flush the lagoon and move the *Ulva* into the Guinea current offshore. (Figs. 2 and 5). The mean depth of the lagoon is about 3.5 m and the two principal basins are more than 23 m deep. It is possible that the *Ulva* may lie dormant in deep water and be brought to the surface during the raining season during mixing of the different layer of the waters.

After the blooms moves through the beach way and out of the lagoon, the prevailing long shore current moves the *Ulva* eastward toward Cape Three Points until driven onto the beaches of Cote D'Ivoire and Ghana by the on-shore winds. Reports of *Ulva* washing up on the beach begin in August and September around New Town then spread to other locations. Reports about the end of the bloom were generally associated with the end of the rainy season (Fig. 5); however, along the coast between Assini-France, New Town, and Half-Assini the bloom can linger into March (EPA 1995).

The greatest biomass of *Ulva* appears on the shore between Aby lagoon and New Town. Moving eastward toward Cape Three Points, seaweed biomass diminished with distance from New Town, the onset of the bloom was delayed, and the duration became more ephemeral. In the 1996 EPA survey, local knowledge of the bloom in Cape Three Points came exclusively from second-hand accounts, with 34% of respondents (highest in the communities surveyed) having no knowledge or opinion of the bloom. Our field observations, along with survey data, established the Ankobra River as the eastern most range of the bloom (Fig 3). Interestingly, we did not find *Ulva* in the other lagoons of Cote d'Ivoire that we sampled, and like the residents of Cape Three Points, local inhabitants of the Fresco and Grand Lahou lagoons did not have direct knowledge of the bloom.

We measured dissolved nutrient concentrations at several points in Ebrie lagoon, in the Vridi canal, and along the shore of Grand-Bassam, to determine nitrogen concentrations in the lagoon and coastal sea water. We also collected samples of fish and took one sediment core in a heavily impacted area near Abidjan. Although *Ulva* does not develop heavily in Ebrie lagoon, the lagoon is highly enriched and provides nitrogen (via the Guinea current) that can support or prolong the *Ulva* bloom.

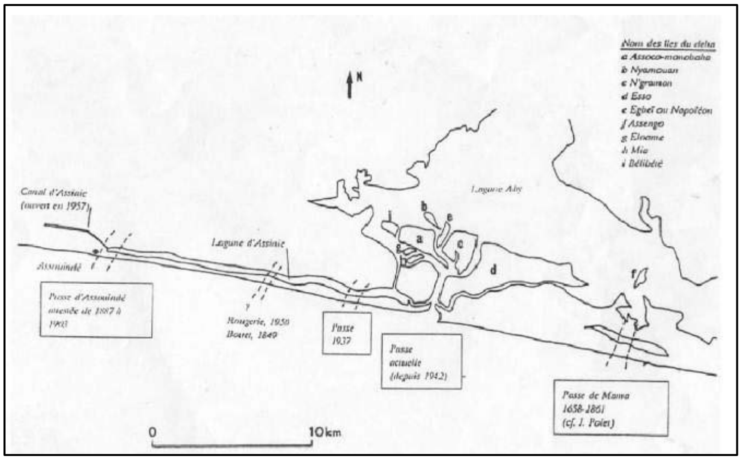

Figure 4: Varios locations of the Aby breach way before reaching its current position in 1942. Reproduced from Les Etoile de Cote d' Ivoire aux XVIII et XIX siecles. Pouvoir lignager et religion. Publications de la Sorbonne.

In our 2011 survey, Grand-Bassam was the most western community that had direct knowledge of the bloom; further west in the lagoons of Grand Lahou and Fresco fishermen had little or no knowledge of the bloom (Fig 5). The mechanism by which *Ulva* is transported from Aby lagoon westward to Grand-Bassam is discussed in the next section. Reports of the bloom from Grand-Bassam indicate a more ephemeral event that does not generate the macroalgae biomass observed around New Town.

The channel or breachway that connects Aby lagoon to the sea is not stabilized and it changes in shape and dimension each year (Figure 4). Changes in the lagoon's connection with the sea can alter the salinity and nitrogen concentrations inside the lagoon. *Ulva* is tolerant of a wide range of salinities but grows best in water from 20-30 psu. The consequences of changing breach way dimensions on flushing time, salinity structure, nutrient regime, etc. in Aby lagoon is unresolved and requires a more advanced hydrodynamic study. Historic water quality information from Aby lagoon is not available for comparison. As a proxy for possible changes in water quality and nutrient concentrations in the lagoon we assembled Landsat satellite images of the breach to determine if changes in the breach way width correlated with years when the bloom was most pronounced (1992, 2000, 2009) (see accompanying movie entitled "Aby Breach Way").

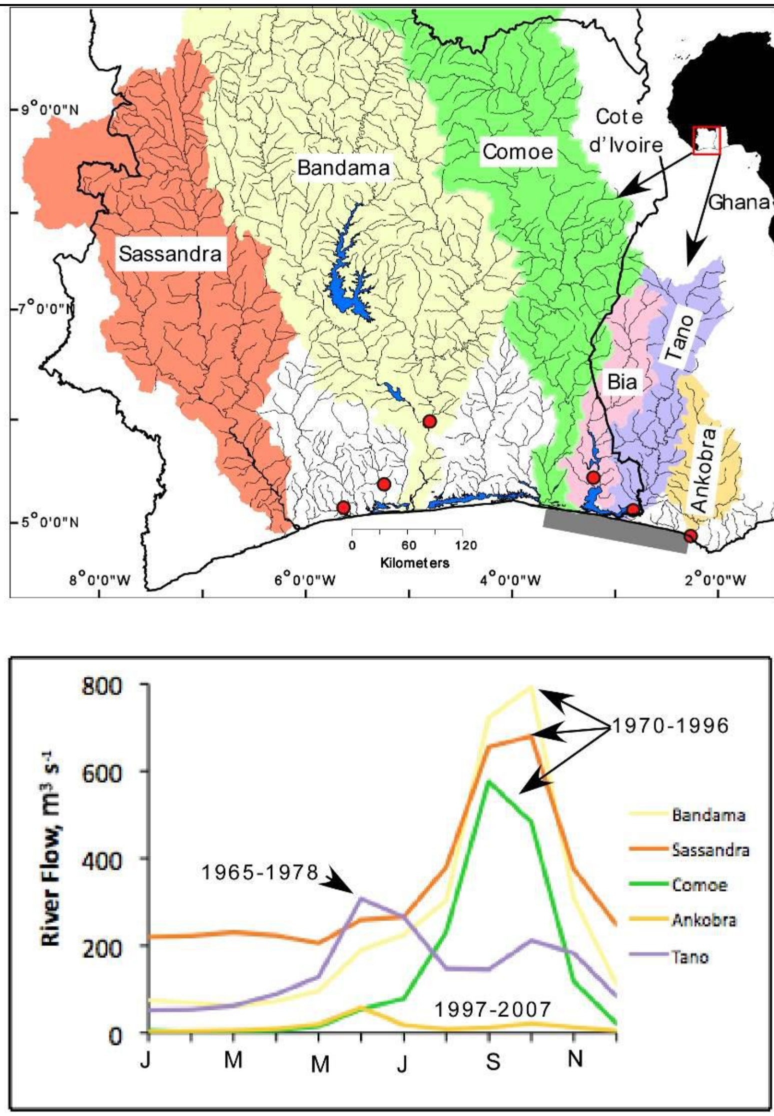

Figure 3. Top Panel; major watershed areas in the study area. Red circles indicate 2010& 2011 river sample stations where dissolved nutrient concentrations were measured. Coastline experiencing the Entermorpha bloom is shown in grey. Bottom Panel; Flow for rivers draining catchment basins pictured in top panel. Flow values are a mean for the years indicated (data from Global River Discharge Center,http://www.bafg.de/GRDC/EN/Home/homepage__node.html). Note the different patterns of flow between small coastal rivers (Ankobra and Tano) and larger rivers (Bandama, Sassandra and Comoe). Maximum flow for the coastal rivers comes in July and for the larger rivers in October.

Figure 5: Map of watersheds and hydrograph of those watersheds.

Upwelling and Deep-sea Nutrients

The Guinea current is a highly productive ecosystem (>300 g C m^{-2} y^{-1}) formed from the convergence of the Canary Current and the North Equatorial Counter Current. Flowing eastward at 3° N along the south facing coast of West Africa, it forms a thin (10 to 60 meters) fast moving (100 cm s^{-1}) surface layer reaching its fastest flow in May through September and slowing during November to February.

Fishermen from Assinie-France (Aby lagoon) to Ankobra report periods when currents near the shore reverse direction and flow westward. The reversal extends a few kilometers seaward, is usually attributed to changes in wind, and can persist from days to a week. This anecdotal evidence of current reversal provides a mechanism by which Ulva moves from Aby lagoon westward to Grand-Bassam, i.e. opposite of the Guinea current. Reassuringly, fishermen in Grand-Bassam were unique in their opinion when they pointed eastward and said the macroalgae was coming from there. Contrary to this opinion, fishermen east of Aby lagoon point westward as source of the seaweed placing Aby lagoon at the nexus of bloom development.

There is a scientific foundation for short-term current reversals in Lemasson, L. and Rebert (1973). They observed the Guinea Current intensifying (e.g. reaches maximum speed) during the intense upwelling season (July and August). Geostrophic forces tilt the isotherms between the two currents upward toward the shore, causing the Ivorian Undercurrent (IU) to displace the Guinea current seaward see Quicktime movie Guinea SST. When the westward flowing IU moves up onto the continental shelf, the direction of the long shore flow can change from east to west and thereby distribute macroalgae west of Aby lagoon. Upwelled water would also allow the *Ulva* access to elevated nutrient concentrations in the IU. We were not able to measure nitrogen concentrations in the Ivorian Undercurrent due to the difficulty of hiring an appropriate boat - as a consequence this source of nitrogen has not been adequately described. Additional attempts at collecting water from the Ivorian Undercurrent will be required to determine nitrogen concentrations and isotopic (N^{15}) signature.

We have provided a short movie-loop of sea surface temperature in the Gulf of Guinea (1 km resolution) to demonstrate the location of upwelling and time varying nature of the event (see accompanying movie entitled "Guinea SST"). The movie includes weekly images of sea surface temperatures during the first major upwelling season from June 2011 to December 2011 while a modest *Ulva* bloom was present (Fig 2). It is interesting to note that the upwelling is very close to the coast where current reversal is observed. Upwelling ended by early October a few months before our 2011 survey. As more information about the time varying nature of *Ulva* biomass becomes available, a correlation between upwelling and the bloom may emerge. It should be noted that upwelling in this region also stimulates phytoplankton growth (Djagoua et al 2011) and increases fisheries yields (Arfi et al 2003). Some fish, mainly herbivorous and grazers, consume *Ulva* as their natural food source, but they also suffer the negative effects of the bloom.

Land-Based Nutrient Inputs

The 2010 and 2011 surveys were conducted during December, the beginning of the dry season and a time when river flow is low and nitrogen concentrations are highest. The Inter Tropical Convergence Zone (ITCZ) is a meterological zone of deep convection located between the dry northeast trade winds (Harmattan) and moist southwest monsoons. The dry season ends when the ITCZ begins a northern migration from 5˚N and allows the southerly monsoon rains to penetrate over land. This annual cycle gives rise to distinct patterns in river flow depending upon the location of the catch basin. Coastal rivers like the Ankobra display peak discharges in June and Oct, marking the north/south passage of the ITZC over the catch basin. In Cote D'Ivoire, river catchments reach north to 10˚N, closer to the northern extreme of the ITCZ migration (20˚N). As a consequence rivers in the catchments display a single large peak discharge in Oct (Fig. 3) Changes in flow of water through the inlet into the Aby Lagoon determine the amount of sea water entering the lagoon to support the devlopment of *Ulva,* which need between 20-30 ppt. That salinity range is found only in the delta zone in the south of the aby lagoon and in deep water. The other sector of the lagoon are fresh water dominated. Time-series of river flow in the study area show that maximum flow occurs at different times in different catch basins. As more information becomes available about the timing and development of *Ulva* biomass during the bloom, the relative role that the Ghana and Cote d'Ivoire rivers play in supporting the bloom can be separated.

Long-term rainfall (1950-1991) (Kumasi, Ghana) and river discharge data (Pra River) in the western region of Ghana display two distinct periods; 1950-1970, a time of greater rain (mean 1,563 mm) and river flow (mean 215 $m^3 s^{-1}$) followed by a low period in 1970-1991 (rainfall mean 1273 mm) when river flow was reduced by almost 50% (mean 119 $m^3 s^{-1}$) (Opoku-Ankomah and Amisigo 1998). A formal request will be submitted to the Global River Discharge Center for flow data from the Tano, Bia and Comoe Rivers to determine if the appearance of the *Ulva* bloom during the early 1990's, or the noteworthy bloom years of 1992, 2000 and 2009, can be associated with changes in freshwater inflow to the sea. Kumasi, with a mean rainfall of 1.2 mm, and the Pra River lie just to the east of the Ankobra River basin Figure 1. Rainfall varies from 1.7 to 2.1 m in the study area (Barbe et al. 2002) so recent rainfall data from stations closer to the coast are needed to perform a similar analysis for our study area.

Our measures of river nitrogen concentrations in the study area (2010 & 2011) represent single observations in time, and it should be noted that human development in the catchment areas continues through time with increases in both agriculture and population (Fig. 6). As an example, during our 2010 survey we obtained fertilizer samples from the local agricultural agent (near Half-Assini) for analysis, and learned that the agency began a program in 1990 of delivering 2.5 kg of muriate of potash and 750 g of urea to each palm tree every year. The effects of this fertilization program may be seen in the nitrogen analysis of well water samples. The upward trend in population and agriculture will reduce forest cover in the catch basins and increase nitrogen inputs to the coastal region.

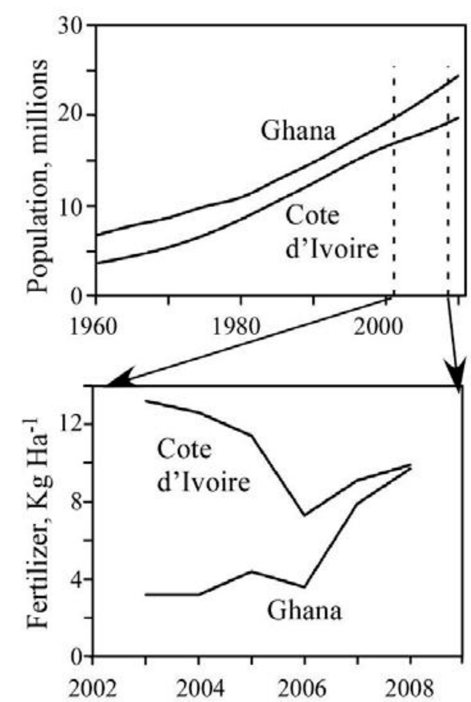

Figure 4. Population and Fertilize Use, Source: Food and Agriculture Organization of the United Nations (FAO). 2009. FAOSTAT Online Statistical Service. Available online at: http://faostat.fao.org/.

Figure 6: Graph showing population growth and increased fertilizer use

Long-term mitigation of chronic nitrogen enrichment should consider growth scenarios in the watersheds

Sample Analysis and Discussion

At the time of this report the analysis of the 2011 samples is ongoing. It would be premature to place too much importance on any one aspect of the data at this point. Sediment samples taken from Fresco and Grand Lahou lagoons are representative of undeveloped systems and will establish the baseline for nitrogen concentrations and aid in the interpretation of future data. However we can present analytical results for the available samples with a brief discussion here.

Well water samples show that the shallow ground water has much higher DIN concentrations than the river water; the enrichment is most likely from fertilizer in the watersheds (Fig 7). When annual discharge records for the rivers become available, we could compare it to the annual rainfall on the watershed and the difference could then be compared with estimates of annual evapotranspiration in this area to see if that left a significant amount of water for groundwater inputs to the coast. It would be a rough estimate, mostly due to uncertainties in the evapotranspiration but would give us an estimate of groundwater inputs to the coast.

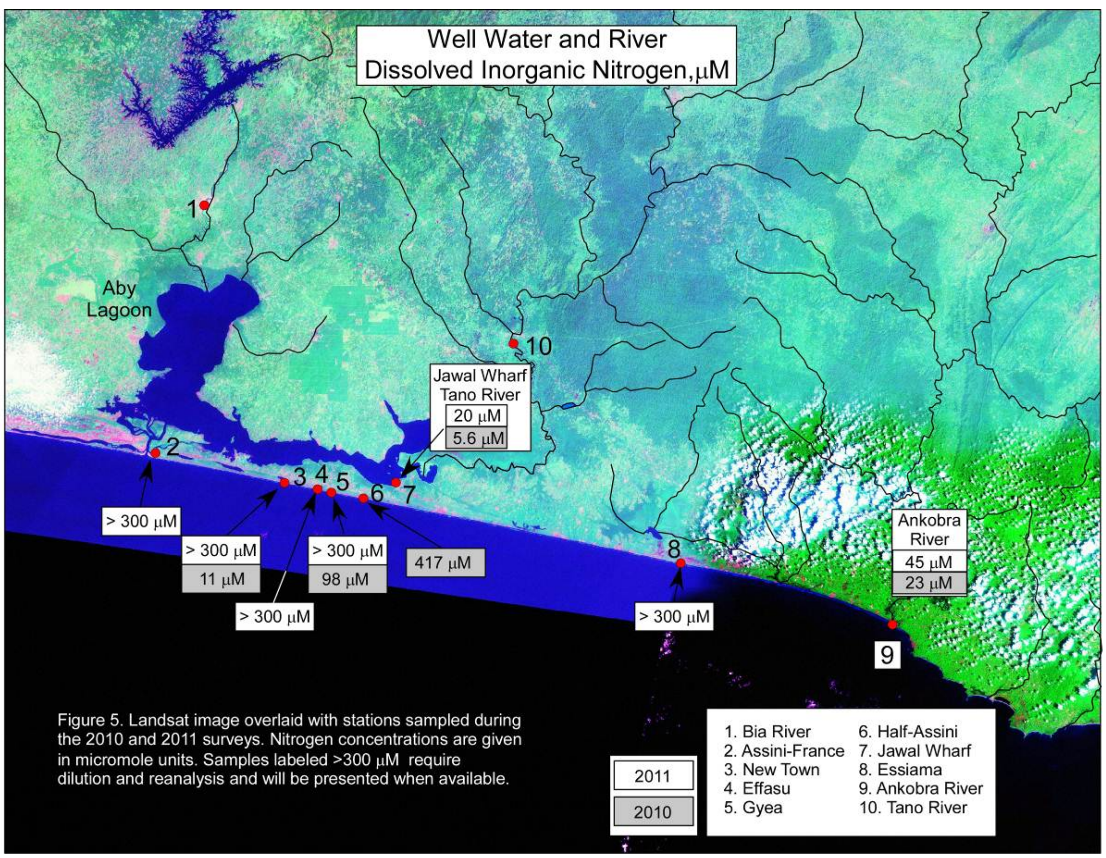

Figure 7: Satellite image with sampling sites indicated. Well Water and River Dissolved Inorganic Nitrogen, µM

Stable isotope values of nitrogen ($\delta^{15}N$) are typically lower in marine systems that have little human impact (i.e. <6 ‰) and higher (>8-10 ‰) in systems that receive significant amounts of human sewage and/or agricultural runoff. Of course, this is a generalization, and exceptions have been documented (Fig 8). Thus, these stable isotope values will need to be interpreted in a broader context and in conjunction with additional information and data. In general, however, the $\delta^{15}N$ values of fish caught between Abidjan and the Ankobra River are consistent with anthropogenically influenced food webs, with values generally greater than 11.5‰. In contrast, fish from Fresco Village, to the west of the Bandama River, had values of about 10‰. One preliminary interpretation of this variation may be that the sources of nitrogen to the fish caught at Fresco Village are slightly different than those caught further to the East. However, these differences may also be accounted for by species differences. The fish collected have not yet been identified.

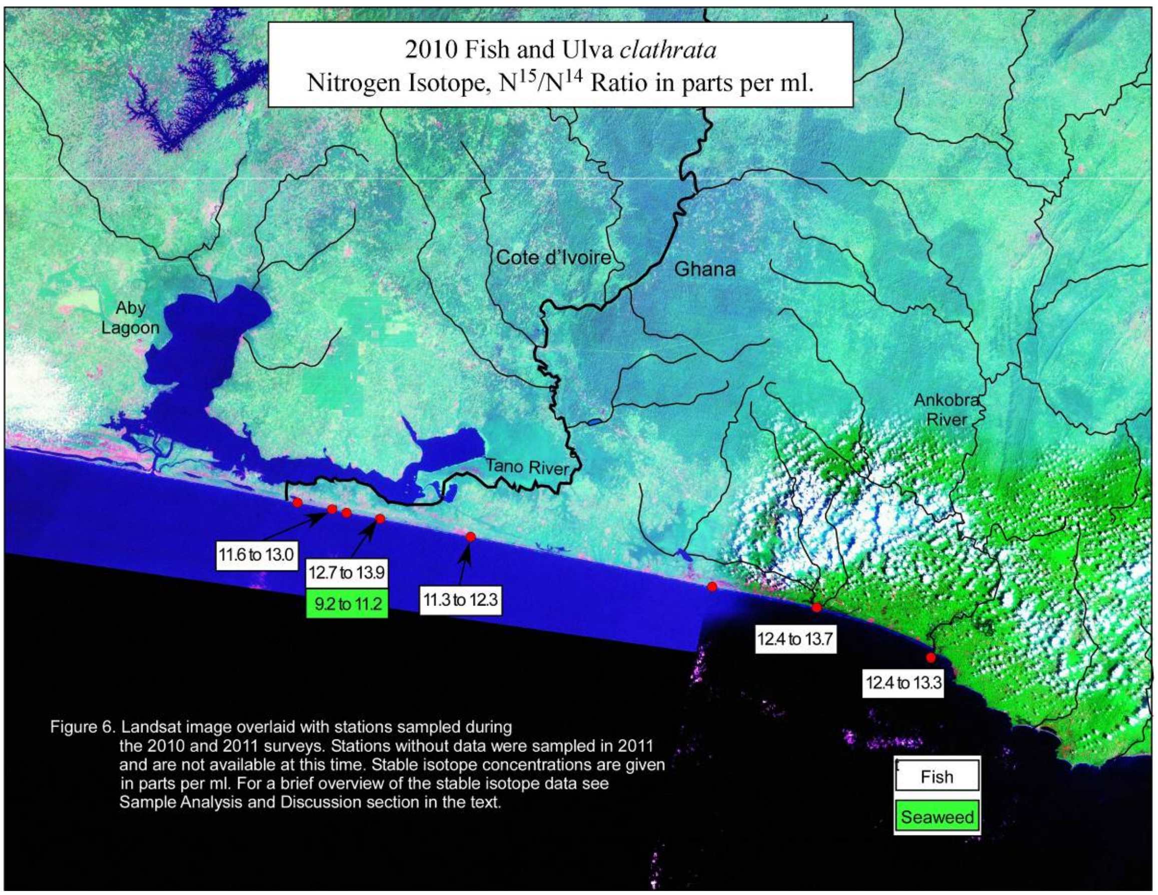

Figure 8: Satellite image with sampling sites indicated. 2010 Fish and Ulva *clathrata* Nitrogen Isotope N $^{15/}$N 14 Ratio in parts per ml.

Nitrogen isotopes fractionate with trophic level, where values increase by 1-4‰ between primary producers (i.e. seaweed) and primary consumers and then again between primary and secondary consumers. Thus, we would expect carnivorous fish to have greater $\delta^{15}N$ values than planktivorous fish. We would also expect the seaweed $\delta^{15}N$ values to be lower than the fish values. Seaweed collected in the second survey had values ranging from about 7.7‰ (Assini France) to 10‰ (Efesu). These values are indeed lower than those measured in the fish, but more samples are needed to determine if values are significantly different among locations.

Samples from two short (0.5 m) sediment cores are pending, as are identifications of the fish collected, and $\delta^{15}N$ values of water collected on the second survey.

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