Satellite remote sensing characterization of fish spawning aggregation sites in Puerto Rico and the United States Virgin Islands

By

Graciela E. García-Moliner Basora

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Approved by:

______________________________ _______________
Jorge R. García-Sais, Ph.D. Date
Member, Graduate Committee

______________________________ _______________
Richard S. Appeldoorn, Ph.D. Date
Member, Graduate Committee

______________________________ _______________
James A. Yoder, Ph.D. Date
Member, Graduate Committee

______________________________ _______________
Roy A. Armstrong, Ph.D. Date
President, Graduate Committee

______________________________ _______________
Manuel Valdés Pizzini, Ph.D. Date
Representative of Graduate Studies

______________________________ _______________
John M. Kubaryk, Ph.D. Date
Chairperson of the Department

ABSTRACT

This work investigates the seasonality of the satellite-derived chlorophyll signal (Chl-a) at eight (8) established fish spawning aggregation sites in Puerto Rico and the United States Virgin Islands and events that might influence this signal. These fish spawning aggregation sites are recurrent, meaning that fish (*i.e.*, red hind *Epinephelus guttatus* (Linnaeus) and mutton snapper *Lutjanus analis* (Cuvier)) aggregate at these sites every year, over the same periods of time. This indicates that these areas present a series of characteristics beneficial for the species to spawn. This approach can then be applied to describe fish spawning aggregation sites of other species, specifically to understand the reasons why these sites appear to be used sequentially by other species.

Satellite images from NASA sensors SeaWiFS, MODIS Aqua and MODIS Terra, averaged over 8 day periods (weekly level 3 images), were used to derive Chl-a values for 12 sites between January 1999 and December 2008 using ocean color radiometry (OCR). Data and results are presented for eight spawning sites and four control sites between 17 and 20° N and 64 and 68° west. This is the basis for the development of the first 10-year climatology of surface chlorophyll fields at fish spawning aggregation sites in the US Caribbean. The results include temporal differences in the seasonality of surface chlorophyll and spatial differences among the sites over the 10-year time series. This climatology will provide the basis of comparison for any Chl-a anomalies in the water column that might impinge upon the success of the spawning at these sites.

The basic question of what are the normal conditions at these sites during spawning months and the rest of the year are addressed as well as what are the possible phenomena responsible for the variability observed. Each site exhibited variability in the Chl-a signal with values ranging

from a minimum of 0.01 (control sites) to a maximum of 0.74 mg/m^3 (at two aggregations sites: Rene station (Rene, a mutton snapper aggregation site) and Tourmaline Bank (Tour, a red hind aggregation site)). Each site exhibited variability among years, for example the highest values of these two aggregations sites occurring in 2002 (Tour) and 2003 (Rene) and during different months (at Rene's during November and at Tour during August). The Chl-a variability observed was discussed relative to other environmental and oceanographic parameters such as rain events and South America river intrusions. *In situ* data were examined to corroborate the satellite-derived values. The satellite-derived Chl-a values obtained from the 10-year time series are all within the discrete *in situ* chlorophyll data available. This 10 year chlorophyll time series is the first available over such an extended period of time to describe a biogeochemical property of the water column at the eight (8) fish spawning aggregation sites. The information presented here adds one more parameter to the complexities of environmental cues for the success of fish spawning aggregations.

RESUMEN

Este trabajo investiga la estacionalidad en la señal de clorofila (Chl-a) derivada de sensores remotos en ocho áreas de desove de peces en Puerto Rico y las Islas Vírgenes Americanas y los eventos que pudieran influenciar esta señal. Estas agregaciones de peces en áreas de desove son recurrentes, esto significa que (por ejemplo, el mero cabrilla *Epinephelus guttatus* (Linneo) y la sama (*Lutjanus analis* (Cuvier)) se agregan en estos lugares cada año, durante el mismo periodo de tiempo. Lo que indica que estas áreas presentan características beneficiosas para que la especie desove. Este método se podría aplicar para describir áreas de agregaciones de desove de otras especies, específicamente para entender las razones por las cuales estas áreas aparentemente las utilizan secuencialmente otras especies.

Imágenes de satélite de los sensores de la NASA, SeaWiFS, MODIS-Aqua y MODIS-Terra, promediadas en períodos de ocho días (imágenes semanales de nivel 3) se utilizaron para derivar valores de Chl-a para las 12 áreas de muestreo entre enero de 1999 y diciembre de 2009 utilizando radiometría del color del océano. Se presentan los datos y resultados de ocho áreas de desove y cuatro áreas de control localizadas entre los 17° y 20° N y 64° y 68° O. Esta es la base para desarrollar la primera climatología de valores de clorofila de superficie de áreas donde se agregan los peces a desovar en el Caribe estadounidense. Los resultados muestran diferencias temporales en la estacionalidad de la clorofila de superficies y diferencias espaciales entre las áreas de desove en base a la serie de tiempo de 10 años. Esta climatología servirá de base contra la cual comparar cualquier anomalía en la señal de Chl-a en la columna de agua que pueda entorpecer el proceso de desove en las áreas de agregación.

Se presentan respuestas a preguntas tan básicas como cuáles son las condiciones normales en estas áreas durante y fuera de los meses de desove y cuáles fueron los fenómenos que causaron la variabilidad en estas condiciones. Se encontró variabilidad en la señal de Chl-a en todas las áreas de desove y se reportaron valores entre un mínimo de 0.01 (en una de las áreas de control) hasta un máximo de 0.74 mg/m^3 en dos de las áreas de desove, el área de desove de la sama (estación de muestreo Rene) y el Arrecife Tourmaline (estación de muestreo Tour) donde desova el mero cabrilla. Se demostró variabilidad interanual en cada estación como por ejemplo los máximos valores en estas áreas ocurrieron en el año 2002 en Tour y en el 2003 en Rene. También se demostró que los valores máximos se registraron durante diferentes meses del año (Rene en noviembre y Tour en agosto). La variabilidad en la señal de Chl-a se relaciona a parámetros ambientales y oceanográficos como los períodos de lluvias intensas y la presencia de aguas de los ríos provenientes de América del Sur. Se corroboraron los valores obtenidos de los sensores remotos con datos *in situ*. Se demostró que los valores obtenidos de la serie de tiempo de 10 años están entre rangos aceptados de Chl-a basado en los escasos datos de campo que hay disponibles. Esta es la primera serie de tiempo que se obtiene sobre un período largo de 10 años para describir una propiedad bioquímica de la columna de agua en ocho áreas donde se agregan peces a desovar. La información que se presenta añade una variable más entre las claves ambientales para un desove exitoso.

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DEDICATION

This work is dedicated to the commercial fishers of Puerto Rico and the United States Virgin Islands. I hope I have proven you right!

I especially want to dedicate this dissertation to Dr. Denise De Vore Borrego-really, without your behind the scenes plotting and your caring this manuscript would not have been finished.

To all my friends and family. To my sister Clara for keeping the secret and to my Mami and Papi, I hope you enjoyed my surprise. To the youngsters in the family: Perseverance pays!

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LIST OF ABBREVIATIONS

ALS	Abrir La Sierra
BDS	Bajo de Sico
CaTS	Caribbean Time Series Station
CDOM	Colored dissolved organic matter
CFMC	Caribbean Fishery Management Council
CTD	Conductivity-Temperature-Depth Sensor
DNER	Department of Natural and Environmental Resources
DPNR	Department of Planning and Natural Resources
FRL	Fisheries Research Laboratory
GCFI	Gulf and Caribbean Fisheries Institute
GSFC	Goddard Space Flight Center
Kd PAR	Water attenuation coefficient Photosynthetic Available Radiation
LB	Lang Bank
MODIS	Moderate Resolution Imaging Spectroradiometer
MRIP	Marine Recreational Information Program
MUT/Mutstx	Mutton Snapper St. Croix
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OCR	Ocean Color Radiometry
Pichi	Los Pichinchos
R/V	Research Vessel
SDCF	Steel-Dwass- Critchlow-Fligner Procedure
SEAMAP	Southeast Area Monitoring Program
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEDAR	Southeast Data Assessment and Review
SEFSC	Southeast Fisheries Science Center
Tour	Tourmaline
TPCP	Total Monthly Precipitation
TSG	Thermosalinograph

CHAPTER 1 . Description and Characterization of the Climatology and Time Series Analyses of Chlorophyll Concentrations at Fish Spawning Sites in the Caribbean Sea

1.1 Introduction

Problem Statement

The purpose of this work is to develop a description of eight widely known fish spawning aggregation sites in Puerto Rico (PR) and the United States Virgin Islands (USVI) using satellite remote sensing ocean color radiometry (OCR) in describing surface chlorophyll (Chl-a). The ocean color imagery has been shown to be very useful in identifying patterns on various scales based on the distribution of the chlorophyll concentration signals. This study will focus on investigating the signal of surface chlorophyll (Chl-a) over time at these sites.

The importance of this description is that since it is extremely expensive to monitor aggregation sites, using this tool (OCR) could prove to be a valuable method for predicting the success of the resulting cohort, which would in turn impact future fish harvesting. The climatology tools available through NASA (National Aeronautic and Aerospace Administration) and NOAA (National Oceanographic and Atmospheric Administration) have been used extensively in supporting the work performed in this investigation.

Description of Fish Spawning Aggregation Sites

Background

Fish spawning aggregation sites at the shelf break of the insular geologic platform of Puerto Rico and the U.S. Virgin Islands have been known and exploited by fishers, for a very long time (*e.g.*, T. Padilla (RIP) 1982, Commercial Fisherman, La Parguera, PR, pers. comm., G. López (RIP) 1982, Fisherman, La Parguera, PR, pers. comm., H. Vega, Commercial Fisherman, Salinas, PR, pers. comm., Ojeda-Serrano *et al.* 2007, García-Moliner 1986). Governments, both State and Federal, have protected these areas where fish aggregate to spawn by first establishing seasonal area closures and then by establishing the first no-take zone at the Hind Bank where red hind aggregate to spawn in the federal waters to protect the coral habitat used by fish at spawning. The areas delineated were squares or rectangles of variable size ranging from 0.24 to approximately 54.9 km^2 but each aggregation itself is reported to take place over much smaller areas such as 0.24 km^2 reported for tiger and yellowfin grouper and red hind (*e.g.*, Sadovy *et al.* 1994, Beets and Friedlander 1999, Nemeth 2005).

Other studies (Johnston *et al.* 2002) have inferred that these aggregations take place along the entire shelf edge but little field assessments of these fish aggregations have been done. Anecdotal information from commercial fishermen, however, supports the available evidence that the aggregations are discrete (Ojeda-Serrano *et al.* 2007). Also, monitoring of these aggregations confirm their repeatability over the years (*e.g*., Nemeth 2005; Rosario 1996; Olsen and LaPlace 1978).

Red hind eggs are reported to hatch in 27 to 31 hours depending on temperature (26.5 and 25.5° C, respectively; Colin *et al*. 1987). Red hind larvae have been shown to feed at 70 to 80 hours after hatching, feeding first on small phytoplankton followed by feeding on small zooplankton (Ojeda Serrano 2002). Food for larvae, in the form of phytoplankton, is obligatory for their survival (Lalli and Parsons 1997). In oligotrophic seas there must be a source of food. The variability in food availability in the form of chlorophyll variability might induce adult spawning. Esteves Amador (2005) found the highest Chl-a values at the spawning site of mutton snapper in La Parguera. Nevertheless, the numbers of identifiable red hind and mutton snapper larvae in the ichthyological collections of the area preclude definite conclusions regarding the spawned larvae fate. The difficulty of tracking fish eggs and larvae perhaps could be transcended if the seasonality of Chl-a at the spawning sites is confirmed. The Chl-a values reported by Esteves Amador (2005) at the mutton snapper spawning site were relatively high over a short period of time. Internal waves have the potential to produce predictable upwelling at the spawning sites as reported by Esteves Amador (2005). The proposed work will include the assessment of the onset of higher Chl-a values at the sample sites, the tracking of the development, temporal extent, and size and magnitude of the event.

Aggregation sites for red hind (*Epinephelus guttatus*) and mutton snapper (*Lutjanus analis*), such as the Hind Bank in St. Thomas, USVI (Marine Conservation District or MCD) and Bajo de Sico (BDS) off Mayagüez, PR and the Mutton Snapper spawning aggregation site in southwest St. Croix, USVI (MUT), have been historically fished (*e.g.*, Olsen and LaPlace 1978, CFMC 1993). These established aggregations take place during the same months, moon phase and sites year after year. There is some variation associated with the timing of the month, dependent on the moon, the strength of the aggregation, that is, numbers of fish aggregated to spawn, and in the numbers of fish that fishers have harvested. The success of the aggregation will be evident a number of years later when the fish recruit to either the population or the fishery.

NOTES:

Throughout this work:

1. La Parguera refers to an area that includes El Hoyo.
2. Abrir La Sierra (ALS) should really be named Abril La Sierra since fishers say that in April, the mackerel run (M. Valdés Pizzini 2013, Scientist, University of Puerto Rico, Mayagüez).

Chronological Description

Erdman (1976) reported “spawning runs” off La Parguera (Southwestern Coast of Puerto Rico) in January or February, one or two days after the full moon from 1954 to 1966. However, Erdman (1976) also stated that these runs did not take place in 1957 and 1965. It was this comment and the input provided by the commercial fishers, noting that sometimes the aggregations do not form, which provoked this work.

In the 1970’s, Olsen and LaPlace (1978) reported red hind present at the Hind Bank in St. Thomas (now MCD) but no aggregation was “observed” during December through February. In 1979, Colin *et al*. (1987) reported that red hind aggregated over an extended area of the shelf of La Parguera where the commercial catches were successful and observed spawning. They estimated the size of the population at “many thousands.”

In the 1980’s, García-Moliner (1986) showed that peaks in gonadosomatic index (GSI, ratio of gonad weight to body weight x 100) of red hind from La Parguera occurred in December 1982, January and December 1983 and January 1984 suggesting that spawning took place at that time. García-Moliner (1986) also reported that fishing was not successful in 1982-1983 at the spawning aggregation sites in La Parguera due to foul weather, and the commercial fishers had also reported small catches during this same period. Fishers reported high catch rates for red hind in January 1984. The known aggregation sites were visited in 1982 and 1983 but the numbers remained very low, thus confirming the observations of the commercial fishers. On January 1983, the maximum number of fish in one day was 11 red hind per 100 m^2. Although no estimates of size of the spawning population could be developed, the fact that there was variability in the numbers of fish harvested by the fishers is indicative of years without an aggregation. Shapiro *et al.* (1993) reported the highest density of red hind during 1984 (7.6 fish per 100 m^2) out of all the aggregations surveyed between 1983 and 1989.

In the 1990's a fishery-independent program monitored the aggregations leading to the seasonal protection of the three sites off the West Coast, Bajo de Sico (BDS), Tourmaline (Tour) and Abrir La Sierra (ALS). The monitoring was based on fishing and examination of the gonads. The three areas were identified as "hotspots" and confirmed as spawning aggregations through the Southeast Area Monitoring and Assessment Program (SEAMAP-Caribbean) fishery-independent surveys (*e.g.*, Rosario 1998).

In the 2000's Marshak (2007) analyzed the red hind fishery-independent and fishery-dependent data from the West and Southwest Coasts of Puerto Rico. This study was based on the data collected through the SEAMAP-Caribbean fishery-independent survey and on the reported commercial fishing landings. SEAMAP-Caribbean data are available for the area since 1989 and monitoring of the fish spawning aggregation sites BDS, Tour and ALS. Marshak (2007) concluded that there were increases in the Catch Per Unit Effort (CPUE) of red hind from both the SEAMAP data and reported landings during the 2003/2004 sampling period, as well as an increase in red hind sizes during this period. "Later increases in nominal CPUE, particularly the 2003/04 sampling period, were likely due to discoveries of other previously unknown and less frequently targeted concentrations of older red hind, including other spawning aggregations (Ojeda-Serrano *et al*., 2007), that may not have been randomly sampled during SEAMAP-C data collections. A recruitment pulse during the 2003/04 project year is unlikely, due to low observations of younger port-sampled individuals, and proportional increases within older cohorts." However, a plausible explanation explored in the present study is that the conditions for a successful aggregation were not present until the 2003/2004 spawning period.

Beets and Friedlander (1999) monitored the aggregation at the MCD and reported a decrease in the number of fish leading to the establishment of the no-take zone to protect the aggregating red hind. Beets and Friedlander (1997, 1999) reported increased numbers of fish at the MCD after protection. Nemeth (2005, 2008) has monitored the aggregation since then and reported on the increasing trend, yet variable from year to year and month to month, in number of red hind over time.

For mutton snapper, the monitoring has not been as recurrent. Esteves Amador (2005) assessed the aggregation of the southwest coast of Puerto Rico (Rene station) and Kojis and Quinn (2010) the aggregation off southwestern St. Croix (MUT). Numerous efforts to monitor and assess these aggregations are underway, all still very time consuming.

Oceanographic features that impact the water column at the aggregation sites off the coast of southwestern PR have been briefly described for red hind (Ojeda 2002) and for mutton snapper (Esteves Amador 2005). However, the synoptic (wide, observed at one time over a large area) view of these areas, the oceanographic features (*e.g.*, internal waves, eddies, fronts, upwelling) and parameters associated with these aggregation sites are not available.

Fish Species in Spawning Aggregations

There are various aspects that are involved in spawning: (1) the development of the gonad in preparation for spawning (*e.g.*, temperature as factor, Ojeda 2002), (2) the migration to these specific sites to spawn (or the dispersal of the adults after spawning *e.g.* Nemeth 2005), (3) the spawning itself (population density dependence, size and numbers of fish, moon phase), and (4) the potential of these sites for increased dispersal and survival of the spawn.

The identification and the conservation of fish spawning aggregation sites has been under consideration for a very long time now due to the vulnerability of the fish when aggregated to spawn and the potential for overfishing at these sites over the years. There have been many attempts at identifying the commonalities of these spawning aggregation sites (SPAGs) and on the possible ways of identifying old sites not being used anymore, new sites still to be discovered, or predicting what conditions are necessary for a good spawn to take place that year and for the larvae to survive and settle.

Groupers are known to use spawning aggregation sites in the same areas every year during the same period of time (*e.g.*, Erdman 1976, Olsen and LaPlace 1978, García-Moliner 1986). Various hypotheses have been proposed regarding the site fidelity shown by species groups during spawning. Red hind, *Epinephelus guttatus* (Linnaeus) is one of the groupers known to occupy the same sites at the same times of the year, during the same moon over many years (*e.g.*, García-Moliner 1986, Shapiro *et al.* 1993, Beets and Friedlander 1999, Nemeth 2005). Other grouper species such as the yellowfin grouper, the Nassau grouper, and rock hind also aggregate for spawning in either the same areas or nearby areas. Other fish families also form spawning aggregations, including the Lutjanidae and specifically the mutton snapper *Lutjanus analis* (Cuvier). Even though they do not co-occur in time and space with the red hind, mutton snapper occupy specific areas for the same purpose over the years (*e.g.*, mutton snapper area St. Croix). Many other species use the same sites for the same purpose but this study focused on the two species of red hind and mutton snapper, which are known to spawn at the sites that were characterized for this work. Although there are descriptions of the habitats at these sites and surveys to determine the spawning population and the changes in these aggregations, there is little work done describing the water column as essential fish habitat for these species that might contribute to the success of the aggregation.

Satellite Data Background

Satellite data have been used to determine the depth and shelf description of the area in which spawning aggregations are known to occur (Heyman 2001) showing the 'elbow like' structures at the shelf edge where grouper aggregations take place in Belize. Also, satellite information has been used to relate sea surface temperature with egg/larvae distribution of fish (*e.g.*, Yoder 1983). This information has been used mainly in pelagic fisheries to correlate the distribution of fish with temperature. Stegmann and Yoder (1996) examined sea surface temperature satellite images to examine the thermal fronts that could be responsible for the movement of fish larvae from offshore spawning sites to inshore areas in the South Atlantic Bight.

In order to determine the changes in the water column at the fish spawning sites, it is necessary to evaluate the long-term records of chlorophyll pigment concentrations (Chl-a) to establish the seasonality of chlorophyll and trends that could explain the continuous use of these sites. The only source of continuous data available from these sites and the only way of obtaining measurements of Chl-a for all sites at once over a period of 10 years is through the examination of satellite images. Satellite-based ocean color radiometry (OCR) measurements of Chl-a have been used to describe oceanographic events in the Caribbean since the 1980s with the Coastal Zone Color Scanner (CZCS, 1978-1986) (Müller-Karger *et al*. 1989). This sensor served to track the river water signal from the Amazon-Orinoco Rivers in South America from their source to the impacted areas such as Puerto Rico and the US Virgin Islands 1,900 km away from the river water sources (Müller-Karger *et al*. 1989). Three other sensors followed, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (1997-2010), and the Moderate Resolution Imaging Spectroradiometers (MODIS) on board the Aqua and Terra satellites. MODIS Terra has been acquiring data since 1999 and MODIS Aqua since 2002. These later sensors have allowed for quantitative measurements of Chl-a since 1997 to present. Additionally, sensors on board these satellites and others also collect data on sea surface temperature (SST) and aerosols. These aerosols include the signal from the dust storms originating in Africa and impacting the Caribbean with a well-established seasonality and long term trend (*e.g.*, Justiniano 2010). The importance of these aerosols is that it has been shown that an increase in these is followed by an increase in satellite-derived Chl-a concentrations (Stegmann 2000; Justiniano 2010). The aerosol optical thickness (AOT) is also derived from satellite-based measurements and this quantity is integrated into the algorithm to derive Chl-a. In general, the presence of particles in the atmosphere is a concern in the derivation of satellite-based measurements of Chl-a because of the impact these have on the transmission of light and thus the amount reaching the ocean. The sensors that measured ocean color include the range of wavelengths in sunlight that are absorbed by chlorophyll (blue) and the accompanying changes in the color of the water toward green as blues and reds are absorbed. It is the signal of the backscattered light that is received by the sensor and which allows for the estimation of Chl-a in the water, and thus the presence of phytoplankton in the water. This is the signal of interest in this study, most significantly in the Caribbean, an area usually described as an oligotrophic region. The values obtained from the satellite images tend to overestimate the Chl-a or pigment values as these include other optically-co-varying material in the water. However, relative values obtained from the satellite images parallel the trends obtained from *in situ* data (*e.g.*, Detrés *et al*. 2006). The advantages of using satellite imagery are noticeable when manpower effort and cost of *in situ* sampling are considered. The synoptic view of the many sampling sites that are proposed for this study cannot be carried out easily or effectively simultaneously at all sites.

The *in situ* data available for the areas of interest are extremely limited. The most data available are from larvae collections on the Southwestern and South Coast of Puerto Rico (Ramírez and García 2003). These datasets are also quite limited in the time covered, but at least they target the species of interest. The largest effort has taken place in the La Parguera area where data from several years and several stations from near shore to 46 km off shore were collected. The offshore station (Control site) is the Caribbean Time Series Station (CaTS, see: http://www.caricoos.org/drupal/node/69), which includes conductivity, temperature and depth sensors (CTD) casts, nutrients and chlorophyll concentrations. Some of these data could be superimposed on the satellite images available for the area, the densities of larvae and Chl-a concentrations correlated to the values extracted from the imagery. These previous studies had a different goal, to establish the distribution of larvae to help in determining the potential retention or dispersal of these larvae from spawning areas.

The purpose of this chapter is to describe and characterize the known fish spawning sites and control areas in PR-USVI by quantifying seasonal patterns of phytoplankton biomass (Chl-a) using OCR data from SeaWiFS and MODIS. From January 1999 through December 2008, a time series of satellite-derived measurements averaged over eight day (weekly average) was developed to evaluate changes in the water column at eight fish spawning aggregation sites over that time period. Four additional areas were used as control sites, away from any potential near shore influence and areas where reef fish spawning is not known to take place. These areas are of interest because there is still no long-term oceanographic description of these sites and what factors might be influencing the selection of these sites for fish to spawn. Specifically, the aim is to describe the chlorophyll field at the known spawning aggregation sites from satellite-derived Chl-a measurements, as well as to document the changes in relation to any known environmental event. Control sites served as virtual stations that are not subject to the same environmental events as the spawning sites, including depth.

Objectives and hypotheses

The objectives of this work are to: (a) quantify seasonal patterns of phytoplankton biomass (chlorophyll a) at known fish spawning sites and control areas throughout the Puerto Rico-Virgin Island insular shelf and surrounding waters using satellite remote sensing data; (b) create a 10-year time series of surface Chl-a and correlate these to the temporal/spatial patterns and strength of fish spawning aggregations; and (c) describe the physical-environmental dynamics at these known fishing aggregation sites to provide additional data not previously utilized in understanding why fish spawning aggregations occur at the same sites year after year (same months). By creating a Chl-a time series of satellite remotely sensed data events that previously were not known to be important might be identified as critical to the survival of larvae, the success of the aggregation and to the recruitment of fish into the fishery.

There are two main issues regarding reef fish spawning aggregations that are the concern of this work:

Number one is the issue of the availability of food for larvae that hatch and begin feeding within hours or days. "Reef fish larvae, including those of aggregation spawners, are believed to feed on small zooplankton that graze on phytoplankton, hence concentrations of phytoplankton in the tropics could have some correlation with the occurrence of aggregation spawned larvae and their food" (Hamner and Largier 2012).

There are few *in situ* data to describe the dynamics of the water column and the "food source" (*i.e.*, chlorophyll) for larvae. Ojeda (2002) and Esteves Amador (2005) stated that for both red hind and mutton snapper, Chl-a is thought to be very important for first feeding larvae of these two species. This follows the common belief that: "The importance of larval first feeding and chlorophyll layers is now widely recognized in fisheries" … (Hamner and Largier 2012 and references therein). Ojeda (2002) further suggested that red hind larvae were feeding on small phytoplankton particles within 82 hours after hatching. There are a number of hypotheses that have been developed to explain larval survival and future changes in the stocks including that larvae must hatch at times of high plankton concentrations (Lalli and Parsons 1997). Lasker (1975, 1978) described the complexity of the success of first feeding anchovy larvae that included the right type of food in terms of species and size of both phytoplankton and zooplankton, the density of the food, and the oceanographic conditions contributing to larvae survival such as high chlorophyll and calm seas. Lasker (1978) stated that anchovy larval first feeding under stable oceanographic conditions would enhance survival whereas unstable conditions would be detrimental.

High values of Chl-a would be indicative of food availability for the larvae to first feed on phytoplankton as suggested by Ojeda (2002). Subsequently, larvae would feed on zooplankton within days of hatching. High Chl-a could thus serve as a cue for adult fish to spawn. These values would have to be coincident with the right moon phase and other described variables that have been shown to be highly correlated to the number of fish at the aggregations (*e.g.*, low temperature and slacking currents, Nemeth *et al.* 2008). Therefore, there is a need to establish a baseline of chlorophyll values at the aggregation sites to determine if Chl-a concentration is high during the spawning season. It could be inferred that this is a significant cue for fish to aggregate at these sites and spawn to enhance larvae survival.

The second issue of concern in this study is fidelity to the spawning site; that is, adult spawners are present at the same sites year after year (for red hind these are MCD, BDS, ALS, Parguera, Tour and LB; for mutton the areas are MUT and Rene), the same time every year (red hind: December-February; mutton: March-June), the same moons (red hind: around the full moon at the MCD; mutton around the new moon at Rene). Yet, there are times when these aggregations are either not found or not formed. Since there are few long-term monitoring efforts to document the number of fish at these aggregations, there is no direct way to determine if the aggregations are not formed. Previous reports (*e.g.*, Erdman 1976, Colin *et al.* 1987, García-Moliner 1986, Shapiro *et al.* 1993, Nemeth pers. comm. and unpublished data 2012) have documented reduced "runs" of red hind, meaning reduced numbers of fish at the aggregation sites in certain years. The descriptions of spawning aggregation sites include information on habitat (*e.g.*, coral), structure (*e.g.,* reefs, spur and grove, "elbow" like structures), rugosity, depth, location with respect to the currents, temperature, currents, moon phase, and time of day, but few describe the water column. These factors all contribute to pinpoint the location and timing of the reproductive activity, in most cases, already discovered by the fishers. The numbers of fish at the sites have been found to vary from year to year, even at areas that are completely protected (*e.g.*, Nemeth unpublished data, Nemeth 2005). There are no long-term time series of the estimated spawning populations at most of the study sites, with the exception of the MCD that has been monitored since the 1990's (Beets and Friedlander 1999, Nemeth 2005, Nemeth *et al.* 2008).

The descriptions of these spawning sites are mostly based on substrate and, for the Puerto Rico and the USVI there is very little information on aspects of the water column, including no long-term dataset on for example, chlorophyll, a proxy for food availability for the larval stages.

Based on the reports of aggregations not forming during certain years, it could be that environmental cues other than those described before (*e.g.*, temperature, moon phase), are considered by the fish. Fish could be attracted to a high-chlorophyll area to improve chances of larval survival; conversely years of low abundance may correspond to periods of low chlorophyll.

The water column over these aggregation sites changes continuously due to currents, wind mixing and tides, for example (Valiela 1984) but there are scarce descriptions of these changes over time at these specific sites. Specifically, there are few *in situ* data on the biological signal of these waters, namely chlorophyll. Of particular interest is to determine how much Chl-a varies during the year and between years at the aggregation sites and to determine if high Chl-a values are found during the months of spawning of the red hind (*Epinephelus guttatus*) and the mutton snapper (*Lutjanus analis*). It is probable that in light of the above arguments, Chl-a values should be higher during the months of spawning. In this case, Chl-a could serve as a proxy for food availability at these spawning sites and fish are induced to aggregate and/or spawn at the sites when there are high Chl-a values. The Chl-a signal could be both a cue to aggregate and a cue to spawn. The high values of Chl-a then should also be correlated to the increase in number of fish at the aggregations.

The hypotheses tested for Chl-a are: (1) there are no significant differences within and among years at any of these spawning aggregation sites; and (2) there is no significant difference among the sites. Therefore, there are no specific Chl-a signals that could be associated with spawning areas.

Specifically:

$H1_0$: There is no seasonality in the Chl-a at the sampling sites
$H1_A$: There is seasonality in the Chl-a at the sampling sites

$H2_0$: There are no temporal differences in the Chl-a among years and sites
$H2_A$: There are temporal differences in the Chl-a among years and sites

$H3_0$: There are no differences in the 10-year Time Series of Chl-a
$H3_A$: There are differences in the 10-year Time Series of Chl-a

The results of this work, monitoring the Chl-a derived from satellite imagery, could provide a tool to establish the timing of the monitoring as additional information to the timing of the moon, the cue being used at the present time. Although it is not the intent of this work to answer the question of the importance of Chl-a at the spawning sites as a cue for spawning, it can be inferred from the literature on behavior, larval ecology and environmental cues that this parameter might be important to explain environmental signals that can induce changes in the spawning populations and thus in the recruitment success of later years. Future work should include looking at the potential of this cue in actual spawning.

1.2. Materials and Methods

Study Sites

The Caribbean Sea has been deemed as oligotrophic but being influenced by intrusions from the South American Rivers, eddies (*e.g*. Corredor *et al*. 2004), upwelling from the coastal area of Venezuela (Müller-Karger *et al.* 1989), and areas within the islands insular platforms being influenced by rain and rain runoff, riverine inputs and internal waves. Furthermore, hurricanes and storms occur seasonally between June and November and are also a source of nutrients. Hurricanes in particular have been shown to create upwelling areas in their paths (Cornillon *et al.* 1987) thus contributing to seasonal changes in the area. The effect of rainfall on the large amount of water discharged from the rivers in Puerto Rico has also been shown to contribute to increased phytoplankton as observed from satellite images (Gilbes *et al.* 2001, Armstrong and Detrés 2010). All these result in increased phytoplankton concentrations, lower temperatures, and changes in salinities (and associated changes in densities) in the water masses influencing the spawning sites. Cold fronts from North America also impact the Caribbean Sea, most commonly during the winter months. The oceanography of the Caribbean Sea is also under the influence of the seasonal movement of the Inter Tropical Convergence Zone. All these events could contribute to detectable changes in the satellite imagery of the "oligotrophic" Caribbean Sea. These events also have been shown to have an effect in waters closer to shore such as the fish spawning aggregation sites.

Wüst (1964) first described the salinity fields in the Caribbean and attributed the seasonal changes to the influence of the South American Rivers. Yoshioka *et al.* (1985) described the changes in zooplankton and salinities off the southeast coast of Puerto Rico and attributed these changes to the intrusions from the South American Rivers. In 1989, Muller-Karger described these river intrusions from South America using satellite images from the CZCS. Using satellite images from SeaWiFS, Gilbes and Armstrong (2004) showed that the annual discharge of the Orinoco River intrudes into the Eastern Caribbean Sea during the fall (with a peak in October) while the discharge of the Amazon River intrudes into the Caribbean Sea during the spring/summer. The Caribbean Sea has been shown to undergo seasonal variations in phytoplankton that are more common than previously thought (González *et al.* 2000).

Table 1.1 lists the study sites selected for this study. There were five (5) fish spawning aggregation sites in Puerto Rico, two (2) in St. Croix and one (1) in St. Thomas. All except two stations are known for the red hind or other grouper aggregations. The other two stations are known sites of mutton snapper spawning. Characterization of these areas included baseline surveys, monitoring of the spawning aggregation, and high-resolution bathymetry. There were four control sites: an offshore site within the Mona Passage known as Los Pichinchos off the West Coast of Puerto Rico; CaTS or the Caribbean Time Series for which *in situ* data are available between 1993 and 2007 and which was used as a control site to track the advancement of the South American Rivers water into the Caribbean Sea; the North Atlantic control station (Justiniano 2010) and also a control area for land-based influences from Africa in the form of dust storms; and Sastre station (Sastre 2004) also an Atlantic Ocean station (no land influence).

The selected sites included the protected and seasonally closed fish aggregation spawning sites off the West Coast of Puerto Rico: (1) Bajo de Sico, (2) Abrir La Sierra, and (3) Tourmaline; the fish aggregation sites off Southwest Puerto Rico (4) Rene and (5) El Hoyo at La Parguera; the protected and seasonally closed fish aggregation spawning off St. Croix (6) the mutton snapper closed area to the southwest and (7) Lang Bank to the east; and (8) the MCD (Hind Bank - a no-take area (http://www.caribbeanfmc.com/mcd_amendment.htm). The coordinates and source of the data from the sampling sites used in this study are summarized in Table 1.1 and shown in Figure 1.1.

The control stations were selected away from local riverine and other land runoffs, in very deep water, as areas without functional significance for the spawning fish.

Table 1.1 List of all sites selected for the satellite-derived characterization of the Chl-a fields from 1999 to 2008

Name of Site	Acronym	Lat (°N)	Lon (°W)	Depth (m)
Spawning Sites				
Bajo de Sico, PR	BDS	18.23	67.41	69
Abrir La Sierra, PR	ALS	18.10	67.41	> 25
Tourmaline, PR	Tour	18.18	67.37	64
Rene, PR	Rene	17.89	67.10	20
El Hoyo, La Parguera	Parguera	17.87	67.17	21
Mutton Site St. Coix	MUT	17.64	64.87	30
Lang Bank, St. Croix	LB	17.82	64.45	30
Marine Conservation District	MCD	18.20	65.00	45
Control Sites				
Los Pichinchos, PR	Pichinchos	18.37	67.76	60 - 80
Caribbean Time Series	CaTS	17.50	67.00	>1,000
Atlantic	Atlantic	19.00	57.00	>2,500
Sastre	Sastre	20.00	67.00	>2,500

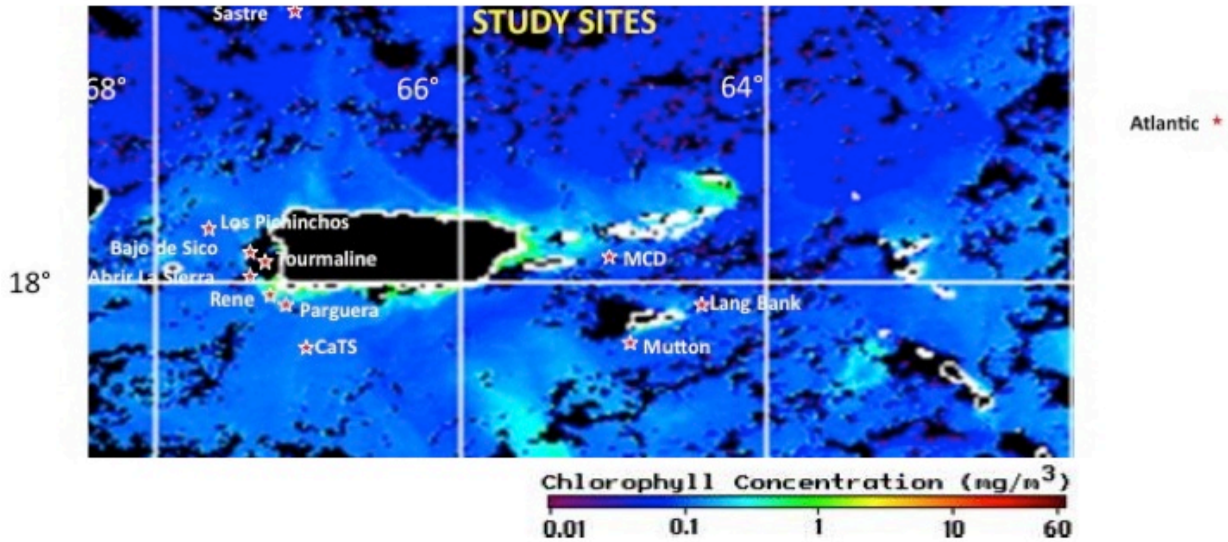


Figure 1.1 Study site approximate locations (not to scale)

Depth information was obtained from various sources including http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html, and http://maps.ngdc.noaa.gov/viewers/bathymetry/ and the NOAA Surveys (http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi_nps.aspx).

The selected sampling sites for the proposed study were all over 6 km offshore and at a depth of over 20 m, where it is expected there will be no reflectance from the bottom but might still be influenced by river output specifically in Puerto Rico (Armstrong and Detrés 2010). Oligotrophic areas in shallow waters, such as the waters in the Caribbean Sea, could result in a problem of bottom reflectance contamination. Adjacent, offshore pixels were used to prevent this. Armstrong and Detrés (2010) showed that for an episodic rain event in November 2003, the influence of river runoff extended to more than 40 km offshore and the baseline values of Chl-a were not back to baseline levels until after 11 days past the rain event. The sites off St. Thomas and St. Croix should not reflect this influence (Idrisi *et al.* 2006) because there are no river outputs but there might still be some land runoff influence that would need to be assessed. Maximum rain for the area is usually May through September (October for PR), while the hurricane season extends from June through November. Fronts move through the area during the winter months. These are environmental conditions that need to be taken into consideration when the satellite imagery is being analyzed.

The satellite images available for the northeastern Caribbean Region were assessed for suitability of use. The data were derived primarily from MODIS with additional data from SeaWiFS. The data were evaluated for the various parameters that might provide a biased estimate of Chl-a (*e.g.*, presence of dust aerosols). The time period studied extended from 1999 to 2008 and 2009 (Chapter 2). The images processed by NASA were selected to obtain a time series of cloud-free images for the various sites of interest and the control sites. Control sites were sites where no fish aggregations have been reported. Sampling was done extracting the values from the available images from matrices centered at the spawning site.

Ocean color images for all years available were browsed and all usable scenes collected from this area were obtained. The scenes available from the area as well as the software (SEADAS in LINUX) and the required hardware were available at the Bio-Optical Oceanography Laboratory, Department of Marine Sciences, UPRM. The products that can be extracted from ocean color algorithms include Chl-a, K490 (as indicator of turbidity in the water column) and tau 865 to detect the presence of high levels of dust aerosols in the atmosphere. The scenes were processed in Mercator projection centered at 18.2°N and 65.0° W to include all the areas of interest around Puerto Rico and the USVI.

The time series of images obtained were assessed for selection of clear pixels over the areas of interest. Specifically, all the selected sites were sampled from each image and the usefulness of the pixels assessed to determine if these would be included in the analyses. Problems with the usefulness of pixels for analyses include no data at the location of interest, presence of clouds, saturation of signal from sun glint or other reasons. The 3 x 3 pixel sampling boxes were drawn around the known coordinates where the fish spawning aggregations take place. The minimum usable number of pixels per sampling area was determined to be 3 pixels or a 25% cut off value for good pixels was used. These sampling boxes were approximately 36 km^2.

Hotspot areas along the shelf edge, meaning areas of high Chl-a, which could be potential spawning sites, were flagged for future work.

Description of Satellite Sensors and Methodology

Ocean Color browser (http://oceancolor.gsfc.nasa.gov) was used to select products available from satellite images: the 3-day, 4 km per pixel resolution images and the 8-day, 4 km resolution imagery. These products are a composite of the daily images available using the arithmetic mean to make the composite of 3 or 8 (weekly) days. These composites offer a more comprehensive view of the potential oceanographic phenomena that could impact the spawning aggregation sites. The weekly (8 day) composites were favored because: (1) more cloud-free data were available for more aggregation sites and (2) more of the complete area could be observed at once. These composites keep the clear pixels and average these to make a new pixel at the same location.

Data were obtained from three sensors: SeaWiFS (launched in August 1 1997), MODIS-Terra (launched in December 18 1999), and MODIS-Aqua (launched in May 4 2002) between 1997 and 2009. These sensors were flown in missions designed to provide quantitative data on, among other objectives, ocean chlorophyll. These sensors, although producing estimates of Chl-a, measure atmospheric radiance in overlapping spectral bands but with SeaWiFS having only eight bands (visible to infrared) while MODIS collect data in 36 spectral bands, visible to near infrared. Table 1.2 indicates the bands in the SeaWiFS instrument and Table 1.3 for the MODIS (TERRA and AQUA) sensors.

Sensors are flown in satellites orbiting the Earth 705 km above the ocean surface. Data are collected at 10:30 am (descending orbit, Terra), noon (SeaWiFS) and 1:30 pm (ascending orbit, Aqua), with a revisiting time of 1 to 2 days. The SeaWiFS image resolution is 1 km at best. The bands of interest in the estimation of Chl-a are between 400 and 700 nm (bands 2 through 5 in SeaWiFS and 8-15 in MODIS) (Tables 1.2 and 1.3).

Table 1.2 SeaWiFS bands and wavelengths.

Band	Wavelength (nm)	Band	Wavelength (nm)
1	402-422	5	545-565
2	433-453	6	660-680
3	480-500	7	745-785
4	500-520	8	845-885

(http://oceancolor.gsfc.nasa.gov/SeaWiFS/SEASTAR/SPACECRAFT.html)

Table 1.3 MODIS bands and bandwidths

Primary Use	Band	Bandwidth
Land/Cloud/Aerosols	1	620 - 670
Boundaries	2	841 - 876
Land/Cloud/Aerosols	3	459 - 479
Properties	4	545 - 565
	5	1230 - 1250
	6	1628 - 1652
	7	2105 - 2155
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420
	9	438 - 448
	10	483 - 493
	11	526 - 536
	12	546 - 556
	13	662 - 672
	14	673 - 683
	15	743 - 753
	16	862 - 877
Atmospheric	17	890 - 920
Water Vapor	18	931 - 941
	19	915 - 965
Surface/Cloud	20	3.660 - 3.840
Temperature	21	3.929 - 3.989
	22	3.929 - 3.989
	23	4.020 - 4.080
Atmospheric	24	4.433 - 4.498
Temperature	25	4.482 - 4.549
Cirrus Clouds	26	1.360 - 1.390
Water Vapor	27	6.535 - 6.895
	28	7.175 - 7.475
Cloud Properties	29	8.400 - 8.700
Ozone	30	9.580 - 9.880
Surface/Cloud	31	10.780 - 11.280
Temperature	32	11.770 - 12.270
Cloud Top	33	13.185 - 13.485
Altitude	34	13.485 - 13.785
	35	13.785 - 14.085
	36	14.085 - 14.385

(http://modis.gsfc.nasa.gov/about/specifications.php)

The chlorophyll algorithm used for SeaWiFS (known as OC4) to estimate Chl-a uses the band ratios in the following manner: 443/555, 490/555 or 510/555. The algorithm developed for MODIS (OC3M) uses the maximum band ratio between 443 and 490 (one ratio only) while SeaWiFS estimates are derived from the greater of the ratios.

The equations for the estimation of Chl-a are as follows:

$$\text{For SeaWiFS Chl-a} = 10\hat{}(0.366 - 3.067R_S + 1.930R_S^2 + 0.649R_S^3 - 1.532R_S^4) \quad (1.1)$$

Where $R_S = \log_{10}$ [max Rrs 443, 490, 510/Rrs 555]

$$\text{For MODIS Chl-a} = 10\hat{}(0.2830 - 2.573\,R_{3M} + 1.457R^2_{3M} + 0.659R^3_{3M} - 1.403\,R^4_{3M}) \quad (1.2.)$$

Where $R_{3M} = \log_{10}$ [max 443/550>490/550]

Campbell (2003) compared the OC3M and OC4 algorithms and concluded that OC3M tended to underestimate chlorophyll at low values while OC4 did not. Values underestimated by OC3M were those below 1 mg/m^3.

The images were obtained from NASA as Level-3 Standard Mapped Images. An attempt was made to utilize single day images for the characterization of the spawning sites but it was not possible due to (1) missing images for the day, or (2) missing data from the single day images for the areas of interest, and (3) cloud cover, problems with the sensor or satellite, among others. NASA produces Level 3, 8-day (weekly) averaged images at a lower resolution (4 km) that result in a higher number of usable images, but do present a different set of problems and propagations of errors. These weekly images increase the number of hits on the areas of interest and interpolate data to fill in the missing gaps. The number of images found for each station that had on average more than 25% area coverage for the sampling sites and the number of pixels used for calculations are summarized in Results and Discussion Tables 1.4-1.7, 1.11-1.13, 1.17-1.18

and 1.20. The maximum number of 8-day composite images per year was 46; the maximum number of pixels per site was nine.

All weekly images available that included any of the study sites were sampled. The data images were from SeaWiFS (1999), MODIS Terra (1999-2003) and MODIS Aqua 2002-2009.

The names of the images are identified by the satellite/sensor such that A20030092003016.Lm3_8D_CHLO_4Km means that it comes from the Aqua sensor for the year (2003) for Julian date 009 to year (2003) Julian date 016 for an eight (8) day composite at a 4 km resolution. SeaWiFS images would have an S and Terra images would have a T at the beginning of the identifier. These are Level 3 (processed) standard mapped images.

Data Processing and Derived Products

Processing of the satellite data images by NASA is done as follows: Level 0 is the raw data available; Level 1 is the geolocation and first assessment of the data to determine problems with the sensor, sun glint, etc.; Level 2 are those that are available for extracting data that has already been processed with default algorithms. In this study, Level 3 images were used to estimate chlorophyll through the NASA standard OC3 and OC4 algorithms. The standard Kd_{490} algorithm was used for determining the attenuation coefficient and assessing the depth of light penetration.

Case 1 water algorithms were used for processing the images. Although the Caribbean Sea is mostly oligotrophic, the number of rivers, the shallower depths of the insular platform and land runoff could require the use of Case 2 algorithms. Table 1.30 (see section on Results and Discussion) indicates the times of the year when the various atmospheric and oceanographic phenomena occur, which may have an impact on the fluctuations of Chl-a in the area. Although these are issues of concern in the propagation of errors in the estimate of chlorophyll from satellite images, these are also the phenomena that contribute to the variability in the chlorophyll fields at the study sites, and are the main topic of this work. The seasonality of these could be expected to influence the conditions that trigger spawning.

The area of interest, the Caribbean and the deltas of the Amazon and Orinoco Rivers in South America, were mostly cloud-covered and forced the use of weekly images to increase sample size. The data from the images were used to analyze values of Chl-a from January 1999 through December 2009 for 12 sites around Puerto Rico and the US Virgin Islands, the Caribbean Sea and the Atlantic Ocean. These images were obtained from NASA's Goddard Space Flight Center (GSFC) Ocean Color website (http://oceancolor.gsfc.nasa.gov). Images from the three sensors were used to construct the time series of Chl-a but were tested to determine the variability among the sensors since the differences in the algorithms could account for somewhat different results.

The images were visualized and analyzed using NASA's GSFC program SeaDAS (SeaWiFS Data Analysis System) with IDL Version 6.3 running in a LINUX platform (Research Systems, Inc.). This program is used for processing, displaying, and analyzing data from the images. The complete kernel is a very large image from which subsets were obtained to acquire the data from the specific sampling sites. A subset of the image was used to facilitate processing and which includes the area between 5°N and 25°N and 50°W to 70°W. This southern subset includes the area from the mouth of the Amazon River to the Tropical North Atlantic and to the west as far as the Hispaniola. The missing values (*e.g.* from clouds) or the values above or below the established range are flagged first by NASA's processing routines and additionally by the researcher during local re-processing. These flagged values are not used in any of the computations. SeaDAS includes a computational package for statistics, including mean, variance, number of values included in the calculation, and standard deviation for both raw data and geophysical values. The data from the 8-day 4 km resolution images were extracted from sampling sites measuring 3 pixels x 3 pixels and the mean, variance and standard deviations calculated for these. These are the means and standard deviations to be used in the characterization of the spawning sites, compared to the off shore sites and further analyzed for a time series analysis. Comparisons were made of the different sizes of the sampling boxes (3 x 3, 7 x 7, and 15 x15) and no significant differences were found. The smaller the sampling boxes, the fewer pixels are available for inclusion in the analysis, but the closer these are to the actual size of the spawning aggregation.

Descriptive statistics were used to establish the first continuous monitoring of the chlorophyll field at fish spawning sites in Puerto Rico and the US Virgin Islands. The weekly data for each of the sampling stations were plotted over time (Figures 3.1 through 3.15).

Los Pichinchos is located off the West Coast of Puerto Rico and is a well-known fishing hotspot for dolphin fish, blue marlin and other pelagic species. The Caribbean Time Series Station (CaTS) is located approximately 51.9 km southwest of Puerto Rico along the 67°W longitude and at 17.5°N latitude (Station 10). The *in situ* data available from CaTS was used to determine how well the *in situ* and satellite derived Chl-a correlated. The Atlantic station is located at 19°N and 57°W approximately 850 km northwest of Puerto Rico and was reported by Justiniano (2010). Finally, Sastre station, situated at 20°N and 67°W about 280 km north of Puerto Rico was the one sampled by Sastre (2002) and recently reported by Justiniano (2010). The information obtained from these other studies was used to compare to the results obtained from this study (*e.g*. compared 3 x 3 sampling areas to 15 x 15 sampling areas). Archives were searched for all other *in situ* data available for any of the sampling stations over the period 1998-2009.

Sampling was done extracting the mean values from the available images from matrices (3 x 3) centered at the spawning site. Data from studies conducted at the spawning sites were used to corroborate the findings (*e.g.*, Nemeth 2005, García-Sais *et al.* 2005).

Time Series Analyses were carried out in MATLAB (Math Works, matrix laboratory software or EXCEL Version 2010) to understand the underlying context of the data and to make predictions of future events. The analysis was done on the Chl-a series for the 12 stations with respect to time and in contrasting spawning sites with non-spawning sites. The interest of the time series lied on being able to determine seasonality in the signal of the satellite derived Chl-a within each station over a year and over the complete time series. The main idea was to be able to predict what other areas might serve as spawning sites and to evaluate their effectiveness based on chlorophyll distributions. The comparison of *in situ* data with satellite-derived data was done to determine the degree to which the remotely sensed data underestimated or overestimated chlorophyll values. The flow-through data from the NOAA Research Vessels transiting through the area were obtained and also used in the comparison between remotely sensed and *in situ* data.

Climatology

Rainfall

The NOAA NWS total precipitation data set was examined for rainfall information for Puerto Rico and the USVI. Priority rain stations were selected based on the location of the river discharge in relation to the sampling sites (*e.g.*, river directly opposite sampling site) or closest rain station to the sampling sites (*e.g.*, Magueyes). This data set was used to explore the impact of rain on the changes observed in the Chl-a data at selected stations. Not all the rain stations that could have direct impact over the aggregation sites were complete over the period of 1999-2009. Nevertheless, because of the importance that rain and runoff might have on the aggregations, the data sets were used as much as possible.

Hurricanes

During the years of interest 1999-2009, there were no major hurricanes that hit Puerto Rico or the US Virgin Islands directly, but the NOAA NHC database was examined for information on storms and hurricanes that passed within 2 degrees of latitude from Puerto Rico and the USVI. Gilbes *et al*. (2001) reported on the impact of Hurricanes Georges (2008) on the river outflow after the impact of the hurricane and determined, from satellite imagery, that the effects of the outflow lasted almost two and a half weeks.

Moonlight

Full moon dates were obtained from http://eclipse.gsfc.nasa.gov/phase/phase2001gmt.html and from http://eclipse.gsfc.nasa.gov/phase/phases1901.html. The fraction of the moon can be calculated from number of days before and after to obtain a fraction of the light intensity. The program in Fortran for illuminance and moon phase intensity could also be used (Austin *et al*. 1976).

These data were used to address the increases in Chl-a observed during the periods of spawning for red hind and mutton snapper. In addition, these were also used to explain rapid changes of Chl-a during the time series. The rate of change in chlorophyll was determined for the MCD and an attempt to correlate this rate of change in Chl-a with number of fish at the spawning sites and the other factors such as the illuminance and full moon occurring at the same time of the perigee were attempted.

1.3 Results and Discussion

A novel quantitative characterization of the surface waters at eight fish spawning aggregation sites was presented by describing the surface Chl-a, a biogeochemical property of the water column, over these sites. A time series of 10 years of Chl-a was available for the first time in Puerto Rico and the US Virgin Islands that characterized the surface waters at spawning sites before, during and after the time of fish spawning activity. The annual variability within each site and over the 10-year time series was analyzed to determine the significant changes over time. The data were also used to establish similarities among these sites.

The Chl-a values (mg/m^3) were derived from 8-day composite ocean color images at a resolution of 4 km^2. This combination of 8-day composites and 4 km resolution resulted in the highest number of images for sampling the 12 sites over the same period of time and provided a maximum number of images per sites (potential for 460 images per site).

The data were analyzed to determine if these were normally distributed over the 10-year time series. The data consisted of 8-day averages of satellite derived surface chlorophyll from 12 sites over a period of 10 years. The tests were run through Excel-XLSTAT add in (www.xlstat.com) and the most appropriate test of normality was the Anderson-Darlington test. All 12 sites were subjected to the same set of tests. The missing observations were removed from the analysis (between 77 and 140 observations per site). The maximum number of observations per site for the 10-year time series was 460. The results are shown in Table 3 and indicate that the data from each of the 12 sites were not normally distributed. The test was selected because it is a modification of the Kolmogorov-Smirnov test and is suited to several distributions including the normal distribution for cases where the parameters of the distribution are not known and have to be estimated (Stephens 1974). The satellite derived chlorophyll values were not normally distributed (Kolmogorov-Smirnov test; all $p < 0.05$ for all sites). The risk of rejecting the null hypothesis when it is true was very low in all cases. Results from the Anderson-Darling test of Normality for the Chl-a data from the sampling sites yielded p values less than 0.0001 for all sites except for Sastre ($p=0.0003$).

Remotely Sensed Data: SeaWiFS, MODIS-Terra and MODIS-Aqua

The number of satellite images available for sampling was increased when images from all three sensors could be used (MODIS Terra and Aqua and SeaWiFS). Justiniano (2010) did not find any significant differences among the three sensors (SeaWiFS and MODIS-Terra and Aqua) for 2 out of 3 sites in the Atlantic Ocean and Caribbean Sea. In this study, results from a sample of two stations to determine if images from all three sensors could be used showed that images from all sensors could be used since there were no significant differences among the three sensors (Wilcoxon signed-rank test, $p=0.371$). The determination of the pixel size was also subject to testing and comparison between sampling boxes of different sizes resulted in non-significant differences (Kolmogorov-Smirnov $p = 0.367$) between the 3 x 3 pixel stations used in this study and the 15 x 15 pixel stations used by Justiniano (2010). A 15 x 15 pixel sampling site would have been too large for the purpose of describing these aggregation sites.

All 8-day composite images available for the Eastern Caribbean study area (between 5° and 25° N and 50 to 70° W) downloaded from NASA were examined using SeaDAS. The number of images available per year varied by site between 25 and 44 and no one site had the possible maximum number of images per year (max=46). Among all 12 sites, a total of 460 images were used in this study over the 10-year period (1999-2008). Each image has the potential to include all 12 sites at once. The locations of the sites are shown in Table 1.1. Extraction of chlorophyll mean values for 3 x 3 pixel matrices was carried out using SeaDAS. The total number of images used for extracting chlorophyll values and annual means varied between 320 (Lang Bank, St. Croix; Table 1.18) and 383 images (Pichincho; Table 1.7). The contrast between high Chl-a (December 27-31) and low Chl-a (January 17-24) can be seen in Figure 1.2 of the 8-day composite images for 2003 of all sites.

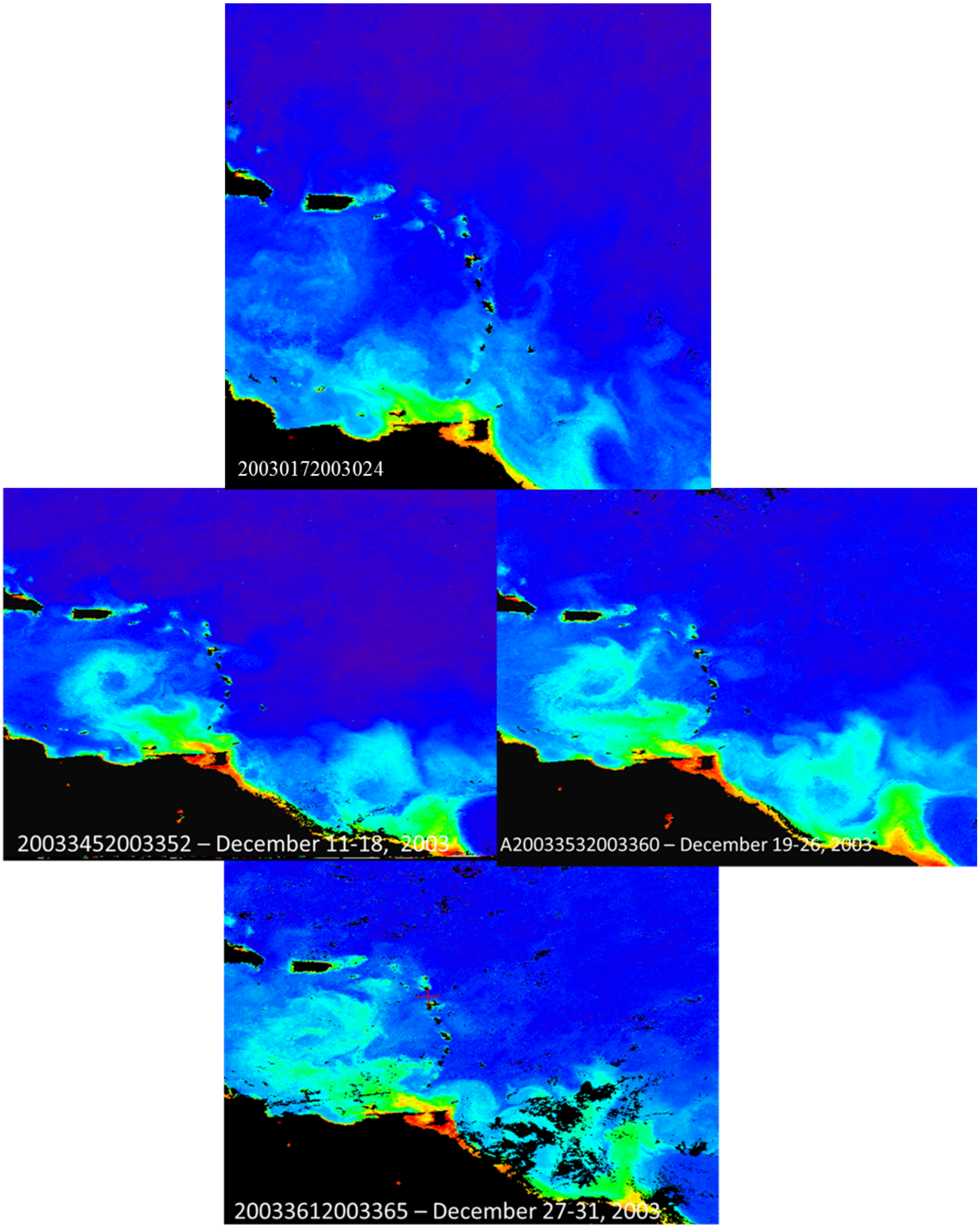


Figure 1.2 MODIS-Aqua images (a) January 17-24, 2003, (b) December 11-18, 2003, (c) December 19-26, 2003, (d) December 27-31, 2003.

Description of the Chlorophyll-a field over the sampling stations

For the first time a qualitative and quantitative 10-year time series description of the chlorophyll fields of eight well-known fish spawning aggregation sites around Puerto Rico and the U.S. Virgin Islands is available. Absolute values of chlorophyll were not the goal of this study but a quantitative description of the dynamics of the water column that could shed some light on the site selection and fidelity to these sites shown by the fish over long periods of time. The complete series of data available from weekly satellite images of chlorophyll showed the variability among years within a site and among sites. The description of the sites is presented beginning with the four (4) areas off the West Coast of Puerto Rico, three (3) spawning sites and one (1) control site.

Western Puerto Rico

Spawning aggregations off the West Coast of Puerto Rico include Bajo de Sico (BDS), Abrir La Sierra (ALS) and Tourmaline (Tour). Los Pichinchos was used as a control site. The annual fluctuations for these four sites are shown in Figures 1- 4 for the years 1999-2008. To describe the time series for the sites, no attempt was made to interpolate the missing data at this stage. These figures show the variability in both the number (gaps) of 8-day satellite images composites for the chlorophyll product available from NASA (See Materials and Methods), the variability within each area during the year, and the differences among areas. All vertical axes have been set to the same scale for easier comparison. The fluctuations in satellite-derived chlorophyll at the spawning aggregation sites are summarized in Tables 1.4-1.6, for the three aggregation sites (Tour, ALS, and BDS) and Los Pichinchos control site (Table 1.7).

Summary tables of the 12 sites show the annual mean and SD, minimum (Min) and maximum (Max) values of satellite derived chlorophyll, the number of pixels used for each value, the number of images used for the annual mean and the date when the maximum value occurred. The calendar day for the maximum value is accompanied by the corresponding moon phase. The information for 2009 is included in this summary but will be discussed in Chapter 2. The date of the moon phase occurring during the week of the maximum Chl-a and corresponding moon phase are shown in the last two columns (Tables 1.4-1.7; 1.12-1.14).

Table 1.4 Annual average of satellite derived Chl-a (mg/m^3) at the Tourmaline site (Tour)

TOUR	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.304	0.099	0.120	0.575	7	43	3-Dec	7-Dec	New
2000	0.295	0.130	0.091	0.672	9	37	7-Oct	5-Oct	1st Q
2001	0.233	0.064	0.062	0.369	9	38	22-Sep	24-Sep	1st
2002	0.278	0.107	0.111	0.739	8	37	29-Aug	31-Aug	Last
2003	0.315	0.092	0.134	0.623	7	36	17-Nov	17-Nov	Last
2004	0.242	0.071	0.114	0.397	9	27	21-Sep	21-Sep	1st
2005	0.239	0.052	0.179	0.411	2	25	9-Nov	9-Nov	1st
2006	0.240	0.059	0.100	0.398	3	33	22-Sep	22-Sep	New
2007	0.243	0.056	0.141	0.413	6	27	1-Nov	1-Nov	Last
2008	0.235	0.077	0.066	0.465	9	34	5-Sep	7-Sep	1st Q
2009	0.255	0.104	0.113	0.489	9	31	24-Oct	26-Oct	1st Q
11 yr avg	0.264	0.092	0.062	0.739		368	2002		
10 yr avg	0.265	0.091	0.062	0.739		337	2002		

avg Average
SD Standard deviation
Min Minimum
Max Maximum
n Number
Date max Calendar day when max Chl-a was detected
Moon max Moon phase date closest to max Chl-a
Note: 1st and Last represent First and Last Quarters of the moon phase

Table 1.5 Annual average of satellite derived Chl-a (mg/m^3) at Abrir La Sierra (ALS)

ALS	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.303	0.085	0.142	0.565	9	42	21-Aug	19-Aug	1st Q
2000	0.292	0.111	0.131	0.599	9	36	29-Sep	27-Sep	New
2001	0.250	0.069	0.062	0.424	5	38	6-Mar	9-Mar	Full
2002	0.267	0.064	0.169	0.455	9	36	30-Sep	6-Oct	New
2003	0.172	0.041	0.090	0.315	9	38	17-Nov	17-Nov	Last
2004	0.250	0.092	0.140	0.569	4	30	21-Sep	21-Sep	1st
2005	0.222	0.051	0.146	0.346	9	25	25-Nov	23-Nov	Last
2006	0.249	0.064	0.093	0.447	4	36	8-Oct	7-Oct	FULL
2007	0.247	0.079	0.127	0.553	4	30	9-Nov	9-Nov	New
2008	0.245	0.070	0.084	0.494	9	34	5-Sep	7-Sep	1st Q
2009	0.235	0.092	0.105	0.482	9	34	25-May	24-May	New
11 yr avg	0.249	0.084	0.062	0.599		379	2000		
10 yr avg	0.251	0.083	0.062	0.599		345	2000		

Table 1.6 Annual average of satellite derived Chl-a (mg/m^3) at Bajo de Sico (BDS)

BDS	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.264	0.110	0.109	0.634	5	42	3-Dec	7-Dec	New
2000	0.185	0.077	0.075	0.374	9	37	25-Jun	25-Jun	Last
2001	0.154	0.040	0.087	0.232	9	38	13-Aug	19-Aug	New
2002	0.174	0.060	0.095	0.327	9	37	9-Nov	11-Nov	1st
2003	0.165	0.057	0.089	0.365	6	38	9-Nov	9-Nov	FULL
2004	0.165	0.056	0.100	0.279	9	29	15-Oct	14-Oct	New
2005	0.141	0.026	0.099	0.190	9	25	10-Feb	8-Feb	New
2006	0.159	0.041	0.085	0.286	2	32	22-Mar	22-Mar	Last
2007	0.155	0.046	0.088	0.240	9	26	1-Nov	1-Nov	Last
2008	0.144	0.058	0.046	0.357	9	36	29-Sep	29-Sep	New
2009	0.160	0.070	0.052	0.354	9	31	25-May	24-May	New
11 yr avg	0.173	0.072	0.046	0.634		371	1999		
10 yr avg	0.174	0.073	0.046	0.634		340	1999		

avg	Average
SD	Standard deviation
Min	Minimum
Max	Maximum
n	Number
Date max	Calendar day when max Chl-a was detected
Moon max	Moon phase date closest to max Chl-a
Note:	1st and Last represent First and Last Quarters of the moon phase

Table 1.7 Annual average of satellite derived Chl-a (mg/m^3) at Pichincho

PICHINCHO	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.095	0.030	0.045	0.178	7	44	4-Jul	6-Jul	Last
2000	0.106	0.044	0.042	0.215	9	36	19-Jul	16-Jul	FULL
2001	0.090	0.028	0.050	0.175	9	37	21-Aug	25-Aug	1st Q
2002	0.078	0.026	0.031	0.148	9	39	17-Jan	21-Jan	1st Q
2003	0.105	0.048	0.050	0.273	3	43	28-Jul	29-Jul	New
2004	0.102	0.042	0.003	0.252	9	38	11-Jul	9-Jul	Last
2005	0.087	0.015	0.051	0.121	8	32	9-Jan	10-Jan	New
2006	0.100	0.033	0.044	0.182	9	39	14-Mar	14-Mar	FULL
2007	0.080	0.024	0.037	0.123	9	36	19-Dec	17-Dec	1st Q
2008	0.085	0.027	0.039	0.186	9	39	11-Jul	10-Jul	1st Q
2009	0.108	0.067	0.044	0.402	9	36	25-May	24-May	New
11 yr avg	0.094	0.039	0.003	0.402		419	2009		
10 yr avg	0.093	0.035	0.003	0.273		383	2003		

avg Average
SD Standard deviation
Min Minimum
Max Maximum
n Number
Date max Calendar day when max Chl-a was detected
Moon max Moon phase date closest to max Chl-a
Note: 1st and Last represent First and Last Quarters of the moon phase

The differences in the 8-day composite time series can be best described when the complete 10-year time series is plotted in one graph for each of the 12 sites. Figure 1 shows a clear pattern in times of the year when Chl-a values were higher. There were also higher values as well as more variability toward the latter part of the year. The values at these spawning sites off western Puerto Rico showed overall ranges of Chl-a between 0.05 and 0.74 mg/m^3 for the 10-year time series. Specifically for each site, Chl-a (mg/m^3) varied as follows, BDS ranged between 0.05 (in 2008) to 0.63 (in 1999); ALS ranged between 0.06 (2001) and 0.60 (in 2000) and Tour ranged from 0.06 (2001) to 0.74 (in 2002). The control site off the West Coast of Puerto Rico showed a range in Chl-a (mg/m^3) between a minimum of 0.003 (in 2004) and a maximum of 0.27 (in 2003) over the 10-year time series.

Off the West Coast of Puerto Rico, the highest annual mean at BDS and ALS was in 1999 with 0.26 and 0.30, respectively, followed by Tour in 2003 with 0.32. Nevertheless, the variability around these means was high as depicted in the following graphs. The 10-year average was plotted to highlight the peaks and valleys of the available Chl-a data.

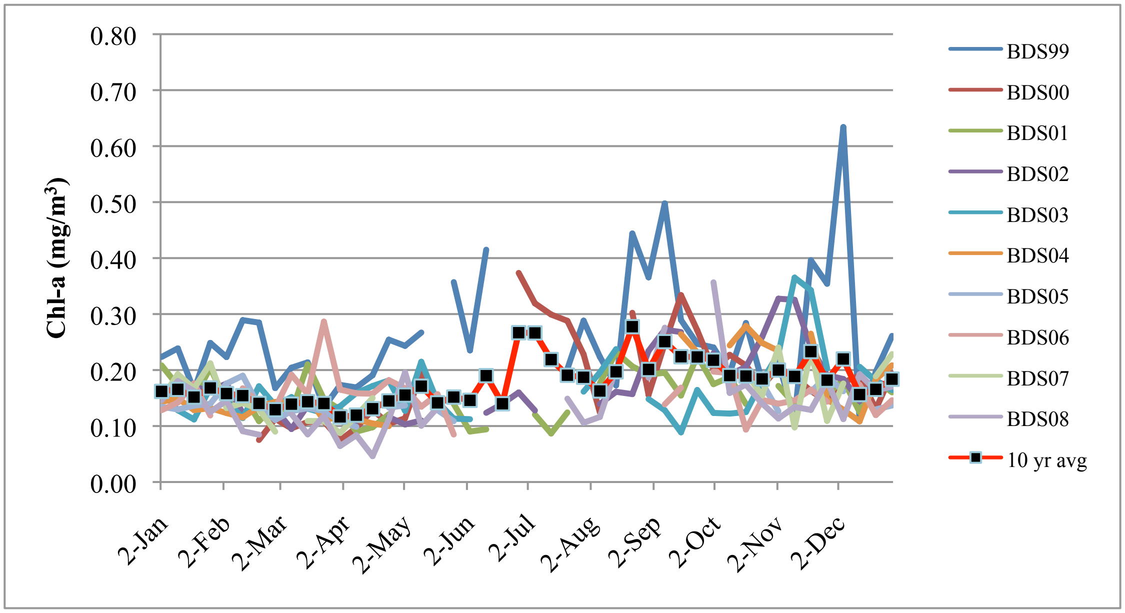


Figure 1.3 Weekly (1999-2008) and 10 year mean of satellite derived Chl-a for Bajo de Sico (BDS) station off the West Coast of Puerto Rico

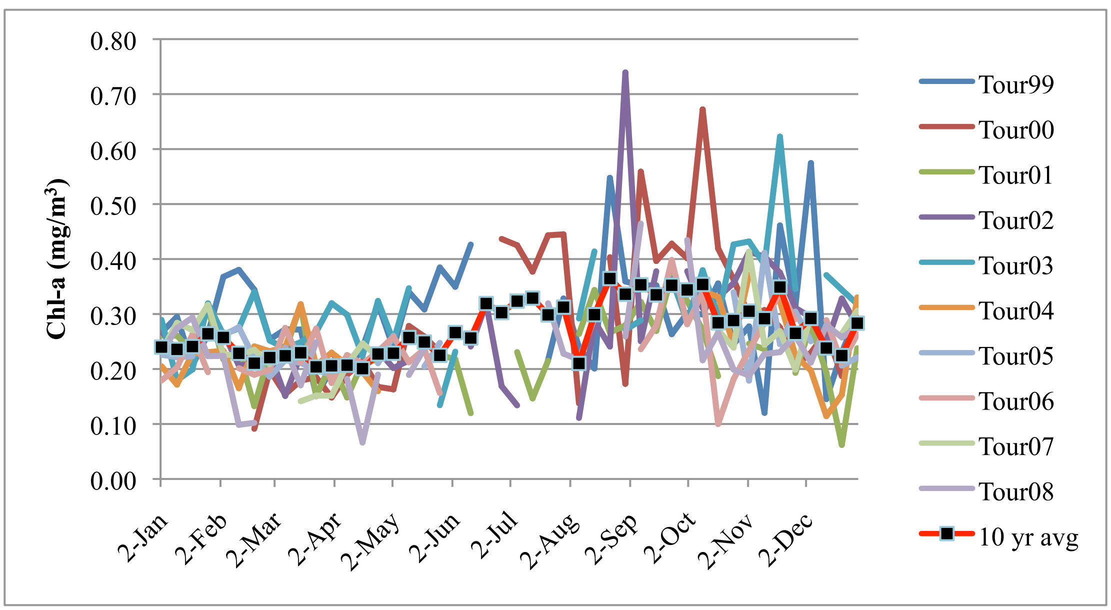


Figure 1.4 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for Tourmaline (Tour) station off the West Coast of Puerto Rico

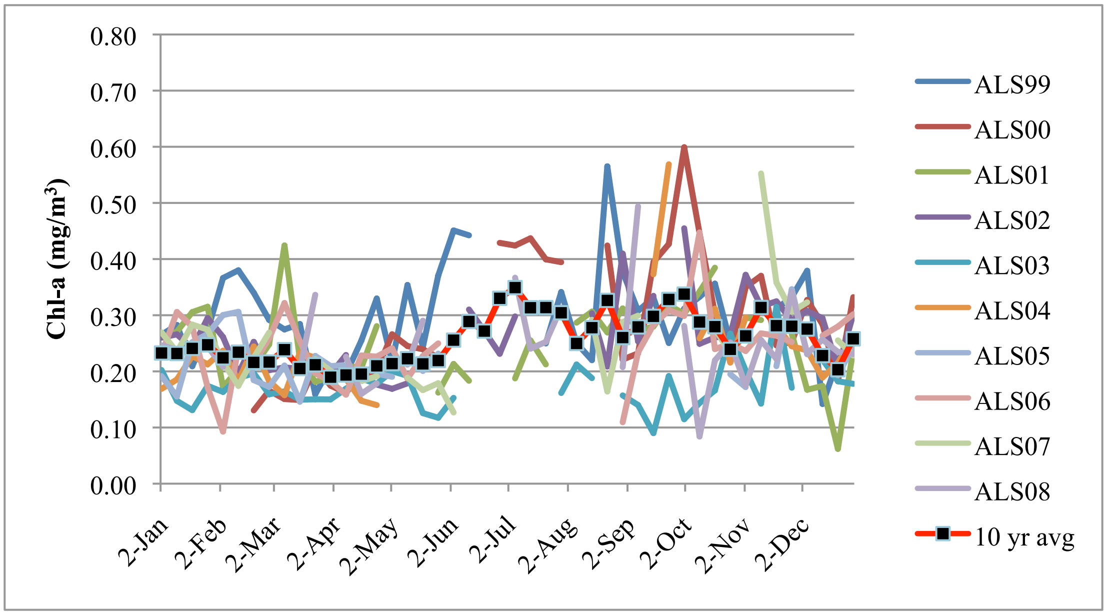


Figure 1.5 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for Abrir La Sierra (ALS) station off the West Coast of Puerto Rico

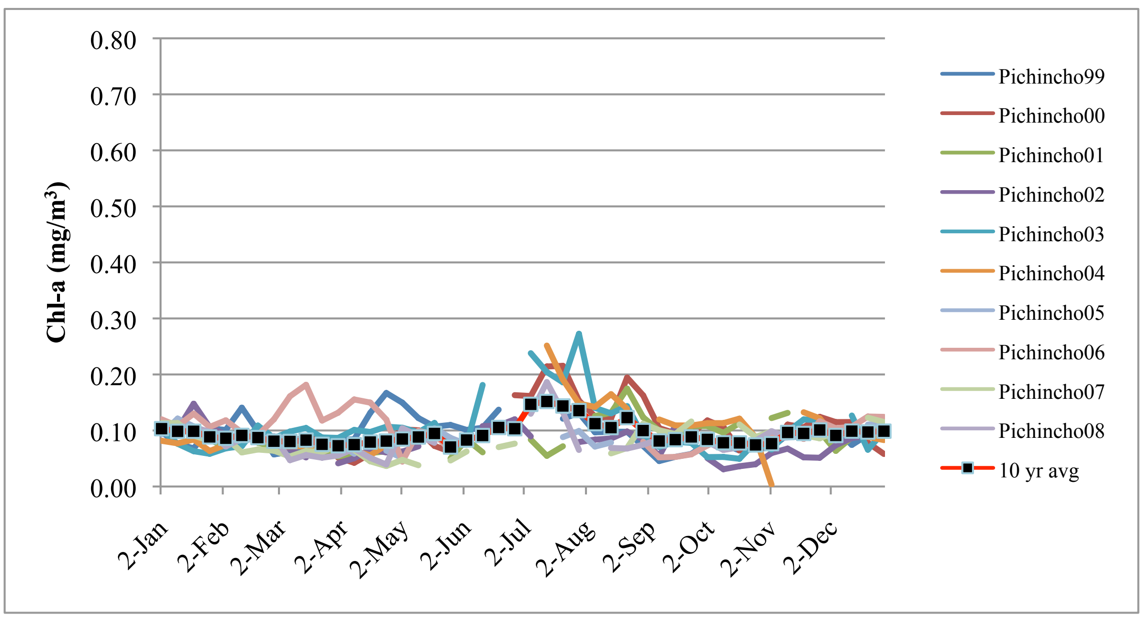


Figure 1.6 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for Los Pichinchos (Pichi) station off the West Coast of Puerto Rico

There were noticeable fluctuations in Chl-a over the 10-year time series at each of the spawning sites. The control site, Los Pichinchos had the lowest values overall in 1999 ranging from 0.05 to 0.18 mg/m^3, as expected, since it is the farthest site from shore, approximately 53.3 km offshore, northwest of Rincón, Puerto Rico. That same year, BDS showed the lowest (0.11 mg/m^3 on December 11) and highest (0.63 mg/m^3 on December 3; the highest value at BDS over the 10 year series) values during this year. The decrease in Chl-a from December 3rd to December 11th was almost a six-fold change over a one-week period. The highest average annual values of the entire 10-year series were recorded in 1999 at BDS, ALS and Tour.

In 2000, the highest value of all three aggregation sites was recorded at Tour (0.67 mg/m^3 in October) while the lowest value was recorded at BDS (0.08 mg/m^3 in February). Pichincho, the control site, showed the lowest overall values (range: 0.04-0.22 mg/m^3) but the maximum was higher than in 1999. The highest average annual value of the entire 10-year series was recorded in 2000 for Los Pichinchos. There were no images available for these areas during the first 6 weeks of this year due to problems with the sensors and continuous cloud cover.

In 2001, the lowest value was recorded at ALS and Tour (0.06 mg/m^3 in December), which was also the lowest for these two sites over the entire 10-year series. The highest value of Chl-a was recorded at ALS (0.42 mg/m^3) during the week of March 6th.

The highest Chl-a value was recorded during the last week of August 2002 at Tour (0.74 mg/m^3) followed by an almost five-fold decrease over the following week, which was also the highest value over the 10-year time series. The rate of change in the Chl-a field over these areas is addressed in the next section. The minimum recorded value was of 0.10 mg/m^3 at BDS during the week of March 6.

In 2003, Chl-a variability at Tour was more pronounced than the other two spawning sites with the highest values at this site during the week of November 17 (0.62 mg/ m^3) and the lowest values overall at BDS and ALS (0.09 mg/m^3). The peaks at these two sites were asynchronous and decreased sharply at ALS. Los Pichinchos Chl-a values ranged between 0.05 and 0.27 mg/m^3. This range includes the highest recorded value for Los Pichinchos (week of July 28) over the 10-year time series.

The lowest Chl-a value was recorded at BDS (0.10 mg/m^3) during the last week of April while the highest recorded value was at ALS (0.57 mg/m^3) during the week of September 21 2004. Los Pichinchos recorded values ranged from 0.00 (0.003, first week in November), which was the lowest value recorded over the 10-year time series, and 0.25 mg/m^3.

There were large gaps in the data during 2005 and 2006 for most if not all the stations. Nevertheless, there were still over 25 images available per area (maximum number of 8-day composite images per year is 46). Lower overall Chl-a values were recorded in 2005 with the highest value at Tour during the week of November 9 (0.41 mg/m^3) and the lowest record at BDS (0.10 mg/m^3) during the week of April 7. Los Pichinchos values ranged from 0.05 and 0.12 mg/m^3, where the high value was the lowest maximum recorded over the 10-year time series.

The latter part of 2006 (October) showed more changes from week to week than the earlier part of the year. The highest value at ALS (0.45 mg/m^3) occurred during the week of October 8th followed by a decrease to 0.23 the next week. The lowest value of the annual series was recorded at BDS (0.09 mg/m^3). The range of values at Los Pichinchos was 0.05 to 0.18 mg/m^3 and the maximum was recorded during the week of March 14.

The higher variability during the latter part of 2007 resulted in a maximum Chl-a value at ALS (0.55 mg/m^3 during the week of November 9), which was more than twice the maximum at BDS. The lowest recorded value was at BDS (0.09 mg/m^3) during the last week of March. Los Pichinchos values ranged from 0.04 to 0.12 mg/m^3.

The last year of the time series appears more monotonous than the other years. The maximum value was recorded at ALS (0.49 mg/m^3 during the week of September 5th) and the lowest value was recorded at BDS (0.05 mg/m^3 recorded the week of April 15th). This was the lowest value recorded at BDS over the entire 10-year series and less than half of most previously recorded minimum values.

Differences in the Chl-a within a given site describe the changes that take place in the surface waters/water column of each of these spawning aggregation sites. To determine differences in the Chl-a between years (1999-2008) at each of the sampling sites, the data were analyzed using Kruskal-Wallis and multiple pairwise comparisons using the Steel-Dwass- Critchlow-Fligner procedure (SDCF).

Kruskal-Wallis results indicated that there were differences among the 10 years of data at BDS ($p < 0.0001$). The result of the SDCF procedure Two-tailed test showed that 1999 was significantly different (p values) from all the other years at this site (see Table 1.8).

Table 1.8 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between years at BDS

	BDS99	BDS00	BDS01	BDS02	BDS03	BDS04	BDS05	BDS06	BDS07	BDS08
BDS99	**1**	**0.014**	**<0.0001**	**0.000**	**<0.0001**	**0.001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
BDS00	**0.014**	**1**	0.899	1.000	0.995	0.998	0.465	0.970	0.966	0.343
BDS01	**<0.0001**	0.899	**1**	0.987	1.000	1.000	0.938	1.000	1.000	0.873
BDS02	**0.000**	1.000	0.987	**1**	1.000	0.999	0.495	1.000	0.992	0.498
BDS03	**<0.0001**	0.995	1.000	1.000	**1**	1.000	0.855	1.000	1.000	0.682
BDS04	**0.001**	0.998	1.000	0.999	1.000	**1**	0.974	1.000	1.000	0.936
BDS05	**<0.0001**	0.465	0.938	0.495	0.855	0.974	**1**	0.410	0.996	1.000
BDS06	**<0.0001**	0.970	1.000	1.000	1.000	1.000	0.410	**1**	1.000	0.724
BDS07	**<0.0001**	0.966	1.000	0.992	1.000	1.000	0.996	1.000	**1**	0.979
BDS08	**<0.0001**	0.343	0.873	0.498	0.682	0.936	1.000	0.724	0.979	**1**

Note: p values in bold are significant at $\alpha = 0.05$

The description of the annual values at BDS indicates that in 1999, the highest Chl a value (0.63 in December) and the highest annual mean (0.26 mg/m^3) was reported at BDS for the entire 10-year series. BDS is the spawning site farthest away from local river influence. High precipitation was recorded at the Mayagüez Airport and Mona Island stations in November 1999, which could explain the high values obtained at BDS (http://www.ncdc.noaa.gov/, http://www.ncdc.noaa.gov/cdo-web/faq_cdo#ANNUAL).

The other two spawning aggregations for red hind off Western Puerto Rico are ALS and Tour, which are closer to shore (about 17 km offshore). The data acquired from these sites, as well as from the control site of Los Pichinchos, were subjected to the same tests as BDS revealing the following results.

ALS results of significant differences (Kruskal-Wallis $p < 0.0001$) and a multiple pairwise comparisons using the SDCF/Two-tailed test (including a Bonferroni correction) showed that the years 1999 and 2003 were significantly different from all others; 2005, 2004, 2007 and 2008 were also significantly different but similar among themselves (Table 1.9). The rains of 2003 could explain these differences because the maximum total precipitation was reported in

November 2003 (maximum reported over the entire 10 year series) at Magueyes Island, the station closest to ALS. The 2003 maximum Chl-a values observed also coincided with the full moon of the month (November 9). The images also showed that there were a number of eddies moving through the Caribbean (Plate 1) and processes associated with these eddies (*e.g.* advection) could influence the Chl-a values observed at the spawning sites. Fronts from the north during the winters, runoff from rivers and the dispersion over the West Coast of Puerto Rico, re-suspension of sediment from swells generated by cold fronts are among other factors that could influence variability in the area in general.

Table 1.9 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between years at ALS

	ALS99	ALS00	ALS01	ALS02	ALS03	ALS04	ALS05	ALS06	ALS07	ALS08
ALS99	**1**	0.998	0.148	0.538	**<0.0001**	0.055	**0.001**	0.075	0.065	**0.026**
ALS00	0.998	**1**	0.954	1.000	**<0.0001**	0.856	0.305	0.980	0.856	0.891
ALS01	0.148	0.954	**1**	0.999	**<0.0001**	1.000	0.771	1.000	1.000	1.000
ALS02	0.538	1.000	0.999	**1**	**<0.0001**	0.817	0.162	0.993	0.874	0.820
ALS03	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**1**	**0.000**	**0.002**	**<0.0001**	**<0.0001**	**<0.0001**
ALS04	0.055	0.856	1.000	0.817	**0.000**	**1**	0.994	0.991	1.000	1.000
ALS05	**0.001**	0.305	0.771	0.162	**0.002**	0.994	**1**	0.488	0.983	0.749
ALS06	0.075	0.980	1.000	0.993	**<0.0001**	0.991	0.488	**1**	1.000	0.996
ALS07	0.065	0.856	1.000	0.874	**<0.0001**	1.000	0.983	1.000	**1**	1.000
ALS08	**0.026**	0.891	1.000	0.820	**<0.0001**	1.000	0.749	0.996	1.000	**1**

Note: p values in bold are significant at $\alpha = 0.05$

Tour is the station closest to the river outflow of the three sites from the West Coast of Puerto Rico. Kruskal-Wallis results indicated that there were differences among the 10 years ($p < 0.0001$). The result of the Steel-Dwass- Critchlow-Fligner procedure Two-tailed test showed the significant differences among the years (p values in Table 10). The years 2001, 2004-2006, and 2008 were different from the others but similar among themselves and 2003 was different from all but similar to 1999-2000 and 2002.

Table 1.10 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between years at Tourmaline

	Tour99	Tour00	Tour01	Tour02	Tour03	Tour04	Tour05	Tour06	Tour07	Tour08
Tour99	**1**	1.000	**0.017**	0.907	1.000	0.143	**0.038**	**0.040**	0.102	**0.017**
Tour00	1.000	**1**	0.843	1.000	0.987	0.957	0.966	0.946	0.978	0.894
Tour01	**0.017**	0.843	**1**	0.664	**0.001**	1.000	1.000	1.000	1.000	1.000
Tour02	0.907	1.000	0.664	**1**	0.437	0.869	0.618	0.822	0.948	0.605
Tour03	1.000	0.987	**0.001**	0.437	**1**	**0.023**	**0.002**	**0.003**	**0.006**	**0.002**
Tour04	0.143	0.957	1.000	0.869	**0.023**	**1**	1.000	1.000	1.000	1.000
Tour05	**0.038**	0.966	1.000	0.618	**0.002**	1.000	**1**	1.000	0.998	1.000
Tour06	**0.040**	0.946	1.000	0.822	**0.003**	1.000	1.000	**1**	1.000	1.000
Tour07	0.102	0.978	1.000	0.948	**0.006**	1.000	0.998	1.000	**1**	1.000
Tour08	**0.017**	0.894	1.000	0.605	**0.002**	1.000	1.000	1.000	1.000	**1**

Note: p values in bold are significant at $\alpha = 0.05$

Los Pichinchos, the offshore control site, showed no significant differences among the 10 years of the time series. The lowest value recorded for Los Pichinchos was 0.00 mg/m^3 (0.0032) during the week of November 1 in 2004 while the highest value was recorded at 0.27 mg/m^3 during the week of July 29 (during a new moon) in 2003. This high value at Los Pichinchos is within the range of Chl-a values obtained *in situ* as a result of an internal wave (Corredor 2008).

Southwestern Puerto Rico

Spawning aggregation sites off the Southwest Coast of Puerto Rico include La Parguera (Parguera) for red hind and Rene's station for mutton snapper. The 10-year time series indicated minimum values at CaTS, the control station 48 km offshore, although this station also showed variability in Chl-a. Figures 1.7-1.9 show the weekly values in Chl-a for each of these three sites for the years 1999-2008.

Table 1.11 Annual average of satellite derived Chl-a (mg/m^3) at Rene

RENE	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.235	0.091	0.117	0.658	2	43	18-Jun	20-Jun	1st Q
2000	0.251	0.103	0.132	0.600	9	34	21-Sep	21-Sep	Last
2001	0.201	0.048	0.089	0.326	7	35	8-Oct	10-Oct	Last
2002	0.218	0.071	0.107	0.395	9	36	1-Nov	4-Nov	New
2003	0.257	0.122	0.099	0.739	5	40	9-Nov	9-Nov	FULL
2004	0.203	0.078	0.024	0.410	9	35	21-Sep	21-Sep	1st Q
2005	0.195	0.053	0.126	0.369	9	29	16-Oct	17-Oct	FULL
2006	0.191	0.050	0.080	0.343	3	34	7-Apr	5-Apr	1st
2007	0.199	0.049	0.121	0.374	9	33	6-Sep	4-Sep	Last
2008	0.192	0.068	0.080	0.428	9	37	30-Sep	29-Sep	New
2009	0.261	0.142	0.111	0.952	8	37	25-May	24-May	New
11 yr avg	0.220	0.090	0.024	0.952		393	2009		
10 yr avg	0.215	0.081	0.024	0.739		356	2003		

Table 1.12 Annual average of satellite derived Chl-a (mg/m^3) at Parguera

PARGUERA	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.228	0.062	0.117	0.434	8	42	29-Aug	2-Sep	Last
2000	0.247	0.096	0.127	0.548	9	34	21-Sep	21-Sep	Last
2001	0.214	0.108	0.089	0.728	8	34	13-Aug	12-Aug	Last
2002	0.214	0.067	0.107	0.367	9	37	1-Nov	4-Nov	New
2003	0.250	0.081	0.112	0.579	7	41	17-Nov	17-Nov	Last
2004	0.197	0.067	0.117	0.383	8	37	21-Sep	21-Sep	1st
2005	0.188	0.057	0.124	0.376	9	29	16-Oct	17-Oct	FULL
2006	0.187	0.048	0.106	0.336	7	34	12-Jul	11-Jul	FULL
2007	0.192	0.059	0.120	0.449	9	33	6-Sep	4-Sep	Last
2008	0.186	0.060	0.106	0.393	9	36	29-Sep	29-Sep	New
2009	0.209	0.104	0.103	0.658	9	36	25-May	24-May	New
11 yr avg	0.211	0.078	0.089	0.728		393	2001		
10 yr avg	0.212	0.076	0.089	0.728		357	2001		

avg Average
SD Standard deviation
Min Minimum
Max Maximum
n Number
Date max Calendar day when max Chl-a was detected
Moon max Moon phase date closest to max Chl-a
Note: 1st and Last represent First and Last Quarters of the moon phase

Table 1.13 Annual average of satellite derived Chl-a (mg/m^3) at CaTS

CaTS	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.124	0.038	0.065	0.266	9	43	4-Jul	6-Jul	Last
2000	0.138	0.047	0.058	0.230	3	29	20-Aug	22-Aug	Last
2001	0.097	0.032	0.047	0.185	7	28	10-Jun	14-Jun	Last
2002	0.125	0.068	0.052	0.365	8	28	24-Oct	21-Oct	Full
2003	0.130	0.046	0.053	0.281	4	39	12-Jul	13-Jul	FULL
2004	0.105	0.030	0.062	0.221	9	33	19-Jul	9-Jul	Last
2005	0.090	0.030	0.049	0.181	3	28	9-Nov	9-Nov	1st
2006	0.106	0.019	0.071	0.147	9	33	15-Apr	13-Apr	FULL
2007	0.102	0.032	0.055	0.204	9	34	3-Dec	1-Dec	Last
2008	0.093	0.031	0.040	0.195	9	37	14-Apr	12-Apr	1st Q
2009	0.130	0.110	0.043	0.605	9	32	25-May	24-May	New
11 yr avg	0.113	0.051	0.040	0.605		364	2009		
10 yr avg	0.111	0.042	0.040	0.365		332	2002		

avg	Average
SD	Standard deviation
Min	Minimum
Max	Maximum
n	Number
Date max	Calendar day when max Chl-a was detected
Moon max	Moon phase date closest to max Chl-a
Note:	1st and Last represent First and Last Quarters of the moon phase

There were noticeable fluctuations in the Chl-a field at these spawning aggregation sites (Figures 1.7 and 1.8). The Chl-a values fluctuated similarly during most of 1999 except for two weeks, in January 17 and June 18. These dates and peaks in 1999 coincided with the spawning activity of red hind at Parguera and mutton snapper at the Rene sites, respectively. These values (Rene) ranged from 0.12 to 0.66 mg/m^3 in June. CaTS Chl-a values ranged from 0.07 to 0.27 mg/m^3, with the highest value during the week of July 4th.

Even though both stations had similar fluctuations in Chl-a that occurred in the same week (September 22, 2000), there was a slightly higher value at the Rene site (0.60 vs. 0.55). The CaTS range of values was between 0.058 and 0.23 mg/ m^3.

Similar Chl-a value fluctuations were observed at these two stations (Rene and Parguera) in 2001, except for two weeks when Parguera values were higher than Rene's the weeks of August 13 and September 30. The maximum value was recorded at Parguera at 0.73 mg/m^3 (week of

August 13). The reason for monitoring the Chl-a values during the months of August and September is that Goliath grouper (*Epinephelus itajarra*) have also been reported to spawn during that period. The commercial landings for many years showed increased landings for groupers for these months suggesting that a spawning aggregation may be occurring at these two sites.

There were differences between the Rene and Parguera stations during the first two weeks of November 2002, with higher values at Rene's with 0.40 mg/ m^3 the week of November 1^{st}. The satellite images used in this study showed the remnants of an eddy present in the Caribbean during the latter part of 2002 and the filaments of the eddy reaching the South Coast of Puerto Rico. The presence of this eddy could explain the highest value (0.37 mg/ m^3) of the 10-year series obtained during the week of October 24 at CaTS.

The latter part of 2003 also showed high Chl-a values at these three stations, with a maximum value of 0.74 mg/ m^3 at Rene's on the week of November 9 and a maximum value at Parguera of 0.58 mg/m^3 during the week of November 17. The significant event of rain recorded at Magueyes and documented by Armstrong and Detrés (2010) would have impacted the two stations, Rene and Parguera, off the Southwestern Coast of Puerto Rico. Figure 1.2 shows the remnants of the runoff in the December 11-18 2003 composite. The possible impact of the eddy to the South of Puerto Rico on the variability in Chl-a values observed cannot be discarded.

In 2004, the maximum value of 0.41 mg/m^3 at Rene's was recorded the week of September 21^{st}. Additional studies should be done to determine which species might be spawning in this site. In 2005, the maximum Chl-a value in Parguera was 0.38 during the week of October 16, the same as Rene's. There were gaps in the data reducing the number of 8-day composite images to 28 from a maximum of 46. The highest value of 2006 at the southwest spawning aggregations was recorded the week of April 7 (0.34) at Rene's and the week of July12 at Parguera (0.34). In 2007 a maximum value of 0.45 was recorded at Parguera during the week of September 4th and both stations had similar Chl-a variability. High Chl-a values in September could be explained by the deposition of dust from the summer African dust storm that would coincide with the lag time in the Chl-a signal documented by Justiniano (2010).

In 2008, most values were very close at the two stations with maximum values (0.43) recorded at Rene's on the week of September 30. CaTS values ranged from 0.04 to 0.20 mg/m^3, the minimum value for the 10-year time series.

There was a marked contrast between the lower weekly Chl-a values for CaTS (Control site) and those of La Parguera and Rene (Figures 1.7-1.9). As was previously discussed, for the West Coast of Puerto Rico, higher values and variability of Chl-a were observed during the latter part of the year. This could be due to higher runoff during the rainy season in the fall and, for the West Coast, sediment re-suspension during the winter months associated with swells generated by cold fronts (Warne *et al.* 2005).

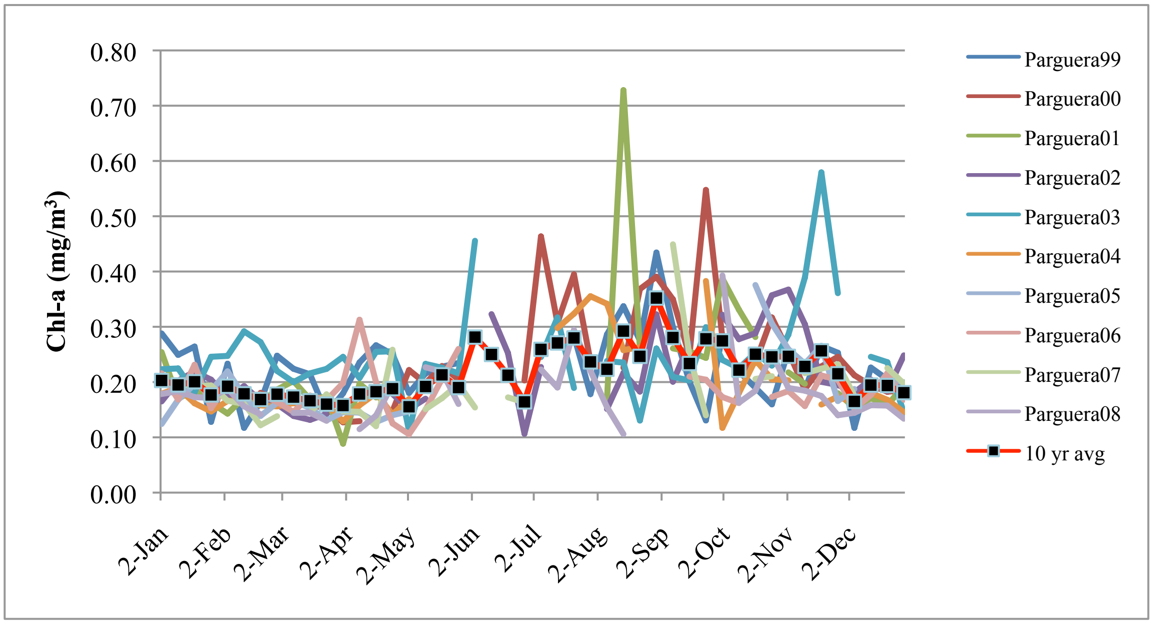


Figure 1.7 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for La Parguera station off the Southwest Coast of Puerto Rico

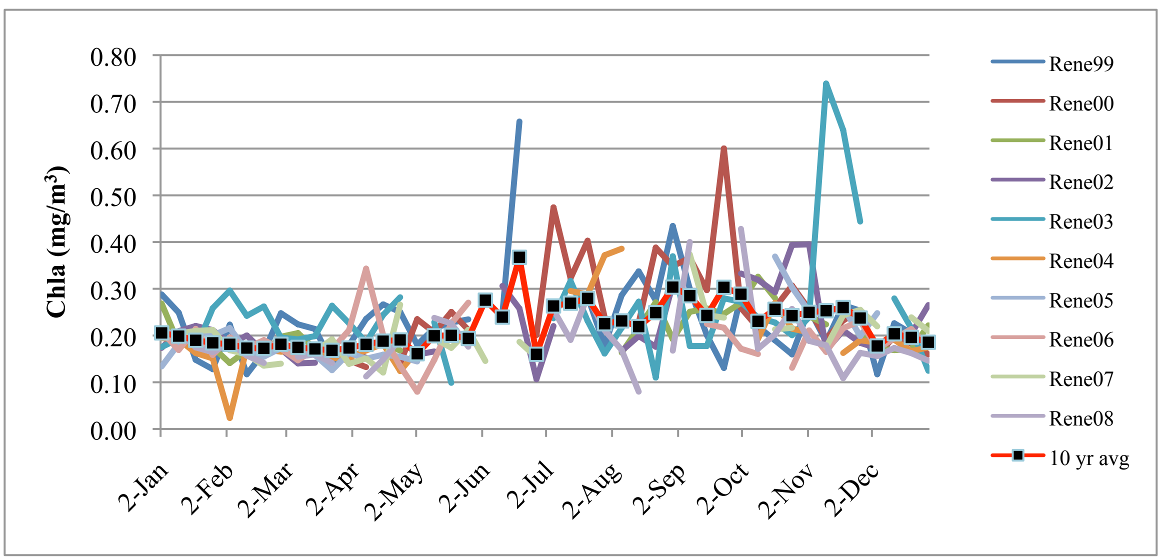


Figure 1.8 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for Rene station off the Southwest Coast of Puerto Rico

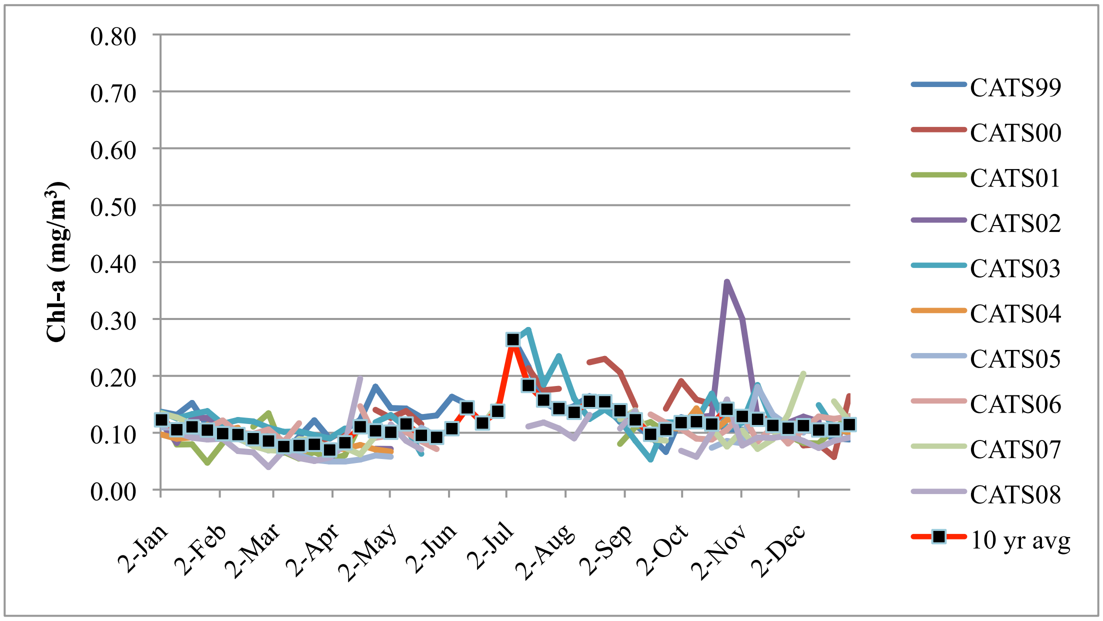


Figure 1.9 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for CaTS station off the Southwest Coast of Puerto Rico

Using the same statistical test (Multiple pairwise comparisons using the SDCF/ Two-tailed test) to determine the differences among the Chl-a values at La Parguera red hind spawning site between 1999 and 2008, different results were obtained than for BDS. The years 2003, 2005, 2006, and 2008 were significantly different from all other years, but not different among themselves. There were other significant differences summarized in the following Tables 1.14-1.16.

The Kruskal-Wallis test ($p < 0.05$) resulted in the rejection of the null hypothesis of no difference between years in La Parguera. When subjected to the same multiple pairwise comparisons for the same time series, the results indicated significant differences between 2003 and 2004 to 2008, with most other years showing no significant differences (Table 1.14). The differences could be explained by the amount of rain registered during a year and the potential of the runoff and fresh water (with nutrients and sediments, etc.) to reach these areas. In 2003, for example, the total amount of rain reported at the Magueyes station was 425 mm during the month of November; the highest for the entire 10-year series and more than twice the average rain registered during that time (average: 189 mm). Otero (2009) reported an average chlorophyll value of 0.24 mg/m^3 for a station at the shelf edge of La Parguera between 2003 and 2005. Daily fluctuations and seasonal cycles influenced by material from terrestrial sources were also reported at the shelf edge station (Otero 2009).

Table 1.14 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between years at Parguera

	Parguera99	Parguera00	Parguera01	Parguera02	Parguera03	Parguera04	Parguera05	Parguera06	Parguera07	Parguera08
Parguera99	**1**	1.000	0.468	0.961	0.997	0.165	0.090	**0.024**	0.061	**0.018**
Parguera00	1.000	**1**	0.556	0.875	0.988	0.119	0.085	0.054	0.133	**0.022**
Parguera01	0.468	0.556	**1**	1.000	**0.033**	0.979	0.978	0.999	1.000	0.891
Parguera02	0.961	0.875	1.000	**1**	0.229	0.881	0.825	0.890	0.951	0.617
Parguera03	0.997	0.988	**0.033**	0.229	**1**	**0.005**	**0.002**	**< 0.0001**	**0.001**	**0.000**
Parguera04	0.165	0.119	0.979	0.881	**0.005**	**1**	1.000	1.000	1.000	1.000
Parguera05	0.090	0.085	0.978	0.825	**0.002**	1.000	**1**	1.000	1.000	1.000
Parguera06	**0.024**	0.054	0.999	0.890	**< 0.0001**	1.000	1.000	**1**	1.000	0.999
Parguera07	0.061	0.133	1.000	0.951	**0.001**	1.000	1.000	1.000	**1**	0.990
Parguera08	**0.018**	**0.022**	0.891	0.617	**0.000**	1.000	1.000	0.999	0.990	**1**

Note: p values in bold are significant at $\alpha = 0.05$

There was more variability among years identified at La Parguera station than at Rene's but 2003 was significantly different from other years (Table 1.15). In 2003, Corredor *et al.* (2004) described a very large (230 km across) cyclonic eddy located at 15°N, 67°W during August 14-16 embedded within the Orinoco River Plume. The stations also had differences in common in the years 2006 and 2008. The highest Chl-a value was recorded at Rene's in 2003 (0.74 mg/m^3 on the week of November 9th, the week of the full moon), and this year also had the highest annual mean recorded for the station over the 10 year series. The rains occurred in November 2003, when the highest value of Chl-a was recorded for the station. There were very high values of total precipitation also recorded in August 2008. Again, both these years (2006 and 2008) had more rain than other years and this station was impacted by the runoff from rivers and land.

Table 1.15 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between years at Rene

	Rene99	Rene00	Rene01	Rene02	Rene03	Rene04	Rene05	Rene06	Rene07	Rene08
Rene99	**1**	1.000	0.639	0.977	1.000	0.574	0.289	0.140	0.402	0.060
Rene00	1.000	**1**	0.712	0.950	1.000	0.484	0.301	0.211	0.514	0.112
Rene01	0.639	0.712	**1**	1.000	0.188	0.999	0.986	0.997	1.000	0.867
Rene02	0.977	0.950	1.000	**1**	0.674	0.971	0.896	0.984	1.000	0.736
Rene03	1.000	1.000	0.188	0.674	**1**	0.112	0.070	**0.017**	0.154	**0.008**
Rene04	0.574	0.484	0.999	0.971	0.112	**1**	1.000	1.000	1.000	0.999
Rene05	0.289	0.301	0.986	0.896	0.070	1.000	**1**	1.000	0.998	1.000
Rene06	0.140	0.211	0.997	0.984	**0.017**	1.000	1.000	**1**	0.999	1.000
Rene07	0.402	0.514	1.000	1.000	0.154	1.000	0.998	0.999	**1**	0.957
Rene08	0.060	0.112	0.867	0.736	**0.008**	0.999	1.000	1.000	0.957	**1**

Note: p values in bold are significant at $\alpha = 0.05$

Statistical analyses of CaTS (control station) data for the entire time series of 10 years showed that there were significant differences among years (Kruskal-Wallis test ($p < 0.0001$)). When subjected to the same multiple pairwise comparisons for the same time series, the results showed the highest significant differences in 2000, 2005 and 2008 (Table 1.16). One of the plausible explanations for these differences at this offshore station is the presence of the South American river waters. The Orinoco plume has been reported at CaTS (Corredor and Morell 2001) and the interaction with meanders from the plume or the interaction with eddies could be responsible for these observed differences. The highest annual Chl-a mean was recorded in 2000 (0.14 mg/m^3).

Table 1.16 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between years at CaTS

	CATS99	CATS00	CATS01	CATS02	CATS03	CATS04	CATS05	CATS06	CATS07	CATS08
CATS99	**1**	0.967	0.066	0.967	1.000	0.206	**0.003**	0.304	0.113	**0.002**
CATS00	0.967	**1**	**0.028**	0.743	0.989	0.054	**0.003**	0.122	**0.039**	**0.005**
CATS01	0.066	**0.028**	**1**	0.861	0.052	0.999	0.991	0.939	1.000	1.000
CATS02	0.967	0.743	0.861	**1**	0.957	0.975	0.247	1.000	0.950	0.327
CATS03	1.000	0.989	0.052	0.957	**1**	0.083	**0.001**	0.112	0.074	**0.001**
CATS04	0.206	0.054	0.999	0.975	0.083	**1**	0.601	1.000	1.000	0.693
CATS05	**0.003**	**0.003**	0.991	0.247	**0.001**	0.601	**1**	0.282	0.928	1.000
CATS06	0.304	0.122	0.939	1.000	0.112	1.000	0.282	**1**	0.988	0.329
CATS07	0.113	**0.039**	1.000	0.950	0.074	1.000	0.928	0.988	**1**	0.982
CATS08	**0.002**	**0.005**	1.000	0.327	**0.001**	0.693	1.000	0.329	0.982	**1**

Note: p values in bold are significant at $\alpha = 0.05$

Corredor and Morell (2001) indicated that the CaTS station is under riverine influence due to the low salinity surface signal continuously detected *in situ*. Riverine influence on Caribbean surface water from the Orinoco River has been determined to have a 3-month lag, August-October, before it is detected in Puerto Rico. The CaTS site is 51 km off Southwestern Puerto Rico (Corredor and Morell (2001; http://www.caricoos.org/drupal/node/71). This station has been shown to receive Amazon River waters during the months of June-July and Orinoco River waters with a peak in August-September (Corredor and Morell 2001). Lee-Borges *et al.* (2002) validated the SeaWiFS chlorophyll data with *in situ* ship data and corroborated the temporal variations in chlorophyll at CaTS over the period 1997-2001. The *in situ* values of surface chlorophyll (approximately 1 m in depth) were obtained from monthly collections. The satellite derived Chl-a values were obtained from the same size sampling box as the present work (3 x 3 pixel). Figure 1.9 shows temporal coincidence with the reported *in situ* values of Lee-Borges *et al.* (2002) and the May-July and October-January signals. The range of Chl-a from ship measurements ranged between approximately 0.04 to 0.33 mg/m^3 (Lee-Borges *et al.* 2002

Figure 1.7). However, the stronger signal between 1999-2008 corresponds to the latter part of the year and thus with Orinoco River displacement into the CaTS.

St. Croix, USVI

The two fish spawning aggregation areas included in this study from St. Croix were Lang Bank (LB), a spawning area for red hind, and the Mutton Snapper area (MUT). LB and MUT had a minimum value of 0.04 and maximum values of 0.43 and 0.50 mg/m^3, respectively. Both of the latter values occurred in June 2000. The variability in Chl-a observed during the entire time series period of 1999-2008 is shown in Figures 1.10 and 1.11. Tables 1.17-1.18 summarize the information for the 10-year times series and include the information from 2009 that is further discussed in Chapter 2.

Table 1.17 Annual average of satellite derived Chl-a (mg/m^3) at Mutton Snapper (MUT)

MUTSTX	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.139	0.046	0.073	0.289	7	43	17-Nov	16-Nov	1st Q
2000	0.162	0.101	0.058	0.499	6	30	17-Jun	16-Jun	FULL
2001	0.123	0.034	0.068	0.193	5	30	4-Jul	5-Jul	Full
2002	0.156	0.060	0.064	0.372	9	35	26-Jun	24-Jun	Full
2003	0.143	0.055	0.053	0.276	5	38	26-Jun	29-Jun	New
2004	0.151	0.063	0.067	0.369	8	26	20-Aug	23-Aug	1st
2005	0.135	0.039	0.063	0.209	8	27	27-Dec	31-Dec	New
2006	0.144	0.040	0.074	0.228	4	30	10-Jun	11-Jun	FULL
2007	0.136	0.043	0.041	0.232	4	30	26-Jun	30-Jun	FULL
2008	0.127	0.055	0.071	0.350	9	35	12-Aug	18-Aug	FULL
2009	0.189	0.125	0.059	0.749	6	31	7-Apr	9-Apr	FULL
11yr avg	0.146	0.067	0.041	0.749		355	2009		
10yr avg	0.142	0.057	0.041	0.499		324	2000		

avg Average
SD Standard deviation
Min Minimum
Max Maximum
n Number
Date max Calendar day when max Chl-a was detected
Moon max Moon phase date closest to max Chl-a
Note: 1st and Last represent First and Last Quarters of the moon phase

Table 1.18 Annual average of satellite derived Chl-a (mg/m^3) at Lang Bank (LB)

LB	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.128	0.037	0.067	0.309	9	42	17-Nov	16-Nov	1st Q
2000	0.134	0.067	0.049	0.425	4	30	25-Jun	25-Jun	Last
2001	0.123	0.038	0.069	0.224	2	27	25-May	23-May	New
2002	0.141	0.050	0.077	0.264	9	32	30-Sep	6-Oct	New
2003	0.132	0.049	0.076	0.300	2	40	2-Jun	31-May	New
2004	0.142	0.066	0.064	0.389	9	28	20-Aug	23-Aug	1st
2005	0.110	0.031	0.070	0.174	9	27	10-Jun	15-Jun	1st
2006	0.134	0.045	0.065	0.239	4	30	26-Jun	25-Jun	New
2007	0.111	0.038	0.041	0.212	2	34	12-Jul	14-Jul	New
2008	0.112	0.031	0.069	0.222	6	30	16-May	20-May	FULL
2009	0.151	0.160	0.063	0.957	2	29	15-Apr	17-Apr	Last
11 yr avg	0.129	0.065	0.041	0.957		349	2009		
10 yr avg	0.127	0.047	0.041	0.425		320	2004		

avg Average
SD Standard deviation
Min Minimum
Max Maximum
n Number
Date max Calendar day when max Chl-a was detected
Moon max Moon phase date closest to max Chl-a
Note: 1st and Last represent First and Last Quarters of the moon phase

The highest values in Chl-a were found at MUT (0.37) also in June 2002. In 2003, the data showed two- and three-fold increases at the MUT station with even higher values at LB (0.30) also in June.

The MUT peak is again shown the week of February 2nd 2004 but the highest value was recorded at LB (0.39) during August. In 2005, low variability was observed at these sites with maximum values during the week of December 27th (0.21) at MUT. The maximum Chl-a value of 0.23 occurred in June in LB. The peak in Amazon River water presence has been reported for the month of June in the waters of the US Caribbean, specifically at the CaTS station (Corredor and Morrell 2001) that could also coincide with the maximum values observed at LB. In 2007, the maximum Chl-a value of 0.23 occurred in June at MUT. The annual series from both stations track each other closely. In 2008, the areas continued to track each other closely in Chl-a values but with higher values at MUT during the week of August 12 (0.35).

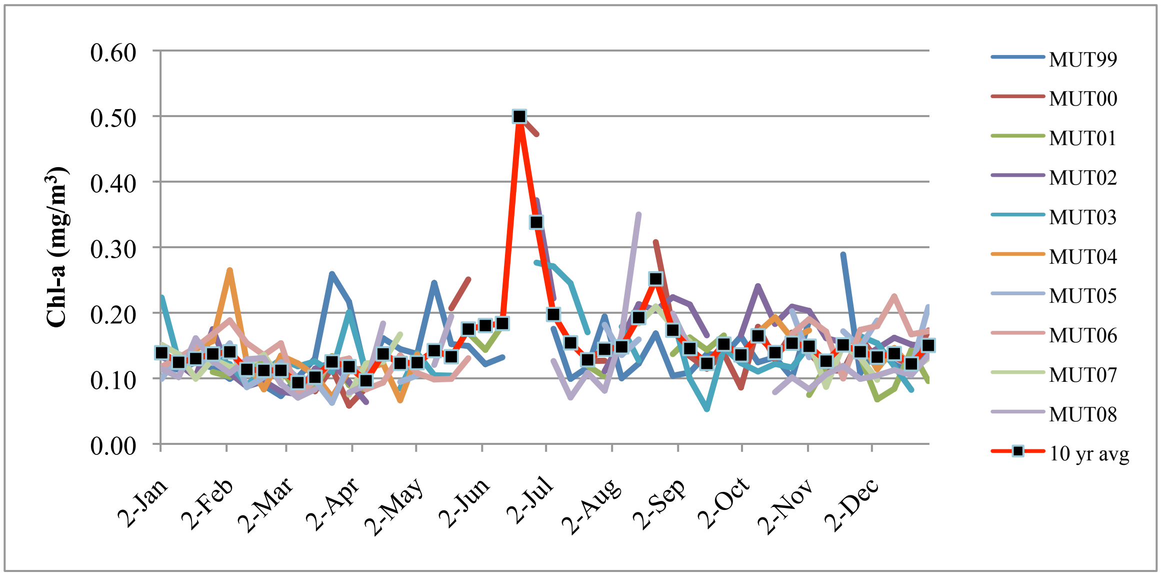


Figure 1.10 Annual (1999-2008) and 10-year mean of satellite derived Chl-a for MUT station off Southwest Coast St. Croix, USVI

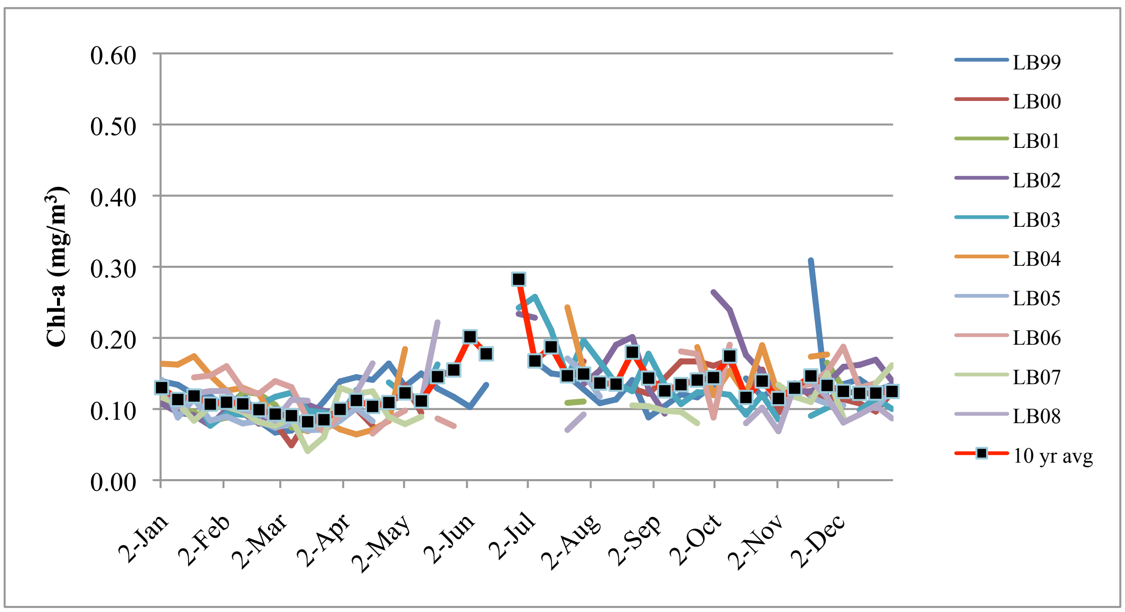


Figure 1.11 Annual (1999-2008) and 10-year mean of satellite derived Chl-a for LB station off East Coast St. Croix, USVI

The two spawning aggregations areas in St. Croix, Lang Bank (LB) and Mutton Snapper (MUT) were analyzed through a multiple pair comparison test with the following results. The MUT data when subjected to the same set of statistical analyses resulted in no significant differences among years (Kruskal-Wallis p=0.184). This surprising result was further investigated by a Friedman's test (p=0.02, significant) based on complete sets of observations only, meaning that no data were missing for the same period of time over the 10 years. A multiple pairwise comparison using Nemenyi's procedure test resulted in the years 2006 and 2008 being significantly different (Table 1.19).

Table 1.19 Table of p values from a multiple pairwise comparison the Nemenyi's procedure to determine differences between years at MUT (Mutstx)

	Mutstx99	Mutstx00	Mutstx01	Mutstx02	Mutstx03	Mutstx04	Mutstx05	Mutstx06	Mutstx07	Mutstx08
Mutstx99	1	0.930	0.377	0.930	0.289	0.289	0.427	0.042	0.724	0.133
Mutstx00	0.930	1	0.427	0.860	0.251	0.251	0.377	0.034	0.791	0.158
Mutstx01	0.377	0.427	1	0.332	0.052	0.052	0.094	0.004	0.596	0.537
Mutstx02	0.930	0.860	0.332	1	0.332	0.332	0.480	0.052	0.659	0.112
Mutstx03	0.289	0.251	0.052	0.332	1	1.000	0.791	0.332	0.158	0.010
Mutstx04	0.289	0.251	0.052	0.332	1.000	1	0.791	0.332	0.158	0.010
Mutstx05	0.427	0.377	0.094	0.480	0.791	0.791	1	0.217	0.251	0.022
Mutstx06	0.042	0.034	0.004	0.052	0.332	0.332	0.217	1	0.017	**0.000**
Mutstx07	0.724	0.791	0.596	0.659	0.158	0.158	0.251	0.017	1	0.251
Mutstx08	0.133	0.158	0.537	0.112	0.010	0.010	0.022	**0.000**	0.251	0
Bonferroni corrected significance level: 0.0011										

Note: p values in bold are significant at $\alpha = 0.05$

The St. Croix areas are not exposed to local river runoff, but are exposed to the Amazon and Orinoco Rivers plumes, eddies, and re-suspension of sediment from the bottom (Kojis and Quinn 2011). Runoff from large rain events and plumes from the rum distillery, the oil refinery and the major waste disposal site all located on the Southwest of St. Croix could also influence MUT. Nevertheless, these plumes mostly run along the shore due west. These could be sources of variability in the near surface Chl-a.

Lang Bank (LB) off the eastern most part of St. Croix also resulted in a significant Kruskal-Wallis result (p=0.012) but, the multiple pairwise comparisons using the SDCF test could not detect significant differences between years.

MCD – Hind Bank, St. Thomas, USVI

The Chl-a values from the time series (1999-2008) for the area of the MCD reached a maximum of 0.29 mg/m^3 in 2004. The 10-year average, 1999-2008, based on 350, 8-day 4 km composite images, was 0.12 mg/m^3 (SD $\pm$0.04), with a maximum annual average value in 1999 (0.14 mg/m^3). Table 1.20 summarizes the information for the 10-year time series and includes the information from 2009 that is further discussed in Chapter 2.

Table 1.20 Annual average of satellite derived Chl-a (mg/m^3) at MCD

MCD	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.139	0.037	0.096	0.253	9	43	25-Nov	23-Nov	FULL
2000	0.118	0.039	0.056	0.239	7	30	11-Jul	8-Jul	1 st Q
2001	0.114	0.030	0.070	0.232	5	33	21-Aug	19-Aug	New
2002	0.119	0.030	0.066	0.183	6	37	26-Jun	2-Jul	Last Q
2003	0.135	0.031	0.059	0.230	9	41	2-Jun	31-May	New
2004	0.117	0.044	0.058	0.287	9	33	20-Aug	23-Aug	1st
2005	0.111	0.034	0.065	0.213	9	28	2-Feb	2-Feb	Last
2006	0.117	0.025	0.082	0.182	5	37	1-May	5-May	1st Q
2007	0.109	0.037	0.043	0.206	4	32	26-Jun	30-Jun	FULL
2008	0.109	0.028	0.076	0.177	9	36	10-Dec	12-Dec	FULL
2009	0.178	0.217	0.066	0.952	4	37	1-May	1-May	1st
11 yr avg	0.125	0.076	0.043	0.952		387	2009		
10 yr avg	0.120	0.035	0.043	0.287		350	2004		

avg	Average
SD	Standard deviation
Min	Minimum
Max	Maximum
n	Number
Date max	Calendar day when max Chl-a was detected
Moon max	Moon phase date closest to max Chl-a
Note:	1st and Last represent First and Last Quarters of the moon phase

Figure 1.12 describes the changes in the chlorophyll field derived from satellite images at the red hind spawning aggregation site (or marine conservation district, MCD) off the South Coast of St. Thomas for the entire time series. The highest value recorded at the MCD was 0.29 mg/m^3 during the week of August 20, 2004. In 2005, the highest Chl-a value was recorded the week of February 2 (0.21 mg/m^3) with the lowest value at 0.07 (week of March 22). In 2006, the

maximum value recorded was 0.18 mg/m^3 during the week of May 1st. The week of June 26 included the highest value of Chl-a (0.21 mg/m^3) of the year. The week of December 10 had the highest value with 0.17 mg/m^3; reported for the year 2008. There was no specific month of the year when highest values of Chl-a were reported at the MCD.

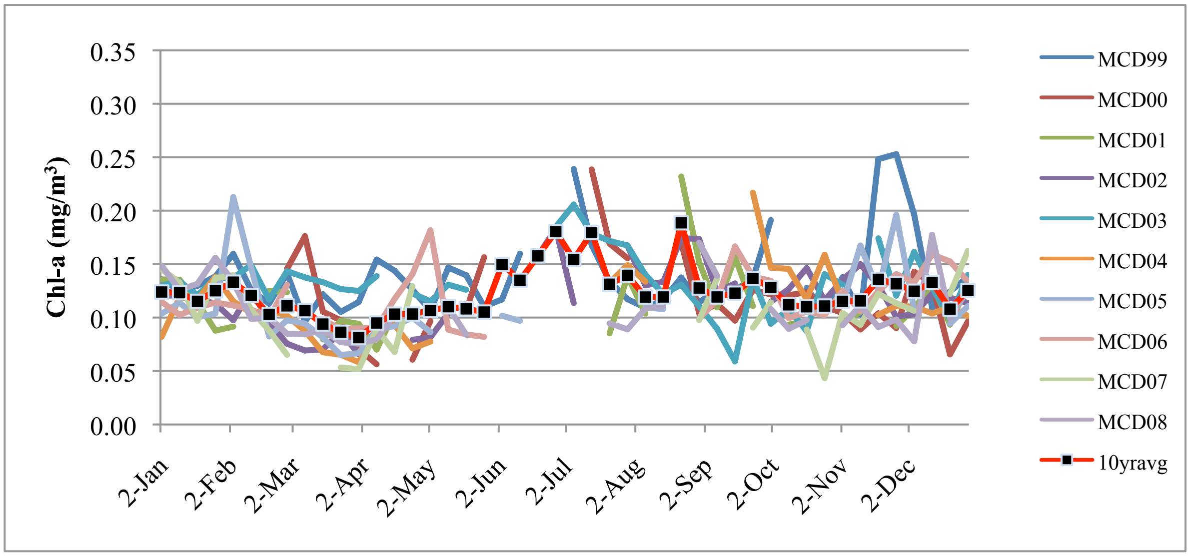


Figure 1.12 Annual (1999-2008) and 10-year mean of satellite derived Chl-a for MCD station off South East Coast St. Thomas, USVI

The MCD showed lower Chl-a values than those in Puerto Rico with a highest annual mean of 0.14 mg/m^3 in 1999, comparable to that described at LB in St. Croix.

The MCD is a red hind aggregation site, although there are numerous other fish that use the same area for spawning (Nemeth 2005), or are permanent residents. Kruskal-Wallis results ($p < 0.001$) and the multiple pairwise comparisons using the Steel-Dwass-Critchlow-Fligner procedure/Two-tailed test showed significant differences among various years (Table 1.21).

Table 1.21 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between years at MCD

	MCD99	MCD00	MCD01	MCD02	MCD03	MCD04	MCD05	MCD06	MCD07	MCD08
MCD99	**1**	0.206	**0.009**	0.351	1.000	**0.040**	**0.001**	0.057	**0.049**	**0.001**
MCD00	0.206	**1**	1.000	1.000	0.327	1.000	0.987	1.000	0.999	0.975
MCD01	**0.009**	1.000	**1**	0.994	**0.038**	1.000	0.999	0.999	1.000	0.992
MCD02	0.351	1.000	0.994	**1**	0.244	0.993	0.700	1.000	0.983	0.750
MCD03	1.000	0.327	**0.038**	0.244	**1**	0.066	**0.006**	0.127	0.068	**0.004**
MCD04	**0.040**	1.000	1.000	0.993	0.066	**1**	0.992	1.000	1.000	0.995
MCD05	**0.001**	0.987	0.999	0.700	**0.006**	0.992	**1**	0.904	1.000	1.000
MCD06	0.057	1.000	0.999	1.000	0.127	1.000	0.904	**1**	0.992	0.784
MCD07	**0.049**	0.999	1.000	0.983	0.068	1.000	1.000	0.992	**1**	1.000
MCD08	**0.001**	0.975	0.992	0.750	**0.004**	0.995	1.000	0.784	1.000	**1**

Note: p values in bold are significant at $\alpha = 0.05$

The year 1999 was significantly different from all other years in the time series at the MCD, namely 2001, 2005, 2007 and 2008. The least variable years were 2000, 2002 and 2006. The highest annual mean was recorded in 1999 with the second highest in 2003. Smith *et al.* (2010) reported a period of warm waters at the MCD in 2007, however, the massive bleaching event did not occur in that year but rather in 2005 (Eakin *et al.* 2012). The only noticeable peak during the early part of the year was in February 2005. The MCD showed variability between years that could be influenced, as in St. Croix for example, by inflow of waters from the South America Rivers, eddies or local rain events. In 2003, there were no storms within 2° of latitude from the USVI. The MCD as well as the other areas could, however, still be impacted by storms or hurricanes farther away.

Control Sites

Finally, the areas where spawning of reef fish has not been documented, where depths are beyond 100 m and that are located more than 40 km offshore are described in Figures 1.13 and

1.14. Tables 1.22 and 1.23 summarize the information for the 10-year time series and include the information from 2009 that is further discussed in Chapter 2.

Table 1.22 Annual average of satellite derived Chl-a (mg/m^3) at Sastre

SASTRE	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.067	0.017	0.041	0.109	5	41	14-Sep	17-Sep	1st Q
2000	0.055	0.016	0.031	0.088	6	33	27-Jul	24-Jul	Last
2001	0.049	0.015	0.015	0.078	6	33	11-Dec	14-Dec	New
2002	0.052	0.015	0.034	0.084	9	35	17-Jan	21-Jan	1st
2003	0.075	0.015	0.046	0.105	9	44	5-Aug	5-Aug	1st
2004	0.054	0.017	0.026	0.087	9	27	15-Oct	14-Oct	New
2005	0.057	0.016	0.038	0.093	9	29	19-Dec	23-Dec	Last
2006	0.062	0.016	0.030	0.091	4	31	17-Jan	14-Jan	FULL
2007	0.057	0.021	0.018	0.107	9	28	9-Jan	11-Jan	Last
2008	0.053	0.013	0.028	0.087	9	35	26-Dec	27-Dec	New
2009	0.065	0.032	0.034	0.225	9	34	21-Aug	20-Aug	New
11 yr avg	0.059	0.020	0.015	0.225		370	2009		
10 yr avg	0.059	0.018	0.015	0.109		336	1999		

Table 1.23 Annual average of satellite derived Chl-a (mg/m^3) at Atlantic

ATLANTIC	Annual avg	SD	Min	Max	n pixels	n images	Date max	Moon max	Phase
1999	0.082	0.032	0.011	0.185	5	42	26-Jun	28-Jun	FULL
2000	0.064	0.023	0.034	0.161	4	26	27-Jul	24-Jul	Last
2001	0.058	0.015	0.026	0.096	9	37	25-May	23-May	New
2002	0.062	0.035	0.024	0.232	3	36	4-Jul	10-Jul	New
2003	0.065	0.039	0.028	0.258	9	42	4-Jul	7-Jul	1st
2004	0.060	0.036	0.034	0.216	2	29	11-Jul	9-Jul	Last
2005	0.055	0.010	0.036	0.070	2	28	9-Jan	10-Jan	New
2006	0.059	0.014	0.035	0.098	8	28	13-Aug	16-Aug	FULL
2007	0.084	0.087	0.024	0.464	2	32	28-Jul	30-Jul	FULL
2008	0.047	0.012	0.016	0.070	9	38	1-Jan	31-Dec	Last
2009	0.089	0.105	0.041	0.618	3	33	27-Jul	28-Jul	1st Q
11 yr avg	0.066	0.048	0.011	0.618		371	2009		
10 yr avg	0.064	0.038	0.011	0.464		338	2007		

avg	Average
SD	Standard deviation
Min	Minimum
Max	Maximum
n	Number
Date max	Calendar day when max Chl-a was detected
Moon max	Moon phase date closest to max Chl-a
Note:	1st and Last represent First and Last Quarters of the moon phase

Weekly values for the two control sites in the Atlantic (Figures 1.13 and 1.14, Atlantic and Sastre stations, respectively) reached a maximum value of 0.11 mg/m^3 at the Sastre station

(1999) and 0.46 mg/m^3 at Atlantic Station (2007). Justiniano (2010) discussed the conditions at these two stations and the atmospheric factors that influence the variability in the Chl-a signal.

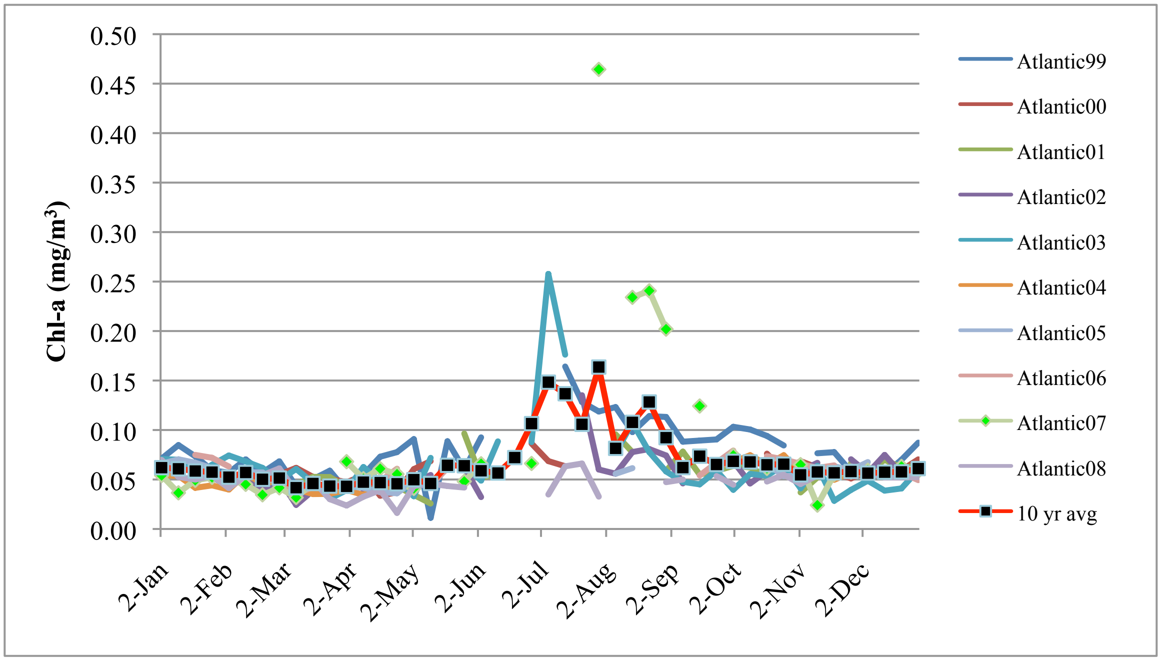


Figure 1.13 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for Atlantic station

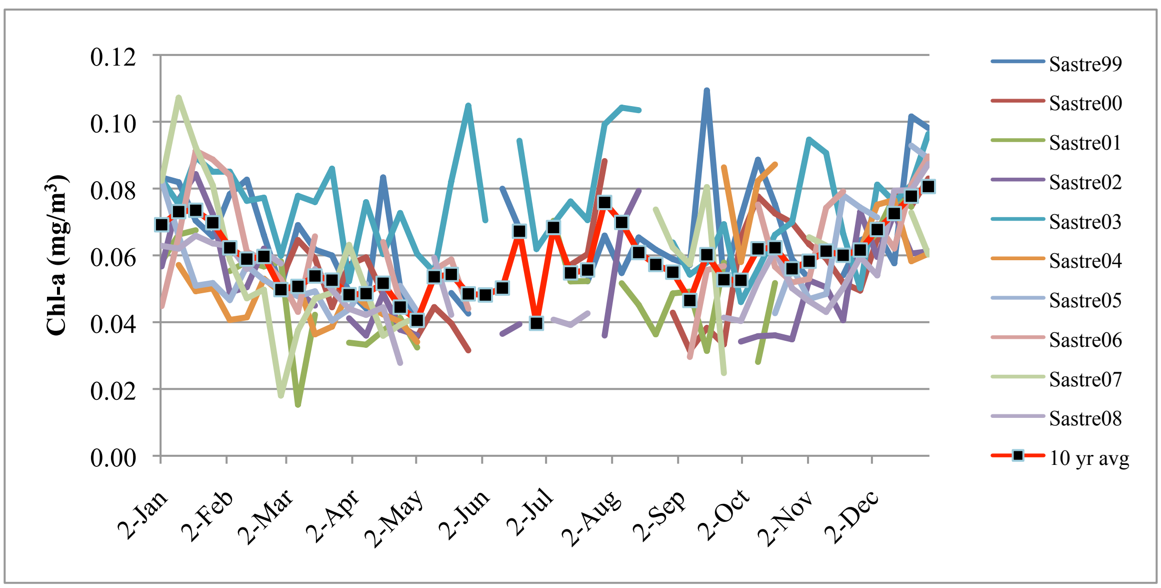


Figure 1.14 Weekly (1999-2008) and 10-year mean of satellite derived Chl-a for Sastre station

Comparison among sites and the various factors impacting these areas

Surface Chlorophyll-a

The variability described in the surface chlorophyll fields at each of the 12 stations, but primarily at the eight spawning sites, represents the dynamic nature of the water column over the aggregation sites. The ranking of the 10-year means (highest to lowest) might be indicative of the geographical closeness to shore and the impacts of river inputs as shown in Table 1.24.

Table 1.24 Ranking of the Sites based on the 10-year Chl-a Means

Rank	Site	Chl-a mean (mg/m3)	Chl-a range (mg/m3)
1	Tourmaline	0.27	0.06-0.74
2	ALS	0.25	0.06-0.60
3	Rene	0.26	0.02-0.74
4	Parguera	0.21	0.09-0.73
5	BDS	0.17	0.05-0.63
6	MUT	0.14	0.04-0.50
7	LB	0.13	0.04-0.43
8	MCD	0.12	0.04-0.29
9	CaTS	0.11	0.04-0.37
10	Pichincho	0.09	0.003-0.27
11	Atlantic	0.06	0.01-0.46
12	Sastre	0.05	0.02-0.11

In addition, four sites had the highest annual mean in 1999 (ALS, MCD, BDS, and Tour), two in 2000 (CaTS and Los Pichinchos), two in 2003 (Parguera and Rene) and two in 2004 (LB and MUT). The 2003 high values could be attributed to the rain events of November especially because these higher values coincided with the rain event. The variability in Chl-a can be best appreciated when all sites are examined together. The means are plotted for all sites (12) and years (1999-2008) in Figure 1.15. The averages ranged between the truly oligotrophic control sites and the more variable sites, from < 0.05 to > 0.3 mg/m^3. There is not a clear distinction between the sites where red hind and the mutton snapper aggregate. Based on the annual Chl-a means, there were no commonalities between these areas. However, there are some of these areas where it is known that other species aggregate for spawning. It would be of interest to have a complete description of all species utilizing these areas to help understand how these are grouped based on Chl-a values.

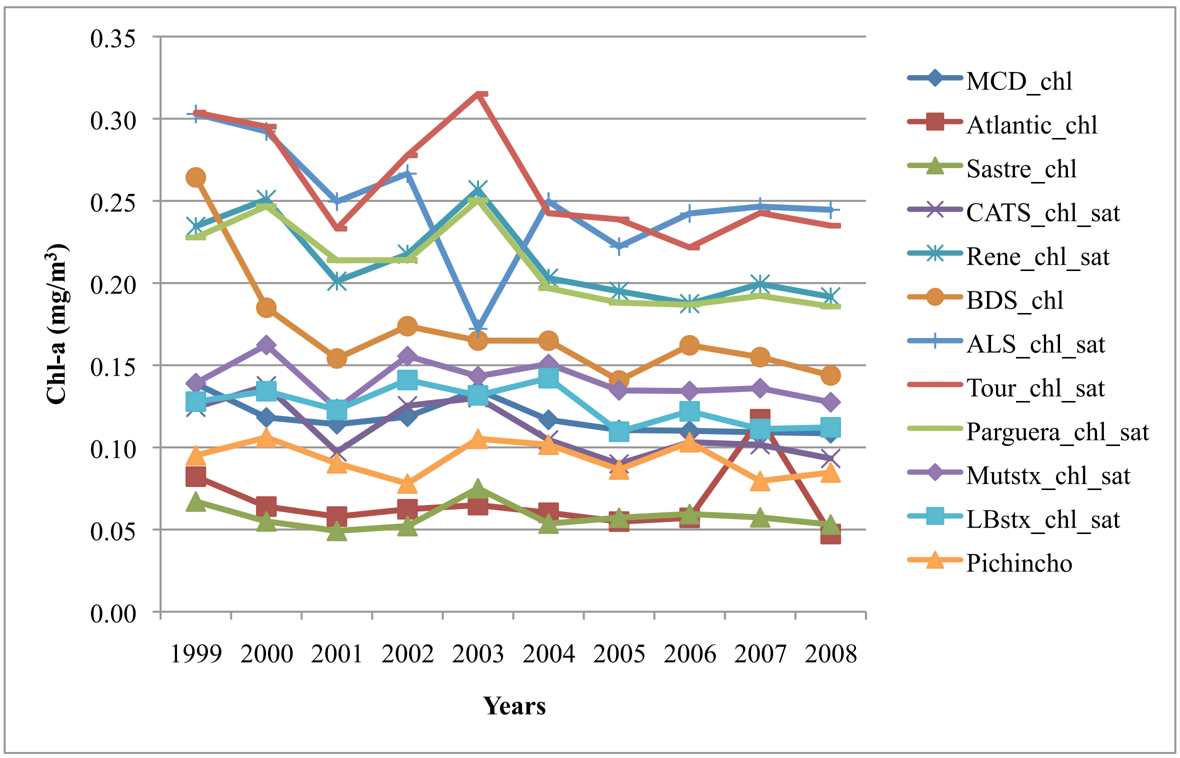


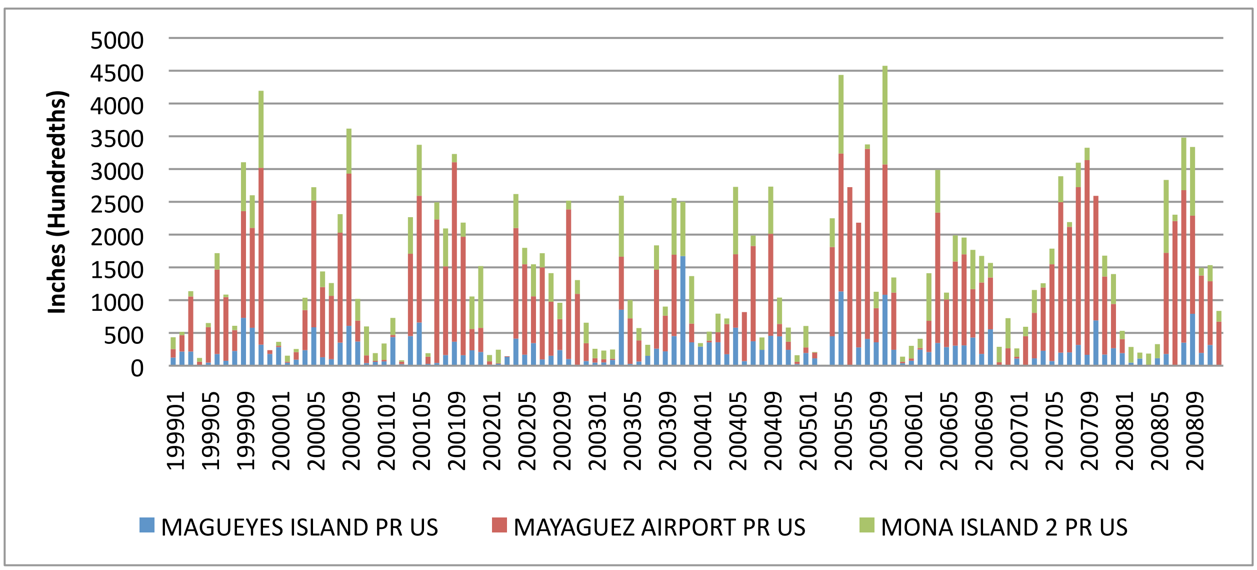
Figure 1.15 Annual Chl-a averages per site (1999-2008)

Rain and Storm Activity

A comparison of the various factors that might influence the observed weekly Chl-a values per year was described for all sites and includes rain events, hurricanes and storms, timing of the full moon, and river water from South America. The information and data on these factors are explored here to describe the changes in the Chl-a observed over the 10 years of data.

The control sites all remained at very low values of satellite derived chlorophyll throughout the year and were only described when there were data to confirm the changes observed. All other sites showed variation throughout the year but not all showed the peaks in chlorophyll at the same time. The year 1999 was described in some detail because it was the year that had the highest means for four of the sites. These descriptions could be developed for each of the 10 years and ideally, the variability in Chl-a would be related to a number of fish aggregations or other events of interest. In 1999, the most significant peak in Chl-a occurred off the Southwest Coast of Puerto Rico at Rene station during the week of June 23, 5 days before the full moon of June 28 and during the peak month of mutton snapper spawning. The increasing trend was also seen in two of the nearby areas, ALS and Tour. Nevertheless, the highest peak at Tour occurred during the week of December 19 (3 days prior to the full moon on December 22) concurrent with the one also observed at BDS. As mentioned previously, December is one of the red hind spawning aggregation months at ALS and Tour. There were no data available on the red hind spawning populations for 1999. The ALS peak occurred during the week of September 3 and could have been associated with a response to the summer dust events and rainfall activity. Nevertheless, there was no spawning in September for either the red hind or the mutton snapper. The Chl-a peaks described herein are 5 times higher than the average recorded for the site. The annual comparisons for each site showed the variability that occurred at each of these sites with the peaks occurring at different times yearly.

Even though information is limited on the changes caused by rain activity on the surface Chl-a regarding fish aggregations, the description of rain events in Puerto Rico described herein were useful to further understand how environmental factors might be influencing fish behavior at these sites. The total monthly precipitation data from the West Coast of Puerto Rico (Mayagüez and Mona) and at the Magueyes stations was examined to determine whether there had been specific rain events (increased runoff, river outflow or localized rain) that could have influenced the Chl-a signal at the aggregation sites. The rain data and documentation were obtained from NOAA (http://www.ncdc.noaa.gov/; http://www.ncdc.noaa.gov/cdo-web/faq_cdo#ANNUAL). Precipitation was reported as total precipitation amount per month (TPCP) and the data from 1999-2008 were examined for the only stations that had sufficient data: (1) Magueyes (17.97°N, 67.046°W), (2) Mona Island (18.1°N, 67.93°W), (3) Mayagüez Airport (18.25°N, 67.15°W), and (4) Rincón (18.34°N, 67.25°W) (Figure 1.16). Mona Island was considered to determine if there were extreme events that might have occurred in the Mona Passage but were not registered on the mainland of PR.



Note: Precipitation is in hundredths of an inch, that is, 5000=50 in.

Figure 1.16 Total Precipitation/Month (1999-2008) at Magueyes, Mayagüez, and Mona Island, PR

The information on the number of storms and hurricanes within two degrees of latitude from Puerto Rico and the USVI was obtained from NOAA (http://www.srh.noaa.gov/sju/?n=tropical02). The following tropical storms and hurricanes passed within two degrees of latitude of Puerto Rico and the U.S. Virgin Islands from 1999 to 2009 (Table 1.25).

Table 1.25 Storms and hurricanes within 2° of latitude of Puerto Rico and the US Virgin Islands

Year	Month	Storm	Hurricane
1999	10	Jose	
	11		Lenny
2000	8		Debby
2001	8	Dean	
2004	9	Jeanne	
2007	8		Dean
	12	Olga	
2008	10		Omar
2009	8	Ana	
	9	Erika	

DATA SOURCE: NOAA (http://www.srh.noaa.gov/sju/?n=tropical02)

Even though there were several named storms in the Atlantic, it should be noted that there were no storms or hurricanes reported for the area between 2002 and 2003 and between 2005 and 2006. For these years, the numbers of named storms in the Atlantic were 12 and 16 in 2002 and 2003, respectively, and 13 and 10 in 2005 and 2006, respectively. The lowest number of named storms occurred in 2009 (nine) and the highest number (16) occurred in both 2003 and 2008. There was an average of 13 named storms overall between 1999 and 2009. During the 10 years of Chl-a data analyzed in this study, there were no major hurricanes making landfall in Puerto and the USVI, as did Hurricane Georges in 1998. Gilbes *et al.* (2001) assessed the impact of Hurricane Georges and concluded that Chl-a concentrations were much higher three days after the hurricane crossed the island (September 25 1998). Filaments of runoff waters, especially to the north of the Island were observed and the conditions did not return to the 10-year average value of Chl-a until October 15, two and a half weeks after the event. As in this study, the possible contamination of runoff waters with sediments and organic matter could not be overlooked. In September 2004, Hurricane Jeanne dropped more than 24 inches (610 mm) of rain over a very short period of time on the Island of Vieques and caused flooding in the USVI (http://www.nhc.noaa.gov/2004jeanne.shtml). However, there were no ocean color images available for the two weeks following the hurricane impact.

Rain episodes appear to play an important role in the variability observed at the spawning aggregation sites such as Tour, Rene, Parguera and ALS. These events can cause large amounts of runoff directly from land or via river overflow (Armstrong and Detrés 2010). In 2003, the highest peaks occurred simultaneously at three of the sites, Rene, Tour and Parguera. These peaks occurred during the week of November 24. The rain information from Magueyes station shows the significant rain event of November 13-15, 2003 (Figure 1.16). Detrés *et al.* (2004) reported on this event and the spatial extent of the rain-induced runoff. The total precipitation registered at Magueyes was the highest over the 10 years of data. Two other rain episodes registered more than 254 mm in total precipitation over a one-month period, in May and October 2005. The May and October 2005 rain events were also recorded at the Mayagüez and Mona stations but with lower precipitation values. These were the only three rain events that were identified as having potential impact on the Chl-a signal.

Rain events also impact the aggregation sites by decreasing the euphotic zone (1% light penetration) due to excessive river runoff. Rivero-Calle (2010) concluded that BDS and La Parguera (except for one transect) exhibited the clearest waters of all the study sites between 2003 and 2008 and Armstrong and Singh (2012) calculated the depth of the euphotic zone of BDS at 109 m. BDS showed the highest values during the week of November 9-15 2005 coinciding with the full moon on November 9. However, the rain station at Mayagüez, the closest to BDS, did not show total precipitation values as high as those recorded at Magueyes. The oceanographic conditions at BDS have been described as having a mixed layer depth of 100 m during the dry season, between January and March and 25 m during the wet season (September to October) (Capella *et al.* 2003). BDS is approximately 25 km west of PR and could be impacted by the rivers off the West Coast – these rivers however were observed to go north, northwest in most of the images showing the river outflow.

These spawning aggregation sites are both deep areas (>30 m) and far from shore (between 8 km– Rene, and 25 km – BDS). These are difficult sites to reach and study by diving on a continuous basis. The water column information from the data gathered through satellite using Chl-a as proxy provides information on the conditions at these sites throughout the year. This Chl-a time series should also help in understanding the condition of the bottom habitat (*e.g.*, percent live coral cover) and to explain the differences or similarities among the spawning sites.

The highest variability of all sites during 2005 was recorded at Tour the week of November 17 and at ALS the week of November 30. Parguera and Rene showed a small increase during the week of October 18. Total precipitation at Magueyes was high during the month of October, but not as high as in November 2003. The peak observed in the Chl-a data coincided with the rain peak of October. Figure 1.17 depicts the rain influence variability at the Rene and La Parguera sites.

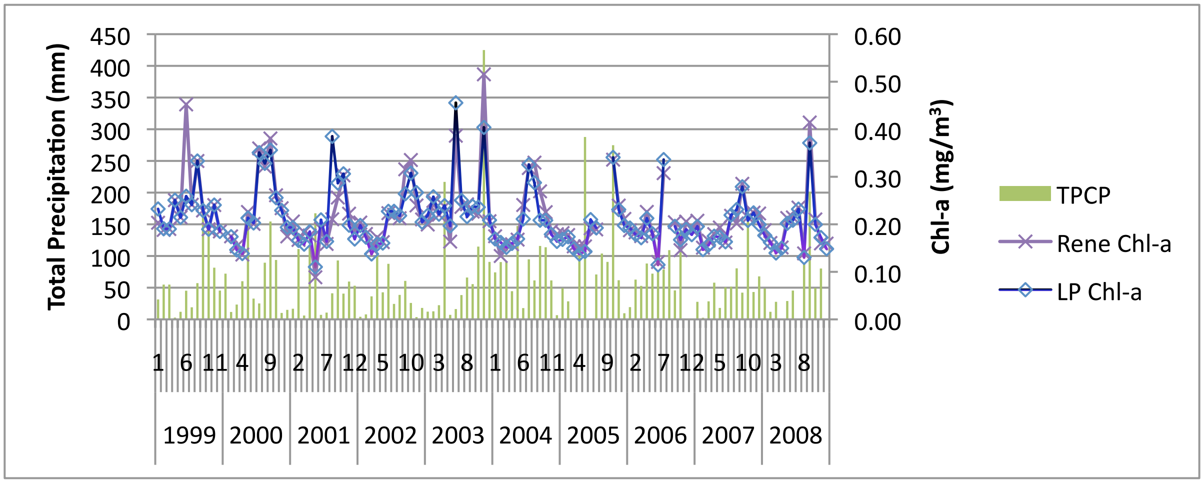


Figure 1.17 Total monthly precipitation (TPCP) at Magueyes and monthly Chl-a averages at Parguera (LP) and Rene (1999-2008)

In 2007, García-Sais *et al.* measured the depth of the euphotic zone at BDS at 70.39 m and compared this measurement to that derived from the MODIS K490 at 62 m. The report indicates that September, the month when the measurements were made, is when BDS is most impacted by terrigenous material as a result of hurricanes (hurricane season runs from June 1 through November 1, with average peak activity in August-September). A chlorophyll profile from a CTD cast at BDS during June 2007 (García-Sais *et al*. 2007) showed values ranging between 2 and 3 mg/m^3 over the first 5 m depths as well as a temperature decline from 28.85°C at the surface to about 27.3°C at 52 m.

Data for Los Pichinchos was collected during October 2007 (Corredor 2008) from a long-range glider-type autonomous underwater vehicle deployed in the Mona Channel. A train of internal waves was recorded impinging upon Los Pichinchos and data recorded at latitude 18° 22.23’ N and longitude 67° 45.39 W during October 29 and 30 show a range of surface chlorophyll values between 0.3 and 0.9 mg/m^3 (unpublished data from J. Corredor). The Chl-a values derived from OCR for the week of October 24 and November 1 2007 varied between 0.08 and 0.09 mg/m^3.

In 2008, there were two episodic events of unprecedented rain registered at the Rincón station in May and December. These rains were also registered at the station in Ponce. Peaks in rain during 2008, although not as high, were recorded at the Magueyes station during September.

Spawning Sites Differences and Similarities

The 10 year means were compared among all areas and the results showed that these were significantly different (Kruskal-Wallis p <0.0001) and specifically there were significant differences among most stations as detected by a multiple pairwise comparisons using the Steel-Dwass-Critchlow-Fligner procedure (SDCF) (Table 1.26).

Table 1.26 Table of p values from the Steel-Dwass-Critchlow-Fligner procedure to determine differences between sites

	MCD10	Parguera10	Tour10	ALS10	BDS10	LB10	MUT10	Rene10
MCD10	**1**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.855	**0.002**	**< 0.0001**
Parguera10	**< 0.0001**	**1**	**< 0.0001**	**0.001**	**0.001**	**< 0.0001**	**< 0.0001**	1.000
Tour10	**< 0.0001**	**< 0.0001**	**1**	0.840	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.000**
ALS10	**< 0.0001**	**0.001**	0.840	**1**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.005**
BDS10	**< 0.0001**	**0.001**	**< 0.0001**	**< 0.0001**	**1**	**< 0.0001**	**0.000**	**0.000**
LB10	0.855	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**1**	0.329	**< 0.0001**
MUT10	**0.002**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.000**	0.329	**1**	**< 0.0001**
Rene10	**< 0.0001**	1.000	**0.000**	**0.005**	**0.000**	**< 0.0001**	**< 0.0001**	**1**

Note: p values in bold are significant at $\alpha = 0.05$

The grouping of these areas was obtained by comparing the 10-year means using this statistical procedure (SDCF). These results highlighted the differences in the mean Chl-a fields in all these areas over a 10-year period. The results showed that BDS was significantly different from all other spawning sites, including ALS and Tour, which are also areas that are located on the West Coast where red hind aggregate for spawning. The difference might be that BDS could have less influence from rivers since it is also the farthest from shore. The BDS is due west of the mouth of the Rio Grande de Añasco but the influence of this river on BDS was never observed on the satellite imagery examined. In most cases the river outflow veered north. The USVI sites (MCD, LB) were more similar to each other than to the other sites and were also not influenced by local rivers. Rene and Parguera grouped together and were significantly different from all other sites. ALS and Tour were similar to each other and significantly different from all other areas. The relationship among these areas is summarized in Table 1.27. It was not expected to find BDS so significantly distinct from the other spawning sites on the West Coast as it was thought that these areas would be connected given their geographic location. The Chl-a signal derived from OCR provides a tool to track the plumes and fronts and the data could be examined further to confirm or deny the lack of connectivity determined in this study.

Table 1.27 Results from the SDCF procedure to determine similarities between sites

Sample	Frequency	Sum of ranks	Mean of ranks	Groups				
MCD10	46	2739.000	59.543	A				
LB10	45	3615.000	80.333	A	B			
MUT10	46	5104.000	110.957		B			
BDS10	46	7751.000	168.500			C		
Parguera10	46	10557.000	229.500				D	
Rene10	46	10826.000	235.348				D	
ALS10	46	13139.000	285.630					E
Tour10	46	13797.000	299.935					E

There were a number of factors that could have influenced the data sampled from satellite images. One of these was the number of pixels used to obtain the mean. Establishing the relationship (correlation coefficient) between the number of pixels and the mean value obtained tested this. There was no significant correlation ($r^2 = 0.0102$) between the number of pixels sampled per area and the maximum mean of Chl-a obtained. Therefore, the minimum usable number of 3 pixels per sampling was acceptable.

Rate of Change in Chlorophyll-a

The time series described in this study showed fluctuations in the Chl-a surface values at these sites. Although there were gaps in the data there were periods of time when the data were continuous and the change at these sites could be calculated.

The change in Chl-a from one week to the next at each of these sites was noticeable for an oligotrophic environment because there was more variability in the water column than would be expected in such an environment. The significant results of the comparison of Chl-a values indicated that the conditions at the spawning aggregation sites vary but there was no further examination of this variability in relation to seasonality, temperature or other parameters at the spawning sites. Hamner and Largier (2012) recently reviewed the oceanographic features that could influence the dispersal of eggs and larvae from aggregation sites, including the importance of larval first-feeding and chlorophyll layers. This work thus identified Chl-a as an additional parameter (Chl-a) that could be used to characterize the spawning aggregation sites. Correlation of Chl-a to, for example, larval densities, fish population densities at the spawning sites or with the actual spawning activity would require more analyses. The 8-day satellite image composites allowed for a more complete series that could be analyzed by looking at the changes in this Chl-a field from week to week. The sites are exposed to the water currents that continuously move through them. The water column environment then is not necessarily homogenous nor is it the same over periods of time. Therefore, the pattern of chlorophyll distribution from week to week was explored to determine its rate of change and corresponding yearly variations. The change experienced at these sites was expressed as the change in Chl-a from week 1 to week 2 by this rate of change or $DELTA_{Chl\text{-}a\_sat}$ (DELTA).

Where:

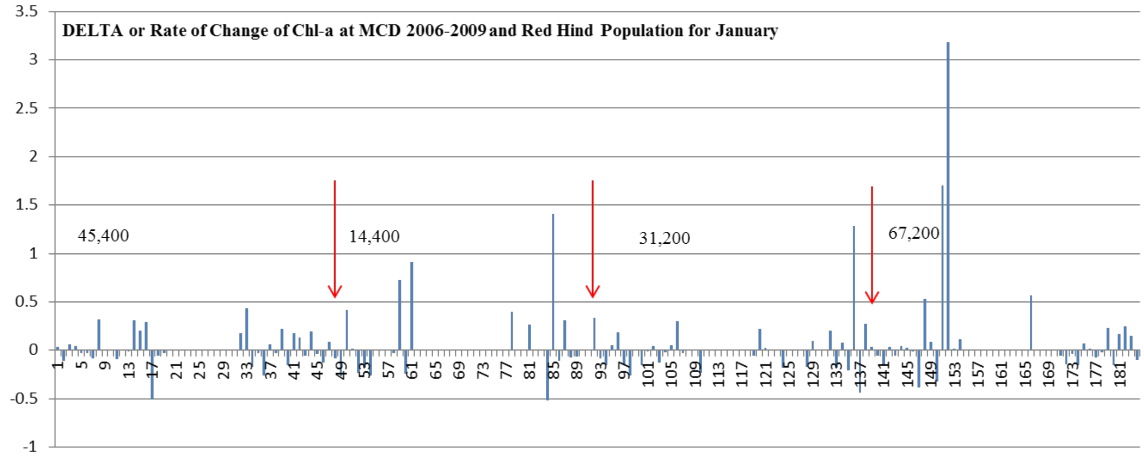
$DELTA_{Chl\text{-}a\_sat}$= [(Chl-a_sat/week2) - (Chl-a_sat/week1)]/absolute (Chl-a_sat/week1) (1.3)

The functionality of chlorophyll is dependent on light and movement of water among other factors. The phytoplankton that serves as food during larval development has to be present for larvae to survive. The hatching of red hind eggs is rapid and larvae feed within the first 48-72 hours (*e.g.*, Colin *et al*. 1987, Tucker 1994, Ojeda-Serrano *et al.* 2007). In general, depending on the species, larvae feed within 5 days of hatching. The main source of food is micro zooplankton and many feed on phytoplankton. DELTA has not been described in relation to fish spawning and larvae survival. The red hind is the only fish for which there is a long time series of spawning fish population density estimates at MCD. Therefore, it was used as an example to correlate Chl-a changes with the size of the spawning populations.

DELTA was calculated for the entire time series (1999-2009) at MCD where red hinds are continuously monitored and data were available. The missing values were not interpolated due to large gaps in the data. DELTA was only explored for periods of time that have continuous weekly means from December through February when red hind spawn. The DELTA (Figure 1.18) in 2006 and 2009 was much more variable during the latter part of the year and the most notable change occurred in December 2008 (Table 1.28). This month showed the highest DELTA in Chl-a, expressed as percent change of between +128.17 (December 12) and - 43.98% the following week. The red hind population in January 2009 was estimated at 67, 200, which was a two-fold increase relative to the previous year. Nevertheless, the information presented here was based on what Nemeth described as the peak spawning month for red hind (*e.g.*, Nemeth 2005) and did not take into account the densities from the aggregations of December and February. This idea was not explored further in this study but is currently being discussed with

Nemeth (R. Nemeth 2013, pers. comm.) to include all the data available on red hind densities. These changes might not occur at the same time every year, as in this example. The proposed impact of changes in the Chl-a field as a cue to spawn will require further testing.

The information from the literature regarding population size estimates of red hind at spawning sites over a long period of time is limited. Nemeth (2005, 2008, pers. comm.) has been monitoring the red hind populations at the MCD since 1999. It was proposed in this study that the red hind populations should have been higher when DELTA was highest (December 2008). The population densities obtained from the literature and from R. Nemeth (Nemeth 2005, Nemeth *et al.* 2008, unpublished data, pers. comm.) were used to calculate numbers of red hind within the spawning area (0.24 km^2) at MCD for the peak month of January between 2000 and 2009. These red hind population densities were compared to DELTA and a relationship between these two variables was noted since the population size increased with the increasing DELTA. There were differences among the years as seen in Figure 1.18 where the arrows indicate the end of a year and the numbers represent the red hind population size for January of the following year. The greater the change in Chl-a and the closer this change takes place to the spawning moon, the more fish will be expected to be found at the aggregation. This would have to be tested further by including the red hind densities at MCD over the entire spawning period December through February from 1999 to 2009. In 2009, a drastic change of + 318.21 (Weeks 149-153) corresponded to an anomaly due to an unprecedented green water event from a South American River plume (see Chapter 2). It should be noted that in 2001, another change of similar magnitude in DELTA was observed at ALS. An increase of +285% was obtained during the last week of December and coincided with the red hind spawning. Nevertheless, DELTA could not be compared to the population estimate because these data were not available.



Note: y-axis = changes in Chl-a in mg/m^3 x-axis = weeks

Figure 1.18 DELTA$_{Chl\text{-}a_sat}$ calculated for 2006 through 2009 at MCD

Table 1.28 Rate of Change (DELTA) for Chl-a at MCD

Year	Month	Week interval	DELTA Range	Red Hind Population[1]
2006	January	1 - 6	-10.57 - +6.34	45,400
	December	43 - 46	-12.36 - +19.77	
2007	January	47 - 50	-27.01 - +41.10	14,400
	December	89 - 92	+33.09	
2008	January	93 - 97	-15.44 - +18.51	31,200
	December	134 - 138	-43.98 - +128.17	
2009	January	139 - 143	-16.54 - +3.47	67,200

[1]Red hind population estimates were calculated based on red hind transect data from Nemeth 2005 and unpublished data, pers. comm.

These results suggest analyses are needed to determine if the rate of change or DELTA could be a useful parameter in describing changes in the water column during the time of spawning. The mechanisms that could be responsible for these changes were not evaluated in this study. The significance of these changes in Chl-a resides in the potential that this could have as a signal of food availability in an otherwise oligotrophic environment.

Comparison of Spawning Sites

The annual means of the six sites (ALS, BDS, Tour, Parguera, MCD, LB) where red hind specifically aggregate for spawning were compared to determine if these areas were significantly different from each other. These six sites were also compared to the two mutton snapper aggregation sites (MUT, Rene) using surface-satellite derived chlorophyll. First, in comparing the red hind aggregations between 1999 and 2008 there were three distinct groups. The differences were tested using the Kruskal-Wallis test ($p < 0.0001$) and the grouping determined by multiple pairwise comparison using the SDCF procedure at an alpha=0.05. The results obtained were summarized in Table 1.29.

Table 1.29 Table of p values from the Steel-Dwass-Critchlow-Fligner procedure

	MCD_chl	BDS_chl	ALS_chl_sat	Tour_chl_sat	Parguera_chl_sat	LB_chl_sat
MCD_chl	**1**	**0.002**	**0.002**	**0.002**	**0.002**	0.657
BDS_chl	**0.002**	**1**	**0.024**	**0.011**	**0.030**	**0.004**
ALS_chl_sat	**0.002**	**0.024**	**1**	1.000	0.241	**0.002**
Tour_chl_sat	**0.002**	**0.011**	1.000	**1**	0.058	**0.002**
Parguera_chl_sa	**0.002**	**0.030**	0.241	0.058	**1**	**0.002**
LB_chl_sat	0.657	**0.004**	**0.002**	**0.002**	**0.002**	**1**

Note: p values in bold are significant at $\alpha = 0.05$

The MCD and LB were similar but significantly different from BDS, Parguera, ALS, and Tour. BDS was the only site that was significantly different from all the other red hind spawning sites tested. Parguera, ALS and Tour were not significantly different from each other and thus were grouped together.

Second, there were significant differences between the mutton area in St. Croix (MUT) and the mutton area off the Southwest Coast of Puerto Rico (Rene) (Page test, $p < 0.002$).
These known spawning areas, both for red hind and mutton show significant differences even when these serve the same purpose. The variability of the sites could be explained by a number of environmental phenomena that impact the areas differently. The variability observed could

respond to, for example, (1) the fertilization of the oligotrophic waters by the African dust storms (Justiniano 2010), (2) the advance of the Orinoco River waters when the variability is observed in the latter part of the year, (3) the contribution from storm events (hurricane season runs June 1-November 30 and September is usually the stormiest month), (4) other confounding variables such as rain (wet season runs May-June; November), (5) local river runoff, and (6) the passage of eddies. Table 1.30 summarizes the potential forcing factors (on average) of the significant variability observed at the fish spawning aggregation sites of Puerto Rico and the US Virgin Islands.

Table 1.30 Environmental forcing factors on Chl-a signal. Times of the year when the various atmospheric and oceanographic phenomena impact the study sites. Additionally, there are currents that allow for waters from the Atlantic to enter the Caribbean and vice versa.

<table>
<tr><th></th><th>January</th><th>February</th><th>March</th><th>April</th><th>May</th><th>June</th><th>July</th><th>August</th><th>September</th><th>October</th><th>November</th><th>December</th></tr>
<tr><td>Hurricane</td><td></td><td></td><td></td><td></td><td></td><td colspan="6">Peak</td><td></td></tr>
<tr><td>Fronts</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Fronts</td></tr>
<tr><td>Rain</td><td colspan="4">Dry Season</td><td></td><td></td><td></td><td colspan="3">Wet Season</td><td></td><td></td></tr>
<tr><td>Aerosols</td><td></td><td></td><td></td><td></td><td></td><td colspan="3">Aerosols</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Spawning</td><td colspan="3">RED HIND SPAWNING</td><td colspan="4">MUTTON SNAPPER SPAWNING</td><td></td><td></td><td></td><td></td><td>RED HIND</td></tr>
<tr><td>Orinoco</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Fall</td><td></td><td></td></tr>
<tr><td>Amazon</td><td></td><td></td><td></td><td></td><td colspan="2">Spring</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Eddies</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="6">Eddies</td></tr>
<tr><td>Chl-a</td><td colspan="2">MINIMUM Chl-a</td><td></td><td></td><td></td><td colspan="3">MAXIMUM Chl-a</td><td></td><td></td><td></td><td>MINIMUM Chl-a</td></tr>
<tr><td>Waves</td><td></td><td></td><td colspan="7">Waves</td><td></td><td></td><td></td></tr>
<tr><td>Wind</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Wind peak</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Salinity</td><td></td><td colspan="3">MAXIMUM</td><td></td><td></td><td></td><td></td><td colspan="2">Minimum</td><td></td><td></td></tr>
<tr><td>Temperature</td><td colspan="2">MINIMUM</td><td></td><td></td><td></td><td></td><td></td><td colspan="3">Maximum</td><td></td><td></td></tr>
</table>

Time Series Analysis

The 10-year data of weekly Chl-a values derived from OCR was evaluated for a time series analysis. The data, as determined in the previous section, showed that: (1) Chl-a values within the range of those measured *in situ* (no outliers); (2) peaks and valleys or highs and lows with some indication of periodicity and frequency. There was more variability and higher Chl-a values during the latter part of the year and during the June-September period in almost every station and every year (Figures 1.3-1.14); and (3) data appeared to be trending. To further explore these three findings, and to establish if there was seasonality or trending in the surface Chl-a of the spawning aggregation sites, time series/spectral analyses were done. Justiniano (2010) described the climatology at the control sites and was able to identify the seasonality and trends by spectral analyses since the data sets had less missing values than the data sets used in this study. Nevertheless, gaps in the data precluded further development of the time series analysis without using complicated interpolation techniques, which would result in questionable biological explanations (P. Yoshioka 2013, pers. comm.).

Numerous attempts were made at interpolating missing data. These gaps in the data were addressed by: (1) replacing the missing values with (a) the average from the 10 year weekly averages, (b) the 10 year average, (c) generating random numbers based on the 10 year distribution of values, (d) the annual mean and e) using both MATLAB and Excel-XLSTAT to interpolate with packaged routines commonly used. The results discouraged the use of interpolation of the data because: (1) the gaps in the data were too large to have confidence in the interpolated values, and (2) the results could not be corroborated since *in situ* data was generally not available to validate these.

The gaps in the data varied between a minimum of one missing weekly value to a maximum of 10 consecutive weekly values missing in a number of years. There were between 77 (Pichincho) and 140 (LB) missing data points (max=460) from the 10-year time series. Overall, the percentage of missing values was very high and varied between 10 and 46%. There were six to 10 consecutive images missing for most sites in 2000, 2005 and 2006. This prevented further time series analysis since the oceanographic processes of interest impacting these areas are resolved in time scales much less than six to nine weeks. There are solutions to the problem of missing data but these were not explored further at this time. Nevertheless, the climatology of the 10-year time series served as the first description of the water column at each of the spawning sites using the satellite derived Chl-a as proxy.

1.4 Conclusions

The 10-year time series (1999-2008) of surface Chl-a description of average conditions at eight fish spawning aggregation sites was developed for Puerto Rico and the US Virgin Islands. The climatology was also developed for the control site known as Los Pichinchos, Puerto Rico.

Results obtained from this investigation did not support the null hypothesis that there was no seasonality in the Chl-a signal at the spawning sites. The proposed alternate hypothesis stated that there would be seasonality at the sampling sites has to be accepted. However, the expectation of high variability of Chlorophyll-a concentrations during the spawning season at the aggregation sites of red hind and mutton snapper was not fulfilled. To the contrary, the ocean color radiometry data showed that there was a very stable low chlorophyll signal at the spawning aggregation sites between January and June each year with very marked changes in Chl-a values during July through December outside the spawning seasons of both species. The only deviation from this observation was found during the month of June when a marked increase in Chl-a was noted at the mutton snapper sites (MUT, Rene) and LB and MCD. This could indicate that the red hind (December-February) and the mutton snappers (March-June) might be responding differently to the Chl-a signal.

The common assumption is that a food source should be present when fish spawn so that first feeding larvae have a better chance of survival. The fisheries literature refers to the presence of chlorophyll as indicative of food availability for the larvae. Nevertheless, results from this study place the red hind and mutton snapper spawning during the winter season, which is characterized by highly stable oceanographic conditions associated with the cold and dry season of the North Caribbean region and its positioning north of the Inter-Tropical Convergence Zone. This implies that there is a marked influence by the highly oligotrophic waters of the North Central Atlantic Ocean and predominantly by the Sargasso Sea, which in turn would minimize any influence by the major South American Rivers in the North Caribbean region.

Although there was significant interannual variability, the lowest 10-year monthly averages of Chl-a for all 12 sites were recorded during the months of January through June coincident with the months of spawning by groupers and snappers. This variability could be explained by a number of exogenous factors such as river and rain runoff and the presence of South America River waters, important in the geographic clustering of the spawning sites. Contrary to the proposed hypothesis that there were no significant differences in Chl-a concentrations among the sites, results showed that Bajo de Sico was the only site significantly different from all the other spawning sites.

An unexpected finding of this study was that fish abundance at the aggregation sites was negatively correlated to Chl-a. The rate of change in Chl-a from week to week (DELTA) indicated that, at least for the MCD and the red hind, the stability in the Chl-a signal appeared to be inversely proportional. That is, the smaller the change in Chl-a, the higher the number of red hind at the site. This suggests that other factors exist that are of potentially greater importance than food availability for the larval survival of these two species. Some of these factors, which could be worthy of further exploration, include the higher water transparency as an advantage for prey capture by larvae, a stable food supply potentially associated with the food web based on molecular Nitrogen-fixing cyanobacteria, and/or the reduction in metabolic expenditure associated with the relatively lower temperatures and stable salinities found off the coast during the winter and spring in the North Caribbean Sea. The follow-up work would require identification of the food source available for the first feeding larvae. Research to be conducted should include determining the spatial and temporal distribution of, for example, *Trichodesmium* spp.

The findings in this study contributed to the understanding of the Chl-a as proxy for food at the fish spawning aggregation sites, the description of the water column at these sites and the changes in the Chl-a fields over time as well as the differences between sites.

CHAPTER 2 . Unprecedented Green Water Intrusions of South American River Waters into the Northeastern Caribbean Sea

"Similar events had been seen before but never as intense as this year " (W. Ledee 2009, commercial lobster fisherman, St. Thomas, pers. comm.)

2.1 Introduction

Background

An unprecedented green water event of notable extent and magnitude took place in the Caribbean impacting the US Virgin Islands and Puerto Rico from April-June 2009. This "green water" event was reported on April 10, 2009 by a commercial fisher from St. Thomas, USVI (W. Ledee 2009, commercial lobster fisherman, pers. comm.) and elicited the near real time documentation of the origin, spread, dispersal and impacts of this large input of river and Atlantic waters into the Caribbean. This green water event was attributed to the outflow of the Amazon River (Plates 1-10). The signal of this event was detected at most of the sampling sites around Puerto Rico and the US Virgin Islands as described by the Chl-a anomaly. This anomaly resulted in much higher values than average at eight of the twelve sites. The extent and magnitude of this Amazon intrusion had not been seen in the past 45 years as reported by seafarers. Do Vale *et al*. (2011) reported that the 2009 rain in the Amazonia resulted in the Óbidos centennial flood. Marengo *et al*. (2012) compared the flood of 2009 to previous floods in 1989 and 1999 and concluded that the 2009 flood was indeed an extreme event. Consequently, this event in South America resulted in an unprecedented Amazon River green water intrusion into the Northeastern Caribbean. The interest of the public in this event was so significant that it resulted in a short film by NASA.

NASA produced this movie (http://www.globcolour.info/gallery.html; USC_animation_2_CHL1_meris_modis_seawifs) to show the influx of Amazon-Orinoco River waters into the Caribbean utilizing images from MODIS, MERIS and SeaWiFS and includes data from 1998 through 2009. The movie was obtained from the GlobColour archive using 8-days composite AVW Chlorophyll-a case I water products. The movie was used for visualization purposes only but facilitated the tracking the signals from various sources of water influx into the Caribbean. Figures 2.1-2.10 show the progression of the green water event of 2009. The figures clearly show the presence of this event in other years and, as shown in this work (Chapter 1), the South America River intrusion events were never as impressive as in 2009. *In situ* data for 2009 confirmed the high values of chlorophyll detected by the sensor (See *in situ* data and Field Observations Section). The film featured the historical satellite imagery showing the dispersal of South American River water through the Caribbean and beyond from 1998 to 2009 (http://www.globcolour.info/gallery.html and follow the link to USC_animation_CHL1). Figures 2.1-2.10 were obtained and evaluated from this film to illustrate the origin, magnitude and extent of the influx of Amazon-Orinoco waters into the Caribbean.

The NASA products (Figures 2.1-2.10) showed a massive outflow of the Amazon River off the coast of Brazil, which coincided with the heavy rains, reported for the area. This outflow appeared to be of higher magnitude than that of the Orinoco River

In January there were no oceanographic phenomena impinging on the areas in the US Caribbean (Figure 2.1). Although there appeared to be marked outflow from the Orinoco at the end of January, the flow remained to the South of Puerto Rico and the US Virgin Islands (Figure 2.2).

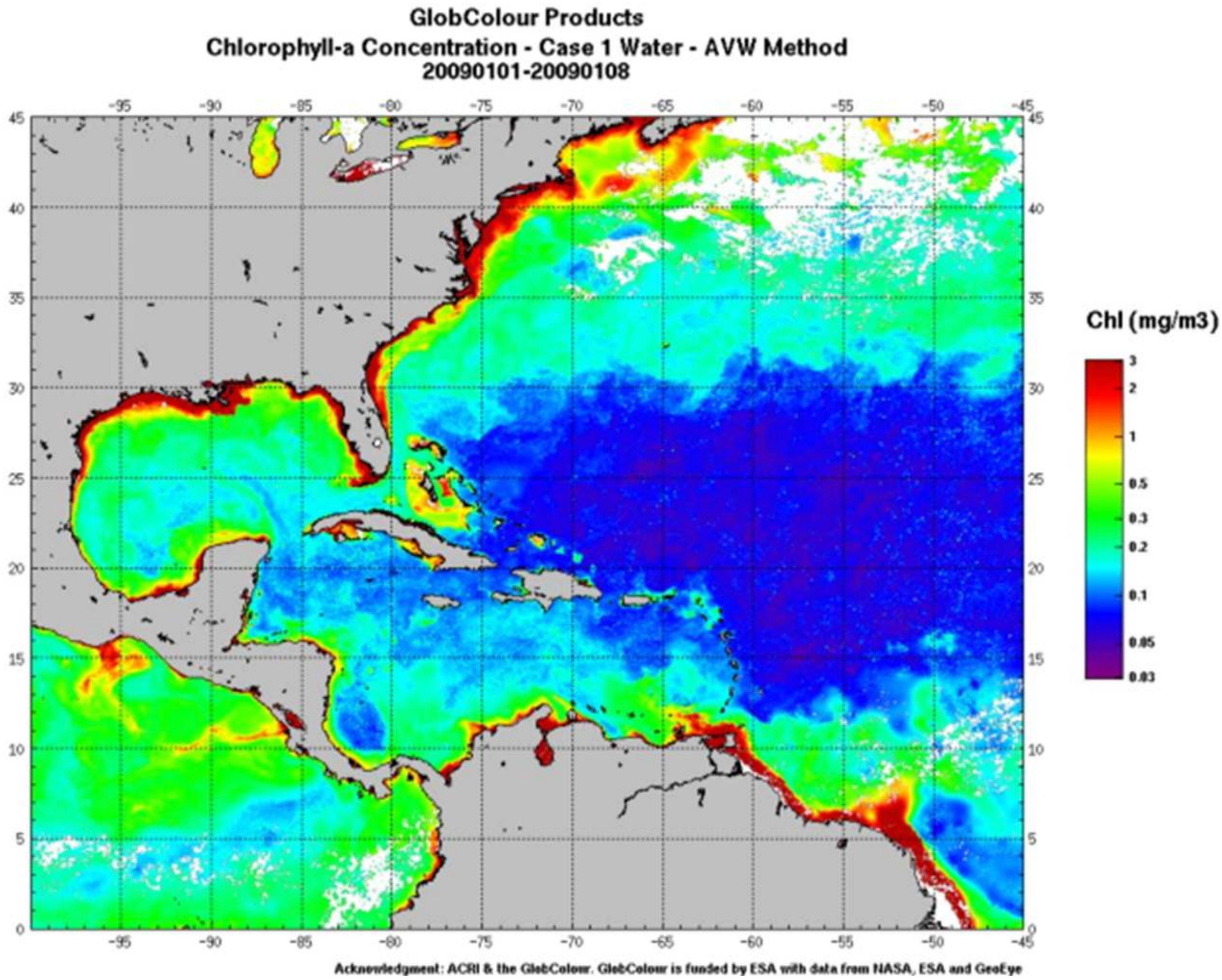


Figure 2.1 Ocean color view of the area between the cloud-covered mouth of the Amazon River and the Gulf of Mexico. The delta of the Orinoco River is also visible. Puerto Rico and the US Virgin Islands are almost in the center of the image. This is the same orientation for all Figures (2.1-2.10). The Chl-a values are shown in the bar to the right. Values are less than 0.1 mg/m^3 around Puerto Rico and the USVI. Dates: January 1-8, 2009.

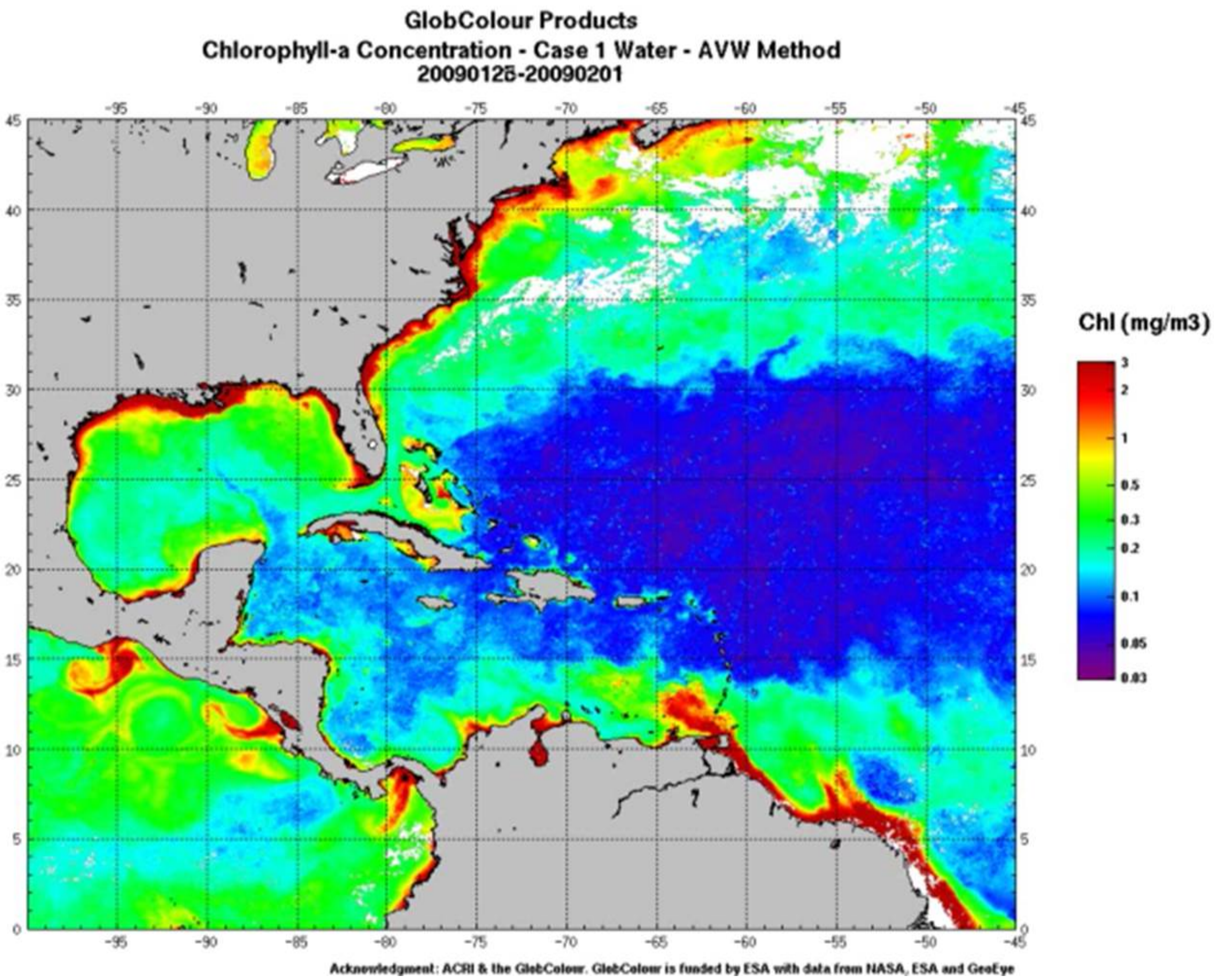


Figure 2.2 Notice the high Chl-a values around Trinidad-Tobago and the Orinoco delta. Dates: January 25-February 1, 2009.

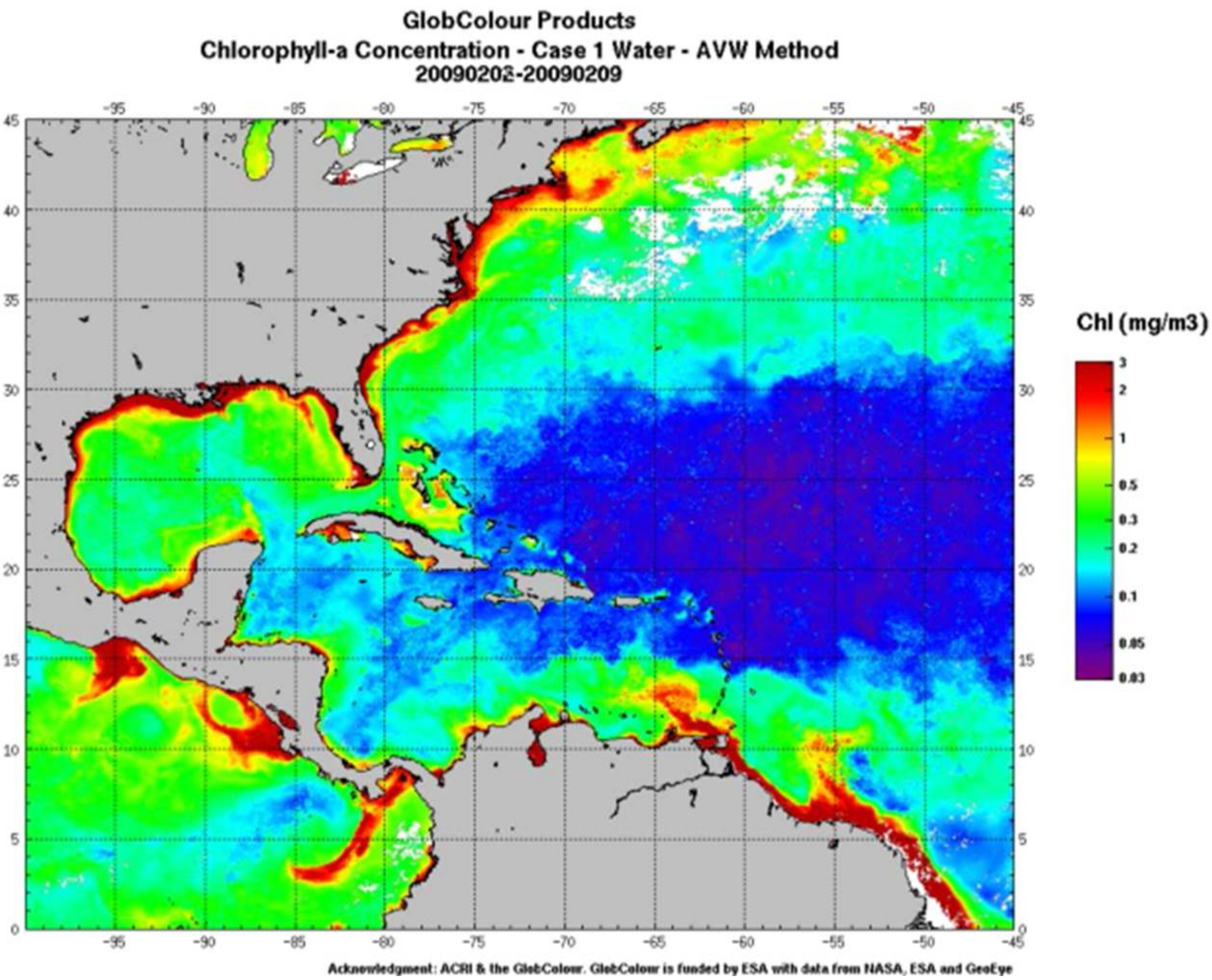


Figure 2.3 The high value area near the Orinoco River remains South of Puerto Rico and appears to be dispersing to the West. The outflow of Amazon water is dispersing northward. Dates: February 2-9, 2009.

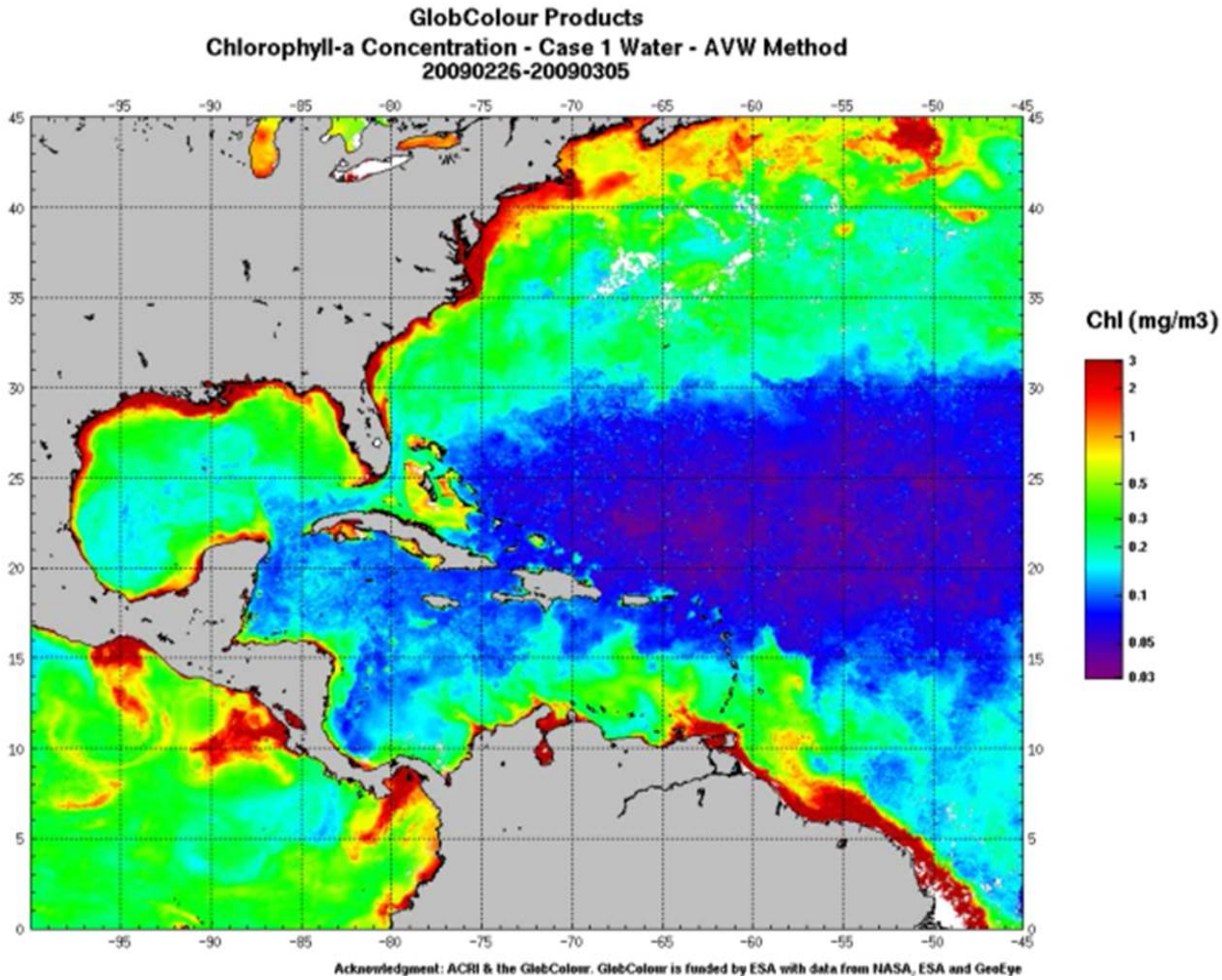


Figure 2.4 The Amazon water is seen near the mouth of the Orinoco. The plume from the Orinoco still South of Puerto Rico with filaments extending to the South of the Mona Channel. Dates: February 26-March 5, 2009.

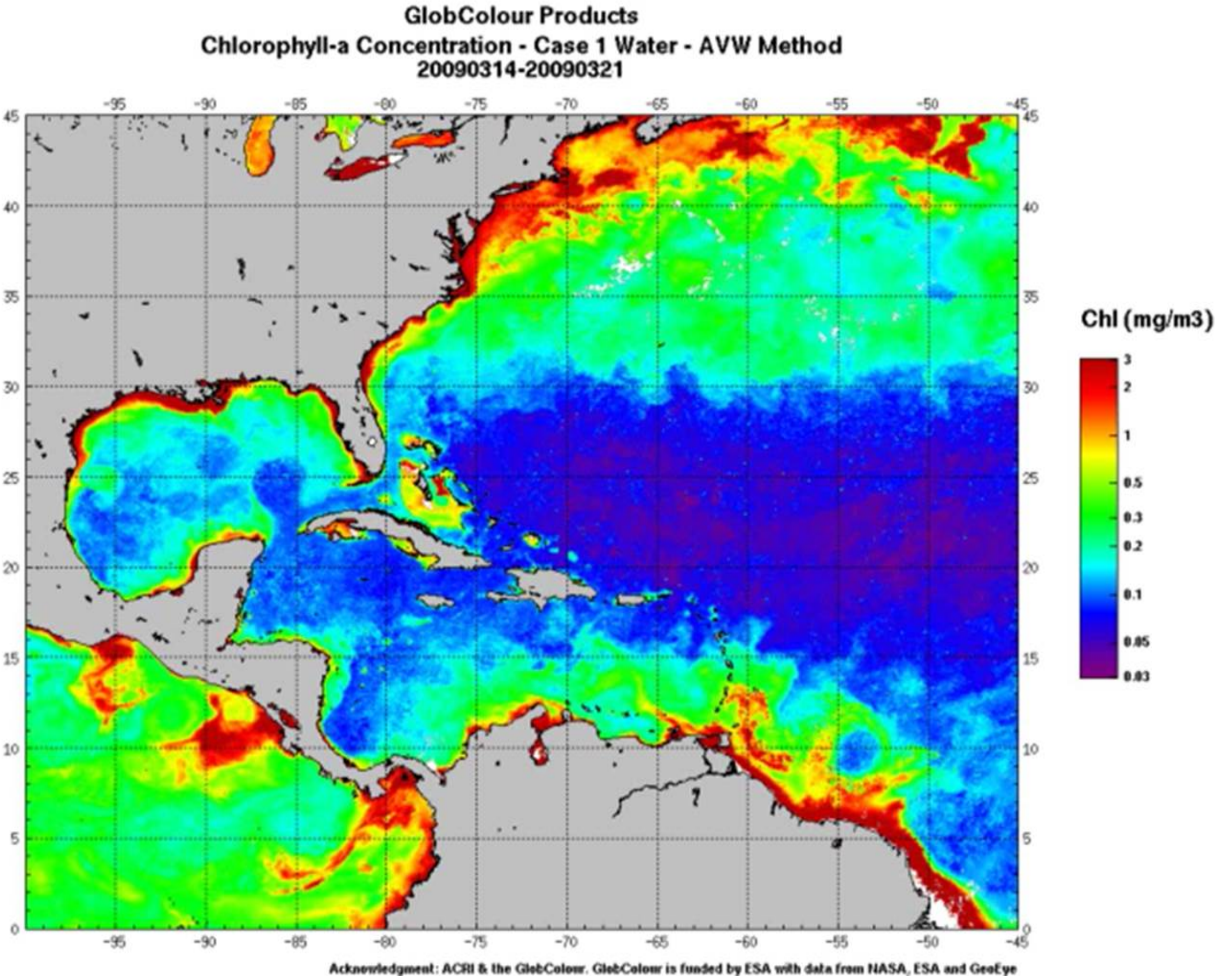


Figure 2.5 High Chl-a values off the Orinoco River delta are from water moving in from the Amazon River. An eddy can also be noted in the image. Dates: March 14-21, 2009

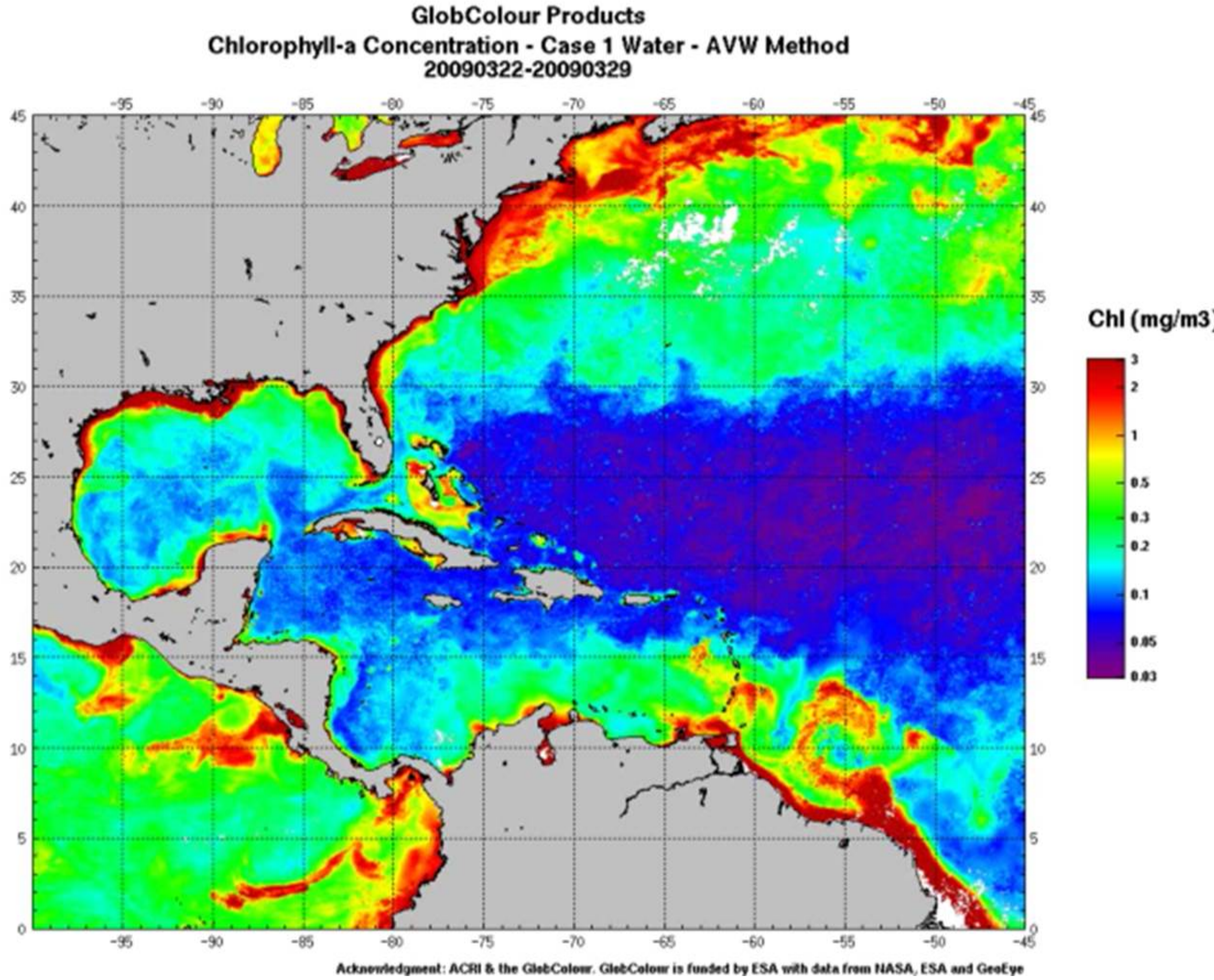


Figure 2.6 **The Amazon River water is moving through the Lesser Antilles and northward. The eddy observed in the previous image has moved toward the Lesser Antilles also. Dates: March 22-29, 2009.**

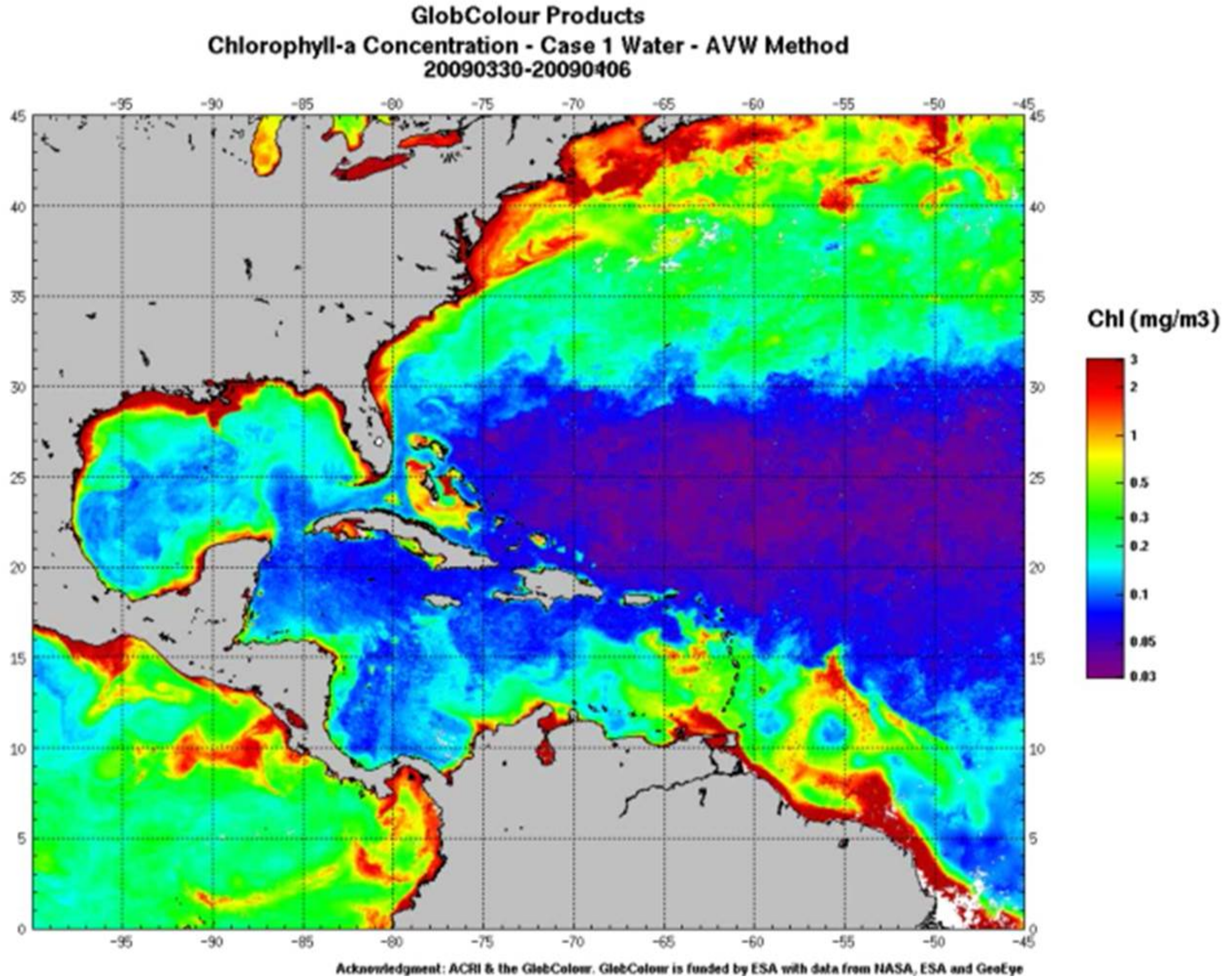


Figure 2.7 The origin of the plume is the Amazon River water entrained by an eddy and moved toward the Lesser Antilles. There is also indication that water from the Orinoco was advected and flowed into the Caribbean. The first filament to reach the St. Croix area is visible in this image. Dates: March 30-April 6, 2009.

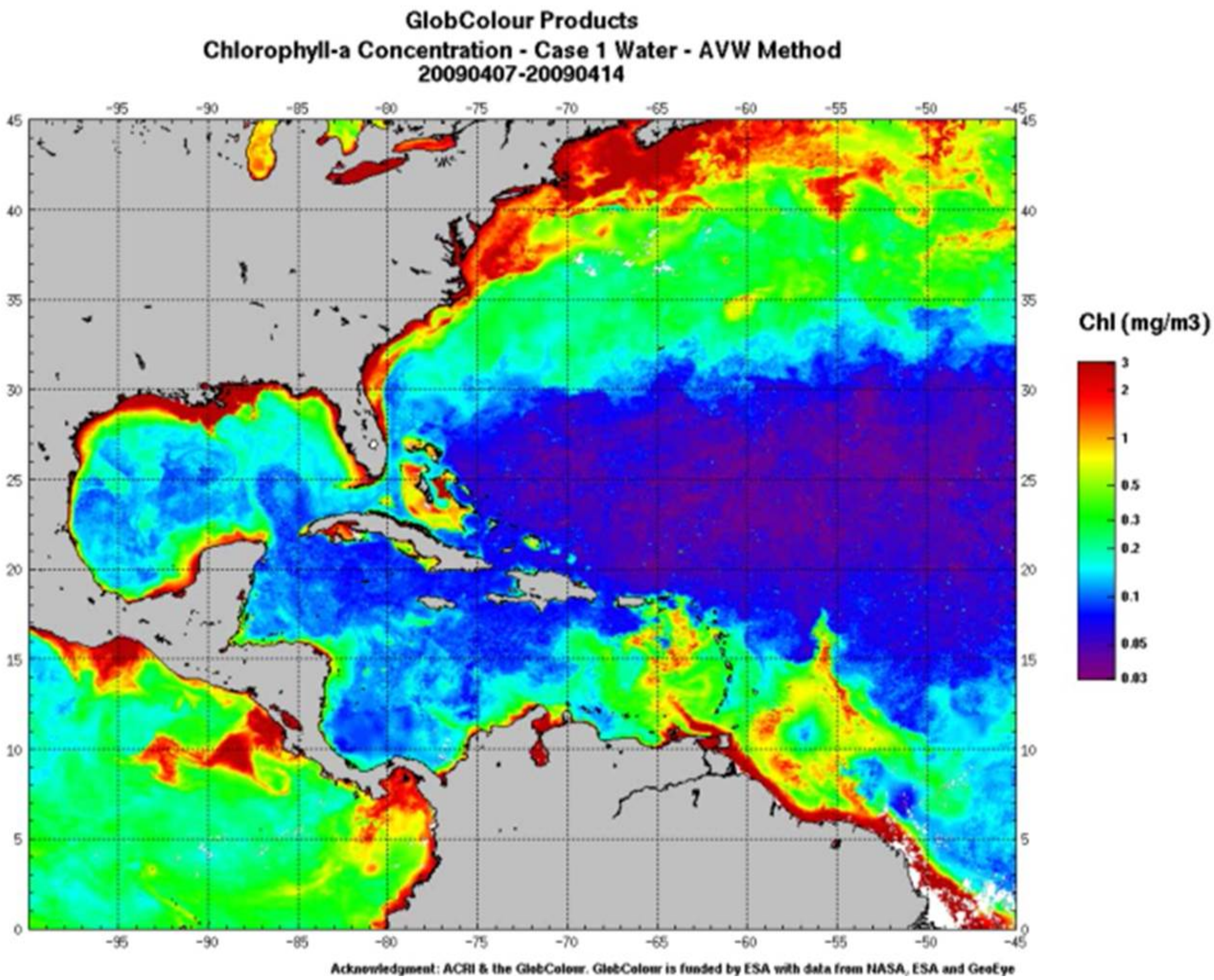


Figure 2.8 The Amazon River water reached the USVI. The green water had already been reported on the East Coast of Puerto Rico by April 5th. Dates: April 7-14, 2009.

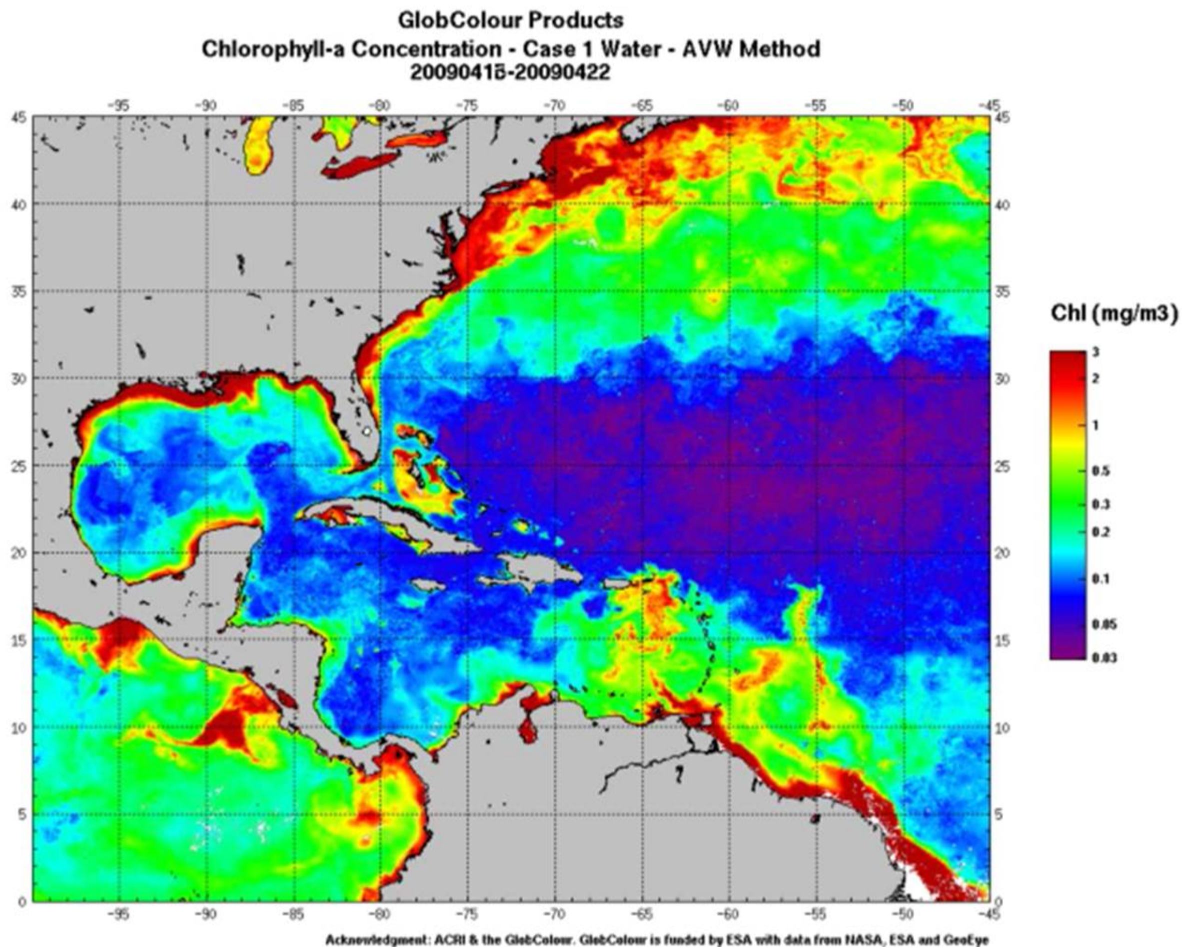


Figure 2.9 The USVI and the East Coast of Puerto Rico fully impacted by the Amazon River plume. The plume took less than a month to arrive in the area. Dates: April 15-22, 2009.

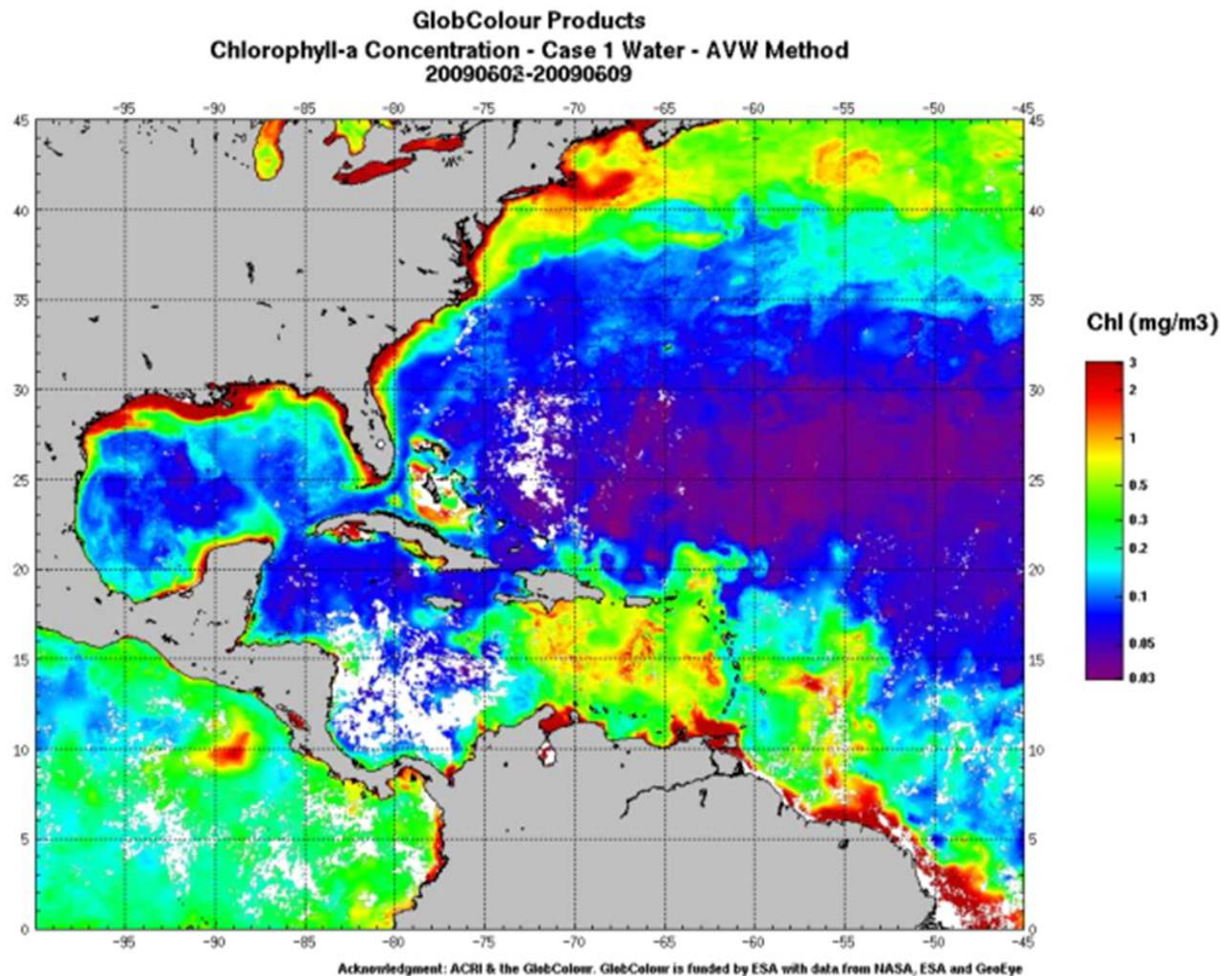


Figure 2.10 The Amazon River plume dispersed through the Caribbean exiting to the north through the Mona, Virgin and Anegada Passages. Dates: June 2-9, 2009.

The green water reached the Puerto Rico-USVI area during the week of 7-14 April 2009. Fishers in the USVI (St. Croix and St. Thomas) first reported the event on April 10, 2009. Satellite images revealed that St. Croix received the first filament of river water the week of March 30 –April 6. Plate 2.10 shows the path followed by the river plume in 2009. In St. Croix during the full moon of April (full moon on the 9th), Martinez (G. Martinez 2009, commercial fisherman, pers. comm.) reported very low visibility and very few fish (both from the collection and observation of fish).

The intrusion of river water from South America was first scientifically documented in the salinity diagrams of Wüst (1964) showing seasonality of lower salinity waters into the Caribbean. These were later attributed to Amazon/Orinoco flows (Froelich *et al*. 1978). Froelich *et al*. (1978) estimated that at least 60% of the fresh water entering the Caribbean through the intrusions of low salinity is from Amazon-Orinoco origin. Peak flow of the Orinoco occurs in August through December (Wüst 1964) while peak flow of Amazon water occurs between May and July (Davis 1964). The Amazon River discharge has been reported at 2×10^5 cubic meters per second, with minimum and maximum volumes in November and June, respectively (Davis 1964) and constituting about 20% of the total river water discharge in the world. The Orinoco estimates vary between 7 and 65×10^3 m^3/s with minimum and maximum volumes in March and August, respectively; a significantly lower contribution than the Amazon. Also, the Magdalena River contribution of about 0.8×10^4 m^3s^{-1} should be considered. Various authors (Wüst 1964; Yoshioka *et al.* 1985; Froelich *et al.* 1978) have further confirmed these intrusions by silica content and salinity as well as other elements. Moore *et al.* (1986) estimated up to 20% of the Caribbean surface water was of Amazon origin based on the water chemistry (228Ra/226Ra activity ratios, and satellite imagery (Müller-Karger, *et al.* 1988; Müller-Karger, *et al.* 1989, Corredor, *et al.* 2004).

Although the Amazon River discharges about four times more water than the Orinoco, the major influence (influx) of river water into the Caribbean is from the Orinoco (*e.g.*, Hochman *et al*. 1994) and its influence reaches as far north as Puerto Rico (Wüst 1964, Yoshioka *et al*. 1985).

The water from the Amazon mixes with the Guiana current, if not sequestered into the equatorial counter current, and is carried northward. These low salinity, high silicate waters have been reported as far north as 34 km South of Puerto Rico (Froelich *et al*. 1978). Yoshioka *et al*. (1985) attributed the variability and seasonality of the zooplankton observed off the Southeastern Coast of Puerto Rico to the seasonality of the Amazon-Orinoco intrusions. Corredor and Morell (2001) described the signature of these rivers at the Caribbean Time Series station (CaTS) between 1994 and 1999. CaTS is located approximately 50 km south of La Parguera, Puerto Rico at 17.5°N, 67°W.

The first description of the river influx into the Caribbean derived from satellite images was that of Müller-Karger *et al*. (1988) using a four year time series of Coastal Zone Color Scanner data and reported a range of chlorophyll surface values of 0.14 to 6.22 mg/m^3 within the plume.

The plumes have been described as having a depth that increases with vertical mixing as the plume moves away from the center of origin; depths of 15 m (900 km from delta); 30 m (1,800 km or near Barbados) and 45 m (2, 600 km from origin) (Hu *et al.* 2004). The last distance from origin corresponds to Puerto Rico, but in 2009, the depth of the plume was reported at 28 m in the USVI and 25 m off the East Coast of Puerto Rico. This would indicate that the plume traveled faster than usual and traveled over that distance fast enough to prevent vertical mixing. This would also imply that the plume was continuous and eddies were not significant enough to disperse it.

South America provides the Caribbean with two or three significant fresh water inputs. These change depending on the amount of rain over the Amazon, Orinoco and Magdalena basins during the rainy season, which typically occurs between August and November. Changes in the climatology of the rains in South America and the amount of land clearing that has taken place (Marengo *et al.* 2012) have resulted in changes in the amount of fresh water influx, the extent and impact of the fresh water plume.

These river water intrusions are probably the most significant front present in the Caribbean. Other oceanographic features in the area include the presence of cyclonic and anticyclonic eddies (Rueda-Roa *et al.* 2008) that can be entrained in river water or that can entrain plume water and can impact the areas of interest.

The massive green water event occurred during the spawning season of a number of grouper and snapper species such as tiger and mutton, respectively. Fishers in the US Caribbean have said for many years that when there is green water, there is no fishing. Among the theories of the fishers to explain the variability in the runs of spawning fish are: (1) the moon; (2) the quality of the water; (3) the currents; and (4) other factors that prevent fish from aggregating or spawning.

The purpose of this chapter is to describe the 2009 green water event from satellite images leading to the maximum extension of the plume and to corroborate the variability in the landings from the fishers before, during and after the event. Specifically, this work will: (1) document the unprecedented event of green water intrusion from South American rivers into the northeastern Caribbean; and (2) investigate the impact of these green waters on fisheries. The spatial and temporal aspects of the green water event can be tracked through the use of satellite images to corroborate the presence of this green water in the near shores of the USVI as reported by fishers.

Therefore, this chapter will investigate the April 2009 green water event in terms of:

(1) Comparing satellite-derived Chl-a values at the 12 sampling sites in 2009 against the 10-year time series

(2) Documenting the description of the 2009 river plume as reported by the fishers and others at sea

(3) Comparing satellite-derived Chl-a data to the *in situ* data

(4) Tracking the origin of the April 2009 river plume (Orinoco or Amazon River)

(5) Evaluating the factors that triggered the green water event to identify other such events in the data

(6) Determining the spread of the river plume over time

(7) Studying the implications of such an event in terms of fisheries (see Chapter 3), as depicted by the catch data, and socio-economics as determined by the information received.

This large-scale oceanographic feature delineated by the South America Riverine Plume traveled more than 3,000 km impacting the spawning sites. The effect that this impact could have on the spawning aggregation is unknown.

The first sighting of the green water event into the US Caribbean waters was reported on April 9, 2009 to the southeast shelf of St. Croix and documented in the email from T. Smith 2009, marine scientist, St. Thomas, pers. comm. on 04/18/09. All records also indicate that the spread occurred to the North-Northwest and West Coasts spreading from St. Croix to St. Thomas and to the North Coast of St. Thomas by April 14, 2009. Nevertheless, earlier that same month on April 5th, divers off the East Coast of Puerto Rico reported on the presence of “itchy” water.

Overall, this work will incorporate all the data obtained from satellite-derived and *in situ* Chlorophyll-a values as well as real-time information from seafarers to aid in the characterization of this unprecedented green water event.

2.2 Materials and Methods

Satellite Data

A 10-year time series of OCR Chl-a for eight fish spawning aggregation sites and four control sites was developed from 1999-2008 (Chapter 1). The methodology for extracting data from the satellite imagery has been described in detail in Chapter 1. The same methodology for obtaining Chl-a values from OCR was applied to the ocean color images of 2009 (January through December; maximum number of images per site would be 46 for each of the 12 sites).

The areas selected with the sampling box of 3 x 3 pixels were surveyed during the time of the "green water event" to assess the variability to which these areas were exposed. The sampling sites described in Chapter 1, for which a time series was developed, were impacted by this green water event. Therefore, the description of these areas from satellite images was important to understand the influences to which the organisms utilizing the area are subjected. Oligotrophic waters are typically expected to show low variability during the year or from year to year. Nevertheless, the impact of these environmental events will increase the variability observed.

The satellite imagery available from NASA were examined for the area between 2°S - 20°N and 60° - 75° W to determine the origin, flow and extent of the plume. The satellite images used had low resolution (9 km per pixel) and "averaged" over eight days. The area of the Amazon

River was not visible in many of the images due to the large amount of clouds, which prevented their use.

MODIS monthly means were used to observe the progression of the plume. First, daily images were browsed (http://oceancolor.gsfc.nasa.gov) and images were selected from the areas of interest that could be seen. The images were also assessed to determine the sources of the river input into the Caribbean where both the Orinoco River delta and the Amazon River mouth were visible. Large amounts of clouds, sun glint, and other issues such as swath missing data significantly decreased the number of daily images that could be used. However, the Ocean Color site offered additional products such as the three and 8-day composites of nine km resolution images and were used for aiding in the determination of the water origin. MODIS Terra and Aqua and SeaWiFS images were reviewed. The images used in this study were MODIS Aqua. MERIS products include 300 m resolution images but these were not available when these were requested.

The image of 2009 097, 1 km MODIS Aqua corresponds to the date prior to the NOAA Ship Nancy Foster cruise (April 8-20, 2009) (Figure 2.11). There were not enough daily images covering the area of interest to be useful in the description of the plume impact over the area of interest.

NASA satellite-derived K_{490} product images were used to determine the depth of the euphotic zone at a number of the fish spawning aggregation sites.

The changes in the depth of the euphotic zone (Z_e) were calculated from the satellite-derived attenuation coefficient (K) at 490 nm as follows:

$$Z_e = 1/K_{490} \quad (2.1)$$

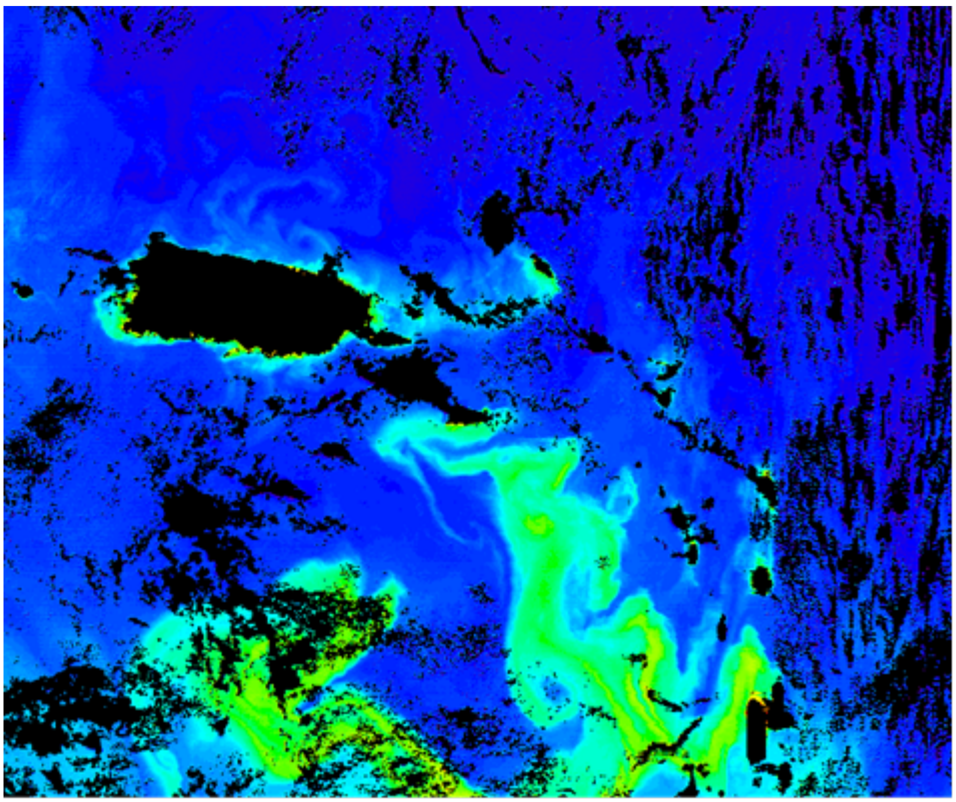


Figure 2.11 MODIS image of April 8-20, 2009 and green water event

Field Observations and Rainfall Activity

There were two types of field observations: (1) information from experienced fishers, divers, scientists, and boaters communicated via phone calls, radio comments, emails and list servers regarding the spatio-temporal dispersion of the green water during April-May 2009 and (2) *in* *situ* measurements from scientists aboard the NOAA R/V Nancy Foster during April 2009. The *in situ* data were only available for the areas in the US Virgin Islands.

First, incidental observations by commercial and recreational fishers, the media, scientific researchers and divers described the presence of green water extending from St. Croix to the north drop in St. Thomas USVI; from the British Virgin Islands to Fajardo, Puerto Rico and as far as the Southwest Coast of Puerto Rico (approximately 17.67°N, 67.05°W). The extent of the river plume was examined by satellite remote sensing imagery (Figure 2.11) to determine the impact on fishing and other marine activities around Puerto Rico and the USVI specifically but also around the Caribbean in general. A detailed log was maintained between April and May 2009 about the presence of the green water and the corresponding impacts on marine activities such as fishing and diving. First hand information was provided on the following: name, email or phone number, location and description of the water and the activity being carried out. For example, one fisher reported the green water off the South Coast of Ponce, Puerto Rico at 21.2 nautical miles (nm) while fishing on April 27, 2009 (Ramirez 2009, recreational fisherman, pers. comm.). Another fisher reported its arrival offshore of La Parguera, Lajas, Puerto Rico, on May 13-14, 2009 (Peña 2009, recreational fisherman, pers. comm.). The summary of these reports is documented in Chapter 3.

The GCFI list server reported on the event during the months of April and May with participants documenting the green water event from Barbados to the Dominican Republic (*e.g.*, http://listserv.gcfi.org/scripts/wa-GCFI.exe?A1=ind0905&L=GCFINET).

Second, two NOAA research vessels were in the area during March-April 2009. The NOAA R/V Nancy Foster was in the US Virgin Islands from 7 – 20 April 2009 (Cruise Report NF-09-

03, 2009) and collected Conductivity-Temperature-Depth (CTD) discrete samples for chlorophyll and continuous flow-through the seawater system with thermosalinograph, or *TSG,* and fluorometer. The data were logged with GPS coordinates and used to compare *in situ* measurements with the satellite data.

The track data from the R/V Nancy Foster were identified for the dates coinciding with the MODIS Aqua image A20090972009104.L3m_8D_CHLO_4; an 8-day composite of chlorophyll concentration at four km. The ASCII file contained the latitudes and longitudes of the ship's track for the dates 04/08 through 04/14 as well as the Chl-a values, dates that coincided with the available imagery. It was then possible to compare *in situ* (flow through and CTD) Chl-a data with satellite-derived Chl-a values

The cruise of the R/V Nancy Foster included chlorophyll data collected throughout the day while at station yielded a total of 98 stations, with 58 CTD casts during the week of April 8 through April 14, coincident with the weekly satellite imagery.

In situ data were also requested from the R/V Nancy Foster from 2007 and 2008. The vessel was in the area during the following dates: March 28- April 9 in 2007 and March 11 – March 24 in 2008. The stations occupied during these years only included the red hind spawning aggregation site on the south of St. Thomas (MCD) and not the sites in St. Croix (no data available for either MUT or LB).

Since rainfall activity is an environmental factor that can impact the Chl-a signal, the experimental product of rain and flood gauges in the Amazon and Orinoco Rivers from NASA's Giovanni's Tropical Rainfall Measuring Mission (TRMM), Figure 2.12 was evaluated and indicated that from the end of 2008 to 2009 there was continuous flooding. Rain data showed a difference in the amount of accumulated rain for 2009, an anomaly when compared to the average accumulated rain of 2006-2008.

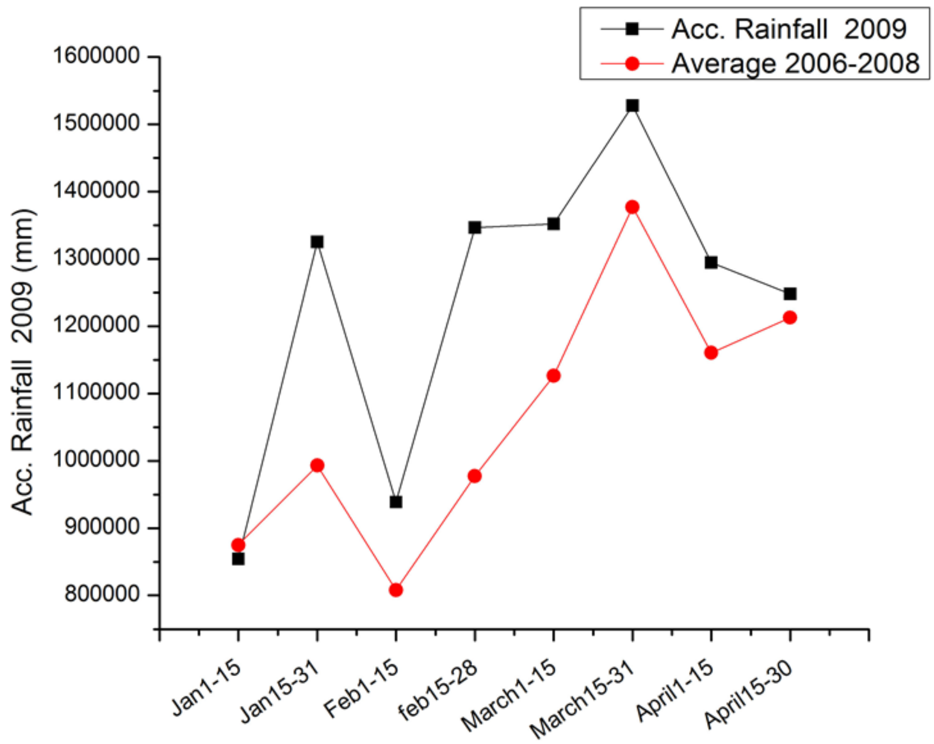


Figure 2.12 Rain data from NASA's Giovanni's Tropical Rainfall Measuring Mission (TRMM, Figure courtesy of J. Morell) indicating the difference in the amount of accumulated rain for 2009.

Anecdotal Information from Marine Users

NOAA/SEFSC and the Caribbean Fishery Management Council sent out a press release requesting information on the green water event. People who called in with information were required to report on what they were seeing (*e.g.*, green water, medusa, debris in the water) and were also briefly interviewed. The dates and times of the interviews were noted and consisted of the following:

(1) Name; (2) Contact information; (3) Activity (*e.g.*, diver, fisher, etc., if they were fishing, what species were targeted, hours fishing, gear and what was harvested); (4) Number of years at such activity (9- 50 years fishing experience); (5) Location (at least miles from shore); (6) Impact of the green water; and finally (7) Date and location of other green water events seen. The information provided by the marine resource users is described in detail in Chapter 3.

2.3 Results and Discussion

Satellite Data

The Chl-a satellite-derived data for 2009 were analyzed in the same manner as the time series data developed for 1999-2008 (Chapter 1). The 8-day 4 km resolution images available for 2009 for all the eight spawning sites and the four control sites are summarized in Tables 1.4-1.7, 1.11-1.13, 1.17-1.18, 1.20, 1.22-1.23 (Chapter 1). The OCR Chl-a values for 2009 ranged from 0.03 mg/m^3 (Sastre control site) to 0.96 mg/m^3 at Lang Bank (LB). High values of 0.95 mg/m^3 were also recorded at MCD and Rene sites during 2009. Higher values than those recorded between 1999 and 2008 were reported at MUT, CaTS and Pichinchos as well as at the two control sites in the Atlantic. The sites that did not show increased Chl-a in 2009 were Parguera (highest value in 2001), ALS (2004), BDS (1999), and Tour (2002). At the control sites, the highest value occurred in August (Sastre), July (Atlantic), and May 25 (CaTS and Pichinchos), concluding that the green water of 2009 influenced only CaTS and Los Pichinchos. Corredor and Morell (2001) had documented the presence of Amazon and Orinoco rivers at the CaTS station for the years 1994-1999. The fish aggregation sites showed the higher values on April 15 (LB), May 1 (MCD), May 25 (Rene), and April 7 (MUT) all coinciding with the presence of green water in the area. La Parguera registered the second maximum value of Chl-a of the 11-year series in

2009 during the week of May 25; the presence of the South American Rivers waters was detected. ALS and BDS showed a maximum value for 2009 during the week of May 25th; however, these were not as high as in other years. Tourmaline showed the maximum value in 2009 during the week of October 24. The weekly averages (8-day composites) clearly show, for most sites, the increase in April-May 2009 (Figure 2.13).

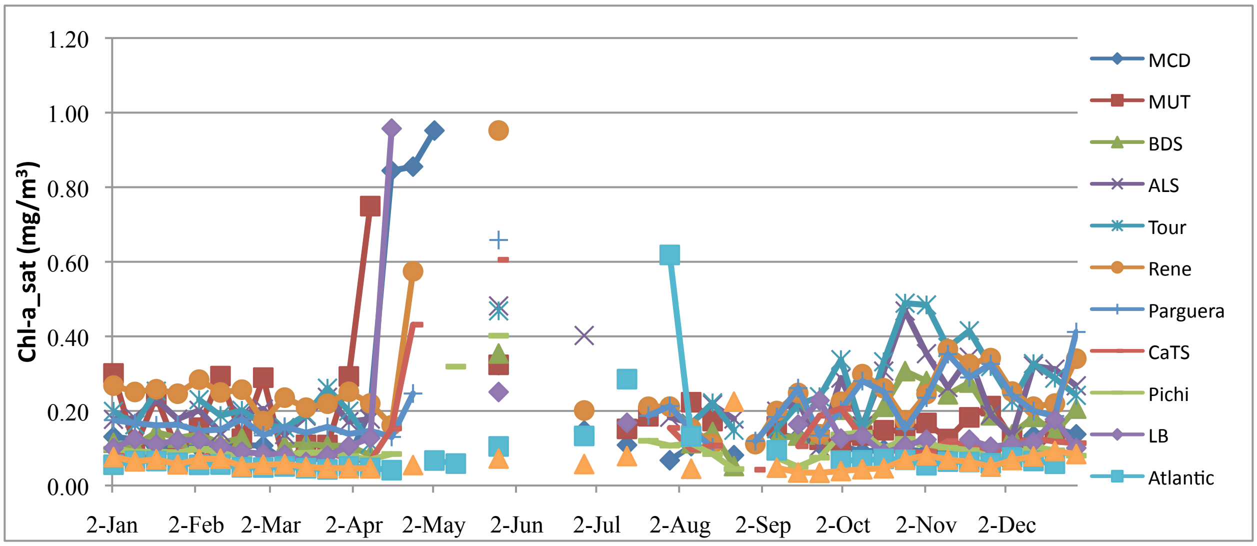


Figure 2.13 Chl-a values at 12 sites in Puerto Rico and the USVI in 2009

There were between nine and 17 weekly images missing per site in 2009, of a maximum of 46 images per year. There is no long term *in situ* Chl-a data for any of these areas, except CaTS. The first of these areas to "feel" the presence of the unprecedented event was the mutton snapper area (MUT) off the Southwest Coast of St. Croix on Julian date 097-104 (the week of April 7 to 14), followed the next week by Lang Bank (LB) on the East Coast of St. Croix and the MCD off the South Coast of St. Thomas.

As determined from the 8-day composite image of March 30-April 6, the mutton snapper area (MUT) was the first to show increased Chl-a values as a filament of South American river waters reached the area in April. These MUT increased values coincided with the first run of the spawning aggregation during the full moon of April 9, 2009. Reports from the field provided by the scientists and fishers included comments on the decreased visibility of the water, the increase in the amount of floating material in the water and the change in the color of the water to green (B. Kojis 2009, marine scientist St. Thomas, pers. comm.; G. Martinez 2009, commercial fisherman St. Croix, pers. comm.).

LB on the East Coast of St. Croix also received the river water before April 10, 2009. The West Coast of Puerto Rico received the river water the week of April 23, first reaching Rene and CaTS on the Southwest Coast and reaching the Mona Passage with lower Chl-a values around the week of May 29th, 2009.

The advance of the green water event, as documented by the weekly images, moved westward after the week of April 23-30 (Julian days 113-120) reaching the CaTS station (67°W), the mutton snapper area on the Southwest of Puerto Rico (Rene), followed by La Parguera shelf (red hind spawning site) and reaching the West Coast of Puerto Rico, between Puerto Rico and the Dominican Republic by May 9-16 and May 25-June 2 (Julian Days129-136 and 145-152). The images show the spread of the green water to the North and South of the Dominican Republic during these last days.

The 2009 data for all the 12 sites were extracted as described in Chapter 1. The weekly averages (8-day composites) were extracted from 3 x 3 pixels. These are the values plotted in Figure 2.13. The 10-year average from each site was compared to the data from 2009 from each site and there were significant differences in five of the 12 sites (Kolmogorov-Smirnov, Table 2.1). The significantly different sites were MCD, BDS, ALS, Tour and CaTS.

Table 2.1 Significance values (p values) from the Kolmogorov-Smirnov test comparison between satellite-derived Chl-a between 2009 and the 10-year average at 12 sampling sites

SITE	MCD	MUT	BDS	ALS	Tour	Rene	Parguera	CaTS	Pichi	LB	Atlantic	Sastre
p values	**0.01**	0.12	**0**	**0**	**0.004**	0.068	1	**0.035**	0.765	0.198	0.058	0.318

Note: p values in bold are significant at $\alpha = 0.05$

To determine if there were differences among the sites in 2009, the data were compared using non-parametric statistics. There were statistically significant differences among these sites in 2009 (Kruskal-Wallis, $p < 0.001$) and the sites varied as shown by the results of a multiple pairwise comparisons using the Steel-Dwass-Critchlow-Fligner procedure (Table 2.2).

Table 2.2 Table of p values from the Steel-Dwass- Critchlow-Fligner procedure to determine differences between sites in 2009

	MCD	MUT	BDS	ALS	Tour	Rene	Parguera	CaTS	Pichi	LB	Atlantic	Sastre
MCD	**1**	0.084	0.163	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.897	0.169	1.000	**<0.0001**	**<0.0001**
MUT	0.084	**1**	0.999	0.114	**0.039**	**0.025**	0.839	**0.007**	**<0.0001**	0.149	**<0.0001**	**<0.0001**
BDS	0.163	0.999	**1**	**0.015**	**0.001**	**0.001**	0.153	**0.024**	**0.000**	0.326	**<0.0001**	**<0.0001**
ALS	**<0.0001**	0.114	**0.015**	**1**	1.000	0.990	0.807	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Tour	**<0.0001**	**0.039**	**0.001**	1.000	**1**	1.000	0.413	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Rene	**<0.0001**	**0.025**	**0.001**	0.990	1.000	**1**	0.214	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Parguera	**<0.0001**	0.839	0.153	0.807	0.413	0.214	**1**	**<0.0001**	**<0.0001**	**0.000**	**<0.0001**	**<0.0001**
CaTS	0.897	**0.007**	**0.024**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**1**	0.999	0.846	**0.000**	**<0.0001**
Pichi	0.169	**<0.0001**	**0.000**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.999	**1**	0.095	**0.001**	**<0.0001**
LB	1.000	0.149	0.326	**<0.0001**	**<0.0001**	**<0.0001**	**0.000**	0.846	0.095	**1**	**<0.0001**	**<0.0001**
Atlantic	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.000**	**0.001**	**<0.0001**	**1**	1.000
Sastre	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	1.000	**1**

Note: p values in bold are significant at $\alpha = 0.05$

Even though the results obtained previously for BDS (Chapter 1) showed that it was significantly different from all the other sites (10-year time series of OCR Chl-a), the 2009 green water event appears to have impacted BDS as it did MUT. BDS and MUT were also not different from Parguera, which in turn was not different from ALS. This means that under average conditions BDS is significantly different from all the other sites, including the other red hind spawning aggregation sites on the West Coast of Puerto Rico. During this event in 2009, BDS appeared to be subjected to oceanographic conditions shared by other red hind sites (MCD, LB, and Parguera) and a mutton snapper site (MUT) (Table 2.3). The images available for 2009 did not show any indications of river run-off on the West Coast of Puerto Rico and rainfall was below normal during April and no total precipitation anomalies were reported for 2009 (http://www.srh.noaa.gov/sju/?n=apr2009cr).

Table 2.3 Grouping[1] of sites during the 2009 green water event

Sample	Frequency	Sum of ranks	Mean of ranks	Groups					
Sastre	34	1632.00	48.00	A					
Atlantic	33	2334.00	70.73	A					
Pichincho	36	4574.00	127.07		B				
CaTS	32	4734.00	147.94		B				
MCD	36	6301.00	175.03		B	C			
LB	29	5111.00	176.24		B	C			
BDS	31	6885.00	222.10			C	D		
MUT	31	7397.00	238.61			C	D	E	
Parguera	36	9871.00	274.19				D	E	F
ALS	34	10153.00	298.62					E	F
Tour	31	9625.00	310.48						F
Rene	37	11583.00	313.06						F

[1]Based on ranking of Chl-a values with the Steel-Dwass- Critchlow-Fligner procedure

Figure 2.14 shows the satellite-derived data for the marine conservation district (MCD) off St. Thomas. The data were obtained for the same coordinates for the years 1999, 2003, 2005, 2006 and 2009. The years compared were selected because upon inspection of the time series for these areas, these showed the most variability. The almost ten-fold increase in satellite derived Chl-a was first detected by the commercial fishers of the US Virgin Islands (visual assessment) and rapidly confirmed by satellite images, the R/V Nancy Foster and numerous other interested parties across the Caribbean. The first day of the green water event was reported on April 10 in 2009 at the MCD, but as explained previously, due to the nature of the imagery used, the increase in Chl-a was not recorded until the week of April 15^{th}. Daily images of the area overall showed the marked increase in the Chl-a field during April 12-14. There were no usable images on the days immediately following until Julian day 144 (May 24) when values were still high although significantly less than before.

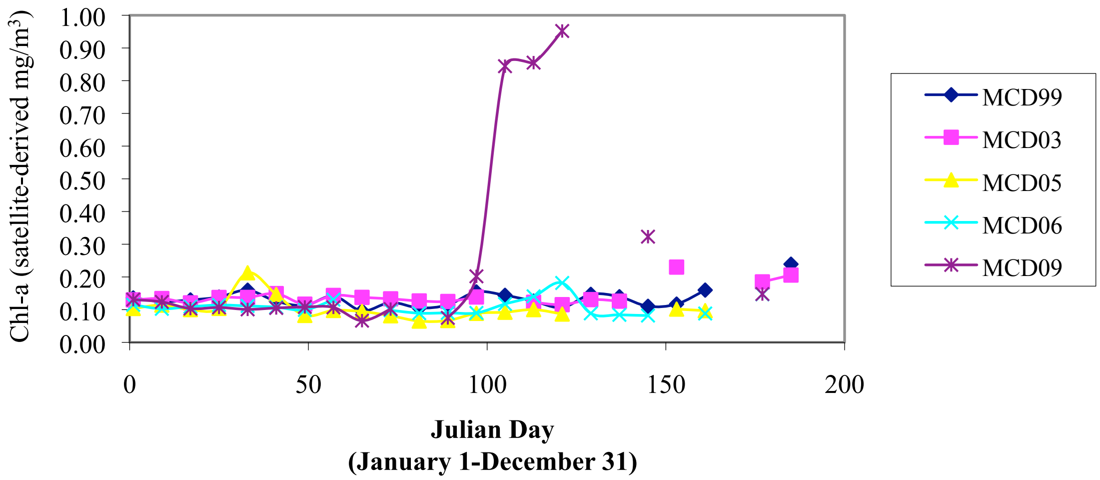


Figure 2.14 Chl-a values at the MCD spawning site comparing data from 1999, 2003, 2005, 2006, and 2009 to show the significant increase due to the green water event of April 2009

Of the stations considered oceanic, only the one off the Southwestern Coast of Puerto Rico (approximately 50 km off shore, CaTS) received the river water. Figure 2.15 indicates the migration of the river water. Although CaTS is an offshore area with little influence of terrigenous material, it clearly showed an increase in the Chl-a-sat signal.

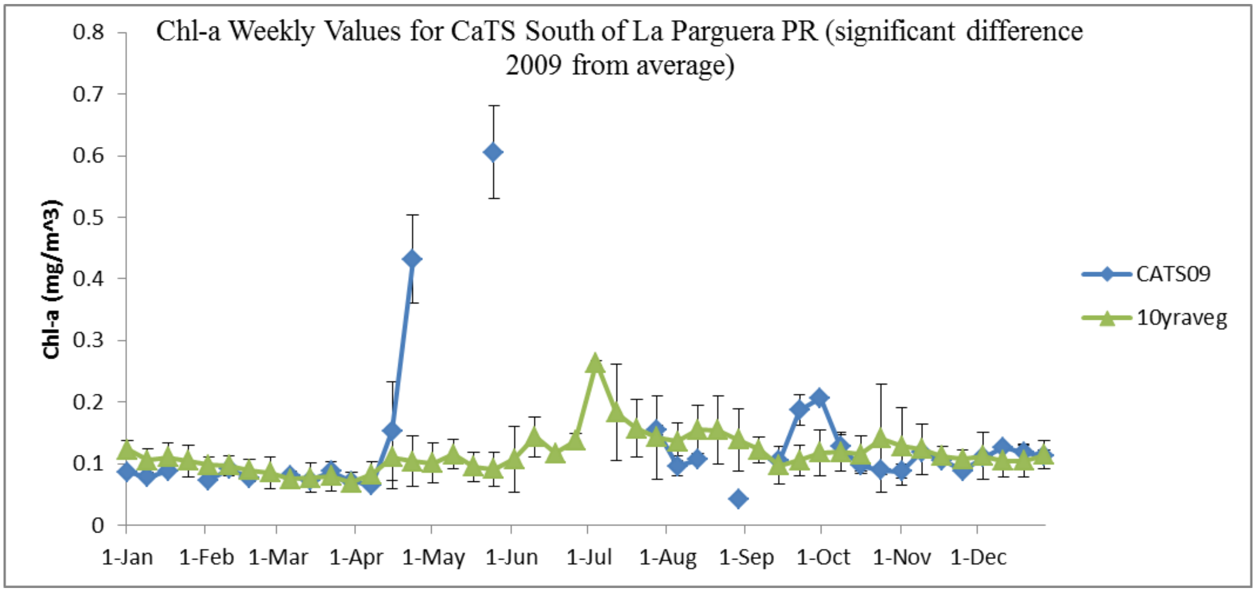


Figure 2.15 Chl-a weekly values for CaTS (2009 and 10 year average)

The areas of ALS, Tour and BDS also showed significant differences between the 10-year average and 2009. The images show Chl-a plume moving northward in the Mona Channel. This might be indicative of the connectivity among these sites as a result of the special oceanographic conditions of 2009. These sites were significantly different as determined from the 10-year climatology developed in Chapter 1 describing the average conditions of Chl-a at the fish spawning aggregation sites.

In situ Data and Field Observations

The R/V Nancy Foster was in the area during the specific dates of the event. Gerard (2009) collected water samples and reported on the data collected during the cruise. The CTD and flow through data were QA/QC by the NOAA's Southeast Fisheries Science Center (SEFSC) (T. Gerard 2009, marine scientist SEFSC; E. Malca 2009, marine scientist SEFSC, pers. comm.) and were provided for inclusion in this study. There were 9,549 records (out of 16,354 total for the cruise) for this period and for the area bound between 18.00°N and 18.93°N and 64.11°W and 66.11°W. The surface chlorophyll (TSG) data were collected every minute. All records were verified for outliers. The minimum and maximum values of chlorophyll from the ship's track collected through the flow through system were 0.0342 and 0.288 mg/m^3 (n=9,549), respectively, while for the satellite derived chlorophyll, the minimum and maximum values were 0.034 and 0.731 mg/m^3, respectively (n=6,823). The records from the ship (GPS location) were used to obtain chlorophyll values from the 8-day composite MODIS image so that the location was as close to the ship's track as possible. Nevertheless, the following issues should be taken into account: (1) the satellite image is an 8-day composite while the ship's track is continuously recording chlorophyll (every minute) for the day and time specified; (2) the image from the data is at a scale of 4 km while the ship's track is in the order of the ship's length; (3) the satellite data are derived from images taken once a day (Chapter 1 Methods) while the ship's track is continuous over 24 hours, but at different locations every minute; and (4) daily satellite images presented large amounts of clouds making it impossible to use the highest resolution imagery (1km). Additional problems with the daily images for this area include areas outside granule – a granule is defined as a section (5 minutes) of the total viewing of the sensor – swath sensor issues, and clouds, among others.

There were 98 CTD casts during the cruise, of which 58 were within the specific areas and times of interest and for which there was also chlorophyll data from the TSG (flow through system) and satellite-derived Chl-a. Minimum and maximum surface chlorophyll values ranged between 0.042 and 0.604 mg/m^3 from 58 casts with a frequency between four and 12 casts per day, all data considered. The sampling days ran from April 8 through April 20 2009 (JD 98-110).

Table 2.4 summarizes the Chl-a information available for the week of April 8-14, 2009. For all 98 stations where CTD and TSG information are available, the values were somewhat different: TSG mean (n=98) is 0.319 (+/- 0.316 and ranged between 0.041 and 1.397); CTD mean (n=98) was 0.336 (+/- 0.350, range 0.042-1.537) all values in mg/m^3 for measurements taken over the planned stations of the R/V Foster cruise. Although these values were not significantly different (p=0.323), the *in situ* Chl-a range of values was comparable to the Chl-a derived from the OCR (0.731 mg/m^3). Furthermore, the values recorded at the spawning aggregations sites and CaTS during 2009 were confirmed.

Table 2.4 Summary information for the 2009 Chl-a *in situ* and satellite-derived values

Source	Min Chl-a (mg/m^3)	Max Chl-a (mg/m^3)	Date Min	Date Max	Number	Mean Chl-a (mg/m^3)	SD
CTD	0.042	0.605	13-Apr	10-Apr	58	0.121	0.103
CTD-TSG	0.047	0.270	10-Apr	14-Apr	58	0.109	0.046
CTD-SAT	0.039	0.700	7-14-Apr	7-14-Apr	48	0.175	0.137
TSG	0.034	0.288	10-Apr	14-Apr	9549	0.117	0.050
SAT	0.034	0.730	7-14-Apr	7-14-Apr	6823	0.202	0.157

Maximum values of Chl-a were reported from most sites in 2009 (Chapter 1) except for Parguera, Tour, ALS, and BDS where maximum values were reported in 2001, 2002, 2000 and 1999, respectively (Table 2.5; see Chapter 1 for discussion of these differences). These differences appear to indicate that the 2009 green water event impacted the areas of the US Virgin Islands more directly and also showed the path of the plume through the area reaching these farther away sites with decreased but still high values of Chl-a. The images showed part of the plume near the area of the Atlantic and Sastre stations exiting through the USVI and Lesser Antilles and through the Mona Passage. The plume appeared to be moving due North (Figure

2.10). This displacement of the plume had not been observed in the imagery between 1999-2008. However, other than the *in situ* data presented here the author is not aware of any other datasets that could further confirm the presence of the river plume at these control sites. There were no statistically significant differences between the 10-year average and the 2009 Chl-a values at these sites.

Table 2.5 Maximum values of Chl-a recorded at the 12 sampling sites between 1999 and 2009

SITE	Max Chl-a	Date (2009)	Max Chla	Date	Year
MCD	0.952	1-May			
Parguera			0.728	12-Aug	2001
Tour			0.739	29-Aug	2002
ALS			0.592	29-Sep	2000
BDS			0.634	3-Dec	1999
LB	0.957	15-Apr			
MUT	0.749	7-Apr			
Rene	0.952	25-May			
CaTS	0.605	26-May			
Pichincho	0.402	27-May			
Atlantic	0.618	27-Jul			
Sastre	0.225	21-Aug			

The residence time of the green water at each of the sites can be estimated from the time the increase in Chl-a was observed to the time Chl-a returned to the 10-year average value for the sites. Table 2.6 shows the Chl-a values for each of the sites during the time of the green water event. It is estimated that the green water remained at least until June. The maximum values observed at the other sites (Parguera, Tour, ALS, and BDS) during other years can be attributed to more transient events than the green water intrusion of 2009 (See the section on Rate of Change in Chl-a in Chapter 1.)

Table 2.6 Residence time of the green water event of 2009 beginning in April 7 and lasting until after June 26 when the Chl-a values returned to the 10 year average. Satellite-derived Chl-a signal (mg/m^3) used as a tracer

SITE	7-Apr	15-Apr	23-Apr	1-May	9-May	17-May	25-May	26-Jun	10 yr avg
MUT	0.749						0.324		0.142
LB	0.127	0.957					0.251		0.127
MCD	0.202	0.844	0.856	0.952			0.323	0.148	0.119
CaTS		0.153	0.432				0.606		0.111
Rene		0.153	0.575				0.952		0.215
Parguera			0.247				0.658		0.212
BDS							0.354		0.174
ALS							0.482	0.400	0.251
Tour	0.110						0.468		0.265
Pichincho		0.080			0.319		0.400	0.149	0.093

There were no significant differences between the *in situ* Chl-a and the satellite derived average values observed in the USVI. The data from the NOAA Ship Nancy Foster were of special interest since the cruise occupied stations at two of the fish spawning sites (MCD and LB).

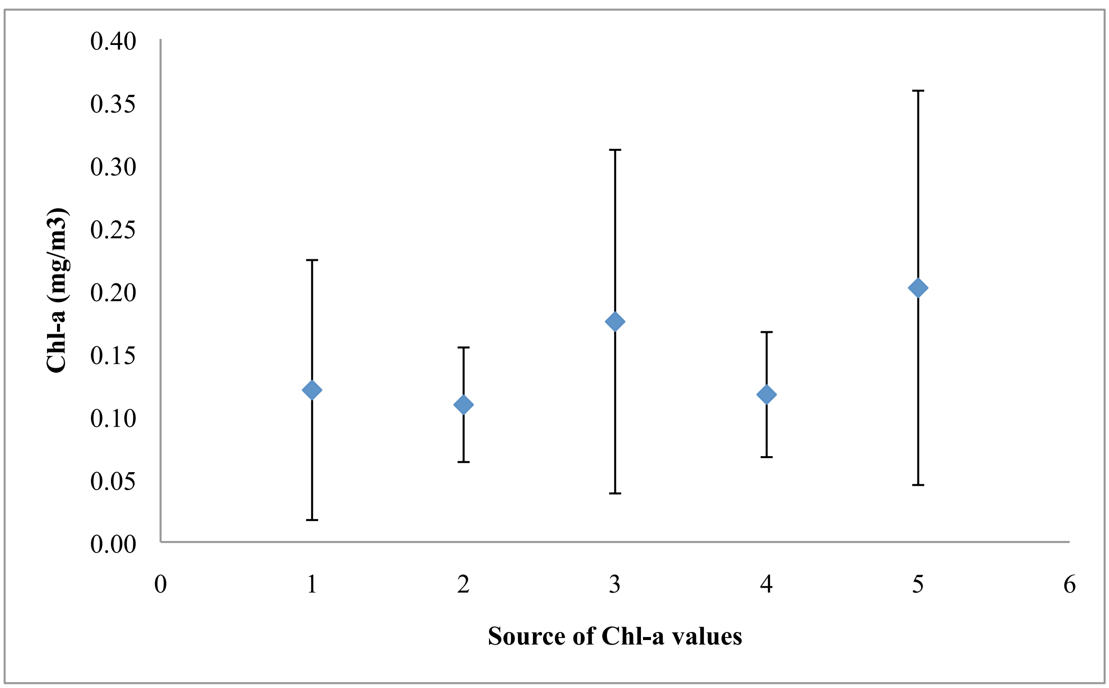


Figure 2.16 Mean Chl-a values and SD obtained from various sources in the USVI during the April 2009 green water event. 1- CTD; 2-TSG, Flow-through system; 3-Satellite; 4-TSG (n=9549); 5-Satellite (n=6823); Data from Table 2.4.

The average of the values extracted from the 8-day satellite image composite were slightly higher than the *in situ* values (Figure 2.16) of Chl-a values. The *in situ* values were obtained from the flow through system of the R/V Nancy Foster and stations occupied for CTDs. The track of the ship was used to extract the values from the satellite images. One of the shortcomings of the comparison between satellite-derived data and *in situ* data was the number of samples that could be taken; *in situ* sampling can result in many samplings over the same area while satellite data is at best 1 daily image per sensor but as in this case, 1 weekly image. The CTD data collected during the cruise resulted in four values per day between April 8 and 20 at different locations that could be compared to the 1 value per image but, if possible, to all sites at once.

The dates for which there were CTD casts and data from the flow through system are April 8 through April 20. The best images available for that period of time was for the week of April 7 - 14 2009.

Figure 2.17 shows the comparison between the *in situ* Chl-a data collected by the flow-through system (TSG) on board the NOAA Ship Nancy Foster between April 7 and 21, 2009 and the satellite –derived Chl-a values from the daily image of April 12. The data were collected along the track of the ship. The Julian date (JD) 102 (April 12) satellite imagery was used to extract the Chl-a values, over the same ship's track. No other MODIS-Aqua daily images were available. This comparison indicated that at low Chl-a values, the satellite overestimated while at high values it underestimated, but the trends were similar. The green water event was first detected in St. Croix at both MUT and LB on April 9 moving northward and reaching St. Thomas on the same day (about 42 km north of St. Croix). W. Ledee reported the event on the same day in Northwestern St. Thomas (W. Ledee 2009, commercial fisherman St. Thomas, pers.

comm.) and Kojis (B. Kojis 2009, marine scientist St. Thomas, pers. comm.) confirmed the presence of green water extending from St. Croix to St. Thomas. The event covered the St. Croix-St. Thomas area and extended over the entire British Virgin Islands (BVI) platform on the same day. Confirmation of the extreme green water event came from a recreational boater, with over 45 years of boating experience in the waters of the Caribbean, transiting between the BVI and Puerto Rico from East to West (A. Rexach 2009, recreational boater PR, pers. comm.). The satellite image also shows the plume extending northward of the USVI/BVI into the Atlantic.

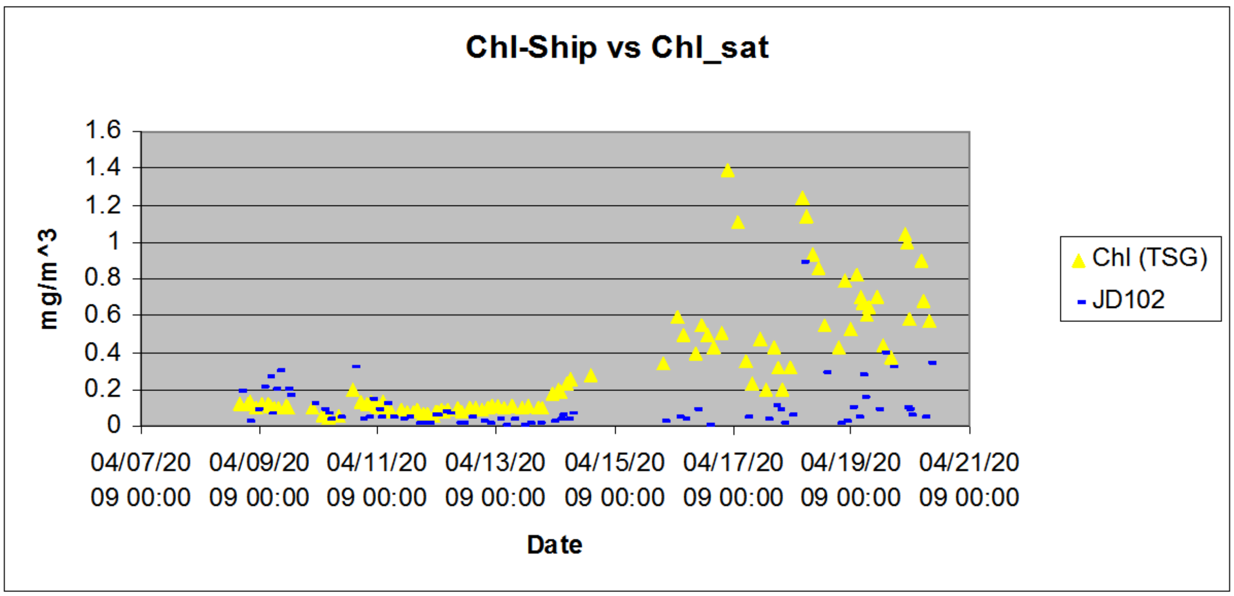


Figure 2.17 Comparison of *in situ* (Chl-Ship; TSG Flow-through system) and satellite-derived Chl-a values (Chl_sat; Julian Date 102-April 12)

Although only two of the sites (MCD and LB) surveyed from the imagery over 11 years were within the path of the Foster, the trend in the data was evident.

The *in situ* data clearly showed elevated chlorophyll values beginning on April 16, 2009 and lasting for the duration of the cruise. This was a significant increase for the oligotrophic conditions normally occurring in the area.

Leg 2 of the cruise took place between April 15 and April 20 2009. The CTD coordinates were used to obtain the Chl-a values from MODIS-Aqua 8-day composite for Chlorophyll (dates between Julian Day 105 and 112, corresponding to April 15 through April 22 2009) and a resolution of 4 km. The amount of clouds during this time precluded acquiring more satellite-derived information. There were 16 useful measurements of chlorophyll obtained from the satellite image based on the 39 measurements taken from CTDs for the dates April 15-20 2009. Flow through Chl-a values (TSG) were selected to match CTD values. These discrete values are shown in Figure 2.18. A maximum satellite-derived Chl-a value of 7.18 mg/m^3 (Point 20) was observed (Figure 2.3.2.7) at 17.54°N, 63.73°W and a minimum value of 0.22 mg/m^3 (Point 3) was observed at 18.41°N, 64.35°W. The values from the CTD chlorophyll fluorometer ranged from 0.06 mg/m^3 (Point 14) to 1.54 mg/m^3 (Point 20) (in April 15 and April 20th at the coordinates 17.88°N, 63.30°W and 17.47°N, 63.48°W, respectively. The TSG flow through system values ranged from 0.19 mg/m^3 to 1.40 mg/m^3 in April 17 and April 16 and the coordinates 17.88°N, 63.30°W and 18.28°N, 63.95°W, respectively.

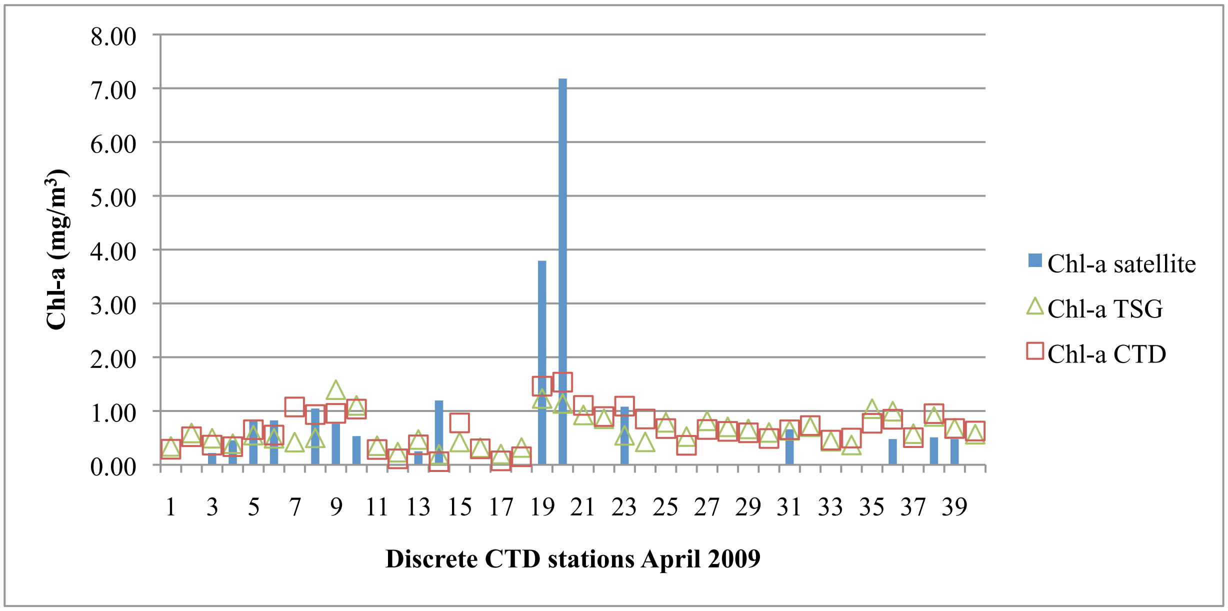


Figure 2.18 Comparison of satellite-derived and in situ Chl-a values during the April 2009 green water event

All data indicated increased chlorophyll values on stations 19 and 20 corresponding to CTD 4/18/2009 early morning measurements. The TSG showed the highest values on 4/16 rather than 4/18 indicating the extension of the plume. The satellite data overestimated chlorophyll values at high concentrations and resulted in the two highest concentrations of 7.18 and 3.79 mg/m^3. This difference could be due to the depth at which the satellite data were obtained (one optical depth = 1/Kd PAR) and the integration over the water column versus the actual surface measurement of the TSG and CTD. A number of factors can contribute to the differences including the algorithm used for the OCR data (Chapter 1).

The complete comparison of all matching stations from Leg 1 and 2 (n=101 CTD, TSG; n= 65) of the April 2009 NF0903 NOAA cruise (April 8 to 20) is presented in Figure 2.19. The satellite data were extracted from the 1-week composite image for JD dates 105-112. The trends observed in the data, albeit the difference in measurements, were similar in all three datasets. No significant differences were found between the three sets of data (Kruskal-Wallis, p=0.630).

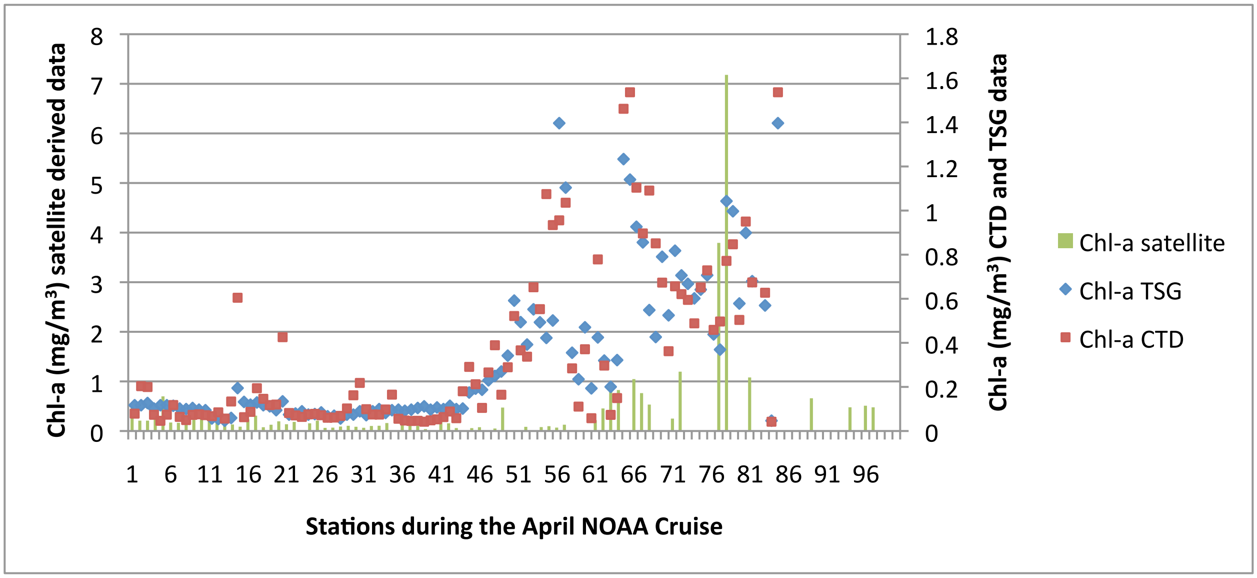


Figure 2.19 Comparison Chl-a satellite derived, flow through (TSG) and CTD data 2009

The comparison of the Chl-a values between the ship tracks (TSG), CTD, and satellite imagery was difficult due to differences in navigation, scale, and time of collection, among others. Nevertheless, these comparisons served to corroborate the range of Chl-a values.

Euphotic Zone

Weekly images of K_{490}, a measure of turbidity, were reviewed to help in determining the origin and extent of the river plume between January and June 2009. All 21 images were usable for the period of January 1 to June 17, 2009. These images were assessed for a qualitative description of the event. The data were extracted from the same coordinates as the Chl-a values. K_{490} covaries with Chl-a meaning that most of the attenuation at 490 nm is due to chlorophyll absorption. There could be an important CDOM (Colored dissolved organic matter) component, however, since Orinoco River water is high in CDOM and the operational chlorophyll algorithm is influenced by CDOM absorption. The Amazon River water has a lower CDOM signal.

The Chl-a values for the period between January and June 2009 showed a marked increase during the green water event of April (Figure 2.13). Figure 2.20 shows increased K_{490} values (higher turbidity) for MCD, MUT, and LB aggregations sites and CaTS, one of the control sites. The truly oceanic areas were not impacted by this event (Atlantic and Sastre) and neither was Pichincho.

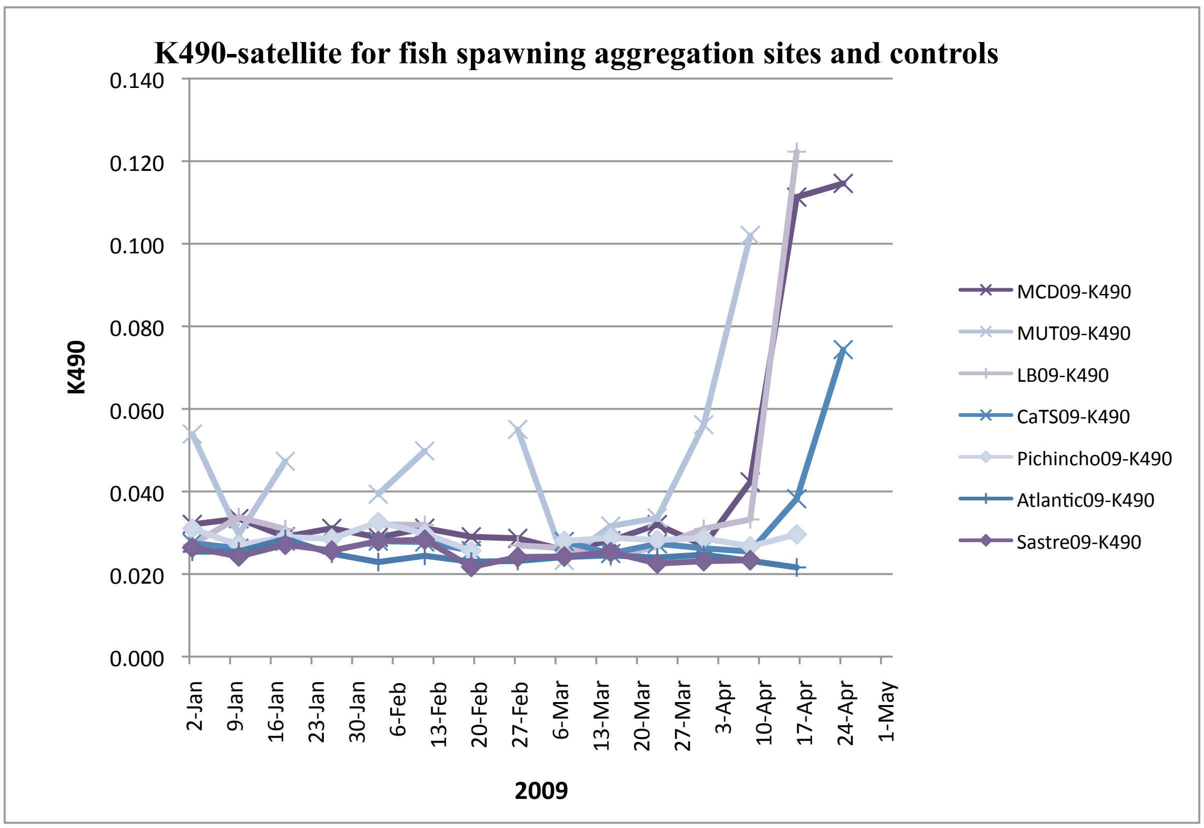


Figure 2.20 K490 (Light Attenuation Coefficient) values for seven sampling sites

Figure 2.21 shows the 1% light penetration at these sites. Armstrong and Singh (2012) had calculated the depth of the euphotic zone in the MCD at 131 m. In 2009, this depth was calculated from satellite imagery at deeper than 30 m early in the year, except for MUT. In April 2009, during the green water event the euphotic zone was at a depth of less than 10 m.

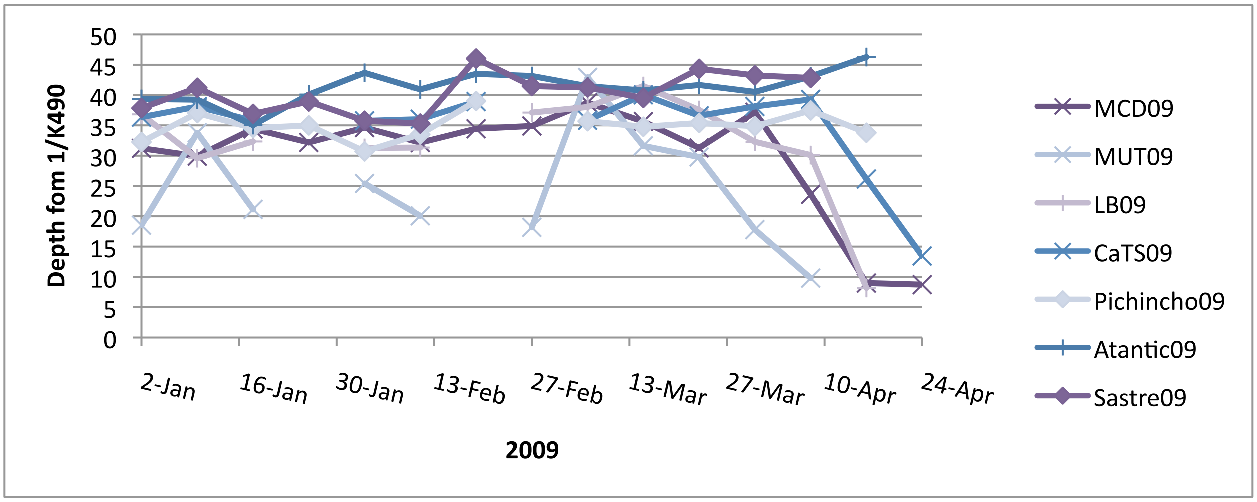


Figure 2.21 Euphotic zone depth (in meters) at aggregation and control sites

The maximum depth of the April plume was reported at 28 m (T. Smith 2009, marine scientist, St. Thomas, pers. comm.) in the MCD and 25 m off the East Coast of Puerto Rico (J. Leon 2009, port agent DNER, pers. comm.). The average depths of the South American River plumes have been reported at 45 m when it reaches Puerto Rico and the USVI. Commercial fishers from St. Thomas reported that during the April 2009 event they could not see their traps in areas where you could normally see the bottom (30-40 m depth; W. Ledee 2009, commercial fisherman, St. Thomas, pers. comm.).

Anecdotal Information Received from Marine Resource Users

The public contributed useful information on the spread and status of the green water event of 2009. The event was reported on the radio, in the published news (La Regata a nautical newspaper, USVI Daily News, among other), and listservers.

Newspaper articles reported on the unusual floods in northern Brazil. The news reported on 5 May 2009, that the "perennial drought stricken area was flooded in the Amazon Bed in Brazil. The Gulf and Caribbean Fisheries Institute (GCFI) listserver reported on the event during the months of April and May with participants documenting the green water event from Barbados to the Dominican Republic (*e.g.*, http://listserv.gcfi.org/scripts/wa-GCFI.exe?A1=ind0905&L=GCFINET).

2.4 Conclusions

Satellite images of ocean color provide a synoptic view of the Caribbean Sea that allowed for the description of an unprecedented intrusion of green water from South American Rivers into the Eastern Caribbean and the Atlantic presented in this work. The trends in the satellite data were corroborated by *in situ* data provided by the NOAA Nancy Foster and the SEFSC mission of 2009. The highest values of Chl-a were recorded at the spawning aggregation sites between April and June 2009, values significantly higher than those previously recorded at all sites, including controls, except at Parguera, ALS, BDS and Tour. This research contributed in understanding the impacts that atypical oceanographic events such as the remarkable green water intrusion have in the Chl-a signal at fish spawning aggregation and control sites.

The 2009 green water was traced to Amazon River origin. The path the plume followed was found to be unusual because it spread very fast (within a month from Brazil to St. Croix), the timing of the event (April), and the extent of its signal which was recorded at the Atlantic control site located at 19° N and 57° W. The control site in the Atlantic had no previous record of high Chl-a due to river water influx.

This remarkable event had not been recorded before nor had the Amazon Plume high Chl-a values been reported for Puerto Rico and the USVI.

CHAPTER 3 . Impacts of the April 2009 Green Water Event

3.1 Introduction

A satellite image from the MODIS-Aqua sensor showed marked differences between the blue-low Chl-a waters south of Ponce, herein named eye in the sea, and the high Chl-a waters of the April 2009 green water event (Figure 3.1). The eye in the sea is an excellent example of the environmental variability faced by commercial and recreational fishers. The image is an 8-day composite and showed the impact of the April 2009 green water event in Puerto Rico and the US Virgin Islands.

Seafarers confirmed the unprecedented green water intrusion from South America that impacted Puerto Rico and the USVI in April 2009. Commercial and recreational fishers, boaters, scientists, and fishing and diving charter operators provided valuable observations on the conditions under which they could not conduct business as usual. For example, divers reported low visibilities at depths of 25-30 m and "itchy" particles in the water. Recreational fishers reported areas of very good dolphinfish runs (Southwest Coast of Puerto Rico) and areas of no fishing at all (East Coast of Puerto Rico). Boaters commented on the extent of the green water while cruising from British Virgin Islands (BVI) to Puerto Rico as being the largest extension of green water they had ever seen in 45 years of boating. The event was described and documented through the changes in Chl-a at eight fish spawning aggregation sites and four control sites (Chapters 1 and 2).

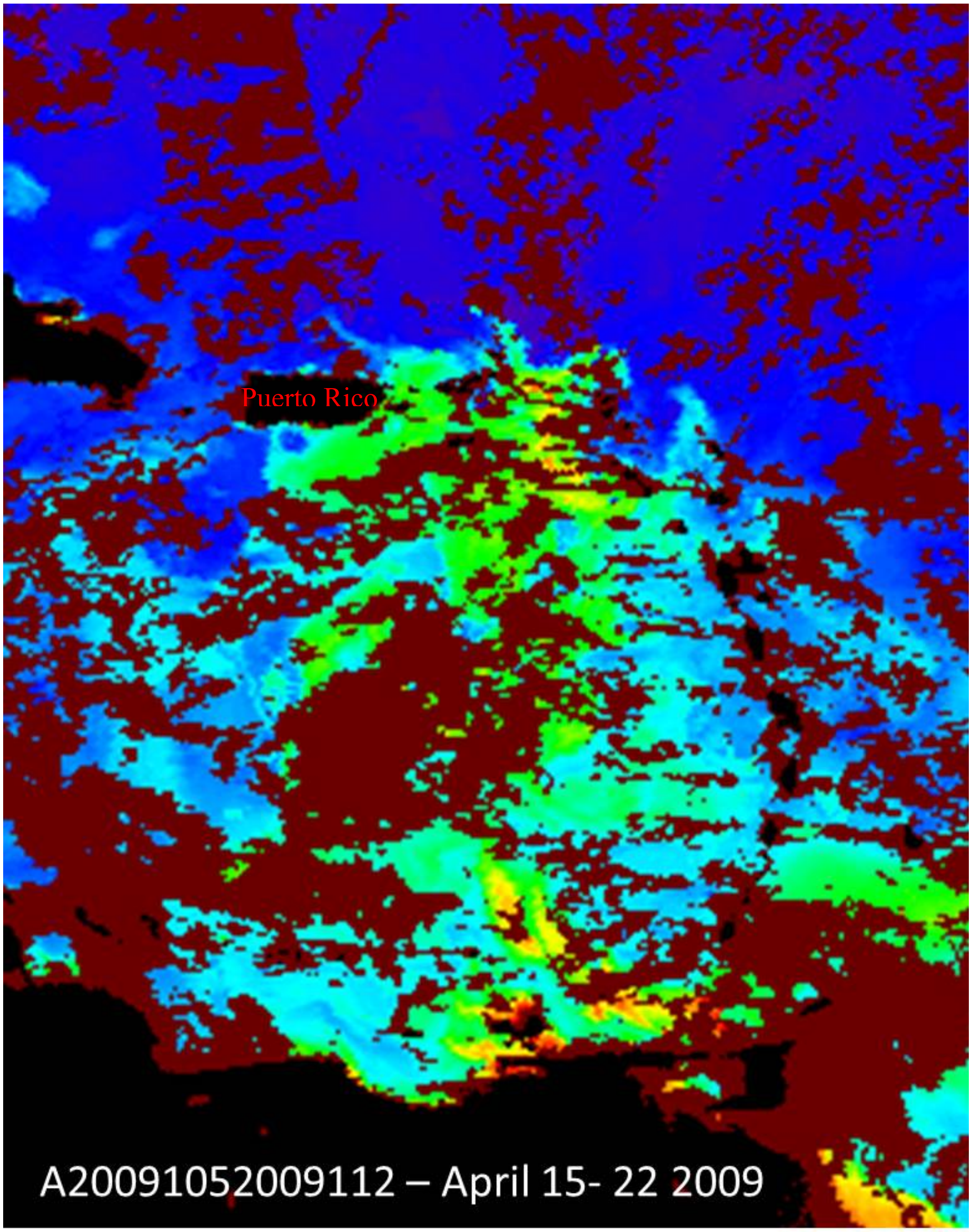


Figure 3.1 MODIS-Aqua 8-day composite ocean color satellite image for April 15-22, 2009

(Legend: Black= land; maroon = clouds; blue= low Chl-a areas in the Southwest of Puerto Rico Caribbean Sea and Atlantic; green= higher Chl-a in the US Virgin Islands, South and Southeast Puerto Rico and south toward Venezuela.

Farrell (2009) described the habitat and movement of *Coryphaena hippurus* or, as commonly known dolphinfish (dorado for gold in Spanish), using satellite imagery. This species is a coastal pelagic with a pan global distribution including the Caribbean. Pelagic fisheries are influenced by a number of oceanographic phenomena including currents, salinity, temperature, the presence of eddies and meanders but principally by the presence of food. Larvae distributions are also influenced by oceanographic phenomena (*e.g.*, Cowen *et al.* 2006). Demersal fish response to environmental and oceanographic phenomena may not be as commonly thought of as with pelagics or the distribution of larvae. Nevertheless, the timing of spawning or the selection of spawning sites by demersal fish, for example, could be influenced by the presence of varied Chl-a concentrations, which would indirectly mean the availability of food for the larvae (Chapter 1). Jury (2011) recently described Caribbean-wide environmental forcing phenomena (*e.g.*, winds, currents, hurricanes, etc.) that impact fish catches based on data between 1971 and 2004. Some of these environmental factors and the associated changes in Chl-a were assessed at the local level (Chapter 1) and examined under the influence of high Chl-a waters from the Amazon (Chapter 2). Jury (2011) identified the 2003 anomaly in chlorophyll in the Caribbean Basin as a result of the spread of upwelled water from Venezuela. The year 2003 was significantly different at several of the sampling sites but the changes were attributed to localized events. Jury (2011) correlated high fish catches in the Caribbean to years without hurricanes, among other environmental factors. The local fishing activity is examined herewith during the time of a green water intrusion from the Amazon after the centennial flood of 2009 (do Vale *et al.* 2011).

These plumes and other oceanographic features have been described by a number of authors for the Caribbean. Müller-Karger *et al.* (1989) cited the diaries of the Spaniards on the presence of black water in the Caribbean; Wüst (1964) described the low salinity presence in the

Caribbean and attributed the low salinity to the intrusions of river water from South America. The presence of eddies and meanders in the Caribbean was reported by Ingham and Mahke (1966), Leming (1971), Corredor *et al*. (2004), Rueda-Roa *et al. (*2008) and much more variability in the Caribbean Sea was described by Molinari *et al*. (1979) with the use of satellite tracked buoy data. Müller-Karger *et al*. (1988, 1989) described the South American river intrusions using ocean color imagery for the first time and established the baseline for this type of work. These plumes have been addressed by various authors including Chérubin and Richardson (2007), Hu *et al.* (2004) and others. Yoshioka *et al*. (1985) were the first to document the presence of these river intrusions near the Southeast Coast of Puerto Rico. More recently, Lee-Borges *et al.* (2002) confirmed the presence of these river plumes at CaTS using SeaWiFS imagery. Armstrong (1994) described a large intrusion of South American river water in the Northeastern Caribbean. Armstrong (1986) was the first to attempt a correlation between the presence of these plumes and fronts to pelagic fisheries around Puerto Rico and the US Virgin Islands using satellite imagery.

The pelagic fisheries of the US Caribbean have had limited investigations yet they are an essential commercial and recreational fishery resource. They are for the most part seasonal in nature and it is this seasonality that was explored in this study in relation to the Chl-a values described in Chapter 1 and the unprecedented green water event described in Chapter 2. SCUBA divers reported decreased fishing activity during the April 2009 green water anomaly described in Chapter 2. Finally, the information from the literature obtained from (1) SEAMAP-Caribbean fishery-independent program (*i.e*., Marshak 2007), (2) the fish spawning population estimates at the MCD (*i.e*., Nemeth 2005), and (3) the commercial and recreational databases from Puerto

Rico and the US Virgin Islands were used to examine changes in the fisheries that could be attributed to the variability in Chl-a fields.

The commercial fishing landings data from Puerto Rico and the U.S. Virgin Islands were evaluated to determine if the anomaly recorded in 2009 (Chapter 2) impacted fisheries-related activities. The monthly harvest data were examined with the Chl-a values obtained from the images. The landings data from the areas closer to the sampling sites or the coast of interest were used.

The landings data for the month of January historically showed higher catches for red hind than the rest of the year. The highest landings of mutton snapper occurred during the spawning months of March or April most years. Preliminary results obtained from Chl-a values derived from MODIS images showed higher values of Chl-a just prior to the full moon of January (2003) at the Hind Bank off St. Thomas as compared to other times of the year. Red hind, a grouper using the Hind Bank as a spawning ground, spawn around the full moon. The higher values, about 300% over values found at other months, could be indicative of the favorable conditions needed for fish larvae to increase survival because of the availability of food.

Among the additional potential impacts of such an event (April 2009) are (1) the great amount of lower salinity water input, (2) the amount of nutrients carried with it, including photomineralization of fluorescent DOM (Morell and Corredor 2001), (3) the potential for non-native invasive species (scaridae larvae carried in plume), (4) the effects of light attenuation dependent on the time the plume remains in place and close to areas were algae and seagrass grow, and (5) spread of diseases that could impact corals and other organisms. These impacts remain to be studied.

This chapter used the information as provided by fishers and was written, on purpose, using pounds instead of kilograms. This chapter aimed to examine the consequences of the green water event on commercial and recreational fisheries. The main emphasis was to determine the relationship, if any, between the Chl-a fields and the fisheries data and to correlate changes in fishing during the time of the green water intrusion from the Amazon (Figure 2.11, Chapter 2). The specific objective was to determine if there were any specific changes in the fisheries that could have been caused by the April 2009 green water event (Chapter 2).

3.2 Materials and Methods

Commercial and Recreational Landings Data

Commercial landings data submitted by the fishers of Puerto Rico to the Department of Natural and Environmental Resources Fisheries Research Laboratory (DNER/FRL) were obtained from Daniel Matos-Caraballo (2009, Biologist, Commercial Statistics Fisheries Program, FRL, pers. comm.) for the years 1999 to 2009. The data sets include information on the landings port (but not the fishing location), species harvested per trip and pounds of fish harvested. These data were used to analyze trends in catches of dolphinfish, red hind and mutton snapper.

Catch reports data submitted by the commercial fishers of the US Virgin Islands to the Department of Planning and Natural Resources (DPNR) was obtained from NOAA SEFSC for the years 2000-2009. These data were used to analyze trends in catches of dolphinfish, groupers and snappers. The data in Chapter 3 were reported in pounds (English system) rather than in the metric system because the chapter was based on information from the general public and it was written for them [1 kg=2.2 lb].

Recreational fishing activity has been monitored in Puerto Rico since 2000. The data collected through the Marine Recreational Fisheries Statistical Survey (MRFSS) (now Marine Recreational Information Program (MRIP)) does not include information on the fishing location but offers an estimate of the poundage by species harvested per year. This is used as an indicator of fish availability in the area. The recreational fish landings were requested from various sources including the PRDNER, USVI DPNR, SEFSC, SERO, and published sources (*e.g.*, CFMC 2011). Some of the information, although limited, can be accessed online in (http://www.st.nmfs.noaa.gov/recreational-fisheries/access-data/data-downloads/index) and also upon request from NOAA's SEFSC.

The data were examined for differences in landings over time (2000-2009). Differences found were examined relative to the Chl-a values and other environmental factors as described in Chapter 1. A baseline for catches reported during April of every year was extracted from the data and compared to the catches of April 2009. Noteworthy at this time is the premise that landings might be influenced by the celebration of Easter Week in March/April of each year, a confounding variable in the assessment of the data. Many people in Puerto Rico and the US Virgin Islands buy fish during Easter Week because it is a traditional religious menu; they especially buy mackerel for "escabeche" but will generally buy any fish during this time.

Fishery-Independent Data

The Southeast Area Monitoring Program (SEAMAP-Caribbean) is the only fishery-independent, continuously running survey sampling reef fish in the U.S. Caribbean since 1990. The survey is conducted off the West Coast of Puerto Rico within a 13.7 km^2 gridded area.

Three areas of interest are Tour, ALS, and BDS corresponding to SEAMAP stations 78-79, 59 and 95-96, respectively. Data collected from these three sites off the West Coast of Puerto Rico are available for the years 1997-2009. The data on depth, date, and reproductive state of red hinds (*Epinephelus guttatus*) were used in this study to: (1) qualify the depth of the aggregations; (2) to determine the number of fish during the aggregation; and (3) to corroborate the reproductive state of the red hind. The changes in numbers over time were also compared to the daily landings reported by commercial fishers. Marshak (2007) reported on the SEAMAP stations numbers and the sampling of red hind over the 1988-2006 period of the survey. The data are important in that these have been used to manage the spawning aggregations of red hind in the area. The SEAMAP data with information on reef fish include the years 1999-2001 and 2004-2006. Other years were not available since the surveys are done for spiny lobster and queen conch at three and four year intervals (A. Rosario 2008, Director FRL/PRDNER, pers. comm.).

Fishing recollection and data

The April 2009 green water event represented an anomaly in the surface Chl-a fields when compared to the baseline developed for fish spawning aggregations and control sites. This anomaly was also a good example to use in (a) evaluating the recollection versus reporting of landings data and (b) examining the environmental heterogeneity in fisheries. The event of 2009 meant excellent fishing to a commercial fisher (C. Velazquez 2009, commercial fisher/diver, pers. comm.), an all-around bad weather year to a light tackle charter captain (M. Hanke 2009, commercial fisherman, pers. comm.) and no diving trips to a SCUBA instructor and charter operator because of the “itchy” particles in the water, the low visibility and the change in the composition of fishes people wanted to see (J. León 2009, port agent FRL, pers. comm.).

3.3 Results and Discussion

This section is divided into:

(1) Commercial data from (a) St. Thomas, (b) St. Croix, (c) West Coast Puerto Rico, (d) Southwest Coast Puerto Rico, (e) East Coast Puerto Rico. The commercial landings data from St. Thomas, St. Croix and Puerto Rico were examined and assessed for changes in the fisheries between the time series of 1999-2008 and 2009

(2) Recreational data for Puerto Rico. The recreational fishing data from Puerto Rico were explored and assessed for changes between the time series of 1999-2008 and 2009 for Puerto Rico. There are no continuous data collection efforts for the recreational harvest of the US Virgin Islands

(3) Fishery independent data for the (a) MCD and (b) West Coast Puerto Rico.

The assessment of the fisheries was done holistically. All data were evaluated together to describe the multispecies fisheries of Puerto Rico and the US Virgin Islands (Figures 3.2-3.4). The total landings reported over the time series showed that: (1) the highest landings by species groups were not the same for all the areas of interest; and (2) the landings varied among years for the most landed species. The data were further examined to identify landings of (a) groupers (identifying red hind, if possible), (b) snappers (identifying mutton snapper, if possible), and (c) dolphinfish. The landings of these three groups were explored focusing on the spawning months for red hind and mutton snapper and the month of April over the complete time series. The landings from the East Coast of Puerto Rico were examined to determine if there were any changes in the data set as a direct consequence of the April 2009 green water event.

The landings data were compared to the variability in Chl-a described in Chapter 1 to determine if there were any events that could explain the variability observed. Chl-a could be indicative of a number of phenomena such as internal waves, shallow depths (optically-clear waters), eddies, and green water events, among others. The months of increased Chl-a were correlated to the periods of time of known spawning by aggregating fish and seasonal presence of pelagics.

The recreational fisheries information from Puerto Rico was explored for the same species/species groups, red hind (groupers), mutton snapper (snappers) and dolphinfish.

St. Thomas, USVI

The commercial landings for St. Thomas were only reported by fish family since 2000 as these were reported by gear type before that date. The data available from 2000 through 2009, listing 24 species groups, indicated that landings have been fairly stable over this time period with total landings varying between a little over 617,000 pounds (minimum in 2000 probably due to the change in reporting format) and a maximum about 817,000 pounds in 2002, less than a 25% difference. The highest landings of 2002 can be attributed to 198% increase above average in landings of dolphinfish and barracuda, 753% increase above average of sharks and 178% increase above average in tunas; all pelagic species. St. Thomas fishers reported the highest landings of pelagics in 2002 out of the complete 2000-2009 series.

Figure 3.2 shows the variation in reported landings by species group in St. Thomas. The groups not included did not amount to more than 3% of the total landings (*e.g.*, whelk). The commercial landings data have been extensively reviewed for those species under management, specifically the reef fish, spiny lobster, and queen conch (*e.g.*, SEDAR (Southeast Data

Assessment and Review) 2009, CFMC 2005, 2011a, 2011b). It was not the intention of this work to review all the data but to use the available information to identify changes in the species groups being landed in this multispecies fishery between 2000 and 2009.

The species groups that make up the largest percent of the catch were identified in Figure 3.2; eight groups amounted to over 75% of the total catch. Snappers had the highest percentages of the catch. The snapper was most likely the yellowtail snapper that makes up the bulk of the snapper landings, but that still remains to be determined. The mutton snapper in St. Thomas is considered ciguatoxic and probably does not make up a large percent of the reported landings (D. Olsen, pers. com). Therefore, snapper landings were not investigated further.

The grouper landings ranked fourth, after lobster and triggerfish. Groupers are a special case because even though there are a number of specific restrictions on their take, such as a seasonal closure (February-April), a no-take zone (MCD) to protect the spawning aggregation of red hind, a seasonally closed area to protect the spawning aggregation of yellowfin grouper, and the prohibition on the take of Nassau and Goliath groupers, they still make up almost about 8% of the total catch. The MCD was established as a seasonally closed area in 1993 and as a no-take zone in 1999. The seasonal closure for groupers (red, black, yellowedge, tiger and yellowfin) was implemented in 2005 and, in 2004, to protect the spawning aggregation of yellowfin at Grammanik Bank. Commercial landings distribution by month for red hind was not available by species from the DPNR data set. Preliminary information of the surface Chl-a values at Grammanik Bank showed values similar to the MCD.

The highest percentage of the grouper catch was probably represented by red hind (J. Magrass, St. Thomas Fishermen Association, pers. comm.). If this were the case, then the overall landings could be reflecting the success of the red hind aggregation at the MCD. Grouper landings were highest in 2009 followed by 2004, 2005 and 2008 with the lowest landings in 2002. The results of the calculation of DELTA (Chapter 1), the change in Chl-a at the MCD from week to week, showed that the highest change was observed in 2009. The estimated population densities of red hind at the MCD increased four-fold between 2006 and 2009. The density estimate of the population was based only on the data for the month of January. These relationships were not examined any further at this time but will be explored in the near future (R. Nemeth, pers. comm.).

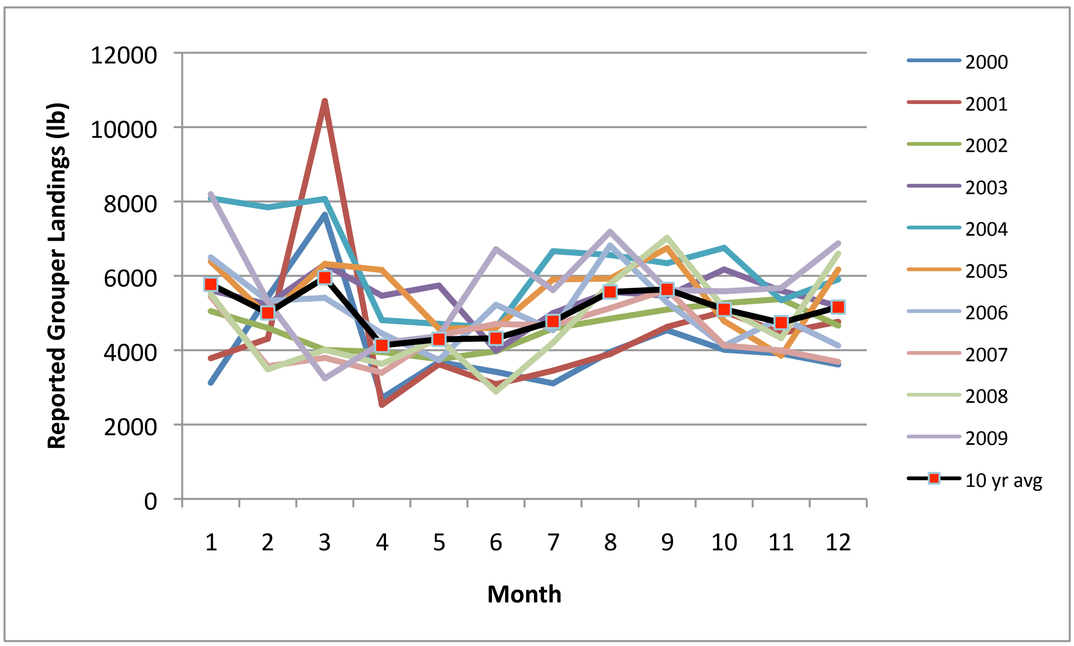


Figure 3.2 Monthly reported landings of grouper in St. Thomas 2000-2009 including the 10-year average

Grouper landings showed the impact of the regulations implemented in 1999, 2004 and 2005. In 1999, the Hind Bank – a seasonally closed area to the protect red hind spawning aggregation became a no-take zone to protect all corals (CFMC 1999). In 2004, Grammanik Bank, the area most fished (J. Magrass, per. com.) by commercial fishers during the aggregation of yellowfin grouper (see March peak in Figure 3.5) became a seasonally closed area during the months of

March through May. In 2005, a seasonal closure on the harvest of red, tiger, black, yellowfin and yellowedge was implemented in the federal waters with subsequent implementation in the territorial waters of the USVI. In 2009, grouper landings showed above average landings in June, August and December. Commercial fishers targeting groupers did not report any direct impacts from the green water event of April 2009, other than not being able to see the bottom in areas where they normally did. Comments included that the “behavior of the hind was not different”.

The increase in pelagic landings in 2002 was significant and resulted in a 25% increase in total landing in St. Thomas. Dolphinfish were reported separately and although two species could be reported within the group (*Coryphaena hippurus* and *C. equiselis*), the most common species was *C. hippurus*. The strongest season for dolphinfish in St. Thomas was during February through May, and commercial fishers reported very little landings during the summer months (Figure 3.6).

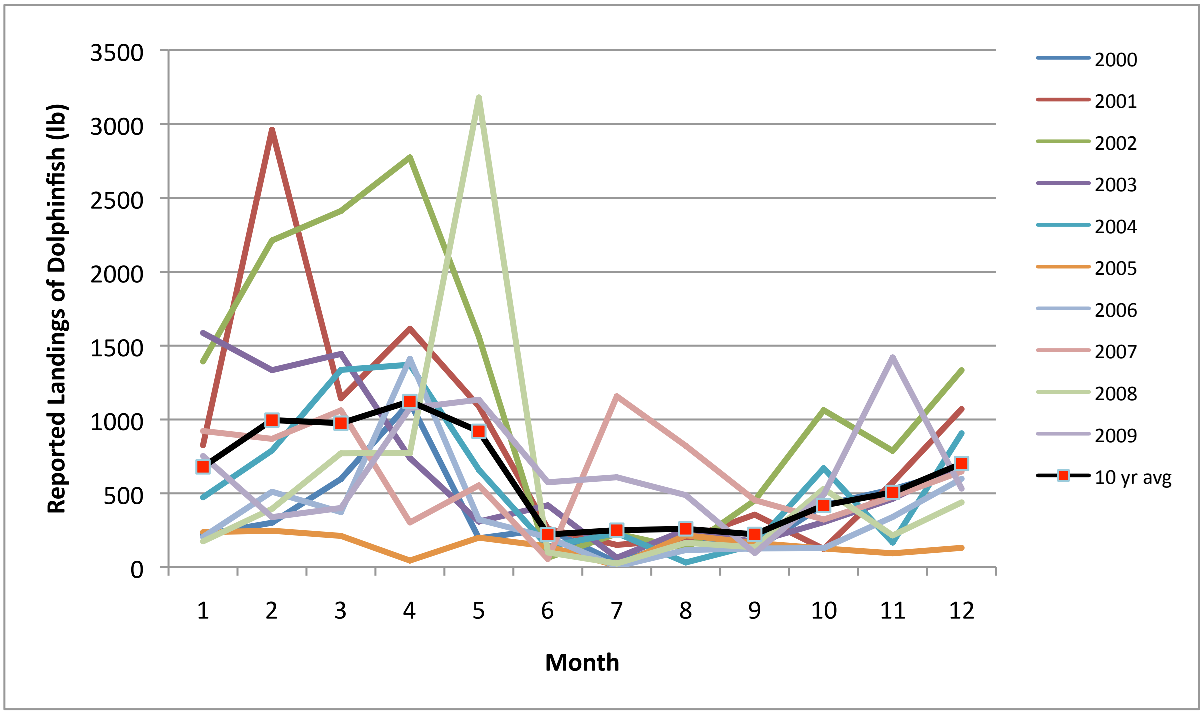


Figure 3.3 Monthly reported landings of dolphinfish in St. Thomas 2000-2009 including the 10-year average

There were increased summer landings of dolphinfish in 2007 and 2009. If the April 2009 green water event resulted in productivity of the waters in St. Thomas, an extended fishing season for dolphinfish could ensue. There were no anomalies (in Chl-a, SST, or total precipitation) reported for 2007 but the extended fishing season for dolphin in both 2007 and 2009 should be investigated further. Additional datasets that could be examined to explain the changes in 2007 are salinity and dissolved oxygen, for example.

The waters of the USVI, based on the April 2009 Chl-a residence time returned to baseline values after June 2009. Over seventy-five percent of the dolphinfish landings in St. Thomas were reported from TNE (Northeast St. Thomas) during the months of May-July 2009.

The seasonal distribution of pelagic species has been associated with oceanographic features such as sea surface temperature, fronts, topographic bumps, and others. To explain the increase in landings of pelagics in 2002 in St. Thomas, NOAA/NHC archives of hurricane seasons between 1999 and 2009 were examined and showed no major hurricanes within 2° of latitude from Puerto Rico and the USVI (Chapter 1). Examination of the total precipitation records for the same time period showed no anomaly for 2002. The Chl-a mean value for 2002 at the MCD was 0.12 mg/m^3 with maximum values of 0.18 mg/m^3 during the week of June 26. This maximum value was on the low end of all maximum values recorded between 1999 and 2009. Given these findings, the year 2002 exhibited very clear waters in the USVI, there were reports of droughts in the area, and thus very little run-off or river plume activity. These conditions of very clear water could be responsible for the increased presence of dolphinfish in the USVI. Other plausible explanations could be explored in the socio-economics realm such as increased demand for dolphinfish (*e.g*., increase in tourism), introduction of a fish aggregating devices (FAD), presence of seasonal fishing boats (charters) with commercial fishing license, increased presence of debris in the area, etc. The presence of *Sargassum* in the area has been documented in recent years but its presence in the USVI in 2002 could not be corroborated at this time. Kleisner (2008) reported oscillations in the abundance of dolphinfish with maximum CPUE as an index of abundance for the dolphinfish in the East Coast of the US in 2002.

Recreational catch of dolphinfish in St. Thomas was not well documented in recent years, only recreational fishing tournament activity was monitored.

Other recreational activities that could have been impacted were the charter boats that take people out snorkeling and SCUBA diving, but most charters in St. Thomas do not allow, or did not use to allow, fishing (García-Moliner *et al*. 2002). Complaints were received from charter operators regarding “itchy” particles in the water and low visibility which prevented them from taking clients out; a direct impact of the April 2009 green water event.

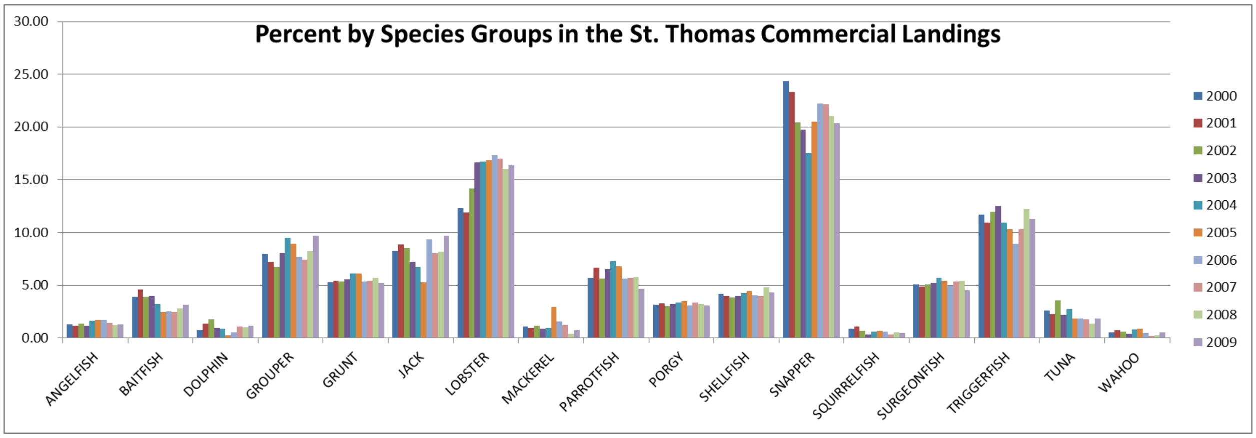


Figure 3.4 Reported commercial landings by species groups (x-axis) expressed as percent of the total catch (y-axis) from St. Thomas, USVI (2000-2009)

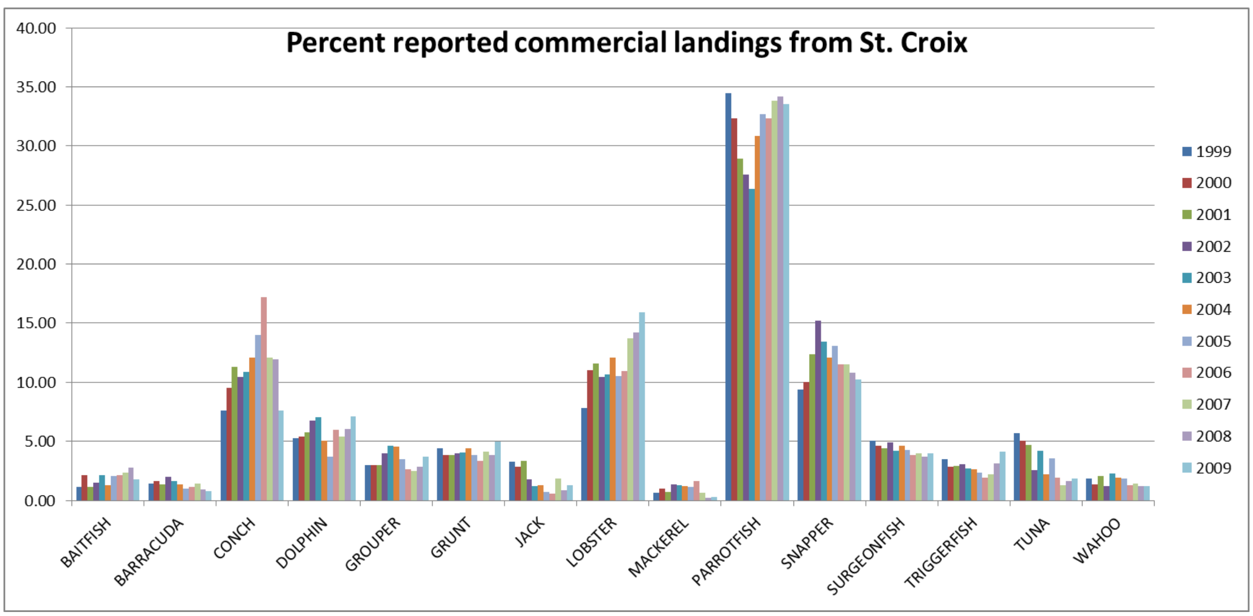


Figure 3.5 Reported commercial landings by species groups (x-axis) expressed as percent of the total catch (y-axis) from St. Croix, USVI (2000-2009)

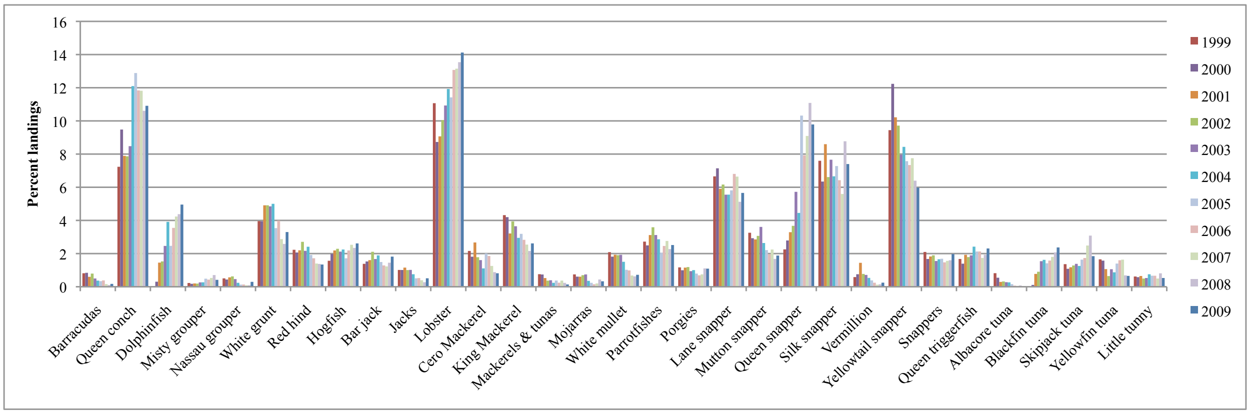


Figure 3.6 Reported commercial landings by species groups (x-axis) expressed as percent of the total catch (y-axis) from Puerto Rico (2000-2009) for species with more than 50,000 pounds reported except for first, second, third class and other species category

St. Croix, US Virgin Islands

As in St. Thomas, the commercial fishing landings data are reported as species groups (families). The data for St. Croix were available since 1998. There were 27 species groups reported between 1999 and 2009. Six species made up over 75% of the landings; parrotfish (probably includes wrasses (pers. obs.), conch, lobster, snapper, dolphinfish, and surgeonfish. Groupers only made up about 3.4% of the catch (rank 9 out of 10) (Figure 3.3). Groupers are subject to management in St. Croix as are the other reef fish, conch and lobster but none of the coastal pelagics (*e.g.*, dolphinfish, wahoo) are managed. Management includes the two seasonally closed areas Lang Bank (LB) and Mutton Snapper aggregation site (MUT). Also, there is a ban on the take of Nassau and Goliath groupers and a seasonal closure on other groupers.

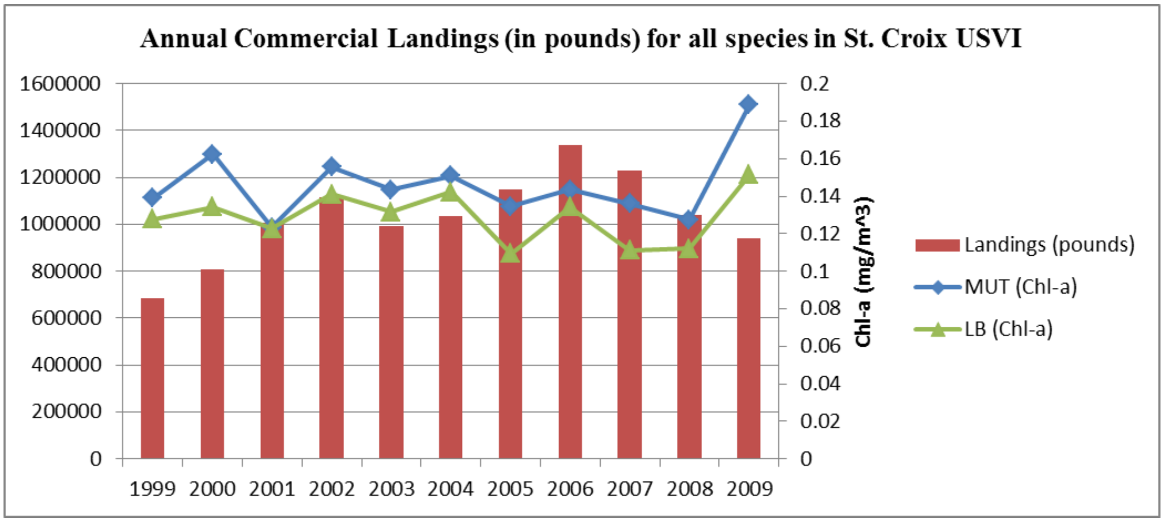


Figure 3.7 Total commercial fishing reported landings in pounds (y-axis) for St. Croix between 1999 and 2009 (x-axis). There were 27 species groups included in the total poundage

Landings increased over this time period with total landings that varied from a little over 684,000 pounds (minimum in 1999 probably due to the change in reporting format) to a maximum of about 1,339,000 pounds in 2006 (Figure 3.7). The increase in 2006 was only due to the landings from queen conch. The information not included in the graph because of the very low reported landings was: (1) released marlin (peaked in 2000), (2) sharks (in 2006), (3) barracuda (in 2002), (4) unspecified shellfish (in 2003), (5) unspecified pelagics (in 1999, probably due to a change in reporting), and (6) whelk (in 2004). These groups amounted to approximately 3% of the total landings. The commercial landings data have been extensively reviewed for those species under management, the reef fish, spiny lobster, and queen conch (*e.g.*, SEDAR 2009, CFMC 2005, 2011a, 2011b, and many others). It was not the intention of this work to review all the data but to use the available information to identify changes in the species groups being landed over the period 1999-2009, including changes due to the April 2009 green water event.

The species groups that made up the largest percent of the catch are included in Figure 3.3; six of these made up over 75% of the total catch. Parrotfish always made the highest percent of the catch. Of the other fin fish, snappers made the second highest percentage; it is probably yellowtail snapper that made up the bulk of the snapper landings. Conch and lobster each accounted for over 11% of the total annual landings, significantly less than the 30% accounted for by parrotfish. The importance of parrotfish is because they are species closely associated to coral reefs; they are also a targeted species in St. Croix and have been important culturally for a very long time. The parrotfish are also under management by limiting the annual catch, the recreational catch and via a prohibition on the take of three species of parrotfish. In this case, management is only in the jurisdiction of the federal government and not in the Territorial waters of the US Virgin Islands.

Compared to St. Thomas, groupers were not a significant percentage of the catch but red hind might be the grouper most landed in St. Croix. But, contrary to St. Thomas, there has been no in depth analysis of the success of the seasonal closure of Lang Bank. Nemeth *et al*. (2008) provided an estimate of the red hind spawning population at Lang Bank. Grouper landings were highest in 2004 followed by 2003, and 2002 with the lowest landings in 1999 (probably because of a change in reporting format). Snappers showed the highest landings in 2002 followed by 2006, and 2005 with the lowest landings in 1999, 2000 and 2009. Pelagic fisheries in general are seasonal in nature and are targeted in St. Croix. These include dolphinfish (6% of the total landings), tuna, mackerel and wahoo. These fisheries and the deep-water snapper fishery are somewhat dependent on baitfish (*e.g*., live bait for deep water snapper and tuna; G. Martinez pers. comm.). The Chl-a annual mean from the LB and MUT, including the maximum annual mean recorded for 2009, was presented against the landings data for a number of species groups (Figures 3.8-3.9).

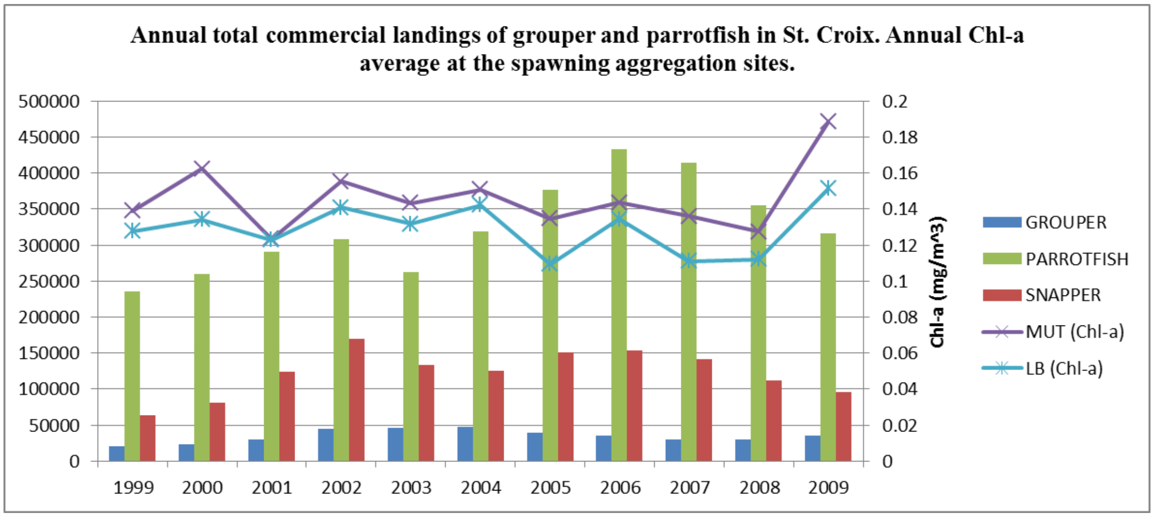


Figure 3.8 Reported annual (x-axis) commercial landings (y-axis in pounds) for grouper, snapper and parrotfish from St. Croix, USVI. The Chl-a annual average from the two spawning aggregations sites is included

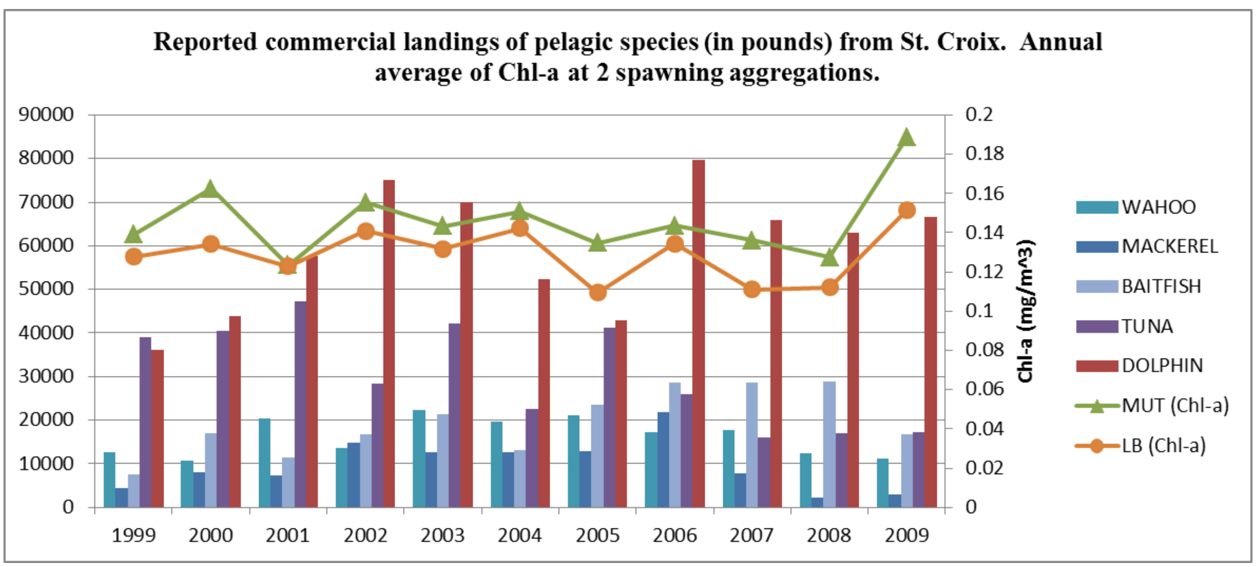


Figure 3.9 Reported commercial landings (y-axis in pounds) for pelagic species in St. Croix plotted with the annual average Chl-a from the two spawning aggregations sites.

The pelagic fisheries are seasonal and are associated with floating objects, including Sargasso mats, flotsam and jetsam, fish aggregating devices (FADs) or fish aggregations that serve as food. Dolphinfish accounted on average between 4% (lowest in 2005) and 7% (highest in 2003 and 2009) of the total landings of St. Croix. The climatology of Chl-a at the aggregation sites of LB and MUT showed that there were no significant differences among years (Chapter 1). In Chapter 2, when the climatology was compared to the 2009 values, there were no significant differences.

The data on dolphinfish showed this seasonality (Figure 3.10) with most landings reported during the first half of the year (February to May). The distribution of dolphinfish has been documented and most recently by Farrell (2009) who concluded from his model that they prefer areas (habitats) of higher surface chlorophyll. Although his work dealt more with the "northern" population of dolphinfish, it is a circumglobal species http://www.iucnredlist.org/details/summary/154712/0) but presented a very marked seasonal distribution in the Caribbean. Nevertheless, neither one of the areas showed a significant increase in Chl-a between 1999 and 2008; there was a slight increase in Chl-a in 2003 and 2004 during the earlier part of the year. In 2009, much higher Chl-a values were recorded at LB and MUT during the month of April. These maximum Chl-a values of 0.75 and 0.96 mg/m^3 were confirmed by *in situ* chlorophyll data collected at LB and MCD in St. Thomas (T. Smith 2009, marine scientist, St. Thomas, pers. comm.; CRCP 2009 (Cruise Report and data analyzed in Chapter 2). The landings data include spatial references to the area of harvest. Ninety-five percent of the harvest of dolphinfish was reported from 6 areas in St. Croix. Although this work did not include areas other than spawning aggregation sites, the dolphinfish data from St. Croix can be further examined and the spatio-temporal information correlated to satellite data from ocean color and SST in order to explore the distribution of dolphinfish.

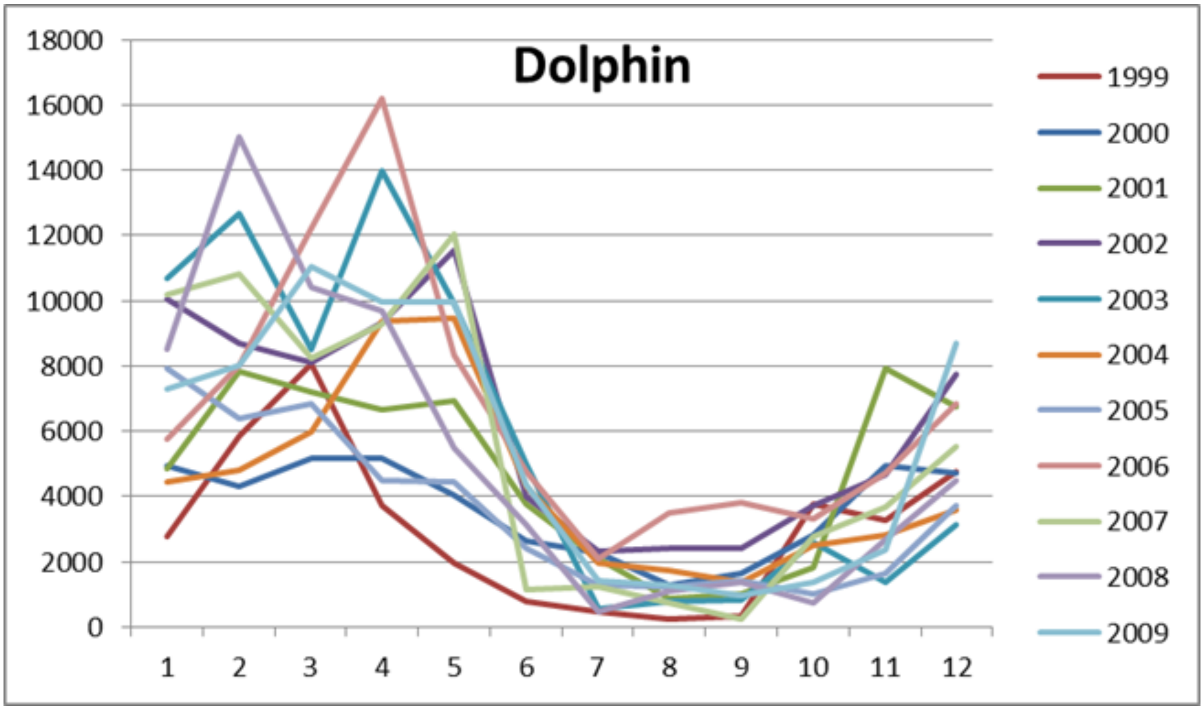


Figure 3.10 Dolphinfish seasonality in St. Croix (y-axis=pounds; x-axis=month)

Data of spatial information and a summary of the harvest at Lang Bank and Southwest St. Croix, mutton) is included herein (http://www.sefsc.noaa.gov/sedar/download/SEDAR4_DW_08.pdf?id=DOCUMENT).

The spatial information is contained within the commercial catch reports. The data for 1999-2009 for groupers and snappers by area showed that the largest proportion of snappers was reported from the Lang Bank area.

The data from the commercial landings was ranked to explore the variability in species catch composition. There was an increase in landings of surgeonfish in 2005 and a decrease in dolphinfish. In 2003, there was a noticeable increase in grouper landings. Although most species groups remained within the average ranking of 11 years, triggerfish had been climbing the ranks since 2007 to rank #7 in 2009 in the commercial landings of St. Croix. Over the 11-year period, the top 5 ranking species groups have remained the same (parrotfish, lobster/conch/snapper and dolphinfish fish).

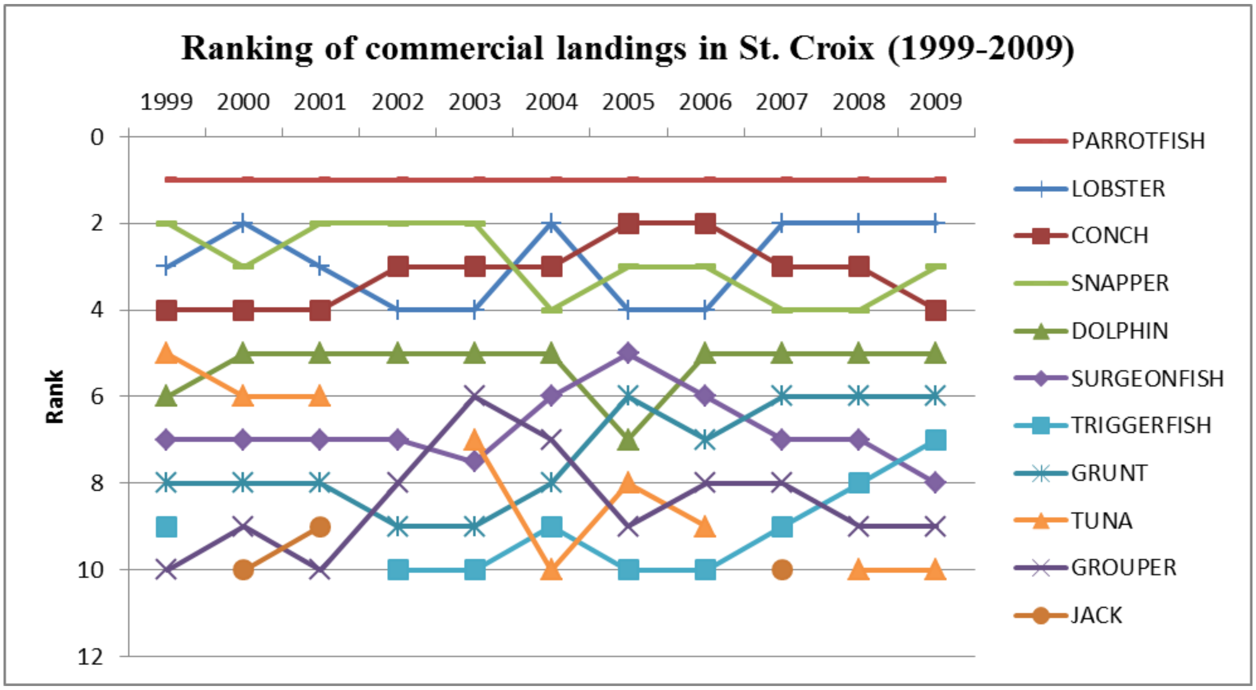


Figure 3.11 Summary of the changes in the landings by species groups for St. Croix

The ranking of these showed that dolphinfish, the 5th species most landed in St. Croix, decreased in 2005 but the reason is currently unknown. Additional attempts were made to correlate the Chl-a signal at LB and MUT with fisheries data but except for an estimate of the spawning population at the LB by Nemeth *et al*. (2008) of 3,000 red hind in 2004 (0.15 mg/m^3), a year with above average annual Chl-a mean, no other data could be found. No additional fishery-independent data for red hind, mutton or dolphinfish were available for this work. Gerard *et al*. (2009) have specific information on the larvae collected at LB, MUT and MCD over the years 2007-2009 as well as TSG and CTD data. The data on Chl-a from the CTD and

TSG were made available from the 2009 cruise by NOAA/SEFSC and analyzed in Chapter 2 to corroborate the high values of Chl-a obtained from OCR.

Kojis and Quinn (2011) studied the mutton snapper spawning site (MUT) in 2009 but the small number of fish at the aggregation precluded an estimate of the spawning population. The timing of the spawning aggregation in 2009 occurred during the intrusion of green water. Kojis (pers. comm.) reported on the low visibility and the amount of stinging cells all around St. Croix, including the aggregation site.

Recreational data from St. Croix was not collected on a regular basis. Data are available from recreational tournaments and sporadic surveys but none of these were concurrent with the green water event.

Recreational Information USVI

The little information that was available for the USVI included three years of the Dolphin Fish Derbys (Data provided by the USVI DPNR). The data are from the month of April 2007, 2008 and 2009. The data showed a decrease in participation, effort, number of fish landed and CPUE from 2007 to 2009.

Puerto Rico

The commercial fishers in Puerto Rico reported as many as 147 species in the landings data. Contrary to the data from the USVI, fish landed were reported at the species level. The database was evaluated to determine if the species of interest (red hind, mutton snapper, pelagic species) were among the top species landed and they were not between 2003 and 2009, except for mackerels in 2003. Between five and nine species made up 50% of the total catch. The top three species in 2003 and 2004 were lobster, conch and yellowtail snapper and between 2004-2009, these were conch, lobster and queen snapper. The only change in the top species landed was in 2003 when mackerel was among the top eight species landed.

Puerto Rico West Coast

The commercial landings from the West Coast were explored to determine changes in red hind reported catches between 1999 and 2009. Red hind showed increased landings in 1999 and 2002. The data from the fishing centers between the towns of Aguadilla to Cabo Rojo were considered landings reported in the West Coast. There were over 1,000,000 fishing records for the period 1999-2009, therefore, only the data from areas close to the fish spawning aggregation sites that were described for surface Chl-a were used. The Puerto Rico reported landings data provided an indication of the species availability. There was no attempt at analyses beyond simple comparisons needed to answer questions about the impact of the green water event of 2009 on the local fisheries. It was necessary to summarize the historical data available on red hind, mutton and pelagic species to determine if there were any changes that could be attributed to the green water event of April 2009.

Total reported landings for all Puerto Rico are shown by coast and year between 1999 and 2009 in Figure 3.4. The largest contribution to the commercial landings has generally been from the West Coast except in 2000, 2001 and 2002 when the South Coast reported the most landings. The trend in decreasing total landings has to be addressed separately for each coast but, most importantly, these trends need to be examined with the following issues in mind: (1) changes in regulations included the implementation of seasonal closures, restrictions on gear, and prohibitions on the take of certain species, (2) changes in the demographics of the fishing sector,

(3) changes in the economy and the resulting impact on fishing businesses (*e.g*., less demand for products), and (4) cumulative impacts to the marine environments resulting in unaccounted loss of essential fish habitats. The West Coast showed the less dramatic decrease in landings. The contribution of each coast to the total landings of Puerto Rico was also shown in Figure 3.11.

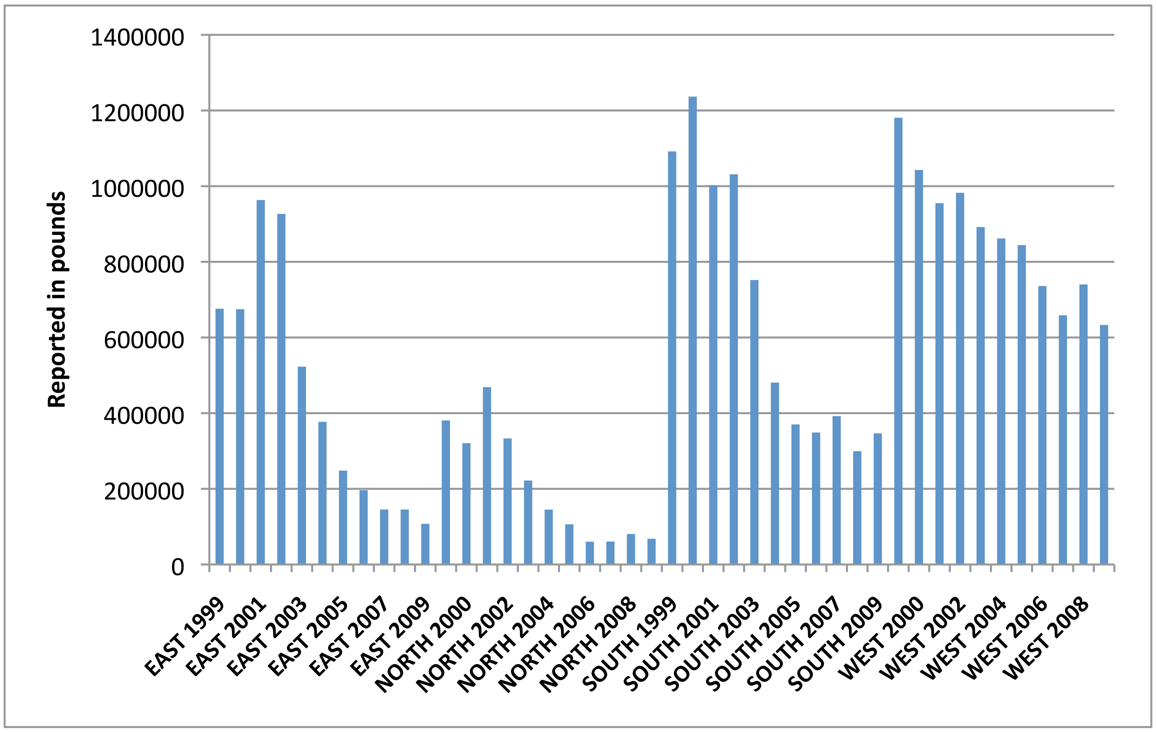


Figure 3.12 Total annual reported commercial landings (x-axis) by coast in Puerto Rico 1999-2009

Although it would be of great interest to report on all the differences among the coasts, the data were only examined for the red hind, mutton snapper and pelagic landings for this study. The annotated list of species landed in Puerto Rico (Erdman 1974, D. Matos-Caraballo, Biologist, Commercial Statistics Fisheries Program, FRL, pers. comm.) included 934 fish and shellfish species codified by the FRL/PRDNER. The fishing centers were also codified by the FRL and although there was no spatial information on the fishing area, there was information on the landing port.

RED HIND

The distribution of red hind landings by coast and year clearly showed the earlier years with red hind landed from all coasts with dominance from the South and West and in the later years only the West Coast reporting a considerable amount of red hind (Figure 3.12). There are a number of reasons for this: (1) the lack of reporting from the South Coast, among other reporting issues, (2) the changes in gear being used (*e.g.*, fewer traps and more spearfishing (diving) in the East Coast), (3) changes in the demographics of the fishing sector, (4) problems with the dataset such as species misidentification and codification, and (5) changes to the regulations that impact fisheries differently. Only three centers reported over 30,000 pounds of red hind in the 11-year time period: Puerto Real, Cabo Rojo; El Seco, Mayagüez; and Playuela, Aguadilla. Puerto Real and El Seco fishers had access to ALS, Tour and Parguera while Playuela fishers had access to BDS and Tour. There were other fishing areas for red hind but the interest of this study was to relate the fishing activity to these specific red hind spawning aggregation sites.

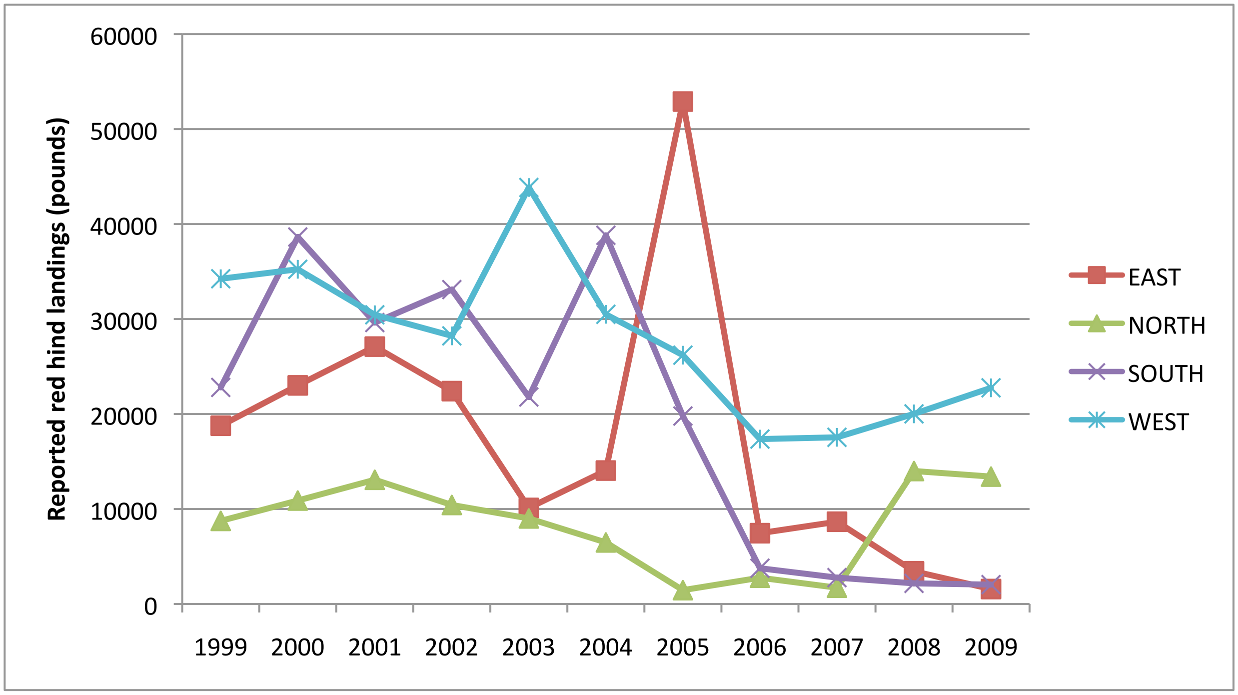


Figure 3.13 Reported commercial landings (pounds) of red hind by coast in Puerto Rico 1999-2009

The red hind fishery is complicated because of a number of management measures that were implemented during the 11-year period, including a seasonal closure (Enmienda al Reglamento de Pesca 2004). The data for the West Coast was examined for variability in the landings and Chl-a in the three aggregation sites (Figure 3.13).

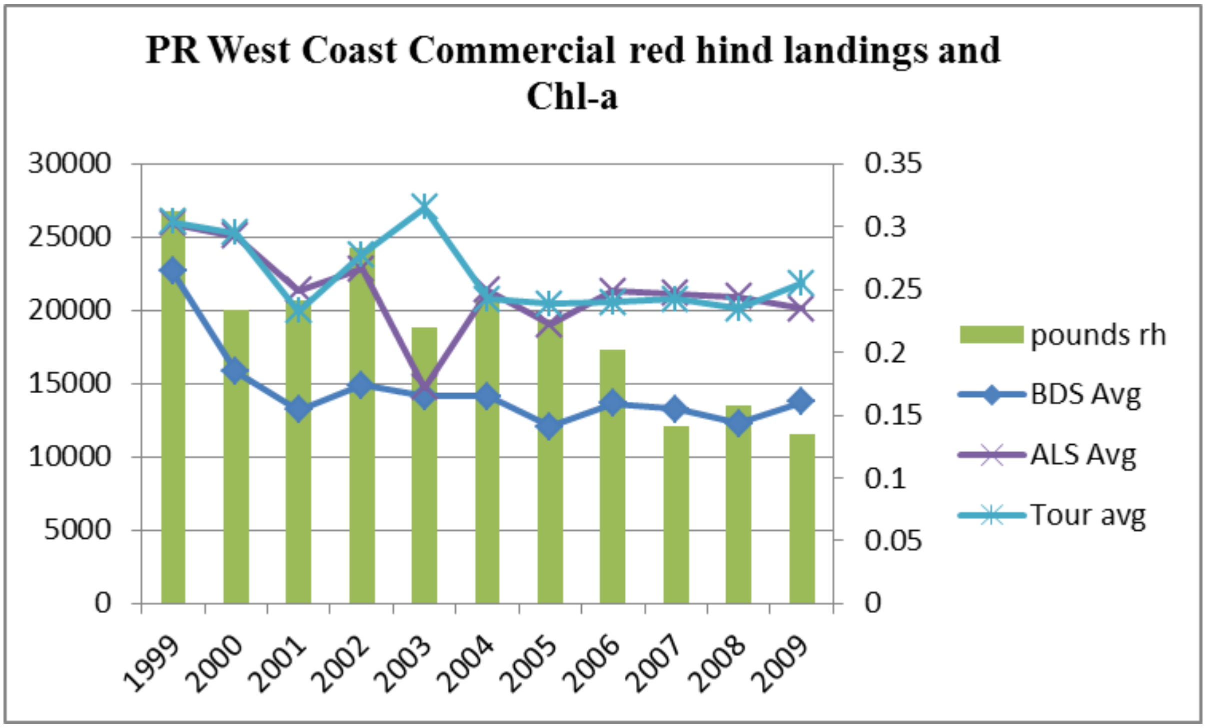


Figure 3.14 Puerto Rico West Coast Commercial Red Hind landings (pounds; left y-axis) and Chl-a concentration (mg/m^3; right y-axis)

These three sites (ALS, Tour and BDS) were seasonally closed in the 1990s and the seasonal closure was established in 2004 and 2005 for the red hind west of 67°10'W. This caused a shift in fishing for red hind from December-February (spawning season) to later in the year.

The annual Chl-a average from two of the spawning aggregations sites was compared to the landings data from the West Coast and results yielded low correlation values (r^2= 0.208 (Tour); 0.325 (ALS)). There were a number of limitations in the use of these two sets of data, namely of scale – both temporal and spatial, cause and effect, among others that could be explored at a later date. The reported commercial landings of red hind (3.14) showed the changes due to the implementation of seasonal area closures and the seasonal closure in both state and federal waters. The drop in landings during the early part of the year was due to the regulations not to a problem with the fishery.

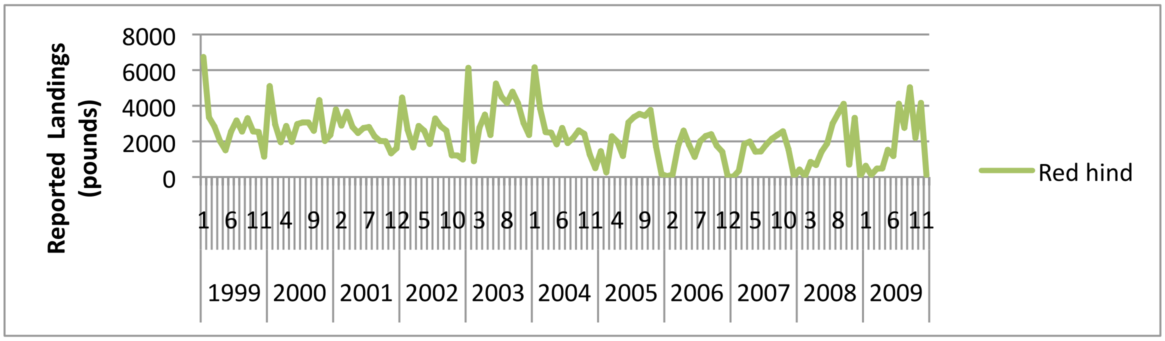


Figure 3.15 Monthly reported commercial landings (pounds) of red hind in Puerto Rico

MUTTON SNAPPER

Mutton snapper reported landings clearly reflected the seasonal closure established in 2004 by the PRDNER, followed in 2005 by the implementation of the seasonal closure in the EEZ (Figure 3.15). There are no seasonally closed areas to protect the spawning aggregations of the mutton snapper as exists for the red hind. The mutton landings were primarily from the South Coast of Puerto Rico. Mutton snapper are targeted primarily during the spawning season (April-May in Puerto Rico, April-June in federal waters (Figuerola and Torres 2001, CFMC 2005).

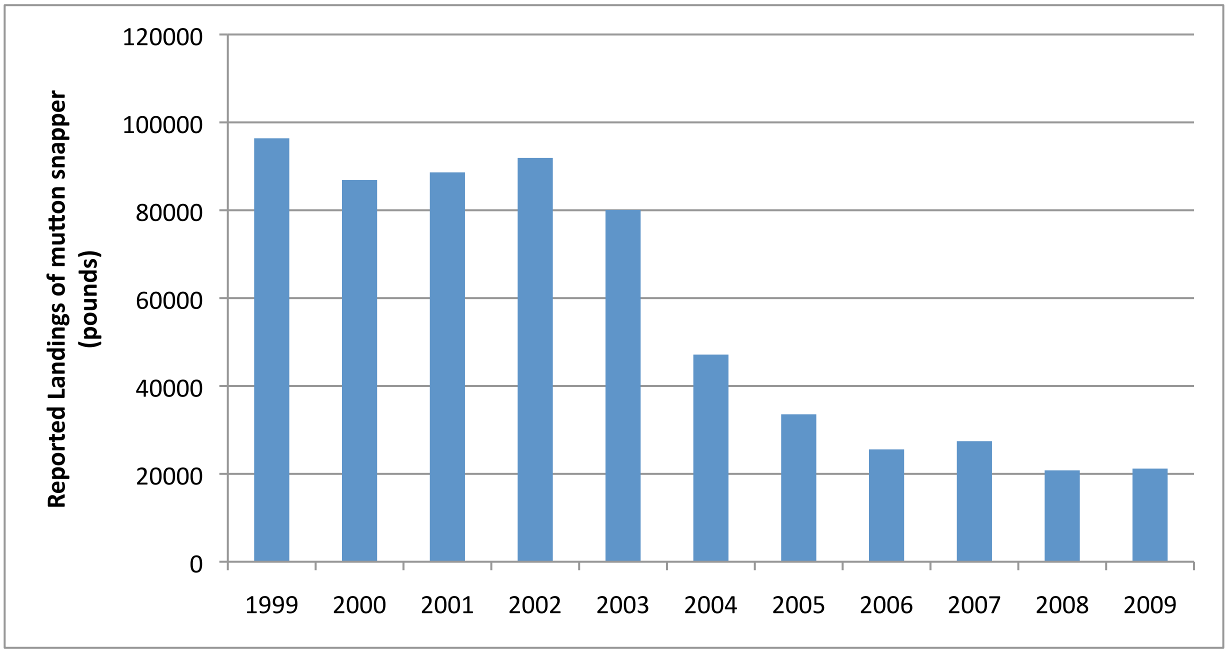


Figure 3.16 Reported commercial landings (pounds) of mutton snapper in Puerto Rico from 1999 to 2009

The landings showed a dramatic decrease due to the seasonal closure and concurrent decrease in reporting. There was no information from monitoring of the mutton snapper except for Esteves Amador (2005). The 2007 peak was in June and corresponded to the fishing center of El Seco, Mayagüez reported about 2,000 pounds on June 7 with a total of 4,930 pounds in 5 days. The full moon was on June 1st, after which the mutton snappers were harvested, the day before the last quarter moon. El Seco is very close to Tour but there were no spatial information in the datasets to identify the fishing area. During the anomaly of the green water event (Chapter 2) Tour and Rene were found to be similar to each other but different from all other aggregation sites. There was no confirmation of a spawning aggregation for mutton at Tour.

Esteves Amador (2005) studied the mutton snapper aggregation in La Parguera, Lajas, Puerto Rico in 2003. The data from 2003 for the various fishing centers in Lajas was examined to determine daily landing in April 2003, the month with the highest landings that year. That same year, La Parguera reported the 3rd highest landings of the time series (1999-2009).

The days of maximum fishing, accounting for more than 63% of the total landings of mutton within a 9-day period, were examined against the Chl-a values derived from OCR and from *in situ* data collected by Esteves Amador (2005). The Chl-a values of 2003 were compared to the 11-year average and these were above average (Chapter 2). Esteves Amador (2005) reported surface chlorophyll values at stations near the aggregation site between 0.3 and 0.8 mg/m^3. These were higher than the weekly averages of < 0.3 mg/m^3.

PELAGICS

Almost 50% of the total Puerto Rico commercial landings of dolphinfish were reported during the months of January-March with about 15% reported in December. This was also the case during the entire time series.

Puerto Rico East Coast

The East Coast of Puerto Rico received the impact of the April 2009 green water event as reported in Chapter 2. The commercial landings data from Puerto Rico were explored to determine if there were any changes in the red hind or mutton snapper harvest during that time. The data were also explored to determine if the SCUBA diving fisheries had been impacted by the decreased visibility and the "itchiness" in the water reported at the time of the event.

The East Coast of Puerto Rico is described by the PRDNER/FRL as including the towns of Fajardo to Maunabo and Culebra and Vieques.

Fishers were required to fill the landings reports with 0 pounds if no fishing was done that day. This field in the data set was explored to determine the difference in trips between 2009 and other years. Surprisingly, fishers submitted more 0 reports in 2008 than in the year 2009

(Figure 3.16). This could be indicative of other issues such as specific weather conditions on the East Coast that prevented fishers from taking fishing trips in 2008 or due to changes in the demographics (J. León, port agent FRL, pers. comm.). There appeared to be no impact on the East coast in 2009 at least from the information on the 0 pound catch reports. These data (0 pounds) were explored because commercial divers complained about poor visibility and diving charters about not being able to take clients out due to low visibility (Figure 3.17) and "itchiness" from the water during the 2009 green water event. Figure 3.17, although not from the East Coast of Puerto Rico, was taken in the MCD (photographs courtesy of T. Smith 2009, marine scientist UVI, St. Thomas, pers. comm.) and clearly showed the differences between average conditions and the green water anomaly of 2009.

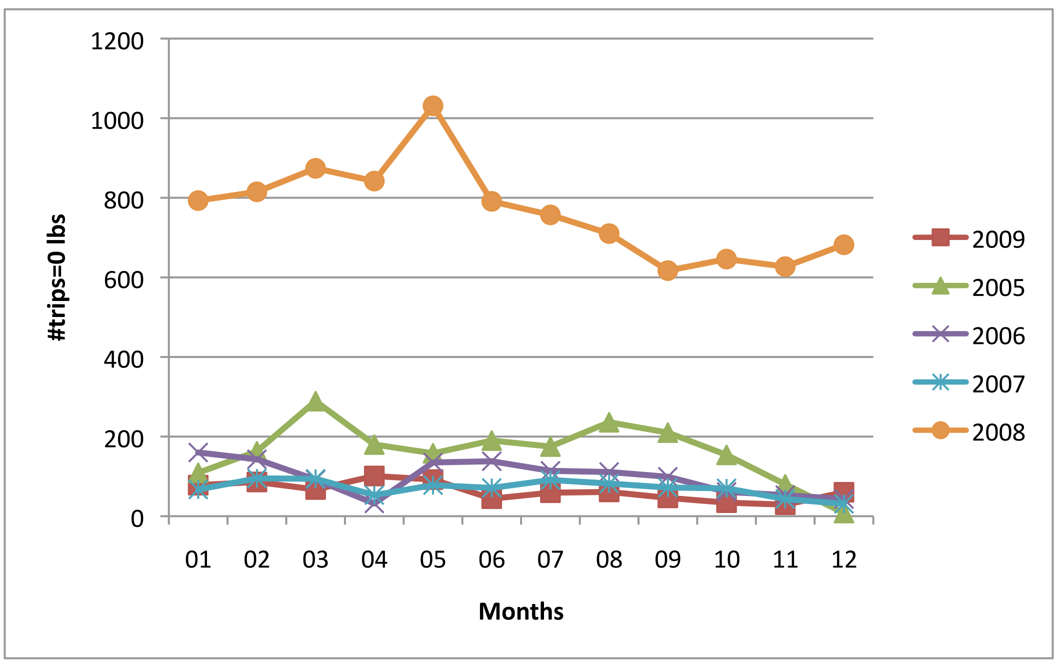


Figure 3.17 Number of fishing trips with reported 0 pounds landings from the commercial catch in the East Coast of Puerto Rico, 2005 to 2009

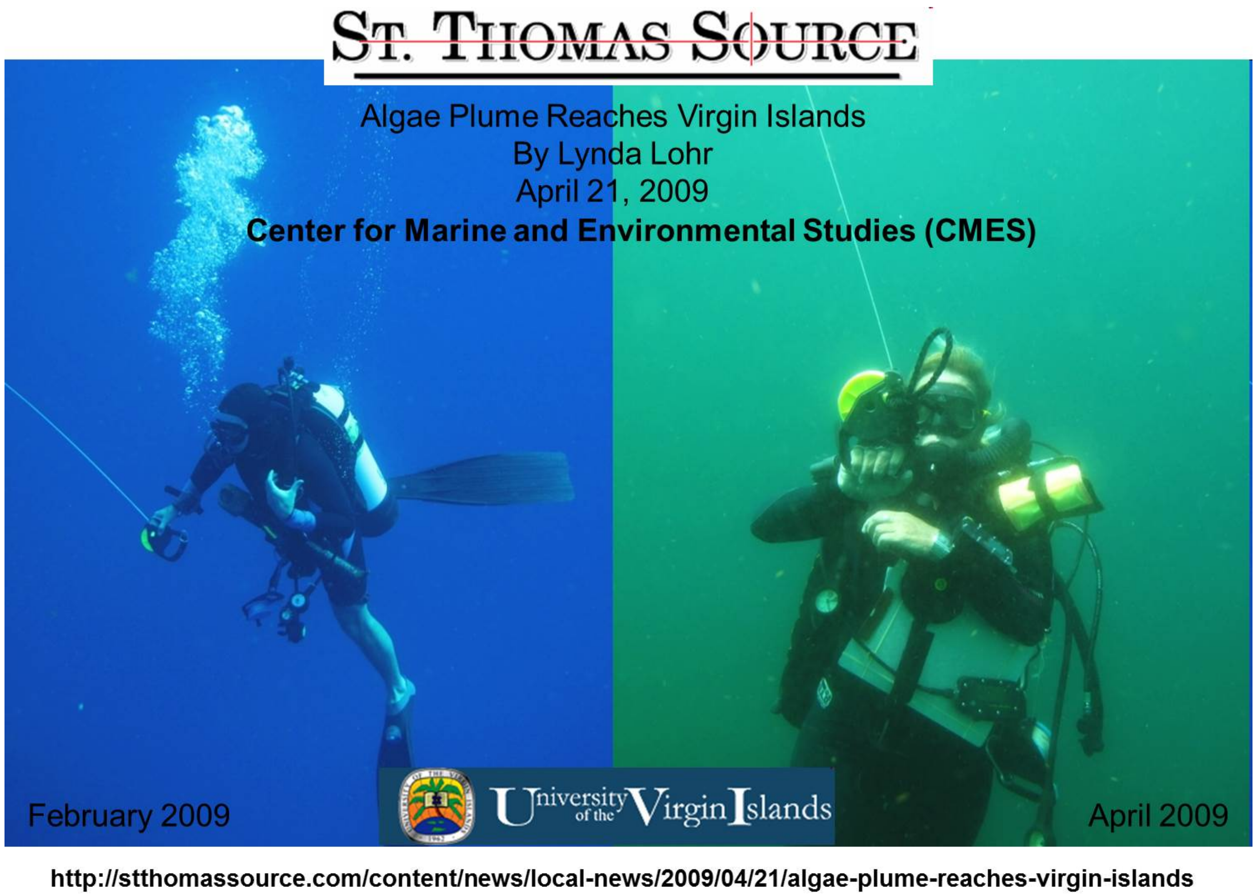


Figure 3.18 Photographs of the water at the MCD before and during the green water event (courtesy of R. Nemeth, T. Smith and the USVI Daily News)

A plausible explanation is that commercial fishers, contrary to dive schools, have fishing grounds further away, in deeper water or in areas that might not have been impacted by the green water event on 2009. The commercial landings data from the East Coast of Puerto Rico have not been examined in detail. The species with highest landings were queen conch and lobster, both targeted by divers. There were indications that the number of trap fishers was decreasing while the number of divers was increasing (D. Matos-Caraballo 2009, Biologist, Commercial Statistics Fisheries Program, FRL, pers. comm. and J. León 2009, port agent FRL, pers. com). The two other species with significant landings were yellowtail and silk snappers.

The commercial data set was examined for noticeable changes due to the 2009 green water event. The recollection of the fishers for 2009 was that it was a good fishing year (C. Velazquez 2009, commercial fisher/diver, pers. comm.). These divers landed spiny lobster "to meet the demand" (C. Velazquez, pers. comm.) but specifically stated that although the demand was steady, it had diminished from previous years because many restaurants had gone out of business.

Due to the changes in regulations, in the reporting and in the demographics of the fishery it was decided to explore the data from the last three years and only for the months related to the April 2009 event. The total landings from the commercial catch were tested to determine significant differences in the landings in April between 2007 and 2009. A chi-squared test indicated that there were no significant differences between years.

Although dolphinfish was not one of the top species landed on the East Coast, there was a slight increase in dolphinfish landings during the time of the April event. The confounding variable in this case would be the celebration of the Easter Week (Good Friday fell on April 10 2009) and the daily records showed an almost four-fold increase in the landings on April 9th. Overall, the reported landings of dolphinfish off the east coast of Puerto Rico were minimal compared to other years (2005-2009) (Figure 3.19).

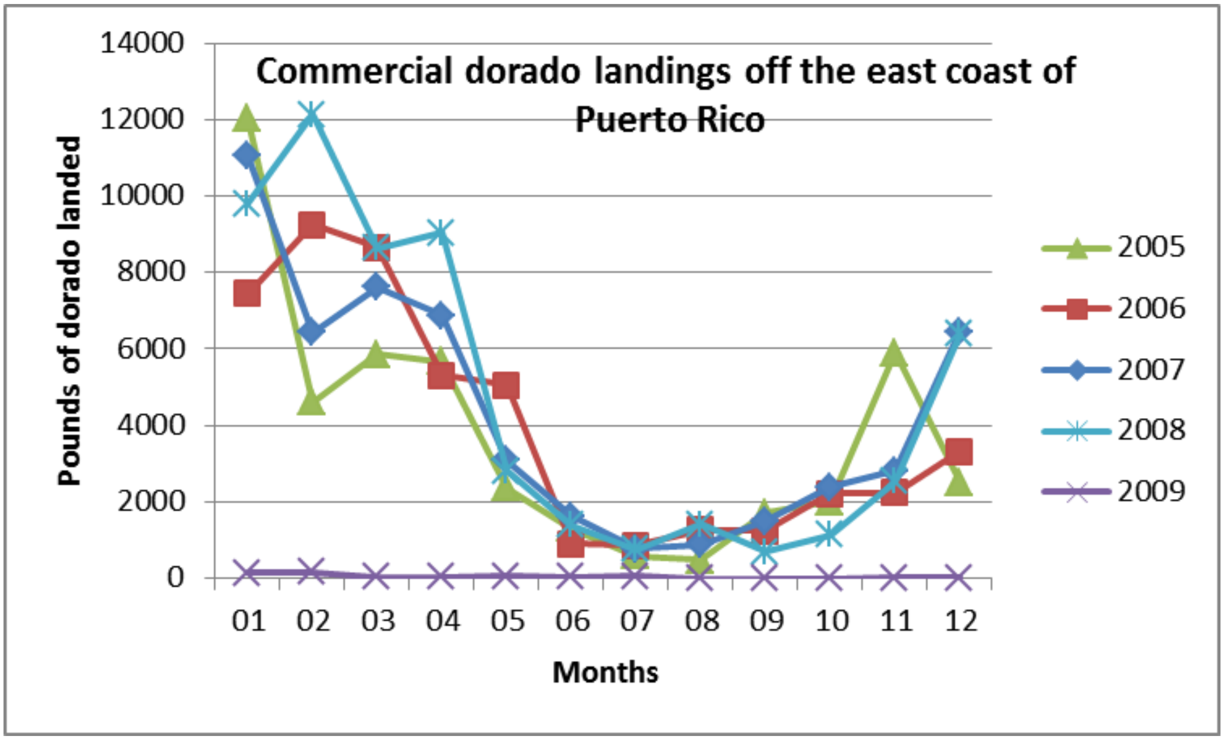


Figure 3.19 Commercial landings of dolphinfish (Dorado) in Puerto Rico, 2005 to 2009

Both D. Matos Caraballo and J. León confirmed this dramatic change from the years 2005 to 2009 as being factual. Matos-Caraballo also provided the unofficial landings for 2010 that showed decreased landings of dolphinfish for the East Coast. There is a need to determine the reasons for the changes in the East Coast but this is beyond the scope of this study. Among the issues to explore are: (1) if the effort has indeed decreased so dramatically because of fishers retiring from the fishery, (2) fishers not reporting their landings, (3) fishers are switching to target other species or (4) if the economy has forced the fishers to remain on-land.

It was initially expected that the most impacted group would be the diving sector during the April 2009 green water primarily due to low visibility but also because of the reported "itchy stuff" in the water. The daily diving trips were assessed to determine if the East Coast harvest by divers had been impacted by the green water event.

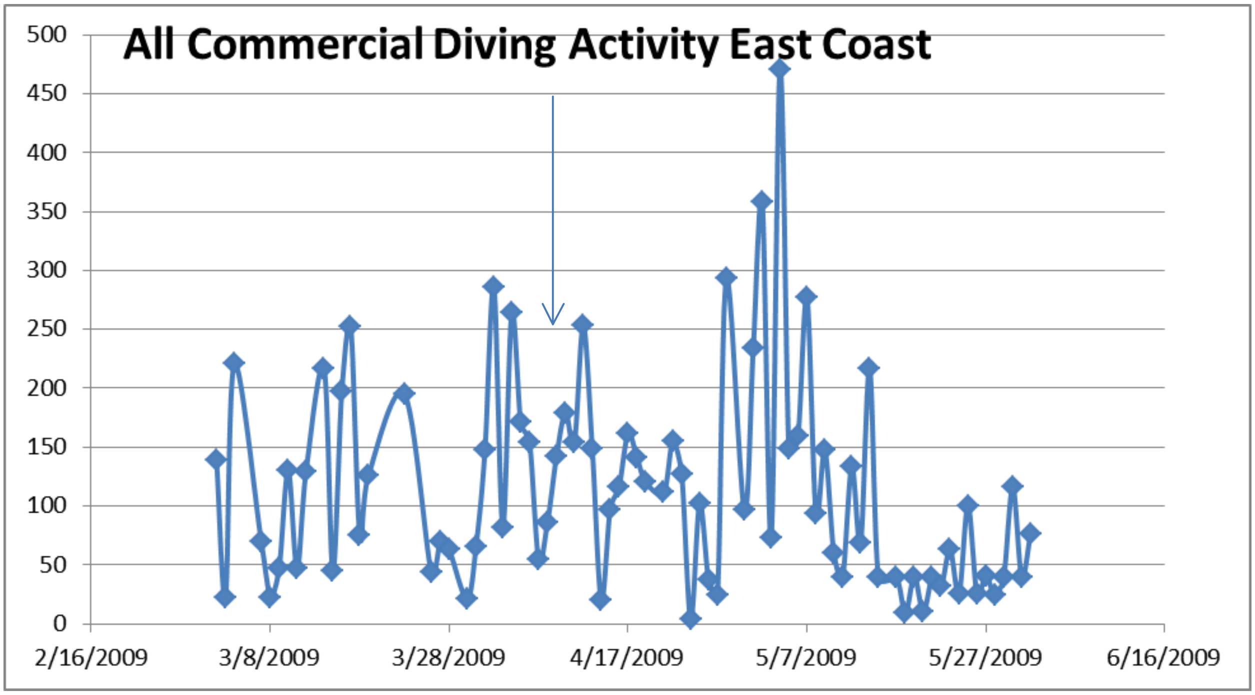


Figure 3.20 Diving activity (fish harvest) off the East Coast of PR before, during and after the green water event. The arrow indicates the time of the green water event (x-axis=date; y-axis=pounds of fish/record).

Although the total pounds reported by fishers from the East Coast of Puerto Rico decreased over the period 2005-2009, the catch per trip (pounds reported of all species while diving) did not decrease significantly (Figure 3.21).

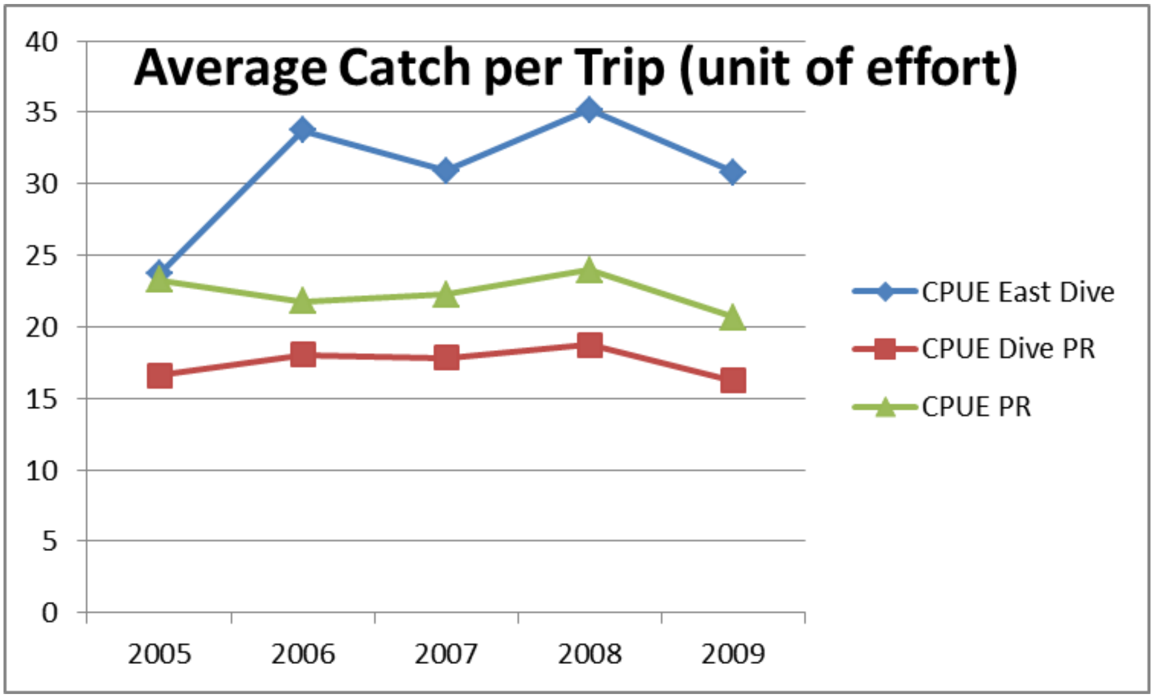


Figure 3.21 Catch per unit of effort (CPUE) calculated for commercial fishing divers in Puerto Rico, 2005-2009

Puerto Rico Recreational Data

The MRIP database was queried to determine if there had been changes that could be attributed to the green water event of April 2009. The recreational fishing data collected to date does not include any information on the shellfish, species like lobster and conch that are collected while SCUBA diving. The finfish data queried was between 2000 (the first full year of MRIP data collection) and 2009. The recreational data were retrieved from the MRIP website (Personal communication from the National Marine Fisheries Service, Fisheries Statistics Division at various dates).

The total recreational harvest for the time series showed that there was an overlap between the species groups harvested by the commercial and recreational fishers. The total recreational landings for Puerto Rico between 2000 and 2009 ranged from 1,166,187 (2009) to 4,601,746 (2000) or an annual average of 2,608,270. Total recreational landings, number of trips and angler participation all showed a decreasing trend. The local recreational participation decreased substantially over the past years.

The data were reported by species (*e.g.*, dolphin, greater amberjack, blue runner), generic scientific name (*e.g.*, *Epinephelus* groupers), or by species groups (*e.g.*, snappers). There were additional data collected by MRIP that included scientific name, lengths, weights, etc. and these were summarized below for red hind and dolphinfish.

RED HIND

The reported recreational harvest of red hind (*Epinephelus guttatus)* varied from 5,420 pounds landed in 2006 to 110,149 pounds landed in 2005. These data showed a dramatic increase in 2005 (Figure 3.22) because over 89,000 pounds were recorded during the November-December reporting period. The bi-monthly data showed that the highest landings of red hind were consistently reported during the March-April reporting period, except for 2005 and 2008. The 2000–2011 data reflected landings for all of Puerto Rico. There were a number of issues with the data, including species misidentification, grouping of species (*e.g.*, groupers instead of red hind), large PSE associated with the data, among others (a review of the program is currently under way and addresses these issues). The MRIP data are reported by waves of two months each.

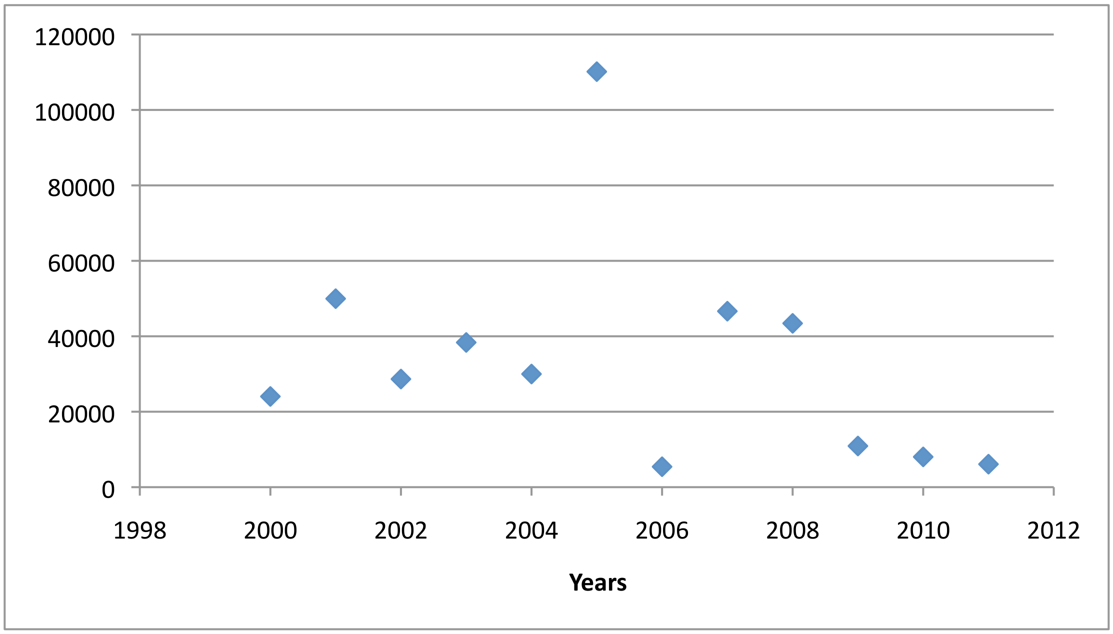


Figure 3.22 Recreational landings of red hind (MRIP data) for Puerto Rico (x-axis=years; y-axis=pounds of fish).

DOLPHINFISH

The data were specifically queried for dolphinfish. Recreational fishing for dolphinfish (*Coryphaena* sp.) in Puerto Rico has always followed a bi modal distribution with peaks in November-December/ January-February. Annual landings ranged from as low as 432,000 in 2005 to over 2,500,000 pounds in 2000. The low value in landings of dolphinfish was reported in 2005, the same year when the maximum landings of groupers and "other species" were reported.

Traditionally, dolphinfish are harvested off the North Coast in November-December and off the Southeast Coast April-May. The data could be more representative of data collection efforts than anything else. In 2007, the peak was reported in January-February and in 2006, in March-April. Another difference was noted in 2009 when the highest peak in landings appeared in March-April. All years, between 2000 and 2009 during the November/December period showed the highest dolphinfish landings (31-69% of the landings per year) of the total annual harvest except for 2007 and 2009 (Figure 3.23). In 2009, the green water event of April was very different than for all other years (Chapter 2). Although the information presented in Chapter 2 addressed the changes in the surface Chl-a field at eight fish spawning aggregation sites, and four control sites, the recreational fishers for dolphinfish were very informative about the fishing conditions and the water quality during the April 2009 green water event.

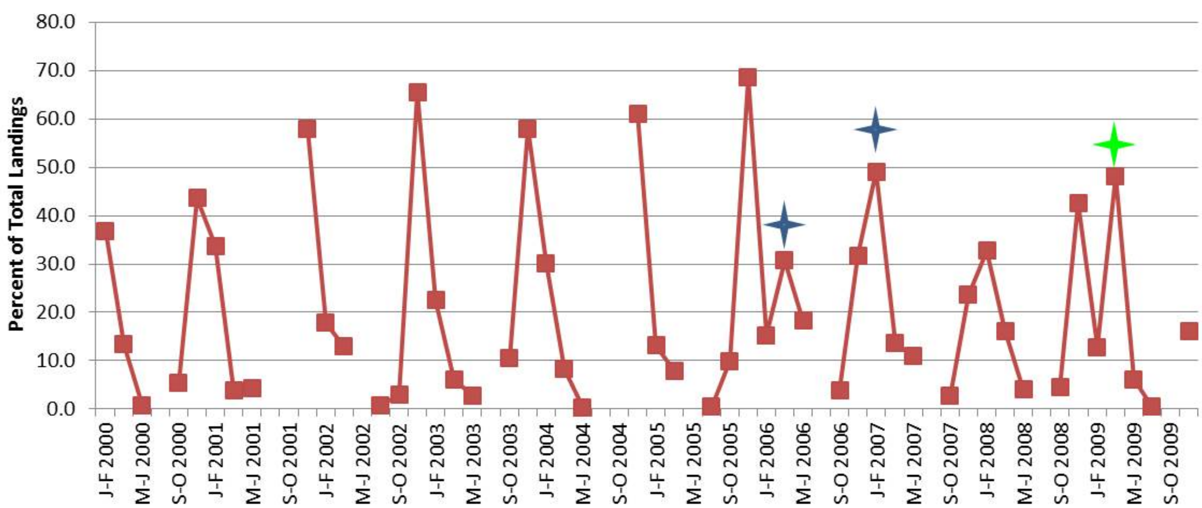


Figure 3.23 Percent of total dolphinfish recreational harvest in Puerto Rico (2000-2009) bimonthly; MRIP data provided by S. Turner SEFSC. Green star March-April 2009; blue stars March-April 2006 and January-February 2007.

MRIP catch time series data for harvest in total weight showed PSE varying between 24 and 100% for waves when no data were recorded (*e.g.*, 2001). Recurrent 0's in the data occurred during the months of July and August except in the years 2002, 2005 and 2009 when a small percent of dolphinfish were reported (Figure 3.23). There appeared to be changes in the harvest of dolphinfish after 2007. This information includes fishing reported in all modes (charter and private boat data) and all areas (state and federal waters).

There were a number of issues with the MRIP data and these were: (1) only data from web queries was available, (2) it did not show the fishing areas, so it was for all of Puerto Rico, and

(3) it did not show the monthly data so it was not known if March or April was the actual peak. The query provides PSEs that vary greatly. The MRIP dataset would have to be reviewed for number of interviews, time of recollection after fishing, participants from Puerto Rico versus out-of-state, area of harvest, etc. The review process is currently underway.

Effort in recreational fishing data was recorded as angler trips and total participation. Private boats reported the highest percentages of the dolphin landings (about 98%).

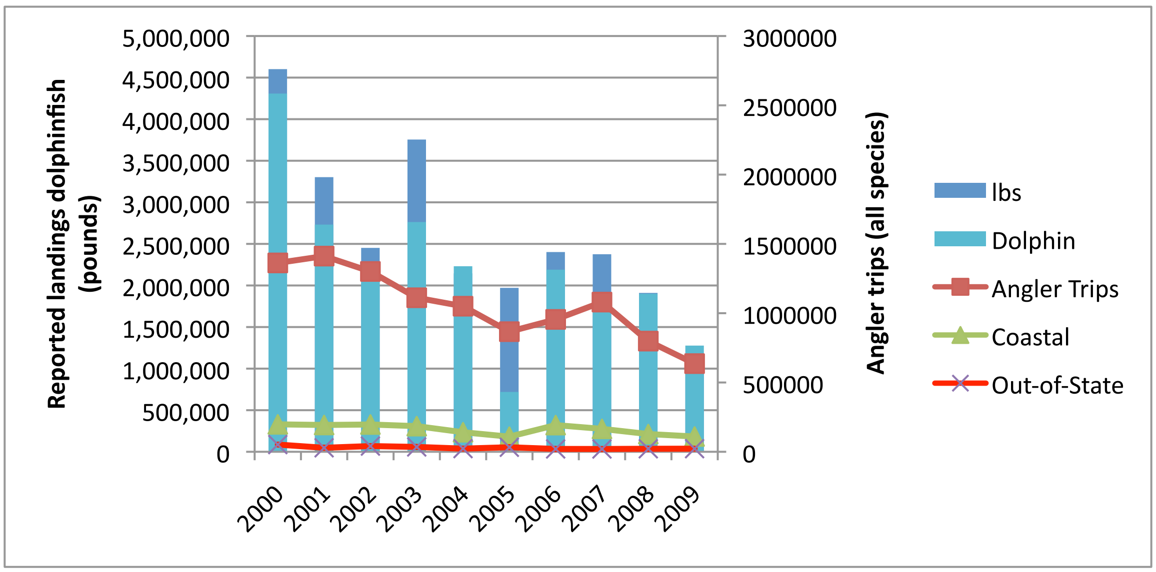


Figure 3.24 Recreational reported harvest of dolphinfish (pounds; left y-axis) and angler trips (number; right y-axis) for Puerto Rico (MRIP), 2000-2009

There was no information on the spatial distribution of the landings except for broad categories such as "< 10 mi" or ">10 mi". About 90% of the total catch was reported from "<10 mi" and probably then from the North Coast where 10 miles are waters over the shelf edge.

Recreational dolphinfish landings were compared to the commercial landings with special consideration given to the April 2009 data. The commercial harvest for dolphinfish also showed an April peak in 2009 **but only** for data from the South Coast of Puerto Rico (Figure 3.25). The increase in dolphinfish in the South Coast of Puerto Rico could be explained by the comments received from recreational fishers and charter captains during the days of the event. Fishers stated that the green water had not reached the area between Guánica and La Parguera. As shown in Figure 3.1, there was an area of clear water, low Chl-a (blue), in the South Coast. Dolphinfish are mostly harvested from areas of clean, clear water. Charter operators reported "good runs" of dolphin fish in the South -Southwest Coasts. The data specifically showed where the commercially caught dolphinfish were being landed (Figure 3.26). Guánica reported 75% of the total landings of dolphinfish in April 2009. In 2009, dolphin landings were higher in April than in March. March, on average showed higher landings of dolphinfish than any other month of the year. However, dolphinfish landings overall in Puerto Rico were very low in 2009 (Figure 3.19).

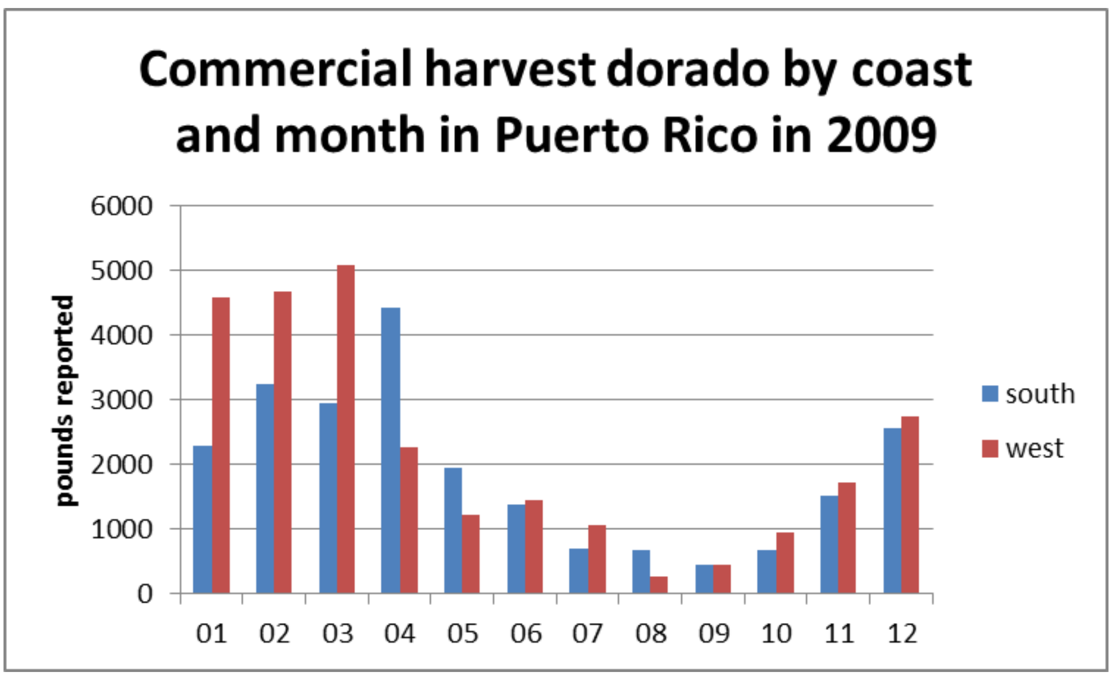


Figure 3.25 Commercial reported landings (pounds; y-axis) of dolphinfish (dorado) showing peak in April 2009 (month; x-axis) on the South Coast of Puerto Rico

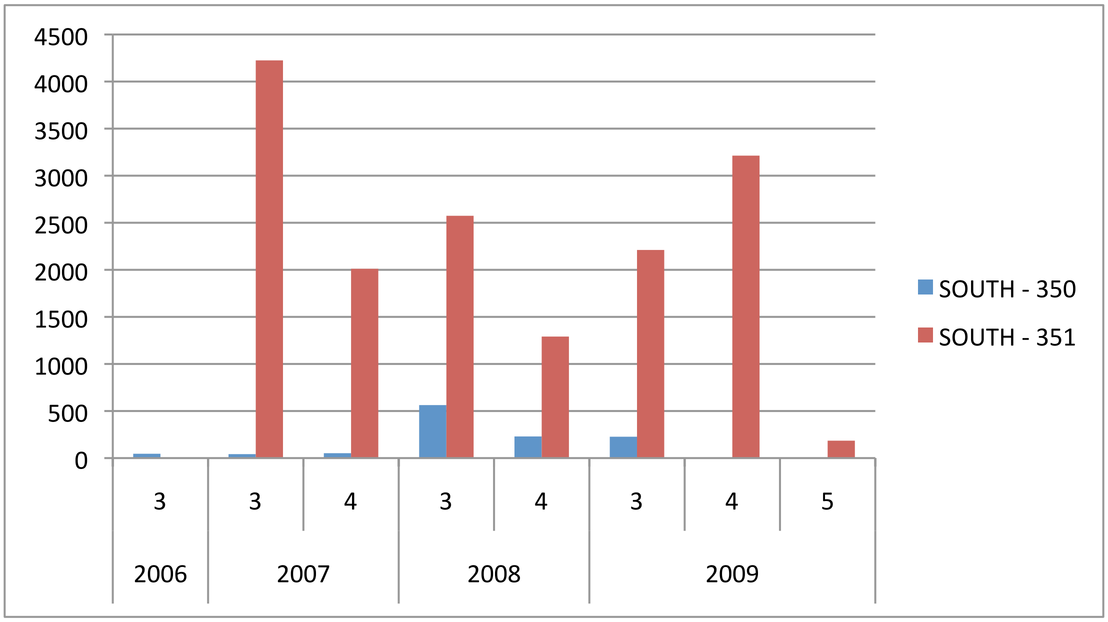


Figure 3.26 Highest reported commercial landings (pounds; y-axis) of dolphinfish from two fishing centers (350 and 351) in the South Coast of Puerto Rico

Dolphinfish is almost exclusively a recreational fishery (Figure 3.27). Although there are no recreational data that indicate the specific areas where fish are landed, both fisheries showed the same decreasing pattern in 2009. The decrease in dolphinfish landings was not as marked as the one observed in 2005, but there were no ancillary data available to describe this change.

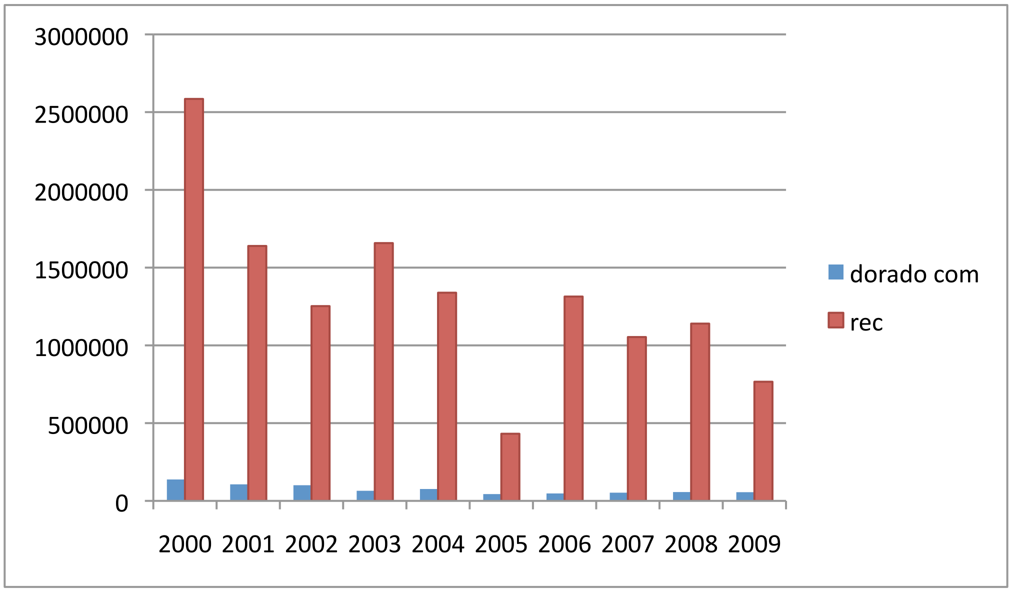


Figure 3.27 Commercial (com) and recreational (rec) landings (pounds; y-axis) of dolphinfish (dorado) in Puerto Rico between 2000-2009 (x-axis)

3.4 Conclusions

Variability in total fish harvested commercially and recreationally is usually attributed to overfishing. Nevertheless, changes in the marine environment can have a direct impact on the availability of certain fish species to be harvested. In 2002, there was an extended dolphinfish season in St. Thomas resulting in higher landings; the same was reported from the East Coast of the US. There was no relationship between the landings reported in St. Thomas and the Chl-a values at the MCD. In 2005, dolphinfish landings were the lowest of the 10-year series and no relationship was established as well with the Chl-a values at the MCD. In 2009, the commercial landings of dolphinfish in St. Thomas were higher in November than during the first part of the year when they are usually harvested in larger numbers possibly due to the green water intrusion. In Puerto Rico, landings of dolphinfish off the East Coast were much lower than in previous years and specifically, most landings were reported from the South-Southwest Coasts where the green water intrusion was not reported. Although there are other variables that could account for changes in the fisheries such as social and economic, the 2009 green water intrusion of Amazon River waters adversely impacted the commercial and recreational fisheries as well as other marine activities such as diving charter operations.

GENERAL CONCLUSIONS

- A 10-year time series (1999-2008) of surface Chl-a description of average conditions at eight fish spawning aggregation sites in Puerto Rico and the US Virgin Islands was developed from satellite-derived ocean color radiometry (OCR).
    - The Chl-a values obtained were within the range of the *in situ* values.
    - The Chl-a data showed very low variability during the months of January-June, the earlier part of all years and at all sites. These are spawning months for red hind (January-February) and mutton snapper (March-June).
    - This finding contradicts the initial hypothesis that high Chl-a values should be expected during the months of spawning at the aggregation sites representing food availability for the spawn.
    - Nevertheless, the data indicate that there are increases in Chl-a during June at the mutton snapper spawning aggregation sites and Lang Bank suggesting that there might be differences between red hind and mutton response to Chl-a signal.
- On average, there was significant interannual variability within sites.
    - The areas were geographically clustered, except for Bajo de Sico, which was significantly different from all other spawning sites.
    - A trend in the distribution of Chl-a values was observed with higher values at sites that are closer to terrigenous inputs from local river waters.
    - The year 2003 resulted in significant differences from other years and various sites.

- The exogenous factors that could be responsible for the variability of the Chl-a signal include:
    - Rain events, for example, in 2003.
    - River runoff.
    - Presence of Orinoco and Amazon River (e.g., 2009) waters.
    - Presence of eddies and filaments extending from these eddies (e.g., 2003, 2004).
- The rate of change (DELTA) calculated for the MCD suggested that during low Chl-a value periods, the number of red hind at the site seemed to increase during the spawning months at the aggregation site.
- The baseline of Chl-a developed was used to describe the 2009 unprecedented intrusion of green water, an anomaly that resulted in increased Chl-a values in all but four of the sampling sites.
- The anomaly of April 2009 point of origin was determined to be the Amazon River, Brazil.
- The magnitude and extent of the plume adversely impacted the local seafarers in Puerto Rico and US Virgin Islands.
    - Seafarers with between seven (7) and 45 years of experience at sea had never seen a green water intrusion of the magnitude and expansion of the April 2009 event.
- In the1999-2008 time series, the highest weekly chlorophyll mean value was 0.74 mg/m^3 (Aug 2002), at the Tourmaline site.
- Only on two other occasions did Chl-a values reach above 0.73 mg/m^3 (Parguera - 2001; Rene - 2003).

- In 2009, Chl-a values exceeding 0.95 mg/m^3 (above the 10-year average) were maintained at various sites between April and June. These values were confirmed with *in situ* data.
- The local impacts were examined through the commercial and recreational fish catch reports combined with satellite imagery and *in situ* information from marine resource users and showed that:
    - Dolphinfish catches were mostly reported from the South Coast of Puerto Rico during the month of April 2009 whereas most catches are usually reported in the West Coast during that time.
    - In January through May 2009, the reported commercial landings of dolphinfish from the East Coast of Puerto Rico were much less than those reported between 2005-2008 for the same period.
    - In 2009, recreational catches of dolphinfish were landed mostly during the months of March-April whereas higher catches were historically reported during the months of January-February.
    - There are confounding variables that were not explored during this work that could contribute to the shifts in landings observed and these include changes in the economic situation in the region, changes in the reporting methodology and regulations, among others.
    - There were changes in the historical commercial catches indicating that environmental factors might influence the availability of the fish.
- There was an area South-Southwest of Puerto Rico that was not impacted by the green water intrusion and maximum chlorophyll values during 2009 were not observed in

Parguera, Tour, ALS, and BDS. This was evidenced by the satellite data that showed the path followed by the Amazon River Plume in 2009.

- Although catch reports did not reflect higher landings of dolphinfish in clearer waters, all survey results from the 2009 green water event suggest this common folk tenet is true.
- Although there were challenges in the use of remote sensing data, the images provided a synoptic view of all sampling sites and provided the basis for multiple comparisons of Chl-a.
- The minimum Chl-a values occurred when the temperatures were lowest; the salinity was highest, and during the peak of the dry season, that is, the most stable period of the year.

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