Monitoring Phenology as Indicator for Timing of Nutrient Inputs in Northern Gulf Watersheds

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Abstract- **Nutrient over-enrichment—defined by the U.S. Environmental Protection Agency as the anthropogenic addition of nutrients, in addition to any natural processes, causing adverse effects or impairments to the beneficial uses of a water body—has been identified as one of the most significant environmental problems facing sensitive estuaries and coastal waters. Understanding the timing of nutrient inputs into those waters through remote sensing observables helps define monitoring and mitigation strategies. Remotely sensed data products can trace both forcings and effects of the nutrient system from landscape to estuary. This project is focused on extracting nutrient information from the landscape. The timing of nutrients entering coastal waters from the land boundary is greatly influenced by hydrologic processes, but can also be affected by the timing of nutrient additions across the landscape through natural or anthropogenic means. Non-point source nutrient additions to watersheds are often associated with specific seasonal cycles, such as decomposition of organic materials in fall and winter or addition of fertilizers to crop lands in the spring. These seasonal cycles or phenology may in turn be observed through the use of satellite sensors. Characterization of the phenology of various land cover types may be of particular interest in Gulf of Mexico estuarine systems with relatively short pathways between intensively managed systems and the land/estuarine boundary. The objective of this study is to demonstrate the capability of monitoring phenology of specific classes of land, such as agriculture and managed timberlands, at a refined watershed level. The extraction of phenological information from the Moderate Resolution Imaging Spectroradiometer (MODIS) data record is accomplished using analytical tools developed for NASA at Stennis Space Center: the Time Series Product Tool and the Phenological Parameters Estimation Tool. MODIS reflectance data (product MOD09) were used to compute the Normalized Difference Vegetation Index, which is sensitive to changes in vegetation canopies. The project team is working directly with the Mississippi Department of Environmental Quality to understand end-user requirements for this type of information product. Initial focus areas are identification of time frames for "pre-plant" fertilizer applications (prior to start of season), "side-dress" fertilizer applications (during rapid green-up), and periods of plant decomposition (during and after senescence). Prototypical maps of phenological stages related to these time frames have been generated for watersheds in the northern Gulf of Mexico. Where feasible, these maps have been compared to existing in situ nutrient monitoring data, but the in situ data is temporally sparse (monthly frequency or less), which makes interpretation challenging. Future work will include integrating effects of rainfall and seeking couplings with estuarine remote sensing.**

I. Introduction

Nutrient over-enrichment—defined by the U.S. Environmental Protection Agency (EPA) as the anthropogenic addition of nutrients, in addition to any natural processes, causing adverse effects or impairments to the beneficial uses of a water body—has been identified as one of the most significant environmental problems facing sensitive estuaries and coastal waters. Understanding the timing of nutrient inputs into those waters through remote sensing observables is important to help define monitoring and mitigation strategies. Remote sensing can trace both forcings and effects of the nutrient system from landscape to estuary through 1) plant canopies, 2) rainfall, and 3) water surface chlorophyll *a* in near-shore waters.

This project is part of the broader NASA Applied Science Program's Gulf of Mexico Initiative (GOMI). To optimize NASA Stennis Space Center (SSC) support for GOMI, the NASA SSC Applied Science and Technology Project Office selected a set of projects to best benefit Gulf of Mexico regional partners with NASA science products and models. The original idea for this project was selected for a "Discovery" phase evaluation in spring 2008; based on those results, it was picked up for an "Investigation" phase feasibility study in summer 2008 and fall 2009. Along the way, the project considered direct integration of vegetation monitoring into nutrient models, such as the U.S. Geological Survey (USGS) SPARROW (SPAtially Referenced

Regressions On Watershed) attributes, but it was determined that such integration would require significant modification to the code of any of the models evaluated. Ultimately, the earlier phases of this work established the feasibility of generating monitoring products and pointed to the usefulness of the products in their own right for understanding the temporal characteristics of nutrient loading in watersheds.

While other work at NASA SSC is focused on the direct marine remote sensing aspects, this project is seeking to extract information from the landscape. The timing of nutrients entering coastal waters from the land boundary is greatly influenced by hydrologic processes, but can also be affected by the timing of the addition of nutrients across the landscape through natural or anthropogenic means. Non-point source nutrient additions to watersheds are often associated with specific seasonal cycles, such as decomposition of organic materials in fall and winter or addition of fertilizers to crop lands in the spring. These seasonal cycles or phenology may in turn be observed through the use of satellite sensors, such as the NASA Moderate Resolution Imaging Spectroradiometer (MODIS). Characterization of the phenology of various land cover types may be of particular interest in Gulf of Mexico estuarine systems with relatively short pathways between intensively managed systems and the land/estuarine boundary (such as the Caloosahatchee in Florida, Weeks Bay in Alabama, Grand Bay on the Mississippi/Alabama border, and Cote Blanche Bay in Louisiana). This study is being performed is to demonstrate the capability of monitoring phenology of specific classes of land, such as agriculture and managed timberlands at a refined watershed level (Hydrographic Unit Code level 10 or better).

The goal of this project is to provide monitoring products to characterize temporal variability in sensitive watersheds that impact the waters of the Gulf of Mexico. Specifically, this work is intended to provide watershed products based on land use/land cover traits and vegetation phenology. The principal notion throughout has been that by monitoring vegetation using data acquired by NASA's MODIS, end users can be provided with indicators of the timing of nutrient inputs in sensitive watersheds.

II. Methods

To create the desired phenology products, it was necessary 1) to gather the appropriate image and ancillary data, 2) to process the image data to create a continuous time series and extract vegetation phenology, and 3) to develop new tools to summarize phenology across a landscape and also isolate phenology patterns specific to land cover classes of interest. Prototypical phenology products were generated for watersheds within the Mississippi Delta region and compared to nutrient monitoring data.

A. Image Data

This project uses MODIS normalized difference vegetation index (NDVI) to create a time series of land vegetation canopies. MODIS provides a near-daily repeat time for the elimination of cloud contamination, and NDVI has been widely adopted for vegetation monitoring. While NASA does provide a standard vegetation index product designated MOD 13, its finest time step is 16 days, which was insufficient to capture phenology with the necessary fidelity. To overcome this problem, the MOD 09 Surface Reflectance was acquired at 8-day time steps and NDVI was calculated by the defined formula

$$\text{NDVI} = (\text{near-infrared reflectance} - \text{red reflectance}) / (\text{near-infrared reflectance} + \text{red reflectance}). \quad (1)$$

B. Other Data

The ancillary input data included gridded land cover information and vector watersheds. The land cover information needed to be specific enough to differentiate between different crops associated with different fertilization practices. Crop-specific information was available in the form of the USDA Cropland Data Layer (CDL)[1]. The CDL did not always have the specificity required for non-agricultural lands, so data from the National Land Cover Database (NLCD)[2] were added to create a synthesized product. The watershed product utilized was the USDA Watershed Boundary Dataset (WBD)[3], which recently has been completed for the 48 coterminous states of the United States. The WBD added much more detail to national watershed definitions, expanding the nationally mapped hydrologic units from 2,149 to around 160,000. The CDL for the Mississippi Delta overlain with the WBD is shown in **Error! Reference source not found.**.

In addition to input datasets, it was also necessary to obtain reference data for validation. The Mississippi Department of Environmental Quality (MDEQ) supplied some nutrient monitoring data for the Delta and Pearl River, and additional nutrient monitoring data were acquired from the EPA STORET water quality database for sites in Mississippi and Alabama.

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[1] The CDL is described at http://www.nass.usda.gov/research/Cropland/SARS1a.htm. It is produced by the Research and Development Division of the USDA's National Agricultural Statistics Service.
[2] The NLCD is described at http://www.mrlc.gov/nlcd.php. It is produced by the Multi-Resolution Land Characteristics Consortium made up of 9 U.S. federal agencies
[3] The WBD is described at http://www.ncgc.nrcs.usda.gov/products/datasets/watershed/. It is produced by the Natural Resources Conservation Service of the USDA.

C. Study Area and Time Frame

The study area included three level 10 hydrologic unit code (HUC) watersheds in the southwest portion of the Mississippi Delta region (**Error! Reference source not found.**). Watersheds were chosen based on available in-situ nutrient monitoring data. It was desirable to find watersheds that would be somewhat isolated from nutrients that might have been transported long-range. The year 2004 was selected as the time frame for study to provide the most intensive available nutrient monitoring along with all necessary remote sensing and ancillary data.

D. Time Series Product Tool

The downloaded MODIS data were processed through the Time Series Product Tool (TSPT) to remove clouds and otherwise to clean and filter the time series temporally. The TSPT software, developed in MATLAB®, was custom-designed at NASA SSC to rapidly create and display single-band and band-combination time series data products, such as NDVI or other vegetation indices' images, for a variety of time-critical applications [1][2]. Although MODIS imagery is acquired daily, clouds and other sources of noise reduce the effective temporal resolution. The TSPT software enables the merging of MODIS Aqua and Terra data collected on a given day, which maximizes quality data retention. By eliminating bad or suspect data, temporally interpolating to replace the contaminated data, and then temporally filtering, NDVIs and other image products can be produced with lower noise. This technique is especially useful in regions and times of high cloudiness; cloud and cloud shadows can be mitigated via interpolation [3]. TSPT allows users to display various MODIS data as arrays of single images, as time-series plots at a selected location, or as temporally processed videos [4].

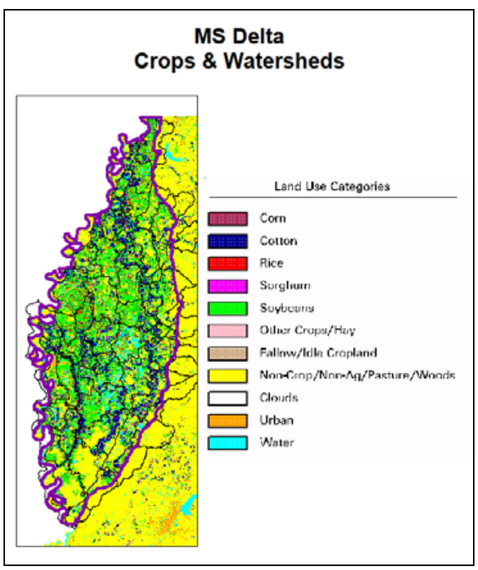

Fig. 1 2004 USDA Cropland Data Layer information for the Mississippi Delta overlain with the watershed boundaries in black.

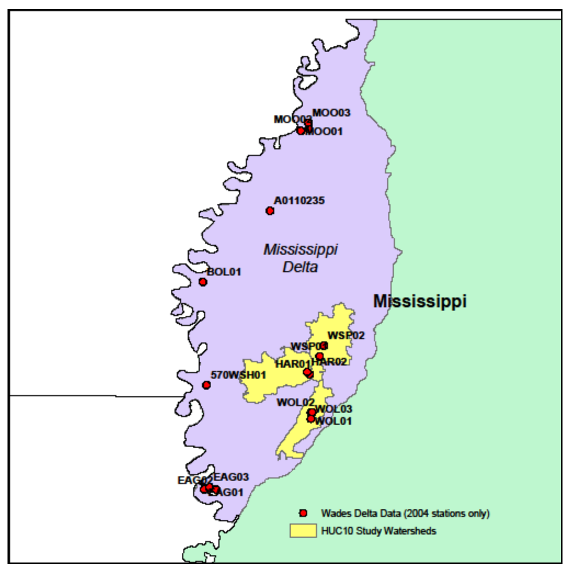

Fig. 2 Study area was composed of 3 HUC 10 watersheds in the Mississippi Delta.

E. Phenological Parameters Estimation Tool

The Phenology Parameter Estimation Tool (PPET) developed in MATLAB® at NASA SSC uses TSPT output time series to estimate parameters indicative of the seasonality of a given pixel. The parameters chosen for PPET do not require fitting any sort of functional form to the time series. Specifically, PPET finds the points on an annual time series where the data reaches 20% and 80% of maximum value during green-up, where it peaks at the actual maximum value, and where it descends to 80% and 20% of maximum value during senescence. At each of those points in the time series, PPET records both the time series value and day-of-year (DOY). In addition, PPET computes integrals of value over time for the full season.

F. Tool Enhancement

New tools were added to TSPT specifically for this project to allow time series results to be summarized across watersheds and then broken out by land cover class. These tools have been applied to areas and time frames of interest, and time series results were further processed to extract seasonal information using PPET.

III. Results

The primary result of the study can be seen by comparing **Error! Reference source not found.** and **Error! Reference source not found.**. **Error! Reference source not found.** shows the 1st difference of NDVI for maize, which is the dominant crop in these watersheds to which farmers typically apply inorganic fertilizer (soybean actually accounted for more planted area in 2004 but is nitrogen-fixing). The strong minima in mid-March indicate the maximum field preparation planting activity for maize. The strong maxima in mid-May indicate the maximum biomass accumulation for maize. The premise of this work is that the minima should roughly correspond to pre-plant application of fertilizer, and the maxima should roughly correspond to side-dress application of fertilizer. While this is not directly validated in this study, it is indirectly supported through local monitoring of Total Kjeldajl Nitrogen (TKN), which peaks shortly after the period bound by the spring 1st difference minima and maxima of maize NDVI (**Error! Reference source not found.**).

Beyond watershed-by-watershed observations, this pilot project demonstrated that useful spatial products can be easily generated that show the spatial distribution of phenological parameters (**Error! Reference source not found.**). Such spatially explicit dating could serve as inputs for nutrient models.

IV. Discussion

While this work is not conclusive, it does suggest that NDVI observables could be helpful in temporally locating certain non-point source nutrient inputs to the landscape. Further study is needed to firmly establish the relationship of the green-up curves with fertilizer application. Furthermore, it will be important to integrate these parameters directly into nutrient modeling and to observe the effects of spatially explicit inputs alongside precipitation. Finally, future work will be needed to reveal how the contributions of phenological characteristics for less-managed landscapes (e.g., wetlands and forests) might relate to the nutrient cycle.

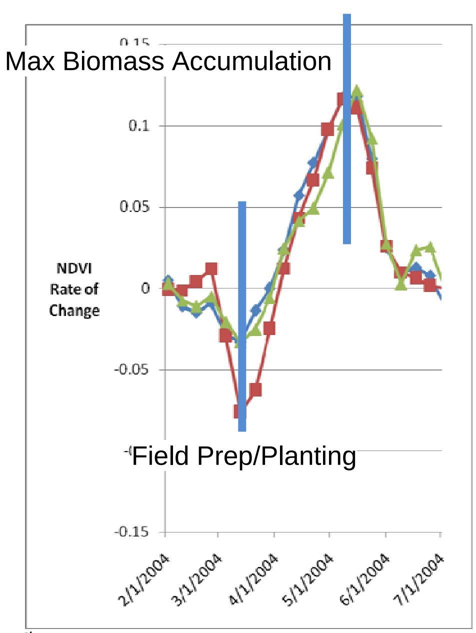

Fig. 3 1st Difference of maize NDVI in 3 study area watersheds in 2004.

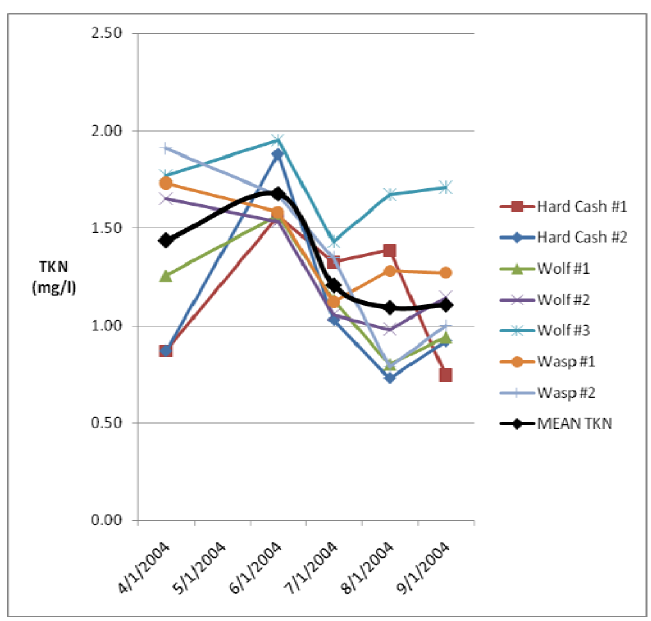

Fig. 4 Total N monitored in lakes within the 3 study area watershed in 2004.

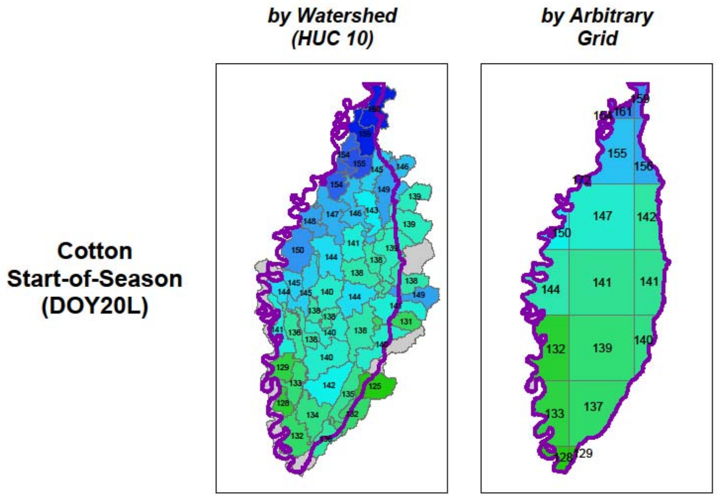

Fig 5 Spatial mapping of the cotton start-of-season phenological parameter across the Mississippi Delta. Mapping can be carried out by watershed or by any spatial gridding most relevant to a given application.

ACKNOWLEDGMENT

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