

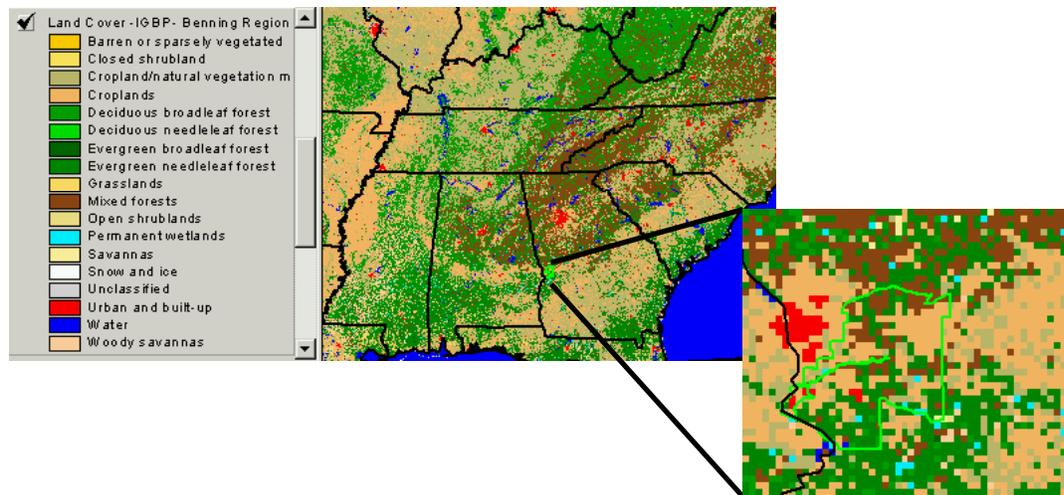


US Army Corps
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Engineer Research and
Development Center

NASA MODIS Products for Military Land Monitoring and Management

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November 2002



Foreword

This study was conducted for the Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Project (SEMP) under project CS-1114, "SERDP Ecosystem Management Program (SEMP)." The technical monitor was Dr. Robert Holst, SERDP Program Manager.

The work was performed by the Ecological Processes Branch (CN-N) of the Installations Division (CN), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigators were Dr. Harold E. Balbach and Robert C. Lozar. The technical editor was Gloria J. Wienke, Information Technology Laboratory. Stephen E. Hodapp is Chief, CEERD-CN-N, and Dr. John T. Bandy is Chief, CEERD-CN. The associated Technical Director was Mr. William D. Goran, CEERD-CV-T. The Director of CERL is Dr. Alan W. Moore.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL John Morris III, EN and the Director of ERDC is Dr. James R. Houston.

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1 Introduction

Background

The Strategic Environmental Research and Development Program (SERDP) is a partnership of the Department of Defense (DoD), Department of Energy (DOE), and Environmental Protection Agency (EPA). The SERDP Ecosystem Management Project (SEMP) was established as a new SERDP initiative in Fiscal Year 1998 (FY98). Research projects were first funded in FY99. There are two major components of SEMP: (1) the creation of long-term monitoring site(s) on DoD lands, to observe trends over time, and (2) the establishment of research projects aimed at gaining a better understanding of the roles of DoD military mission activities and land management practices at various spatial scales (from plot to managed unit to installation-wide to regional and ecoregional) and temporal scales.

The overall project objective is to plan, coordinate, and manage, on behalf of SERDP, an ecosystem management project initiative that focuses on ecosystem science relevant to DoD ecosystem management concerns. This includes:

- Addressing DoD requirements and opportunities in ecosystem management research, as identified by the 1997 SERDP Ecosystem Science Workshop (Botkin et al. 1997);
- Establishing and managing one (or more) long-term ecosystem monitoring sites on DoD facilities for DoD relevant ecosystems research;
- Conducting multiple ecosystem research and monitoring efforts, relevant to DoD requirements and opportunities, at these and/or additional facilities; and
- Facilitating the integration of results and findings of research into DoD ecosystem management practices.

Although SEMP is a research effort, it fits well with the intent of existing Army Regulations, such as AR 200-3 (20 March 2000, paragraph 2-1).

It is the Army's goal to systematically conserve biological diversity on Army lands within the context of its mission. The Army recognizes that natural ecosystems play a vital role in maintaining a

healthy environment. Natural ecosystems can best be maintained by protecting the biological diversity of native organisms and the ecological processes that they perform and that they are a part of. Habitat management is the key to effective conservation of biological diversity and the protection of listed species...

However, for monitoring purposes, AR 200-3 relies heavily on the Land Condition Trend Analysis (LTCA) method (Tazik et al. 1992). At both a detailed and large-scale level, SEMP research is looking at applying both traditional and emerging technologies to the questions of land management. Since AR 200-3 was written, new technologies, such as those illustrated by the products presented in this report, have become available. A revision of the current monitoring methods to reflect a better, faster, cheaper philosophy might now be appropriate.

The SEMP project is currently sited at Fort Benning, GA. The goals of SEMP are to provide knowledge, tools, and techniques to enhance sustainable mission use and stewardship of military installations, and to contribute to understanding and enhancing the ecological role of military installations within their ecoregions.

Another goal of the SEMP is to transfer the technology developed at Fort Benning to other installations and managed landscapes in shared ecoregions, with a special focus on the Fall Line Sandhills region that stretches across Georgia into the Carolinas, just coastward of the Piedmont. DoD installations, other federal and state-managed lands, and corporate lands are interspersed throughout this region. These lands share ecosystem management issues, including management of federally endangered species such as the red-cockaded woodpecker, and restoration of forest and wetland ecosystems.

Currently, the National Aeronautics and Space Administration (NASA) has a program to use remote sensing capabilities to study the Earth from space. As part of the Earth Observing System (EOS) the Terra mission (also called EOS AM-1) is part of NASA's Earth Science Enterprise (ESE, formerly Mission To Planet Earth). The Terra satellite was successfully launched from Vandenberg Air Force Base, CA, on December 18, 1999. Several of the instruments aboard Terra provide data and products of interest to military land managers. Most importantly, products derived from the suite of Terra instruments are:

- interrelated (e.g., atmospheric instruments provide data to correct for atmospheric effects in land sensing instruments — a coordinated configuration never available before).

- built from a series of steps using different instruments.
- available on a regular basis for most of the Earth (planned for at least the next 15 years).

In theory, there seemed to be a fit between the long-term SEMP monitoring needs and some of the products being created through the NASA EOS program, particularly for the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument/ Several SEMP researchers were becoming interested in this potential relationship at the same time MODIS products were being evaluated for application in other research (i.e., regional habitat fragmentation). It was deemed appropriate to document the initial investigation and use Fort Benning and the related on-going SEMP work as an area of focus.

Objectives

The major objective of this research is to process and present actual examples of MODIS products and to relate these to potential uses for military installation land managers and scientists, principally those working at Fort Benning, GA, on the SERDP SEMP project. In line with the SEMP objectives, information in this report is intended to make the application of this technology easier at other installations, particularly those in the Southeastern United States.

Additional objectives are:

1. Explain why the Terra satellite and its instruments and products are unique.
2. Provide a document that makes the products easier to understand.
3. Help to integrate the ESE technology more quickly and easily into military land management activities.
4. Document the actual Terra files stored in the SEMP data repository.
5. Document the processing steps to translate the files from the NASA standard hierarchical data format (HDF) to a standard geographic information system (GIS) format.
6. Provide sources of documentation for the MODIS products.

Approach

The approach here is to describe the NASA EOS program in general and then more specifically to focus on those products and ideas that have the most rele-

vance to military land managers, using the Fort Benning area and on-going SEMP research to illustrate points. Intermediate steps were to:

- Describe the NASA EOS program basic issues and highlight not only its characteristics, but also why it is unique. Particularly, this document explains why the MODIS instrument and its products are of interest.
- Describe a quick overview of the project and product specifications.
- Describe in detail the files that were obtained and their characteristics. A brief review of the current “Validation” status of the NASA products is given in general and specifically for those illustrated in this report.
- Review NASA’s description of the applications possible for the products illustrated and make a connection as to how these may be applicable to military land management.
- Present illustrative examples of how the described products can be applied to land management questions at Fort Benning and for SEMP researchers.
- Recommend logical next actions.
- Provide detailed instructions on acquiring and formatting the products to a georeferenced form that is useful in standard GIS and Image Processing systems.

Scope

This report focuses on the Fort Benning, GA, region. The example applications in this region are only examples, and are not intended to represent solutions to real questions that may exist at the installation. This report does not attempt to address other locations and does not represent the entire ecoregion of the Sandhills nor the Southeastern United States, although the MODIS images do cover the entire Earth. Further, a vast amount of literature about EOS has been published and much of it is available over the World Wide Web (the Internet). This report only touches the surface of the material that describes the EOS data and products. Some of the references listed at the end also have an Internet location at which more in-depth information is available. Note that NASA is still in the development stage for the products described here; revisions of this data may occur in the future. For a discussion of the levels of development for each product, see the **Products Status** section in Chapter 4. Finally, this work covers only a single temporal period (roughly the beginning of 2001). NASA products are being made available continuously so that land character monitoring can be carried on. Availability of products described in this report are correct as of 15 July 2002.

Mode of Technology Transfer

This report documents some examples of MODIS data and provides realistic illustrations of how it might be used by researchers and installation personnel. At the SEMP data repository, a Microsoft Power Point® presentation coordinating with this report is available to SEMP researchers. This report is intended as a milepost in the road of good land management practices and is expected to encourage similar activities and research presentations and papers for applications at other military installations.

This report will be made accessible through the World Wide Web (WWW) at URL: <http://www.cecer.army.mil/> and also on the SERDP site through: <http://www.serdp.org/general/publications/publications.html>

2 NASA Earth Observing System

NASA has had a long history of developing satellite instruments that provide remote sensing imagery for civilian purposes. Probably best known is the Landsat satellite series, first launched in 1972. The Landsat series provided high-resolution multi-spectral images of the Earth's surface. The Multispectral Scanner (MSS) instrument provided detail at roughly 60- x 80-meter pixel size in four broad spectral bands. Beginning in 1982, the Thematic Mapper (TM) instruments were launched. The TM images continue to provide detail at about 30-meters resolution in seven spectral bands. Though highly useful, the Landsat series of instruments have some shortcomings:

- They are too detailed and slow to cover the entire Earth in a short period.
- They are surface sensing instruments without collateral atmospheric instruments to provide corrections for atmosphere and sensing angle effects.

In response to the scientific investigation of global climatic change, NASA developed a program to use remote sensing capabilities to study the Earth from space. As part of the EOS, the Terra mission (also called EOS AM-1) is part of NASA's ESE. The Terra satellite was successfully launched from Vandenberg Air Force Base, CA, on December 18, 1999. Several of the instruments aboard Terra provide data and products of interest to military land managers.

The Terra platform and its products represent cutting edge science as applied to remote sensing. Specifically, products derived from the EOS are physical process based, meaning that they are:

- Based on "first principle" physical processes,
- Objectively derived, and
- Calculated and repeatable.

Though this may seem obvious for any science, Terra products come closest to obtaining this goal in the remote sensing discipline.

Land managers have a need for the products from Terra. Most of the instruments generate a suite of products, some for atmospheric or oceanographic studies and some for land monitoring. Of particular interest to military land managers are those products of greater detail (high resolution) that dependably cover

their installations. Though the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument has high resolution (15 meters), coverage is spotty. A survey of ASTER products done in May 2002 showed no images cover Fort Benning, though two exist adjacent to the installation (to the northwest and to the south). MODIS and Multi-angle Imaging Spectroradiometer (MISR) instruments sense the entire globe every 2 days; some of the spectral bands are at roughly 250 meters resolution. Though this scale is gross for most installation management purposes, it still provides some unique advantages over other sources of imagery. Further, products derived from the images are:

- Available at no cost.
- Available on a dependable schedule (daily, monthly, yearly; planned for at least the next 15 years).
- Built through a series of steps using data from other instruments on the Terra satellite that correct for atmospheric, directional, and seasonal effects. This is a unique benefit of Terra available with no other existing satellite.
- Based on the most advanced scientific understanding (still in development).
- Based on objective “first principle” physical science of the objects being derived (e.g., vegetation characteristics are based on the physical response of chlorophyll to radiation).
- Developed for environmental monitoring purposes (for military land managers, land/habitat/monitoring and change detection).
- Standardized and comparable through time.
- Spatially stable. On a Terra product, the location and size of a single pixel will be the same in March 2001 as in December 2018 to within 10 meters for a 250-meter pixel.
- Coordinated with legacy products in some cases. The Normalized Difference Vegetation Index (NDVI) product is coordinated with a 20-year-old National Oceanic and Atmospheric Administration (NOAA) product. Together, these characteristics provide an excellent potential base for land and ecological monitoring over a nearly five-decade horizon.

The MODIS instrument

<http://eosdatainfo.gsfc.nasa.gov/eosdata/terra/modis/modis.html> is of particular interest to military land managers. The MODIS hyperspectral sensor is the key instrument aboard the Terra satellite. MODIS views the entire Earth’s surface every 1 to 2 days, acquiring data in 36 spectral bands. These data, along with data from the second EOS satellite called Aqua that also carries a MODIS instrument, will improve the understanding of dynamics and processes occurring

on the land (as well as in the oceans and the lower atmosphere). The series of MODIS instruments will play a vital role in the development of validated, interactive Earth system models able to predict change accurately enough to assist policymakers in making sound decisions concerning the protection of our environment. To do this, not only are the raw spectral band data made available, but also many calculated (level 2 and 3) products, some of which are of interest and use for regional ecosystem monitoring and management.

The purpose of the MODIS instrument and its products coordinates with the objectives of military land managers. The stated objective (from <http://eosdatainfo.gsfc.nasa.gov/eosdata/terra/modis/modis.html>):

MODIS helps scientists to understand the Earth as a system, from which they can develop the capability to predict future change and differentiate between the impact of human activities and natural activities on the environment. The goal is to construct models of Earth's global dynamics — atmospheric, oceanic, and terrestrial — and predict changes before they occur. *Consequently, MODIS data will assist policymakers worldwide in making sound decisions concerning protection and management of our environment and resources.* [Emphasis added.]

Technically, MODIS is an imaging radiometer employing a cross-track scan mirror and collecting optics, and a set of linear arrays with spectral interference filters located in four focal planes. The optical arrangement provides imagery in 36 discrete bands between 0.4 and 14.5 μm selected for diagnostic significance in Earth science. The instrument provides long-term observations from which an enhanced knowledge of global dynamics and processes occurring on the surface of the Earth and in the lower atmosphere can be derived. This multidisciplinary instrument yields simultaneous, congruent observations of high-priority atmospheric (aerosol and cloud properties, water vapor and temperature profiles), oceanic (sea-surface temperature and chlorophyll), and land-surface features (land cover changes, land-surface temperature, and vegetation properties). The instrument is expected to make major contributions to understanding the global Earth system, including interactions among land, ocean, and atmospheric processes. The MODIS instrument provides daylight reflection and day/night emission spectral imaging of any point on the Earth at least every 2 days, operating continuously.

Ordering, manipulating, and documenting the MODIS data is not difficult. The software is stated to be available over the Internet. However, the primary author's experience is that the difficult issue is to set up the method to go from NASA's (roughly) standard EOS HDF and unique projections to a format that can be used easily by SEMP researchers in standard GIS formats (specifically ArcInfo,^{®*} ArcView,[®] and ArcGIS[®]). Though NASA Web locations and even their training courses claim to have these capabilities available, in fact, the primary author has tried many of them and found they do not provide the capabilities to accomplish what action item 4.c. requires. In general, the online Web descriptions do not always describe the limitations of a software product. For example, one NASA contractor software package was described as doing exactly what was needed for the tasking. Only after it was downloaded and implemented did it become apparent that it was designed for another (atmospheric sensing) instrument on Terra and did not have the capabilities to deal with MODIS data. To manipulate the files into the SEMP data set, it was necessary to request software that was not yet released and step back and forth between a UNIX system (NASA's supported operating system for EOS data) and a Microsoft-Windows operating system. A technician may carry out the work once this configuration is in place. Figuring out the actual steps to implement the configuration consisted of several trial and error attempts. The final procedure is described in the **Appendix: Procedure to Translate MODIS HDF Products to GIS Format**.

The development of each of the EOS products for distribution is an ongoing process. NASA requires that the products go through a series of refinements (depending on the product type — there are 44 data products just for the MODIS instrument) until they are fully acceptable as state-of-the-art data sets. Three major levels are recognized. Beta Products are minimally validated, early release products that enable users to gain familiarity with data formats and parameters. A Beta Product is probably not appropriate as the basis for quantitative scientific publications. Provisional Products are partially validated and improvements are continuing. They are viewed as early science, validated products and are useful for exploratory and process scientific studies. Quality may not be optimal since validation and quality assurance are ongoing. Users are expected to review product quality summaries before publication of results. Validated Products have well defined uncertainties. They are high quality prod-

* Citing specific products does not imply endorsement by the Corps of Engineers, U.S. Army, or Department of Defense.

ucts suitable for longer term or systematic scientific studies and publication. There may be later, improved versions. Users are expected to review product quality summaries before publishing the results. Products illustrated in this report are all at the Provisional level. See the **Products Status** section in Chapter 4 for additional details.

3 Project Specifications

The purpose of the MODIS instrument and its products coordinated with the objectives of military land managers so it was felt that SEMP and ERDC would benefit from an initial evaluation of the possible opportunities as well as defining some of the initial limitations inherent with the imagery and products. Since researchers had already acquired the experience necessary to complete the investigation at low cost, the work was carried out at ERDC/CERL. Although the initial thrust was to get some MODIS data into the SEMP data repository, it soon became clear that applications were the real key to acquiring MODIS data. But if the example applications were not clearly explained, the potential value might be lost. So to ensure the full worth of the research effort would be available, particularly to SEMP researchers, this report was developed. Additionally, researchers wanted to broaden the experience base in exercising the SEMP data repository by submitting the MODIS data to it electronically.

Task Specifications

The initial products identified to be accessed were:

- MOD12 Land cover/Land cover change
- MOD13 Gridded vegetation indices (Max NDVI and Integrated Enhanced Vegetation Index [EVI])
- MOD15 Leaf area index (LAI) and FPAR (Fraction-of-Photosynthetically Active Radiation)
- MOD17 Net Photosynthesis and Primary productivity
- MOD44 Vegetation cover conversion

Coordinates and the projection information specific to the Fort Benning region:

Lower Left — 680749.39, 3561817.3

Upper Right — 743383.29, 3617834.42

Projection — Universal Transverse Mercator (UTM)

Zone — 16

Units — meters

Datum — North American Datum (NAD) 83

Spheroid — Grid Reference System (GRS) 1980

Product Specifications

In Chapter 4, a description of each of the umbrella products is given, followed by a discussion of each of the individual data themes that exist. For each of the products listed above, there are usually sets of associated files. The associated files might include a variety of classifications of the product, information on the quality evaluation of the product, secondary classifications, the corrected spectral bands from which the product was derived, and other data. Below is a list of the associated products for all the files presented in Chapter 4.

MOD12 Land cover/Land cover change

- International Geosphere-Biosphere Programme (IGBP) Global Vegetation Classification Scheme
- International Geosphere-Biosphere Programme (IGBP) Global Vegetation Classification Scheme — Secondary Land Cover
- University of Maryland (UMD) Vegetation Classification Scheme
- Leaf Area Index/Fraction-of-Photosynthetically Active Radiation (LAI/FPAR) Biome Scheme.

MOD13 Gridded vegetation indices (Max NDVI and Integrated EVI)

- Normalize Difference Vegetation Index (NDVI)
- Normalize Difference Vegetation Index (NDVI) quality
- Enhanced Vegetation Index (EVI)
- Enhanced Vegetation Index (EVI) quality
- Blue — Band 3 (459-479 nm)
- Red — Band 1 (620-670 nm)
- Near Infrared — Band 2 (841-876 nm)
- MIR (Millimeter-wave Imaging Radiometer) — Band 7 (2105-2155 nm)
- Average Azimuth Angle
- Average Sun Zenith Angle
- Average View Angle

MOD15 Leaf area index (LAI) and FPAR

- Fraction-of-Photosynthetically Active Radiation (FPAR)
- Fraction-of-Photosynthetically Active Radiation (FPAR) — Data Quality Evaluation
- Leaf Area Index (LAI)
- Leaf Area Index (LAI) — Data Quality Evaluation

MOD17 Net Photosynthesis and Primary productivity

- Net Photosynthesis (PSN)
- Net Photosynthesis (PSN) Quality Assessment
- Yearly Primary productivity — Not Yet Available

MOD44 Vegetation cover conversion

- Not Yet Available as of August 2002

4 Products and Descriptions

Products Status

The development of each of the EOS products for distribution is an ongoing process. Currently released MODIS land data products represent Provisional data sets. (Initial products can be “Beta” or later “V001”.) Provisional data sets are collections where some of the issues affecting Beta data have been resolved and improvements such as multilevel processing refinements continue to be made. All products used in this report were of type V003. The release of several products in the MODIS V003 land data set began on July 6, 2001. Based on multilevel processing refinements, the V003 data accommodate instrument and calibration stabilization. Additional V003 product releases will occur as data become available. The confidence and significance of this processing evolution has prompted MODIS to close V001 and begin populating a V003 data set. It was anticipated that by the end of 2001 the V003 data set would contain a continuous year of data with consistent science quality. Although V003 will eventually replace V001, both appear for at least 6 months following V003 production of any data granule. (As of May 2002, V001 products are still available). All 250-meter data (in this report, that is the Vegetation Indexes) appear only as V003.

As an example, MODIS project scientist Juri Knyazikhin reported (Lindsey and Salomonson 2002) that LAI and FPAR could be considered provisionally validated according to the following criteria:

- The algorithm doesn't produce values when uncertainties in input data exceed 15 percent,
- Retrievals obey known relationships (e.g., LAI is related to NDVI appropriately),
- The algorithm identifies situations when single angle data convey little information about the canopy structure and reports this with a special flag in the Quality Control (QC), and
- Product fields are comparable with those derived from other instruments (e.g., MISR).

To move to a validated status, the LAI/FPAR will be tested against field data collected at various sites representing major biome types. Other MODIS products

will have a similar set of criteria designed to test and validate their specific characteristics.

The status of those products used for this report (in May 2002) is as follows:

| Product | Science Quality Status |
|-----------------------------|--------------------------------|
| MOD12Q1 Land cover | Provisional as of Jun 11, 2000 |
| MOD13Q1 Vegetation Indices | Provisional as of Nov 1, 2000 |
| MOD15A2 LAI & FPAR | Provisional as of Nov 1, 2000 |
| MOD17A2 Net Photosynthesis | Provisional as of Mar 6, 2001 |
| MOD44 Vegetation conversion | Not Yet Available |

Geo-Location Quality

The pixels that are sensed at the satellite must be correctly located on the earth. Images that have been located on the ground are said to be georeferenced. All of the products discussed here are distributed georeferenced from NASA. (Other products are available that are not georeferenced.) How well are these pixels located on the earth's surface? NASA production specifications state that pixels are to be correct to within 10 percent of the pixel size. The products here have 1-kilometer pixel sizes, so the specifications imply that the pixels are correctly located to within 100 meters. In a recent presentation,* the actual current registration for pixels is in the range of 50 to 70 meters (depending on the product). The ultimate goal is to get the registration correct to the 50- to 55-meter range. MODIS has sensors for 36 spectral bands, 2 bands of which are 250-meter pixel size (bands 1 and 2), 5 bands of 500-meter size (bands 3 through 7), the rest at 1-kilometer. The 10 percent specification in this case refers to the 1-kilometer size, so that a 250-meter pixel has a georeferencing requirement of only 100 meters. This becomes an important consideration because the Vegetation Indices all use the 250-meter pixel size. Even a 50-meter registration on these represents a 20 percent georeferencing accuracy. To put this discussion into proper perspective, normally when georeferencing is carried out, a root mean square (rms) error in the range of .5 to 1.5 of the pixel size is considered acceptable. In this light, the MODIS georeferencing is extraordinarily high.

* By Robert Wolf of Goddard Space Flight Center at the MODIS Vegetation Workshop, Missoula, MT, June 2002.

MOD12 Land cover/Land cover change

Discussion

Land cover and human or natural alteration of land cover play a major role in ecosystem condition. The land surface has considerable influence on the planet's biogeochemical cycles. The objective of the MOD12 land cover products is to identify land cover types amenable to identification by exploiting the spectral, temporal, spatial, and directional information content of MODIS data. Inputs include:

1. EOS land/water mask
1. Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectances (NBARs) derived from the MODIS BRDF/Albedo product (MOD43B4) in the MODIS Land Bands (1-7), adjusted to nadir view at the median sun angle of each 16-day period.
2. Spatial texture derived from Band 1 (red, 250-meter) at 1000-m resolution MODAGTEX.
3. Directional reflectance information at 1k for 16-day periods (MOD43B1).
4. MODIS EVI at 1km for 16-day periods (MOD13).
5. Snow cover at 500m for 8-day periods (MOD10).
6. Land surface temperature at 1km for 8-day periods (MOD11).
7. Terrain elevation information (MOD03).

These data are composited over a 1-month time period to produce a globally consistent, multitemporal database on a 1-km grid as input to classification and change characterization algorithms.

MOD12 Land cover/Land cover change Products

- International Geosphere-biosphere Programme (IGBP) Global Vegetation Classification Scheme (Figure 1)
Data Granule:SC:MOD12Q1.003:2003481690
Local Granule ID: MOD12Q1.A2001001.h10v05.003.2001193164050.hdf
MODIS Data Set: MODIS/Terra Land Cover 96 Day L3 Global 1 km ISIN Grid
Date: 3 Months ending 2001-01-16
Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The land cover product, MOD12Q1, identifies 17 classes of land cover in the International Geosphere-Biosphere Programme global vegetation classification scheme. This scheme includes 11 natural vegetation classes, 3 developed land classes, (1 of which is a mosaic with natural vegetation), permanent snow or ice,

barren or sparsely vegetated, and water. Produced quarterly, the MOD12 classification schemes are multitemporal classes describing land cover properties as observed during the prior year (12 months of input data). Quarterly production of this "annual" product makes new land cover maps with increasing accuracies as both classification techniques and the training site database mature.

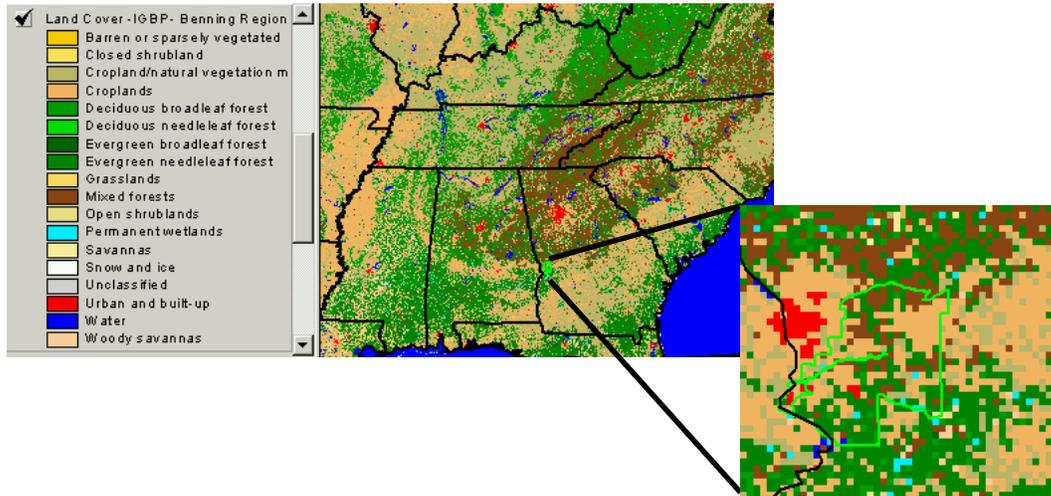


Figure 1. IGBP global vegetation classification scheme.

- International Geosphere-biosphere Programme (IGBP) Global Vegetation Classification Scheme - IGBP Secondary Land Cover (Figure 2)
 Data Granule:SC:MOD12Q1.003:2003481690
 Local Granule ID: MOD12Q1.A2001001.h10v05.003.2001193164050.hdf
 MODIS Data Set: MODIS/Terra Land Cover 96-Day L3 Global 1 km ISIN Grid
 Date: 3 Months ending 2001-01-16
 Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The land cover product, MOD12Q1, also identifies the second most common land uses within a grid. The Unclassified category is more common. In the future an additional related data set will calculate the percent of a cell that is covered by the secondary land cover type.

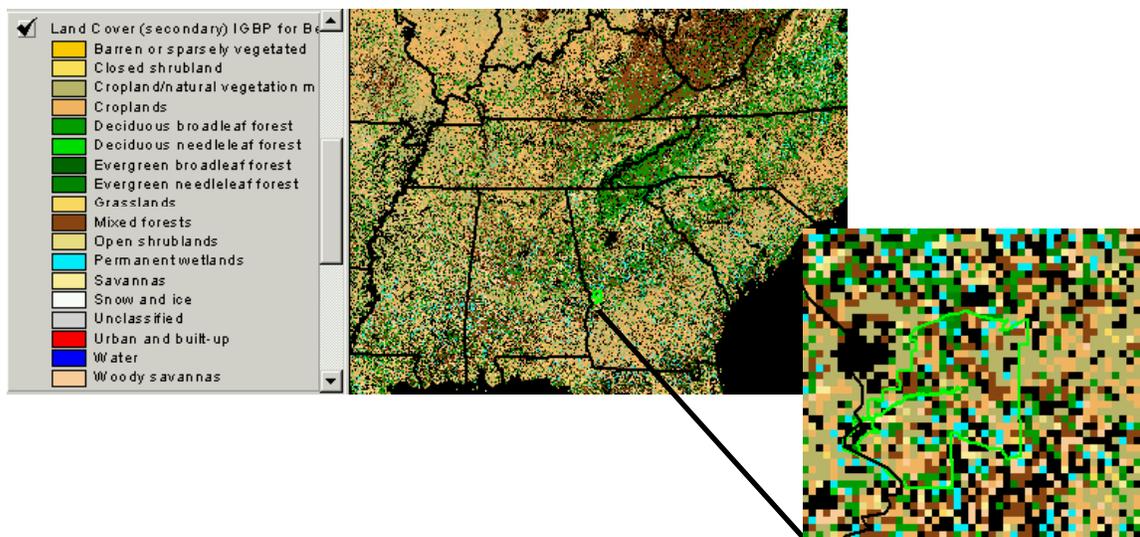


Figure 2. IGBP global vegetation scheme – secondary land cover.

- University of Maryland (UMD) Vegetation Classification Scheme (Figure 3)

Data Granule: SC:MOD12Q1.003:2003481690

Local Granule ID: MOD12Q1.A2001001.h10v05.003.2001193164050.hdf

MODIS Data Set: MODIS/Terra Land Cover 96-Day L3 Global 1 km ISIN
Grid

Date: 3 Months ending 2001-01-16

Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The land cover product, MOD12Q1, also identifies 14 classes of land cover in the University of Maryland (UMD) global vegetation classification scheme.

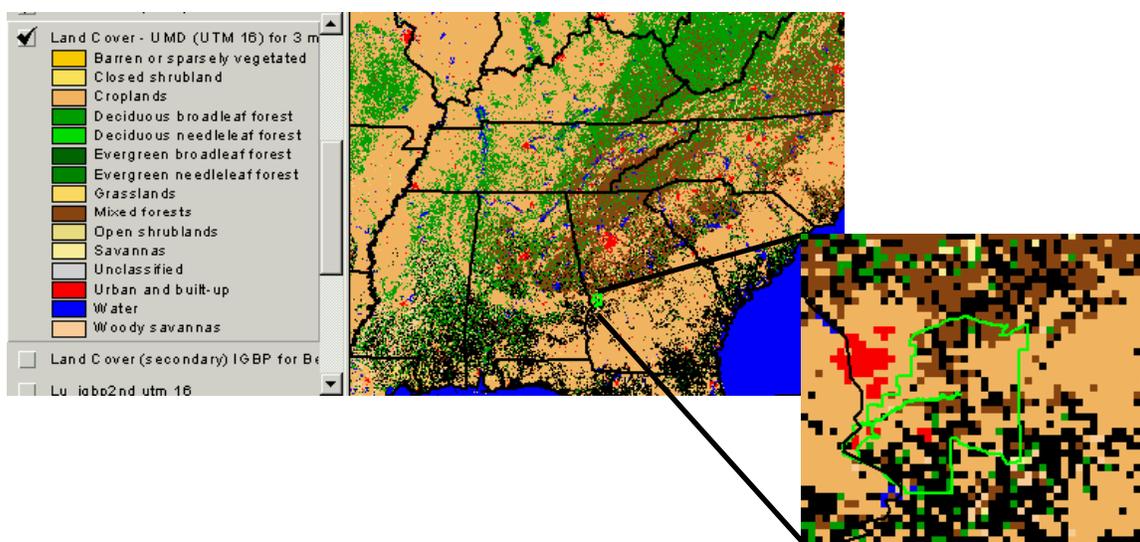


Figure 3. UMD vegetation classification scheme.

- LAI/fPAR Biome Scheme (Myneni et al., 1997) (Figure 4)
Data Granule:SC:MOD12Q1.003:2003481690
Local Granule ID: MOD12Q1.A2001001.h10v05.003.2001193164050.hdf
MODIS Data Set: MODIS/Terra Land Cover 96-Day L3 Global 1 km ISIN
Grid
Date: 3 Months ending 2001-01-16
Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The land cover product, MOD12Q1, LAI/fPAR biome scheme shows global vegetation stratified into six canopy architectural types, or biomes. These biomes span structural variations along the horizontal (homogeneous vs. heterogeneous) and vertical (single- vs. multi-story) dimensions, canopy height, leaf type, soil brightness and climate (precipitation and temperature) space of herbaceous and woody vegetation globally.

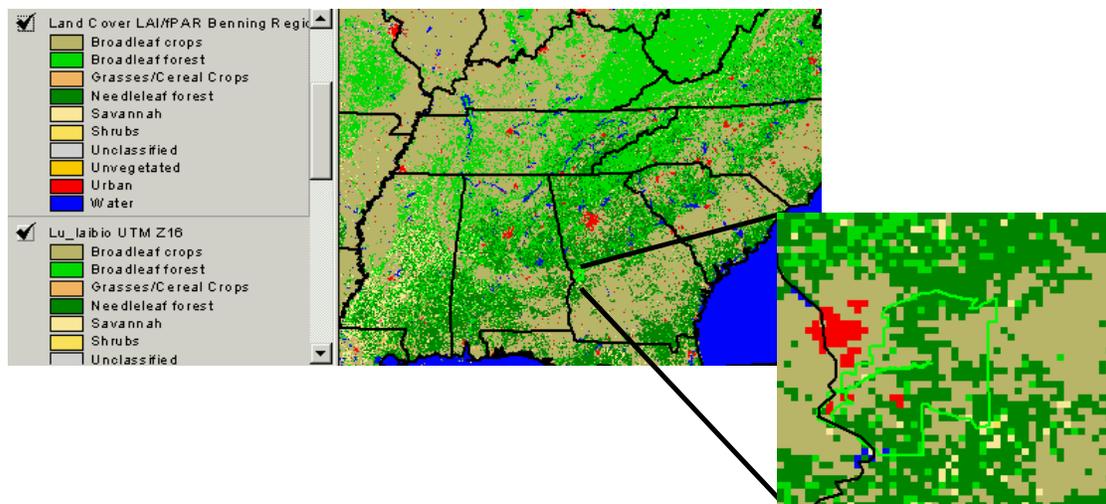


Figure 4. LAI/fPAR biome scheme.

Other MOD12Q1 Files

As of February 2002, several other products associated with MOD12Q1 are not yet available:

- Land cover type 5 (Open) – file completely filled with 255 values
- Land Cover Type 1 Secondary Percent – completely filled with 255 values
- Land Cover Types 1-4 Not Available
- Land Cover Properties 1-3 – not processed
- Land Cover QC – completely filled with 255 values

Derived Products – MOD13 Gridded vegetation indices (Max NDVI and Integrated EVI)

Discussion

The level 3 gridded vegetation indices are standard products designed to be fully operational at launch. The level 3 spatial and temporal gridded vegetation index products are composites of daily bidirectional reflectances. The gridded vegetation indices are 16-day spatial and temporal, resampled products designed to provide cloud-free, atmospherically corrected, and nadir-adjusted vegetation maps.

Many studies have shown the relationships of red and near-infrared (NIR) reflected energy to the amount of vegetation present on the ground (Colwell 1974). Reflected red energy decreases with plant development due to chlorophyll absorption within actively photosynthetic leaves. Reflected NIR energy, on the other hand, will increase with plant development through scattering processes (reflection and transmission) in healthy, turgid leaves. Unfortunately, because the amount of red and NIR radiation reflected from a plant canopy and reaching a satellite sensor varies with solar irradiance, atmospheric conditions, canopy background, and canopy structure and composition, one cannot use a simple measure of reflected energy to quantify plant biophysical parameters nor monitor vegetation on an operational basis. This is made difficult due to the intricate radiant transfer processes at both the leaf level (cell constituents, leaf morphology) and canopy level (leaf elements, orientation, nonphotosynthetic vegetation [NPV], and background). This problem has been circumvented somewhat by combining two or more bands into an equation or 'vegetation index' (VI).

Vegetation indices are derived from spectral reflectance signatures of leaves. The reflected energy in the visible spectrum is very low as a result of high absorption by photosynthetically active pigments with maximum sensitivity in the blue (470 nm) and red (670 nm) wavelengths. Nearly all of the near-infrared radiation is scattered (reflected and transmitted) with very little absorption, in a manner dependent upon the structural properties of the canopy. As a result, the contrast between red and near-infrared responses is a sensitive measure of vegetation amount, with maximum red - NIR differences occurring over a full canopy and minimal contrast over targets with little or no vegetation. For low and medium amounts of vegetation, the contrast is a result of both red and NIR changes, while at higher amounts of vegetation, only the NIR contributes to increasing contrasts as the red band becomes saturated due to chlorophyll absorption.

The Normalized Difference Vegetation Index output represents a “continuity index” to NOAA’s existing NDVI derived from an Advanced Very High Resolution Radiometer (AVHRR). It is standard to calculate it using:

$$\frac{\text{Bandnir} - \text{Bandred}}{\text{Bandnir} + \text{Bandred}}$$

The advantage of the Terra platform is that many instruments are working in unison. Major corrections that are therefore now possible include atmospheric clarity, direction (up/down, right/left) of sensor to target, direction of sun, vegetation or land cover type, and soil character. The Enhanced (soil and atmosphere resistant) Vegetation Index (EVI) is:

$$\frac{2 * (\text{surf directional reflectnir} - \text{surf directional reflected})}{(L + \text{surf directional reflectnir} + C * \text{surface directional reflected} + D * \text{surface directional reflectblue})}$$

where: surface directional reflectances are ‘apparent’ (top-of-the-atmosphere),
L is a canopy background adjustment term, and
C and D weigh the use of the blue channel in aerosol correction of the red channel.

It is useful to keep in mind that the VI products are calculated on simple algorithms and depend on **no** other inputs (contrast with the discussion under the PSN and NPP products). It is suggested that the simplicity and independence of their derivation strongly recommends their usage and reliability.

MOD13 Gridded vegetation indices (Max NDVI and Integrated EVI)

- Normalized Difference Vegetation Index (NDVI) (Figure 5)
Data Granule:SC:MOD13Q1.003:2003509399
Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
GLOBAL 250M ISIN GRID V003
Date: 16 days ending 2001-03-06
Resolution: Original: 231.6564 Reprojected: 334.8242 meters

The MODIS vegetation indices are robust spectral measures of the amount of vegetation present on the ground. They involve transformations of the red (620-670 nm), near-infrared (841-876 nm), and blue (459-479 nm) bands designed to enhance the “vegetation signal” and allow for precise inter-comparisons of spatial and temporal variations in terrestrial photosynthetic activity. The NDVI output represents a “continuity index” to NOAA’s existing AVHRR-derived NDVI. Values in this file are NDVI * 10,000; the normal range for NDVI is -1 to +1. Thus, the NDVI in the Fort Benning region is roughly 0.6 in this product.

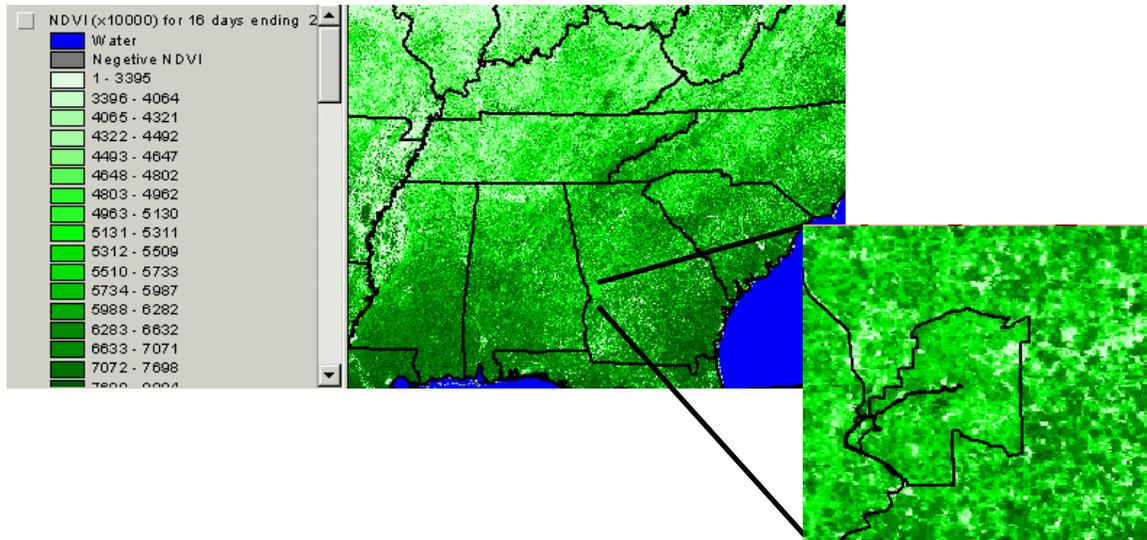


Figure 5. Normalized Difference Vegetation Index.

- Normalize Difference Vegetation Index (NDVI) quality (Figure 6)
 Data Granule: SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL 250M ISIN GRID V003
 Date: 16 days ending 2001-03-06
 Resolution: Original: 231.6564 Reprojected: 334.8242 meters

Since the input to the NDVI is based on two bands, the least good QC flag from the reflectance product will be representative for the VI QC flag. Appendix D in Huete and van Leeuwen (1999) gives the usefulness scale interpretation key for MODIS Level 3 products.

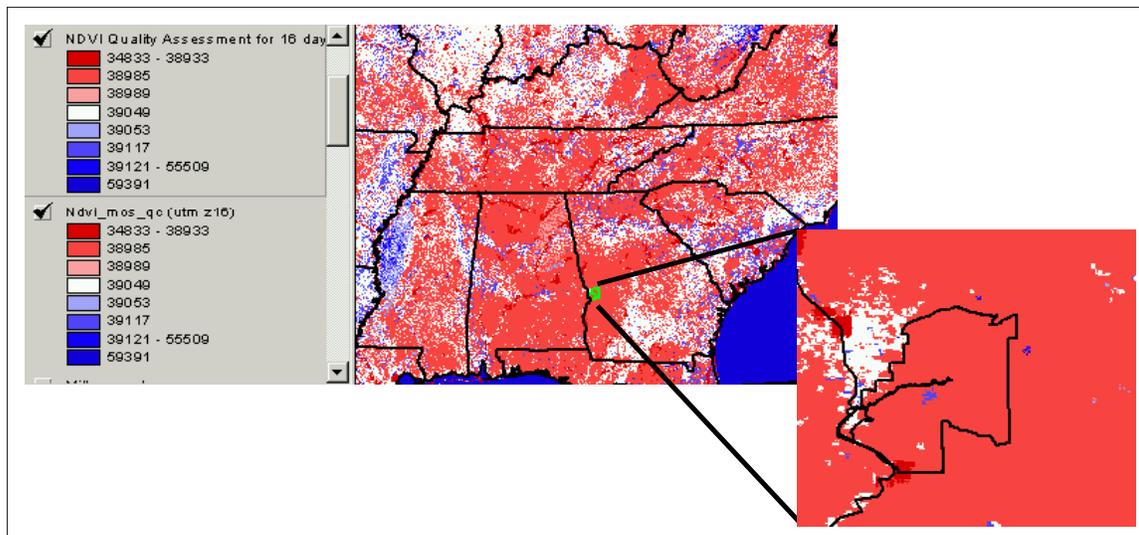


Figure 6. NDVI quality.

- Enhanced Vegetation Index (EVI) (Figure 7)
 Data Granule:SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL 250M ISIN GRID V003
 Date: 16 days ending 2001-03-06
 Resolution: Original: 231.6564 Reprojected: 334.8242 meters

The MODIS vegetation indices are robust spectral measures of the amount of vegetation present on the ground. The EVI is MODIS-specific and offers improved sensitivity in high biomass regions and improved vegetation monitoring through a decoupling of the canopy background signal and a reduction in atmospheric influences. A new compositing scheme is used, which reduces angular, sun-target-sensor variations, using the Constrained View Maximum Value Composite (CV-MVC) and an option to use BRDF models. Values in this file are EVI * 10,000; the normal range for EVI is -1 to +1. In the Fort Benning area, a normal value would be about 0.25.

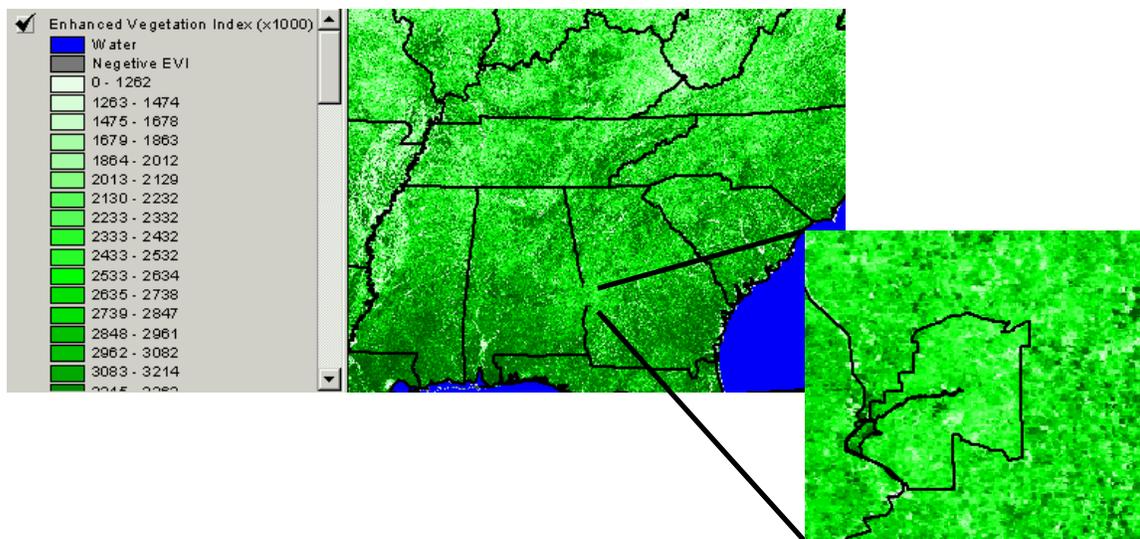


Figure 7. Enhanced Vegetation Index.

- Enhanced Vegetation Index (EVI) quality (Figure 8)
 - Data Granule: SC:MOD13Q1.003:2003509399
 - Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 - MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3 GLOBAL 250M ISIN GRID V003
 - Date: 16 days ending 2001-03-06
 - Resolution: Original: 231.6564 Reprojected: 334.8242 meters

The EVI will have three input QC flags from the reflectance product (three spectral bands), and thus the least good QC flag will be chosen to represent the VI QC. Appendix D in Huete and van Leeuwen (1999) gives the usefulness scale interpretation key for MODIS Level 3 products.

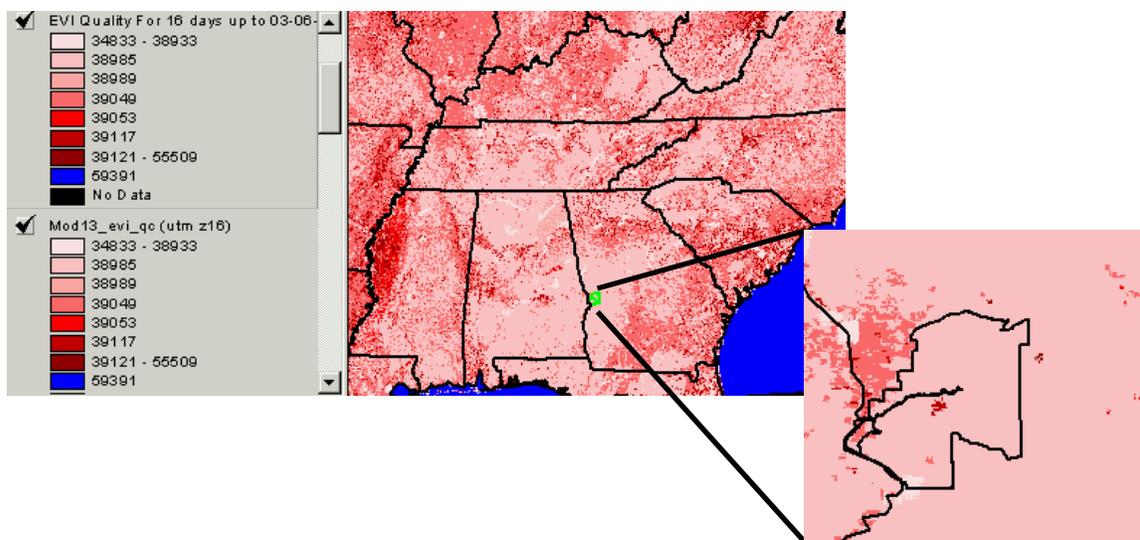


Figure 8. EVI quality.

- Blue – Band 3 (459-479nm) (Figure 9)
 Data Granule:SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL 250M ISIN GRID V003
 Date: 16 days ending 2001-03-06
 Resolution: Original: 500 m blue channel resampled to 231.6564 Re-
 projected: 334.8242 meters

The MODIS vegetation indices use the blue (459-479 nm) band to enhance the “vegetation signal” and allow for precise intercomparisons of spatial and temporal variations in terrestrial photosynthetic activity. The character of the blue band is used to correct for top-of-the-atmosphere conditions. Kaufman (1992) developed the atmospherically resistant vegetation index (ARVI) for atmosphere correction, using the difference of the blue and red bands as an indicator of atmospheric noise. The ARVI accounts for atmosphere aerosol scattering and requires atmospheric correction of molecular scattering and ozone absorption prior to its use. Myneni et al. (1993) found the ARVI to reduce atmospheric effects and to mimic ground-based NDVI data. The atmospheric resistance concept (blue/ red) is applied in the EVI to aid with highly variable aerosol conditions, such as smoke from biomass burning.

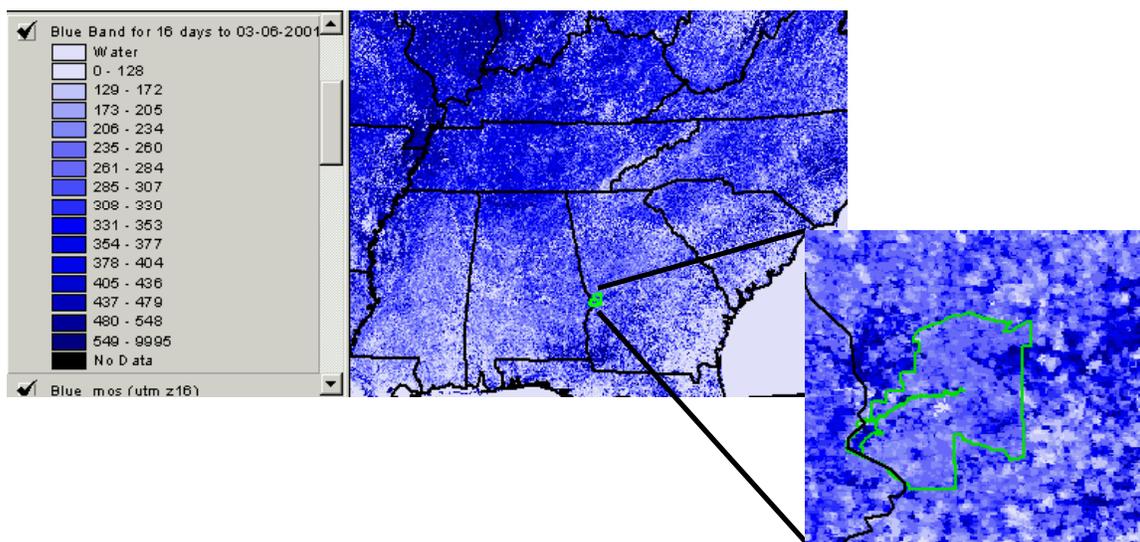


Figure 9. Blue — Band 3.

- Red – Band 1 (620-670nm) (Figure 10)
 Data Granule:SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf

MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
GLOBAL 250M ISIN GRID V003

Date: 16 days ending 2001-03-06

Resolution: Original: 231.6564 Reprojected: 334.8242 meters

Many studies have shown the relationships of red and near-infrared (NIR) reflected energy to the amount of vegetation present on the ground (Colwell, 1974). Deering (1978) developed a ratio from -1 to +1, called the normalized difference vegetation index (NDVI), by ratioing the difference between the NIR and Red bands by their sum;

$$\text{NDVI} = \frac{\text{Bandnir} - \text{Bandred}}{\text{Bandnir} + \text{Bandred}}$$

The red band is thus a primary component of VIs in general and the NDVI and MODIS specific EVI.

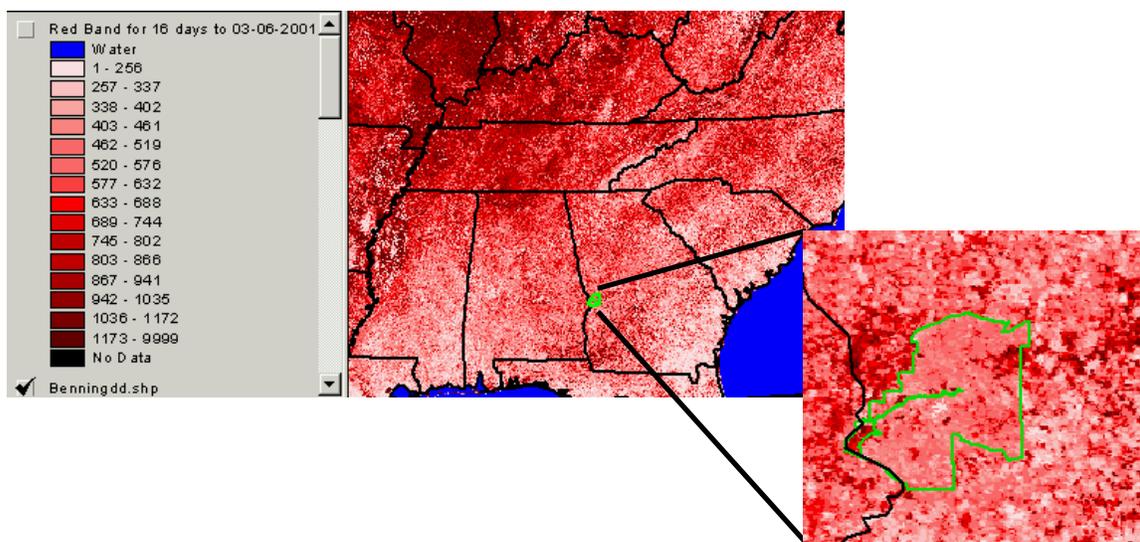


Figure 10. Red — Band 1.

- Near Infrared – Band 2 (841-876 nm)(Figure 11)
Data Granule:SC:MOD13Q1.003:2003509399
Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
GLOBAL 250M ISIN GRID V003
Date: 16 days ending 2001-03-06
Resolution: Original: 231.6564 Reprojected: 334.8242 meters

Deering (1978) produced a ratio from -1 to +1, called the normalized difference vegetation index (NDVI), by ratioing the difference between the NIR and Red bands by their sum;

$$\text{NDVI} = \frac{\text{Bandnir} - \text{Bandred}}{\text{Bandnir} + \text{Bandred}}$$

The NIR band is thus a primary component of VIs in general and the NDVI and MODIS specific EVI.

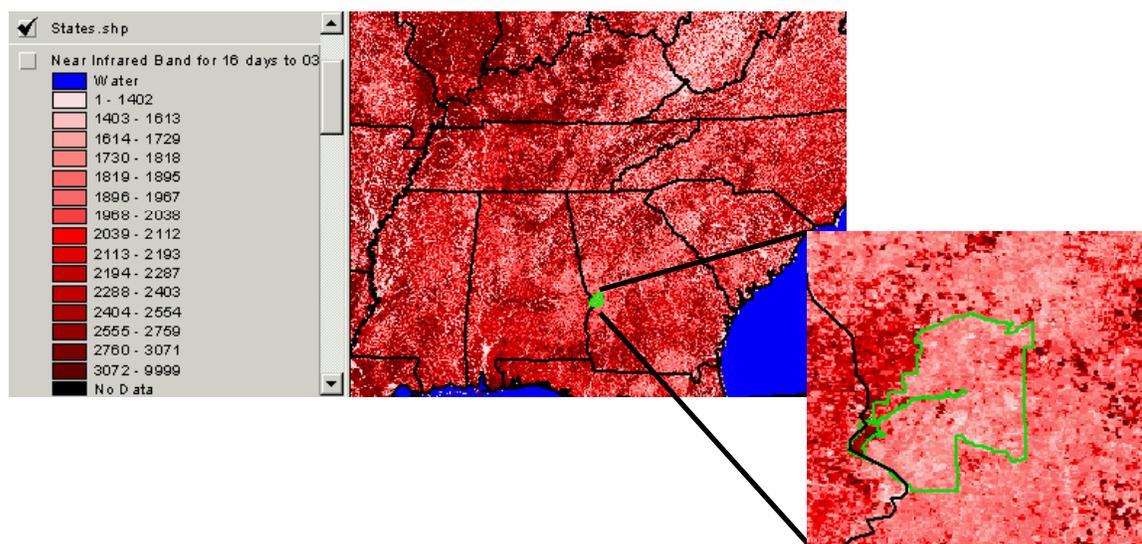


Figure 11. NIR — Band 2.

- MIR – Band 7 (2105-2155 nm) (Figure 12)
 Data Granule:SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL 250M ISIN GRID V003
 Date: 16 days ending 2001-03-06
 Resolution: Original: 500 m MIR channel resampled to 231.6564 Reproj-
 ected: 334.8242 meters

In the VI product, the MIR band is currently not used. It will be used in later versions for cleaning atmospheric anomalies such as smoke from fires and burns. In the VI product, it will become part of the quality assurance (QA) analysis.

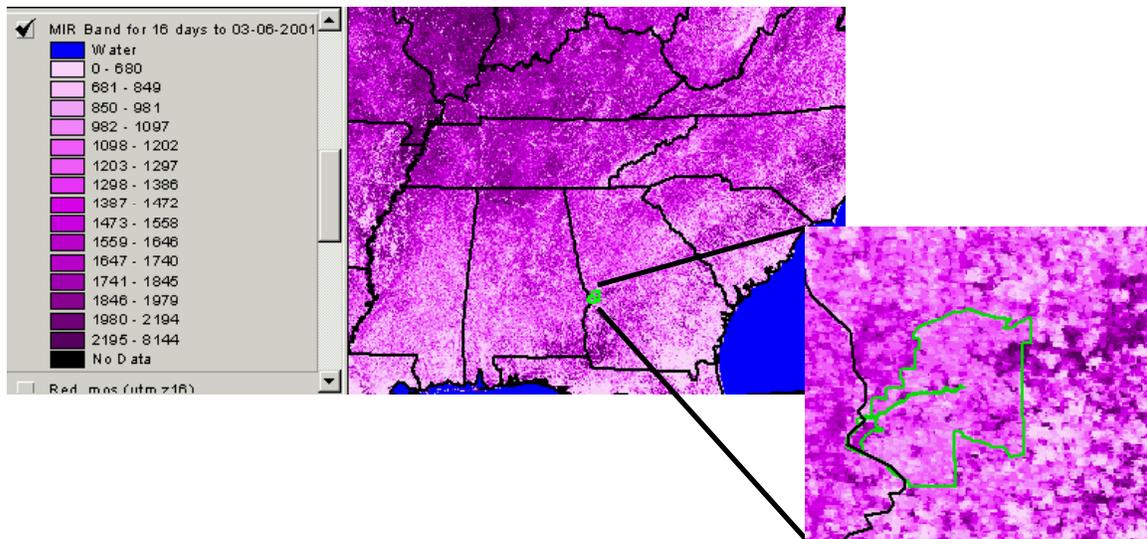


Figure 12. MIR — Band 7.

- Average Azimuth Angle (Degree X 10) (Figure 13)
 Data Granule: SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL 250M ISIN GRID V003
 Date: 16 days ending 2001-03-06
 Resolution: Original: 231.6564 Reprojected: 334.8242 meters

The NDVI is affected by variations in bidirectional reflectances resulting from differences in sun-target-sensor geometries. MODIS viewing angles (horizontal direction from instrument to target) will vary + or - 55 degrees cross-track. The strong anisotropic properties from vegetation canopies seriously affect vegetation indices, and vary with land cover type, relative amounts of characteristic vegetation, and soil components. The azimuth angle is important for the seasonal and interannual comparison of vegetative covers. Since the VI tends to increase with both larger view azimuth and larger solar zenith angles, bidirectional reflectance distribution function (BRDF) model parameters can be used to normalize and interpolate the surface reflectance to nadir view angles. Azimuth angles are included with the composited data (reflectance and vegetation index data) to be used for post-process standardization of the vegetation indices.

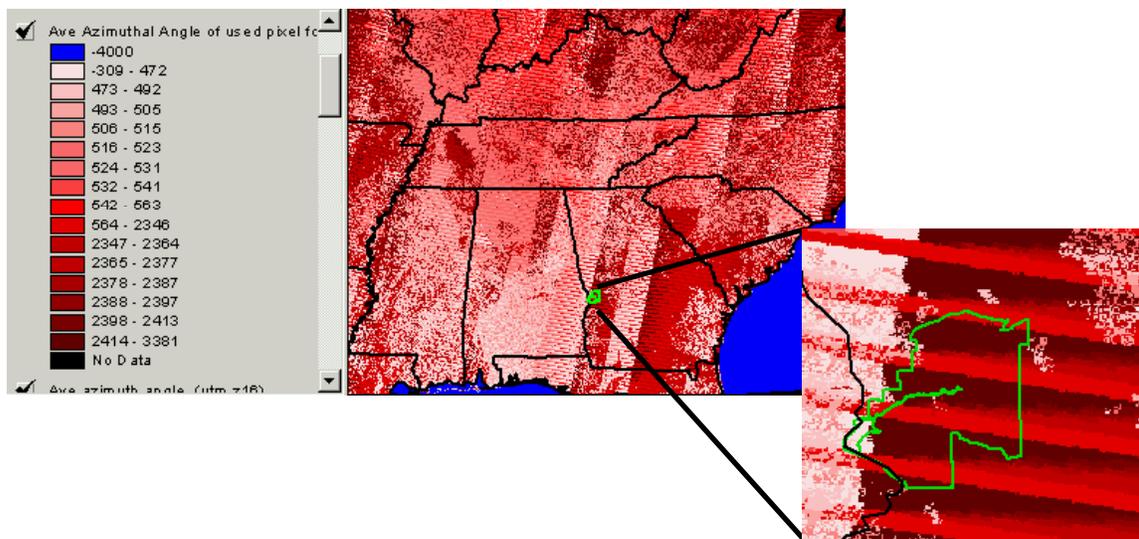


Figure 13. Average azimuth angle.

- Average Sun Zenith Angle (Degree X 100) (Figure 14)
 Data Granule:SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL 250M ISIN GRID V003
 Date: 16 days ending 2001-03-06
 Resolution: Original: 231.6564 Reprojected: 334.8242 meters

The NDVI is affected by variations in bidirectional reflectances resulting from differences in sun-target-sensor geometries. Solar illumination angle differences will occur of up to 20 degrees from edge to edge of the MODIS swath. In addition, sun angles will vary with latitude and time of the year. The sun-earth-sensor geometry can seriously affect vegetation indices. Variability in sun angles is important for the (seasonal and interannual) intercomparison of vegetative covers. Established biophysical parameter relationships with vegetation indices are based upon nadir-viewing angles. VI tends to increase with larger solar zenith angles. Sun angle variability is minimally incorporated in the BRDF correction, because the data necessary to standardize to a certain sun angle for each composite time interval (16 days in the case of MODIS) is very limited. Therefore, the solar zenith angles can be used for post-process standardization of the vegetation indices.

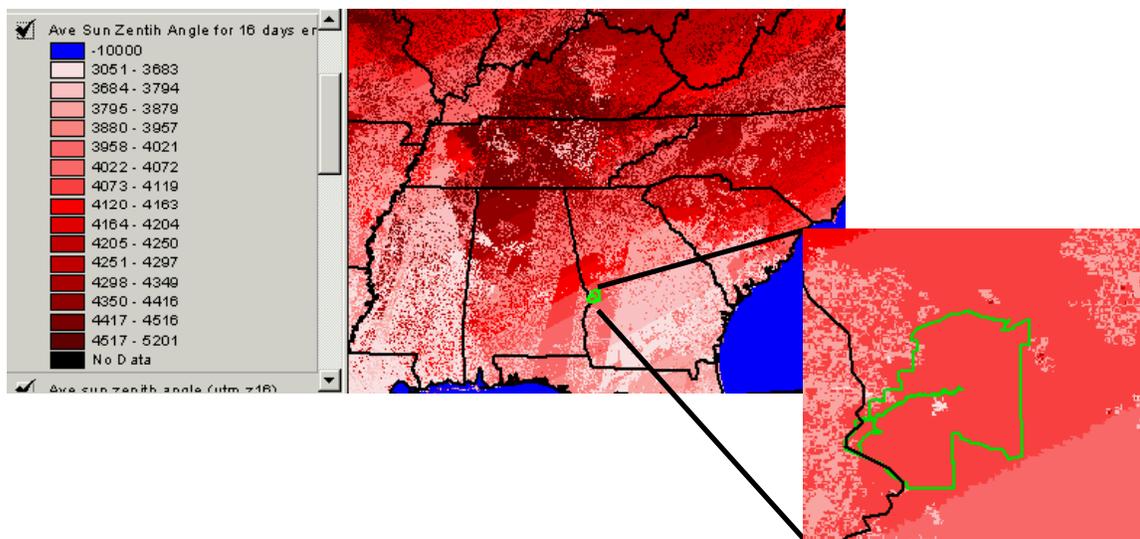


Figure 14. Average sun zenith angle.

- Average View Angle (Degree X 100) (Figure 15)
 Data Granule:SC:MOD13Q1.003:2003509399
 Local Granule ID: MOD13Q1.A2001065.h10v05.003.2001206131733.hdf
 MODIS Data Set: MODIS/TERRA VEGETATION INDICES 16-DAY L3
 GLOBAL 250M ISIN GRID V003
 Date: 16 days ending 2001-03-06
 Resolution: Original: 231.6564 Reprojected: 334.8242 meters

The NDVI is affected by variations in bidirectional reflectances resulting from differences in sun-target-sensor geometries. MODIS viewing angles will vary + or - 55 degrees cross-track. The variability in view angle is important for the (seasonal and interannual) intercomparison of vegetative covers. The most desirable situation uses standardized reflectances to nadir view angle since established biophysical parameter relationships with vegetation indices are based upon nadir-viewing angles. Vegetation index “saturation” problems become greater with off-nadir view angles. The VI tends to increase with larger view angles. The BRDF model parameters can be used to normalize and interpolate the surface reflectance to nadir view angles. The view angle distribution at nadir view angles has the finest spatial resolution and least atmospheric pathway and is thus the most desirable situation.

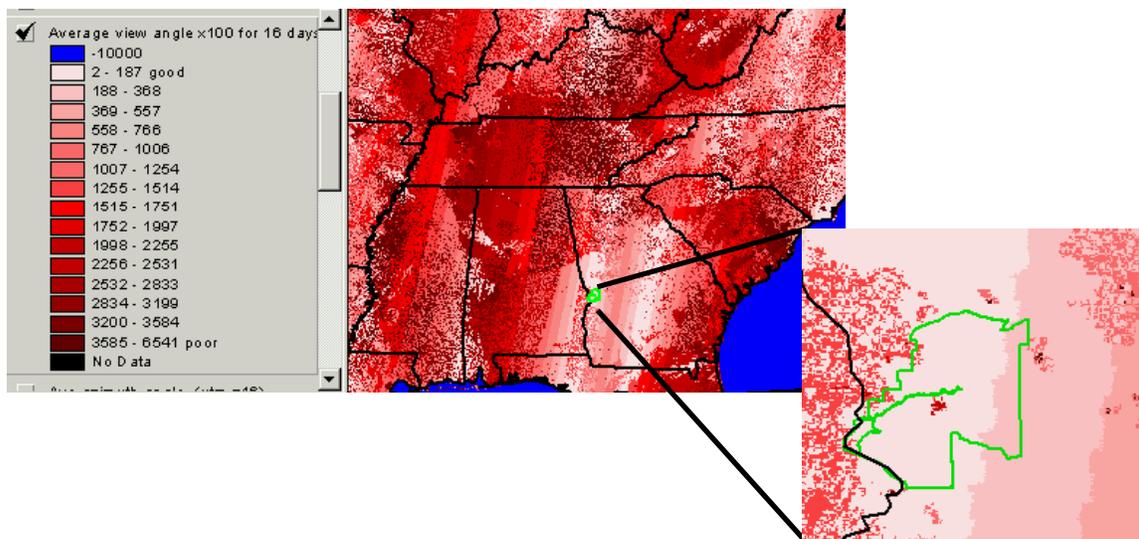


Figure 15. Average view angle.

Derived Products – MOD15 Leaf Area Index/Fraction-of-Photosynthetically Active Radiation

Discussion

The MOD15 Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation absorbed by vegetation (FPAR,) are 1-km global data products updated once each 8-day period throughout each calendar year.

- LAI defines an important structural property of a plant canopy as the one-sided leaf area per unit ground area.
- FPAR measures the proportion of available radiation in the photosynthetically active wavelengths (400 to 700 nm) that a canopy absorbs.

LAI and FPAR are biophysical variables that describe canopy structure and are related to functional process rates of energy and mass exchange. Both LAI and FPAR have been used extensively as satellite-derived parameters for calculation of surface photosynthesis, evapotranspiration, and annual net primary production. These products are essential in calculating terrestrial energy, carbon, water cycle processes, and biogeochemistry of vegetation. These products are derived from the atmosphere-corrected surface reflectance product MOD09, land cover product MOD12, and ancillary information on surface characteristics using a three-dimensional (3D) radiative transfer model.

MOD15 Fraction-of-Photosynthetically Active Radiation (FPAR) and Leaf Area Index

- Fraction-of-Photosynthetically Active Radiation (FPAR) (Figure 16)
 Data Granule:SC:MOD15A2.003:2003423004
 Local Granule ID: MOD15A2.A2001065.h10v05.003.2001190120507.hdf
 MODIS Data Set: MODIS/TERRA LEAF AREA INDEX/FPAR 8-DAY L4
 GLOBAL 1KM ISIN GRID V003
 Date: 8 days ending 2001-03-06
 Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The MOD15 Fraction-of-Photosynthetically Active Radiation absorbed by vegetation (FPAR,) is a 1-km global data product updated once each 8 days. FPAR measures the proportion of available radiation in the photosynthetically active wavelengths (400 to 700 nm) that a canopy absorbs. FPAR is a biophysical variable that describes canopy structure and is related to functional process rates of energy and mass exchange. FPAR has been used extensively as a satellite-derived parameter for calculation of surface photosynthesis, evapotranspiration, and annual net primary production. This product is essential in calculating terrestrial energy, carbon, water cycle processes, and biogeochemistry of vegetation.

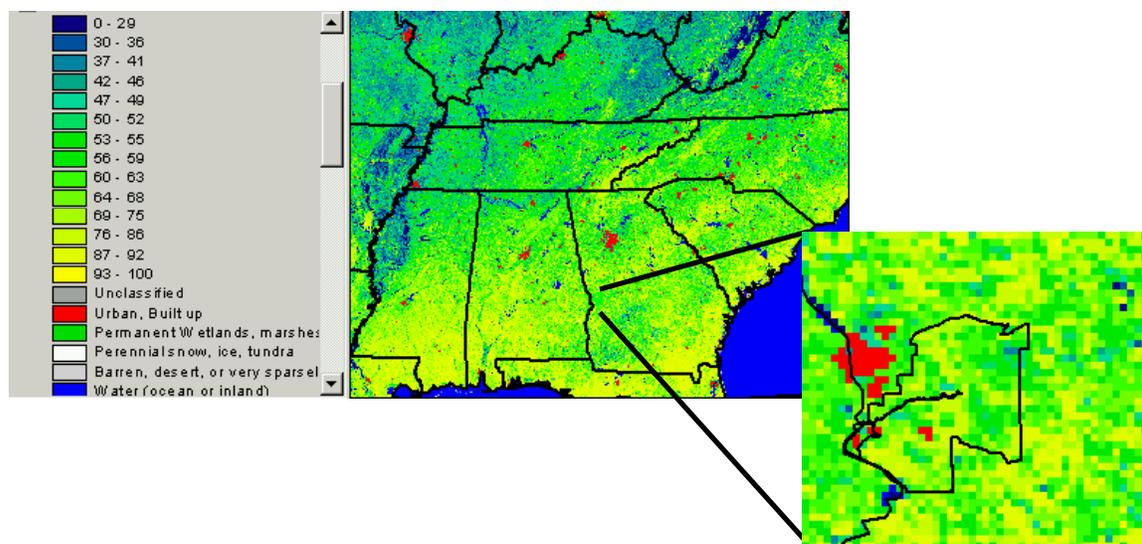


Figure 16. Fraction-of-Photosynthetically Active Radiation.

- Fraction-of-Photosynthetically Active Radiation (FPAR) – Data Quality Evaluation (Figure 17)
 Data Granule:SC:MOD15A2.003:2003423004
 Local Granule ID: MOD15A2.A2001065.h10v05.003.2001190120507.hdf

MODIS Data Set: MODIS/TERRA LEAF AREA INDEX/FPAR 8-DAY L4
GLOBAL 1KM ISIN GRID V003

Date: 8 days ending 2001-03-06

Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The quality evaluation of the MOD15 Fraction-of-Photosynthetically Active Radiation absorbed by vegetation (FPAR) is a 1-km global data product updated once each 8 days. Virtually all MODLAND products include quality control scores (e.g., error estimates) in their products. Quality control measures are produced at both the file (e.g., 10-deg tile) level and at the pixel level. At the pixel level, quality control information is represented by one or more separate data layers, whose pixel values correspond to specific quality scoring schemes that vary by product Earth Science Data Type (ESDT). Key to the quality assessment can be found in Knyazikhin et al. 1999, p114. This product takes into account cloudiness, clearness, location and type of water bodies, and processing limitations.

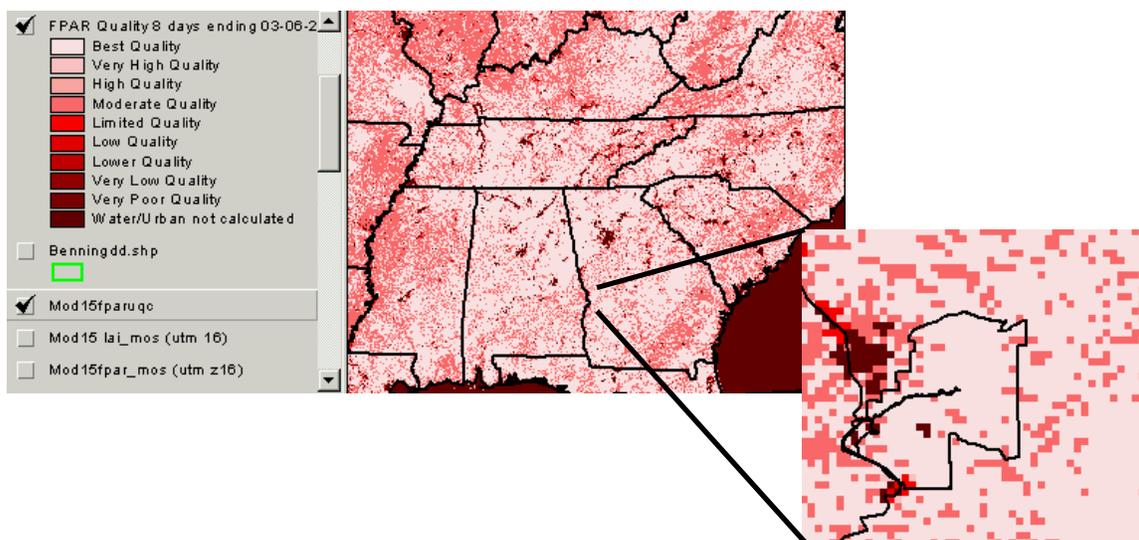


Figure 17. FPAR data quality evaluation.

- Leaf Area Index (LAI) (Figure 18)
Data Granule:SC:MOD15A2.003:2003423004
Local Granule ID: MOD15A2.A2001065.h10v05.003.2001190120507.hdf
MODIS Data Set: MODIS/TERRA LEAF AREA INDEX/FPAR 8-DAY L4
GLOBAL 1KM ISIN GRID V003
Date: 8 days ending 2001-03-06
Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The MOD15 Leaf Area Index (LAI) is a 1-km global data product updated once every 8 days. LAI is a biophysical variable that describes canopy structure and is related to functional process rates of energy and mass exchange. LAI has been used extensively as satellite-derived parameters for calculating surface photosynthesis, evapotranspiration, and annual net primary production.

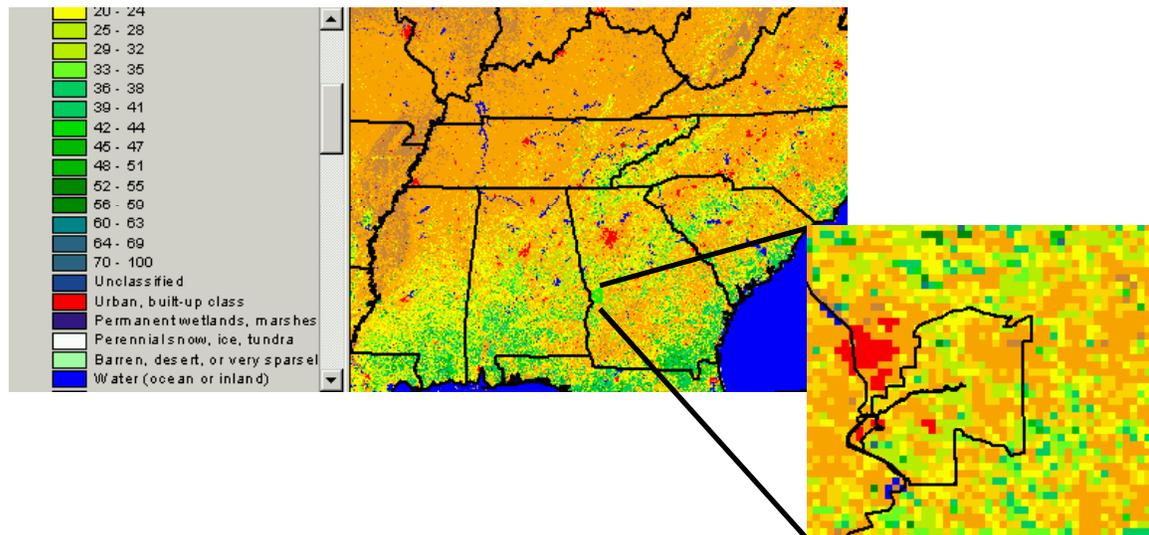


Figure 18. Leaf Area Index.

- Leaf Area Index (LAI) – Data Quality Evaluation (Figure 19)
 Data Granule: SC:MOD15A2.003:2003423004
 Local Granule ID: MOD15A2.A2001065.h10v05.003.2001190120507.hdf
 MODIS Data Set: MODIS/TERRA LEAF AREA INDEX/FPAR 8-DAY L4
 GLOBAL 1KM ISIN GRID V003
 Date: 8 days ending 2001-03-06
 Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

Quality evaluation the MOD15 Leaf Area Index (LAI) is a 1-km global data product updated once every 8 days. Virtually all MODLAND products include quality control scores (e.g., error estimates) in their products. Quality control measures are produced at both the file (e.g., 10-deg tile) level and at the pixel level. At the pixel level, quality control information is represented by one or more separate data layers, whose pixel values correspond to specific quality scoring schemes that vary by product Earth Science Data Type (ESDT). Key to the quality assessment is to be found in Knyazikhin et al. 1999, p114. This product takes into account cloudiness, clearness, and processing limitations.

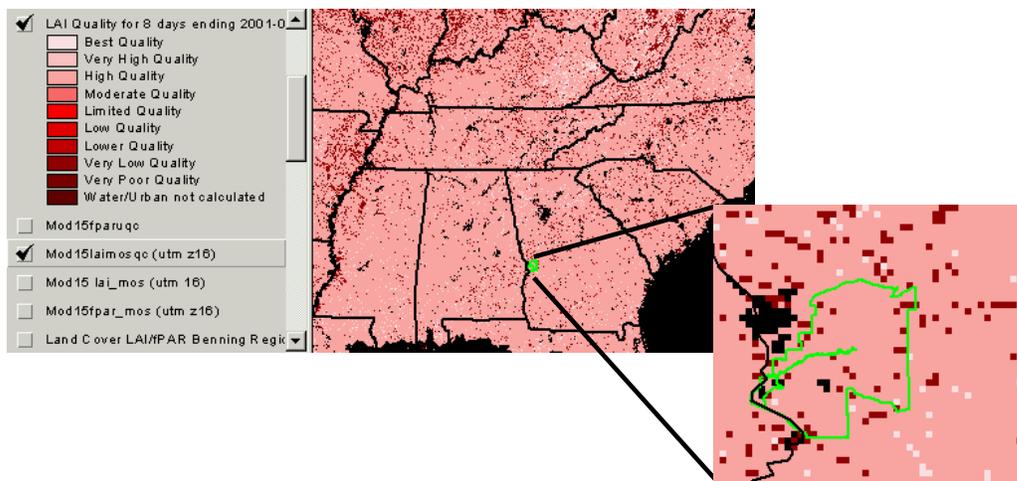


Figure 19. LAI – data quality evaluation.

Derived Products – MOD17 Net Photosynthesis (PSN)

Discussion

The MOD17 PSN and Net Primary Production (NPP) products are Level 4, 1-km global data collections used in calculating terrestrial energy, carbon, water cycle processes, and biogeochemistry of vegetation. The MOD17A2 is expressed as the mass of carbon per square meter.

MOD17A2 is produced based on the original work of Monteith (1972), which relates PSN and NPP to the amount of Absorbed Photosynthetically Active Radiation (APAR). The algorithm uses input from MODIS LAI/FPAR (MOD15A2), land cover, and biome-specific climatologic data from NASA's Data Assimilation Office (DAO).

The 8-day PSN will be integrated over a year to produce MOD17Y (not available, March 2002), an annual NPP product. Both have theoretical applications towards defining the seasonal dynamic flux of terrestrial surface carbon dioxide for climate modeling.

It is useful to realize that PSN and NPP are the last products in a long line of calculations and interim products (land cover is used in the generation of the LAI and FPAR products, which are used in the generation of the PSN and NPP products). Although each product has to be validated, uncertainties in one are **multiplied** in the derivation of the next. After a few steps of multiplied uncertainties, one may end up with a product that is derived from “first principal” physical processes but is not highly representative of reality. NASA overcomes this issue with their research at the validation sites. Still, the fact that PSN and NPP are highly calculated products is worth keeping in mind.

MOD17 Net Photosynthesis and Primary Productivity

- Net Photosynthesis (PSN) (Figure 20)
 Data Granule: SC:MOD17A2.003:2003943741
 Local Granule ID: MOD17A2.A2001073.h10v05.003.2001205094830.hdf
 MODIS Data Set: MODIS/TERRA NET PHOTOSYNTHESIS 8-DAY L4
 GLOBAL 1KM ISIN GRID V003
 Date: 8 days ending 2001-03-14
 Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

The MOD17 PSN and NPP products are Level 4, 1-km collections used in calculating terrestrial energy, carbon, water cycle processes, and biogeochemistry of vegetation. This image is an 8-day composite of cumulative PSN: mass of carbon per square meter. For this period, around Fort Benning, the values are about 0.015 gC/m². Note that PSN are absolute values rather than ratios or arbitrary ranges. The algorithm uses input from MODIS LAI/FPAR (MOD15A2), land cover, and biome-specific climatologic data.*

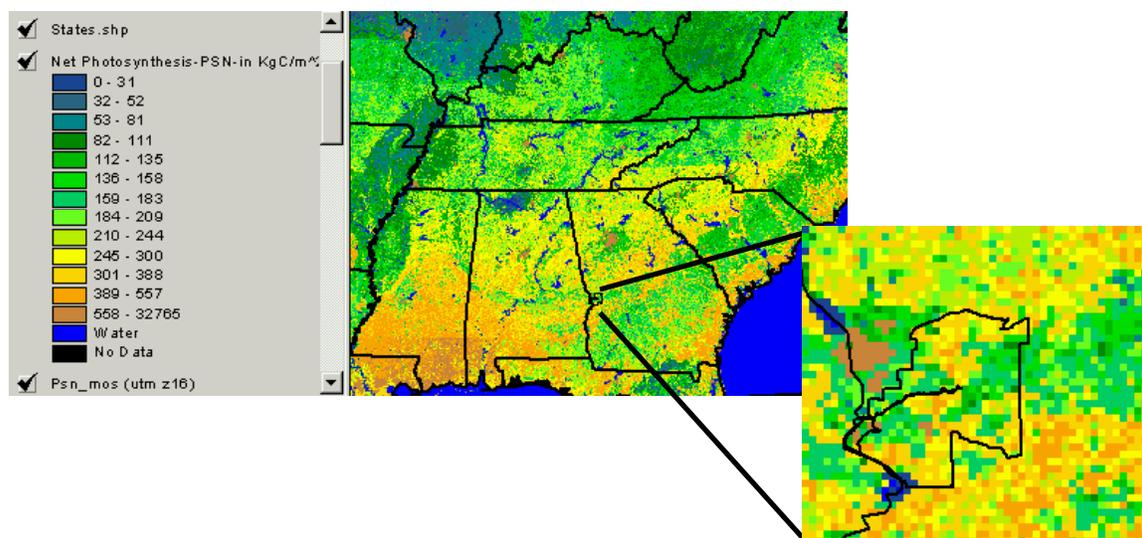


Figure 20. Net photosynthesis.

* It has recently been discovered (as presented by Robert Wolf of Goddard Space Flight Center at the MODIS Vegetation Workshop, Missoula, MT, June 2002) that some of the climatologic data used in the algorithm is incorrect by a factor of 1000. In sensitivity tests, this inaccuracy has the highest effect on calculations in polar and arid areas, but little on other biome types such as the one presented here for the Fort Benning region. The PSN in being recalculated. The correct PSN products are expected to be available no later than October 2002.

- Net Photosynthesis (PSN) Quality Assessment (Figure 21)
 Data Granule: SC:MOD17A2.003:2003943741
 Local Granule ID: MOD17A2.A2001073.h10v05.003.2001205094830.hdf
 MODIS Data Set: MODIS/TERRA NET PHOTOSYNTHESIS 8-DAY L4
 GLOBAL 1KM ISIN GRID V003
 Date: 8 days ending 2001-03-14
 Resolution: Original: 926.6254 Reprojected: 1339.2966 meters

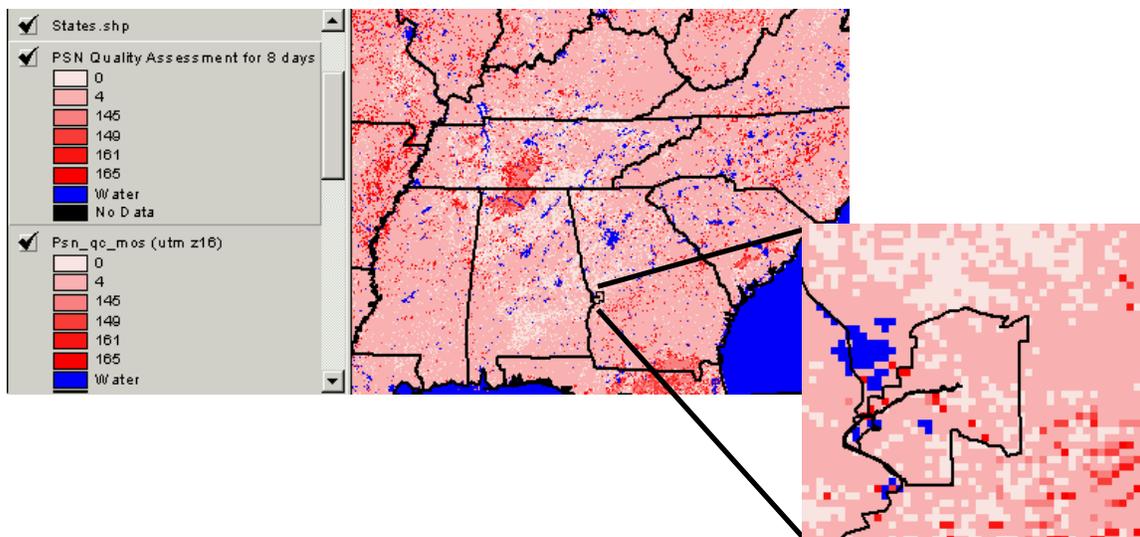


Figure 21. PSN quality assessment.

Derived Products – MOD44 Vegetation Cover Conversion

Discussion

MODIS will be searching for changes specifically to vegetation. Using the red and NIR bands, monthly, quarterly, and yearly vegetation cover conversion products will be generated. Scenes with 250-m spatial resolution will be placed in 10-km grids to provide regular summaries of green cover. MOD44 is one product directly participating in predictive modeling, as it will help flag areas where significant changes can be expected.

As of May 2002, the first of the MOD44 products were not yet available.

MOD44 Vegetation cover conversion

- Not Yet Available

5 Applications for Military Land Monitoring and Management

NASA Applications Descriptions

When NASA describes the products from Terra, it is focusing on its mission to detect and predict the direction and amount of potential global climatic change. NASA descriptions of their products emphasize the climatic application. However, a review of NASA's descriptions can better help extrapolate (and limit) the use of their products to military land management. NASA documents describe the following uses of each of the listed MODIS products. These sections are generally quoted directly from the referenced Algorithm Theoretical Basis Document (ATBD) for each product series.

MOD12 Land cover/Land cover change

Human activity increasingly modifies the land surface cover. These modifications arise through direct actions, such as deforestation, agricultural activities, and urbanization, or indirectly, through human-induced climatic change. The importance of mapping, quantifying, and monitoring changes in the physical characteristics of land cover has been widely recognized in the scientific community as a key element.

The objective of the Land Cover Change product is to detect and quantify the changes in land cover and the natural and anthropomorphic processes that bring about the changes so global and regional models may be projected forward through changes in their driving surface parameters.

Global and regional studies are appropriate to detect abrupt land cover changes such as forest clearing, biomass burning, or the impact of a severe drought. The detection of more subtle forms of change, such as those associated with climate change or with slow rates of land degradation, requires a more sophisticated approach such as change vector analysis.

Land cover information is useful to infer the parameters that influence biophysical processes and energy exchanges between the atmosphere and the land sur-

face as required by regional and global-scale climate and ecosystem process models (Townshend et al. 1991). Examples of such parameters for climate modeling include

- Leaf area index (LAI),
- Roughness length,
- Surface resistance to evapotranspiration,
- Canopy greenness fraction,
- Vegetation density,
- Root distribution, and
- Fraction-of-photosynthetically active radiation absorbed (Sellers 1991a, 1991 b).

These parameters serve as input variables that control surface energy and mass balances. Taken together, the sets of natural vegetation and developed lands units can be used to differentiate several fundamental distinctions among cover types that are essential for ecological process modeling. One of the comparisons is annual vs. perennial habit, distinguished by whether or not the vegetation retains perennial or annual above ground biomass. This attribute separates vegetation with permanent respiring biomass (forests and woody stemmed shrubs) from annual crops and grasses that go through non-growing season periods as seeds or below-ground structures only. The annual-perennial distinction allows inference of several critical physiological attributes of plants. For example, in a global synthesis of plant gas exchange rates, Korner (1993) found on average that annual plants maintained a 50 percent higher leaf photosynthetic capacity than perennial plants. Another fundamental attribute that is distinguishable using this set of units is leaf longevity, which distinguishes between evergreen and deciduous plant covers. The MOD12 leaf longevity attribute is a critical variable in: carbon cycle dynamics of vegetation, and is important for seasonal albedo and energy transfer characteristics of the land surface.

The leaf longevity class defines whether a plant must completely regrow its entire canopy each year, or merely a portion of it, with direct consequences to ecosystem (i.e., carbon partitioning, leaf litter fall dynamics, and soil carbon pools).

Reich et al. (1992) suggest that canopy conductance and maximum photosynthetic rate are inversely proportional to leaf longevity. Hence, certain global attributes of canopy gas exchange capacity may be inferred based on a leaf longevity criterion. A third vegetation attribute recognizable within the IGBP categories is the leaf type or shape of the dominant vegetation cover. Three leaf shapes are distinguished among the various categories: needle leaf, broadleaf,

and graminoid (grasses). This attribute also correlates well with key ecological parameters for biogeochemical modeling. Running and Hunt (1993) defined maximum leaf area index values of 10, 6 and 3, and maximum canopy conductance values of 1.6, 2.5, and 5.0 mm/sec, for needle-leaved trees, broad-leaved trees, and grass covers, respectively. Still other intrinsic biophysical parameters may be inferred from these values. In a somewhat different application, Sellers et al. (1994) devised an algorithm for determining global FPAR, LAI, and canopy greenness fraction from monthly composited NDVI at 1-degree resolution. Although the method is based on NDVI, the algorithm stratifies NDVI-FPAR-LAI relationships by vegetation cover types, using broad structural classes similar to those of the IGBP classification. Note that FPAR and LAI will be produced from MODIS using separate biogeophysical algorithms in MODIS product MOD15.

Besides the obvious need to know what types of land uses exist and therefore the dynamics associated with change due to economic and environmental pressures, land cover type can also be translated to represent several other ecosystem significant parameters such as:

- Leaf area,
- Photosynthetic capacity,
- Canopy conductance,
- Type of photosynthetic system and
- Maximum photosynthetic rate.

MOD13 Gridded vegetation indices (Max NDVI and Integrated EVI)

Vegetation Indices are also used for a wide variety of land applications, including natural resource management, agriculture, global-coverage vegetation condition and human activity monitoring (e.g., clear-cutting forested areas), and operational famine early warning. The latter example is an example of where derived satellite data are being used to drive policy decisions.

Vegetation indices have a long history of use throughout a wide range of disciplines. Some examples are:

- Inter- and intra-annual global vegetation monitoring on a periodic basis;
- Global biogeochemical, climate, and hydrologic modeling;
- Net primary production and carbon balance;
- Anthropogenic and climate change detection;
- Agricultural activities (plant stress, harvest yields, precision agriculture);
- Famine early warning systems;

- Drought studies
- Landscape disturbances (volcanic, fire scars, etc.);
- Land cover and land cover change products;
- Biophysical estimates of vegetation parameters (percent cover, fAPAR, LAI);
- Public health issues (rift valley fever, mosquito producing rice fields).

Two VI algorithms are to be produced globally for land. One is the standard Normalized Difference Vegetation Index (NDVI), which is referred to as the “continuity index” to the existing NOAA-AVHRR derived NDVI. There is a nearly 20-year NDVI global data set (1981 - 1999) from the NOAA-AVHRR series that could be extended by MODIS data to provide a long term data record for use in operational monitoring studies. The other is an ‘enhanced’ vegetation index with improved sensitivity to differences in vegetation from sparse to dense vegetation conditions.

As a vegetation-monitoring tool, the NDVI is used to construct seasonal, temporal profiles of vegetation activity enabling interannual comparisons of these profiles. The temporal profile of the NDVI has been shown to depict seasonal and phenologic activity, length of the growing season, peak greenness, onset of greenness, and leaf turnover or ‘dry-down’ period.

MOD15 Leaf area index and FPAR

Large-scale ecosystem modeling is used to simulate a range of ecological responses to changes in the distribution of terrestrial plant communities. LAI is a state parameter in all models describing the exchange of fluxes of energy, mass (e.g., water and CO₂), and momentum between the surface and the planetary boundary layer. The FPAR absorbed by vegetation is a key state variable in most ecosystem productivity models and in global models of climate, hydrology, biogeochemistry, and ecology. Research shows that we can relate the vegetation indexes to the fundamental physical principle (i.e., the law of energy conservation).

LAI and FPAR are biophysical variables that describe canopy structure and are related to functional process rates of energy and mass exchange. Both LAI and FPAR have been used extensively as satellite derived parameters for calculating: surface photosynthesis, evapotranspiration, and annual net primary production. These products are essential in calculating terrestrial energy, carbon, water cycle processes, and biogeochemistry of vegetation.

MOD17 Net Photosynthesis and Primary productivity

Biological productivity is the source of all the food, fiber, and fuel that humans survive on, and so defines most fundamentally the habitability of the Earth. The PSN/NPP products are designed to provide an accurate, regular measure of the production activity or growth of terrestrial vegetation.

The practical utility of these PSN/NPP products is:

- As a measure of crop yield,
- Range forage and forest production, and
- Other economically and socially significant products of vegetation growth.

The value of an unbiased, regular source of crop, range, and forest production estimates for global political and economic decisionmaking is immense. This daily computed PSN more correctly defines terrestrial CO₂ fluxes than simple NDVI correlations currently done to increase understanding on how the seasonal fluxes of net photosynthesis are related to seasonal variations of atmospheric CO₂. The notion of a conservative ratio between absorbed photosynthetically active radiation and net primary production was proposed by Monteith (1972). Monteith's original logic suggested that the NPP of well-watered and fertilized annual crop plants was linearly related to the amount of solar energy they absorbed. APAR depends on the geographic and seasonal variability of day length and potential incident radiation, as modified by cloud cover and aerosols, and on the amount and geometry of displayed leaf material. This logic combined the meteorological constraint of available sunlight reaching a site with the ecological constraint of the amount of leaf area absorbing that solar energy, avoiding many complexities of carbon balance theory.

A strong relationship has been shown to exist for vegetated surfaces between the fractional absorption of incident PAR and the surface reflectance of incident radiation (Sellers 1987). A robust predictive theory for this relationship has also been established (Sellers et al. 1992). This relationship makes the radiation conversion efficiency logic an attractive avenue for predicting NPP from remote sensing inputs.

The eddy fluxes and ecophysiological measurements provide process level understanding of ecosystem function that can be incorporated into ecosystem models. Mechanistic ecosystem models have the potential for predicting how ecosystems will respond to future changes in atmospheric CO₂, temperature, land use change, nitrogen loading, and precipitation.

MOD44 Vegetation cover conversion

The important influences of vegetation-cover change are the following:

- It strongly affects changes in many biophysical factors such as surface roughness and albedo.
- It has a major effect on changes in sensible heat flux, because it affects global albedo and surface roughness, which in turn affects atmospheric drag.
- It is of crucial importance for determining the biogeochemical cycling of carbon, nitrogen, and other elements at regional-to-global scales.
- It has a major impact on the runoff characteristics of catchments through its effects on evapotranspiration and partitioning of precipitation into overland flow, interflow, and groundwater accretion.
- It gives direct insight into ecosystem response related to climate change and anthropogenic influences.
- It affects biodiversity through direct impacts on habitat.
- It provides increasingly important information for natural-resource managers.

Generalized Military Applications

From this review of the NASA literature, we can develop a series of general applications of the MODIS products to military lands monitoring and management. For the discussed MODIS products, the list includes:

Land Cover

- Regular ecosystem condition monitoring
- Encroachment
- Change Detection
- Change Prediction (straight-line or geometric)
- Presence/change in edge characteristics
- Degree of patchiness/fragmentation
- Nearby forest clearing
- Degree of drought in an area
- Leaf area index
- Roughness length
- Surface resistance to evapotranspiration

- Canopy greenness fraction
- Vegetation density
- Root distribution (predicted from biome type)
- Fraction of photosynthetically-active radiation absorbed
- Annual vs. perennial habit
- Carbon partitioning
- Leaf litter fall dynamics
- Soil carbon pools
- Needle leaf, broadleaf, and graminoid (grasses) amounts (e.g., forest conversion)
- Leaf area
- Photosynthetic capacity
- Canopy conductance
- Type of photosynthetic system
- Maximum photosynthetic rate.

By these objective indices (plus many others not illustrated here), ecological condition of a habitat may be followed over time. Critical to monitoring for INRMP management, the condition of a habitat is the fragmentation of that habitat due to transportation, commercial, residential development. GAP fragmentation analysis is used to determine areas at risk. For example, one can do patch analysis with land cover data (see specific example below). How areas at risk relate to military installation TES management responsibilities will help determine how best to expend limited land management resources.

Vegetation Indices

- Natural resource management
- Agriculture and forestry condition monitoring
- Net primary production and carbon balance
- Anthropogenic change detection
- Agricultural activities (plant stress, harvest yields, precision agriculture)
- Drought studies
- Landscape disturbances (fire scars, etc.)
- Land cover and land cover change products
- Biophysical estimates of vegetation parameters (percent cover, fAPAR, LAI)

- The NDVI for 20 year plus long term change detection
- Seasonal and yearly productivity and condition comparisons.

LAI and FPAR

LAI is a state parameter describing the

- Exchange of fluxes of energy,
- Mass (e.g., water and CO₂), and
- Momentum.

FPAR is a key state variable in most ecosystem productivity models for

- Biogeochemistry and
- Ecology.

Net Photosynthesis

- Productivity for food, fiber and fuel
- Production activity or growth of terrestrial vegetation
- As a measure of crop yield
- Range forage and forest production
- Other economically and socially significant products of vegetation growth
- Radiation conversion efficiency
- *Predicting* how ecosystems will respond to future changes in:
 - Atmospheric CO₂,
 - Temperature,
 - Land use change,
 - Nitrogen loading, and
 - Precipitation.

Vegetation Cover Conversion

- Has a major impact on the runoff characteristics of catchments through its effects on evapotranspiration and partitioning of precipitation.
- Ecosystem response related to anthropogenic influences.
- It affects biodiversity through direct impacts on habitat.
- It provides increasingly important information for natural-resource managers.

Example Military Installation Applications

The MODIS product files have been translated into GIS format and are therefore useful for carrying out additional analyses. Many useful GIS software tools have been developed in the past several years. This section examines how the data can be used with some of the most influential spatial metrics. It should be noted that these examples are limited to simple illustrations with the MODIS data products.

Regional Spatial Forestry Fragmentation Statistics

ArcView®* GIS is a software product of ESRI (founded as Environmental Systems Research Institute). It provides manipulation capabilities for spatially referenced digital data. The standard ArcView module can be added to, either with ESRI products or those from companies and individuals that build on the ArcView framework. One ESRI module, the Spatial Analyst, deals with gridded data, such as the MODIS products described here. With the Spatial Analyst module, many manipulations can be carried out. To make the analysis of the spatial characteristics easier, another module, Patch Analyst can be obtained from the ESRI web site (<http://www.esri.com/>). Patch Analyst is an extension to the ArcView® GIS system that facilitates the spatial analysis of landscape patches, and modeling of attributes associated with patches. Patch Analyst 2.0 contains most of the analysis and modeling functions (including functions formerly held in Habitat Analyst), while Patch Analyst (Grid) 1.0 extends analysis capabilities to grids, and therefore requires Spatial Analyst. Patch Analyst (Grid) includes a user interface to FRAGSTATS, as well as separate spatial analysis functions. The extension was designed for the Win95/NT version of ArcView 3.1. A modified version of FRAGSTATS (McGarigal and Marks 1995), J. Lane's modified geoprocessing wizard, and ESRI's buffering and spatial transformation wizards are included with the extension.

Within Patch Analyst, numerous spatial metrics are calculated, including mean and median patch size, patch size coefficient of variance, edge density, mean shape index, fractal dimension, interspersion and juxtaposition, Shannon's diversity index, and core area index. The program can also create a new shape with patch metric attributes attached. Summary statistics are reported at either

* Citing specific products does not imply endorsement by the Corps of Engineers, U.S. Army, or Department of Defense.

the patch or landscape scale. The various patch metrics follow the definitions in FRAGSTATS (McGarigal and Marks 1995). Processing of grid format themes is done through a specially compiled version of FRAGSTATS, the UNIX raster version, recompiled for Win 95/NT and modified slightly to run with Patch Analyst.

Attribute modeling capabilities allow the user to translate vegetation age and composition into habitat units, or forest age/seral classes, according to pre-defined rules. An editable, text-based query allows the user to assign each polygon or grid clump to a vegetation class, seral stage, habitat unit, etc.

A spatial analysis component allows the user to assign values to specific spatial configurations of the vegetation or landscape elements. Proximity, interspersion, and insularity of habitat patches are assessed within a user-defined spatial unit. The hexagon cell structure is used to delineate the spatial units; the cell size may be set as a function of an animal's home range, or the area required to maintain a viable population, thus allowing hierarchical analyses.

As an example, using the Fort Benning Region MODIS IGBP land cover data, the theme was reclassified into forested or non Forested area (Figure 22). Researchers then used Patch Analyst (GRID) to compare the spatial character of forested versus nonforested areas within and without the installation. From this, a standard set of output indices was generated (Table 1.)

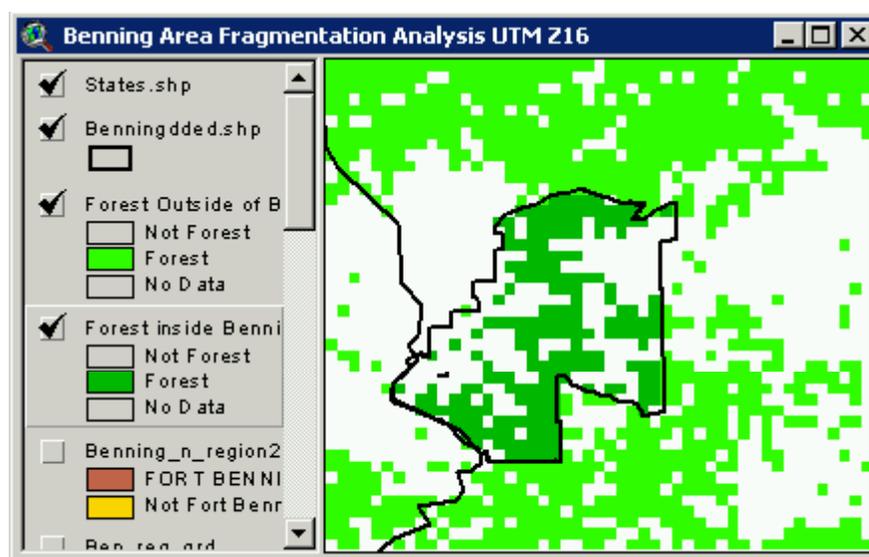


Figure 22. Fort Benning area fragmentation analysis.

The spatial statistics on this set of data show that the forested area within Fort Benning is relatively homogeneous (compared to the other three areas), but there is a significant difference between the core area characteristics within the region on the nonforested areas (i.e., the white areas outside of Fort Benning in Figure 22).

There are obvious next steps in following through to more complicated analyses; however, these are outside of the scope of this paper. For example it may be helpful to know the availability of habitat, how it is changing, and if that will affect the military mission at the installation. So, if you would like to follow how these characteristics change over time, you should access more of these products to provide a temporal as well as spatial example. It is important to realize, that unlike any other source, MODIS 12Q1, IGBP global vegetation classification scheme product will be generated on a quarter-year and yearly basis. No other agency in the world can completely update their land cover data every 96 days. So although a 1-kilometer product at first glance may seem like a gross resolution, in comparison to any other source in the world, it is astoundingly detailed and unique in both spatial and temporal resolution. With this in mind, a land manager now has the ability to:

- determine nearby land cover,
- determine Changes in land cover,
- determine the direction of change (the change vector in time),
- determine the spatial character of the change and thus,
- provide the ability to make rational predictions of likely changes that may affect military mission readiness.

Table 1. Fort Benning area fragmentation results and interpretations.

| Patch Metric | Name | Not Forest Inside Benning | Forest Inside Benning | Not Forest Outside Benning | Forest Outside Benning | Interpretation |
|----------------------------------|--------|---------------------------|-----------------------|----------------------------|------------------------|---|
| | Class | 1 | | 3 | 4 | |
| Class Area | CA | 31,748.93 | 35,695.12 | 166,637.02 | 152,645.97 | Area of forested and nonforested land is about equal within Benning and the region. |
| Landscape Area | TLA | 67,444.05 | 67,444.05 | 319,282.97 | 319,282.97 | Total area of forested area outside Benning is about six times greater than within Benning. |
| Number of Patches | NumP | 9.00 | 8.00 | 40.00 | 29.00 | There are many more patches of nonforested land outside Benning. This is unlike Benning with about equal patch numbers. |
| Mean Patch Size | MPS | 3,527.66 | 4,461.89 | 4,165.93 | 5,263.65 | Patches of forested land outside of Benning are larger. |
| Patch Size Standard Deviation | PSSD | 5,979.68 | 10,665.29 | 16,116.42 | 17,749.49 | There is much higher variation in the size of forested areas inside Benning than outside. |
| Total Edge | TE | 366,968.20 | 377,682.60 | 1,336,621.40 | 1,350,014.40 | Amount of edge is distributed about equally. |
| Edge Density | ED | 5.44 | 5.60 | 4.19 | 4.23 | Average amount of edge per patch is roughly similar everywhere. |
| Mean Shape Complexity Index | MSI | 1.55 | 1.47 | 1.37 | 1.42 | Patches are not square in shape (not = zero and the index is greater than 1). |
| Area Weighted Mean Shape Index | AWMSI | 3.08 | 4.17 | 3.96 | 4.77 | Forest Complexity greater than nonforested areas (determines shape complexity independent of its size). |
| Mean Patch Fractal Dimension | MPPFD | 1.03 | 1.02 | 1.03 | 1.02 | The patches are simple shapes (mean fractal dimension approaches 1 for shapes with simple parameters and approaches 2 when shapes are more complex). |
| Area Weighted Mean Patch Fractal | AWMPFD | 1.12 | 1.14 | 1.13 | 1.15 | Forest and nonforest area complexity is about the same everywhere (determines patch complexity independent of its size). |
| Total Core Area | TCA | 5,919.29 | 7,354.27 | 75,157.06 | 50,224.29 | Forested core area is distinctly different outside of Benning where nonforested core predominates. |
| Core Area Density | CAD | 0.01 | 0.01 | 0.00 | 0.01 | Number of disjoint core areas per hectare of total landscape is distinctly less for nonforested areas outside Benning. |
| Mean Core Area | MCA | 845.61 | 919.28 | 6,263.09 | 2,183.66 | The average size of disjoint core patches per hectare for forested areas on Fort Benning is distinctly higher in the non-Benning, nonforested areas. |
| Core Area Standard Deviation | CASD | 1,404.92 | 2,432.20 | 13,926.02 | 7,661.91 | Variability in core area size is significantly higher for off-installation nonforested areas. |
| Total Core Area Index | TCAI | 18.64 | 20.60 | 45.10 | 32.90 | Nonforest, off Benning core area is much greater than anywhere else, being distinctly greater (by 2X) than on Benning. (TCAI suggests the amount of core area – it is low when no patches contain core and higher as the relative proportion of core area increases.) |

Forestry productivity comparison

Now let us carry the analysis a little further. “How different is the productivity of the forested vegetation inside Fort Benning compared with that outside?” Another way to put this is “Are the forestry practices on Fort Benning comparable enough to nearby commercial practices that there is no difference in the condition of the forests?” This is a very useful bit of information for military land managers to know. To answer the question, we will use the new VI, the MODIS unique EVI. To carry out the analysis, we use previous analysis to mask out all nonforested areas, and separate the productivity between that on the installation and that off the installation (Figure 23 – Note: the color tables are different on the fort and off the fort to more easily see the distinction). Table 2 compares the statistics.

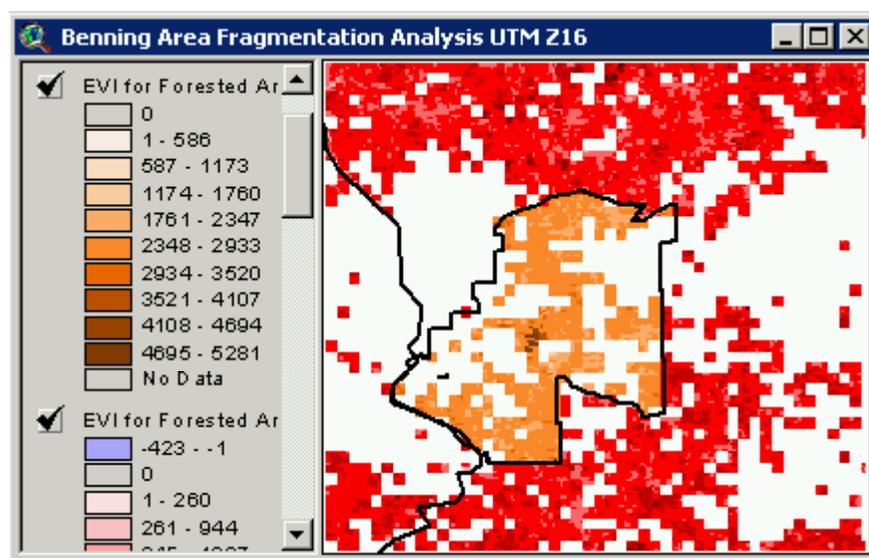


Figure 23. Fort Benning area forestry EVI comparison.

Table 2. Fort Benning area forestry EVI statistics.

| EVI Statistic | On Benning | Off Benning |
|---------------|------------|-------------|
| Mean | 1349 | 1287 |
| Std Dev | 1295 | 1368 |
| Min | 0 | -423 |
| Max | 5281 | 5729 |

Table 2 suggests that the forested areas on Fort Benning are at least similar and possibly even more productive than nearby areas. Further, that the variation in the productivity, if really higher, is less across the installation's forested lands. So, Fort Benning is doing at least as well as nearby land managers in managing the fort's forested lands. Of course, a yearlong comparison would be more interesting.

Following seasonal forest type productivity at SEMP research sites

Suppose we wish to know for a 16-day period in March which forest vegetation types on Fort Benning were the most productive. To answer this question, we intersect the forest EVI map (Figure 23) with the 2001 vegetation map from Fort Benning, and then summarize the productivity data by vegetation alliance type. From this, we can determine the relative productivity of alliances* (Table 3). So while Sweet Gums, planted Pines, and Willows in saturated soils were very productive, Pecans, Oaks and Alders were not. The next question is "Where are these highly productive areas on the Fort?" To find out, we extract those alliances in the top quintile of productivity and remove the boundaries left over from the intersection of the vegetation and EVI maps. A portion of the installation is presented in Figure 24.

As stated at the beginning of this report, the SEMP project is being hosted at Fort Benning. Several teams of researchers have study areas within the installation. There are 88 out of 800 study areas within these high productivity types for the 16 days near the beginning of March 2001. In fact, within the area shown in Figure 24, study sites for the Savannah River Ecology Laboratory (SREL) and the second of the Oak Ridge National Laboratory (ORNL2) teams occur in the top percentile zone. Thus, it is possible for these researchers to follow the productivity of their sites on a nearly bi-weekly basis throughout the year, every year.

* Vegetation Types map from the *Fort Benning Vegetation Type Map Using the National Vegetation Classification System (NVCS)*, draft as of 1 August 2001.

Table 3. Forest (alliance) types highest EVI productivity.

| Alliance * | Count | Avg EVI |
|--|-------|---------|
| <i>Liquidambar styraciflua</i> saturated forest | 11 | 6.82 |
| <i>Pinus elliotii</i> planted forest | 76 | 6.34 |
| <i>Salix nigra</i> temporarily flooded shrubland | 6 | 6.17 |
| <i>Platanus occidentalis</i> - (<i>Fraxinus pennsylvanica</i> , <i>Celtis laevigata</i> , <i>Acer saccharinum</i>) temporarily flooded forest | ?? | 5.60 |
| <i>Quercus hemisphaerica</i> forest | 39 | 5.54 |
| <i>Fagus grandifolia</i> - <i>Quercus alba</i> forest | 31 | 5.42 |
| <i>Quercus nigra</i> forest | 254 | 5.41 |
| <i>Pinus taeda</i> planted forest | 626 | 5.21 |
| <i>Quercus (michauxii, pagoda, shumardii)</i> - <i>Liquidambar styraciflua</i> temporarily flooded forest urban | 196 | 5.15 |
| urban | 48 | 5.15 |
| <i>Pinus taeda</i> - <i>Quercus (phellos, nigra, laurifolia)</i> temporarily flooded forest | 161 | 5.10 |
| <i>Nyssa biflora</i> - <i>Acer rubrum</i> - (<i>Liriodendron tulipifera</i>) saturated forest | 823 | 5.05 |
| <i>Pinus taeda</i> - <i>Quercus nigra</i> forest | 69 | 5.00 |
| <i>Quercus (phellos, nigra, laurifolia)</i> temporarily flooded forest | 228 | 4.96 |
| <i>Liquidambar styraciflua</i> - (<i>Liriodendron tulipifera</i> , <i>Acer rubrum</i>) temporarily flooded forest | 291 | 4.92 |
| <i>Pinus palustris</i> woodland | 430 | 4.91 |
| <i>Quercus laevis</i> woodland | 189 | 4.91 |
| <i>Typha (angustifolia, latifolia)</i> - <i>Scirpus</i> spp. semipermanently flooded herbaceous | 10 | 4.90 |
| <i>Quercus alba</i> - <i>Quercus (falcata, stellata)</i> forest | 483 | 4.89 |
| <i>Quercus falcata</i> forest | 292 | 4.88 |
| <i>Pinus taeda</i> - <i>Quercus (alba, falcata, stellata)</i> forest | 195 | 4.88 |
| <i>Pinus palustris</i> / <i>Quercus</i> spp. woodland | 626 | 4.82 |
| <i>Pinus taeda</i> forest | 1343 | 4.80 |
| <i>Pinus taeda</i> - <i>Pinus echinata</i> forest | 373 | 4.78 |
| <i>Betula nigra</i> - (<i>Platanus occidentalis</i>) temporarily flooded forest | 4 | 4.75 |
| <i>Nymphaea odorata</i> - <i>Nuphar</i> spp. permanently flooded herbaceous | 3 | 4.67 |
| <i>Pinus taeda</i> - (<i>Liquidambar styraciflua</i> , <i>Liriodendron tulipifera</i>) forest | 189 | 4.61 |
| <i>Liriodendron tulipifera</i> forest | 5 | 4.60 |
| <i>Liquidambar styraciflua</i> forest | 261 | 4.56 |
| <i>Pinus taeda</i> temporarily flooded forest | 38 | 4.50 |
| <i>Fraxinus pennsylvanica</i> - <i>Ulmus americana</i> - <i>Celtis (occidentalis, laevigata)</i> temporarily flooded forest | 76 | 4.46 |
| <i>Pinus palustris</i> planted forest | 593 | 4.40 |
| <i>Quercus alba</i> - (<i>Quercus nigra</i>) forest | 182 | 4.24 |
| <i>Alnus serrulata</i> seasonally flooded shrubland | 40 | 4.13 |
| <i>Pinus taeda</i> - <i>Liquidambar styraciflua</i> - <i>Nyssa biflora</i> temporarily flooded forest | 28 | 4.07 |
| <i>Nyssa (aquatica, biflora, ogeche)</i> floodplain seasonally flooded forest | 149 | 4.05 |
| <i>Pinus taeda</i> - <i>Liquidambar styraciflua</i> - <i>Acer rubrum</i> saturated forest | 20 | 4.00 |
| <i>Quercus stellata</i> - <i>Quercus marilandica</i> woodland | 2 | 4.00 |
| <i>Arundinaria gigantea</i> saturated shrubland | 9 | 3.89 |
| <i>Pinus echinata</i> forest | 22 | 3.55 |
| <i>Nyssa (aquatica, biflora, ogeche)</i> pond seasonally flooded forest | 10 | 3.30 |
| <i>Quercus velutina</i> - <i>Quercus alba</i> - (<i>Quercus coccinea</i>) forest | 1 | 3.00 |
| <i>Alnus serrulata</i> temporarily flooded shrubland | 2 | 2.00 |
| <i>Carya illinoensis</i> planted woodland | 1 | 1.00 |
| * Polygons and categories from the <i>Fort Benning Vegetation Type Map Using the National Vegetation Classification System (NVCS)</i> , draft as of 1 August 2001. | | |

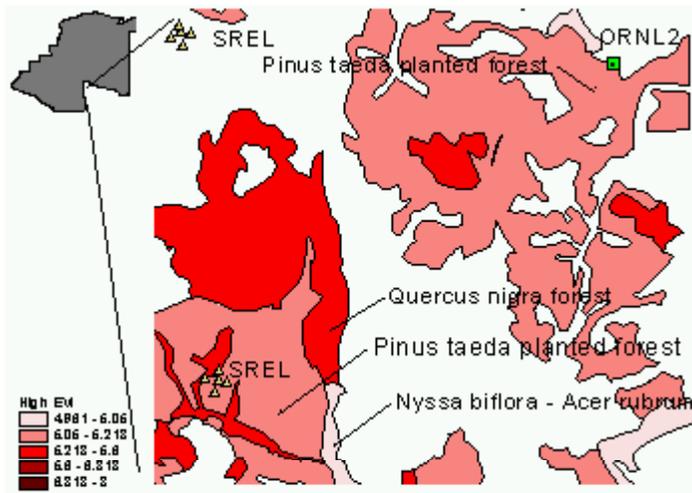


Figure 24. Fort Benning forest types productivity based on EVI.

Net photosynthesis and research site stratification

Some individuals may believe the 1-km resolution is too gross. Let's look at the question of resolution in a more familiar context. Remotely sensed images and their products are point samples over a grid. In this way they are similar to digital elevation models (DEMs or topography data). In a DEM it is customary to take samples and from these create a surface that is a model of the topography. In the same manner, MODIS products are point samples, sometimes of continuously varying data. An example would be net photosynthesis (PSN - MOD17). We can therefore translate gridded PSN (Figure 25) into a point file. Removing land cover types that would interfere with surfacing (i.e., cleared or urban and water areas) we can generate a photosynthesis surface (Figure 26).

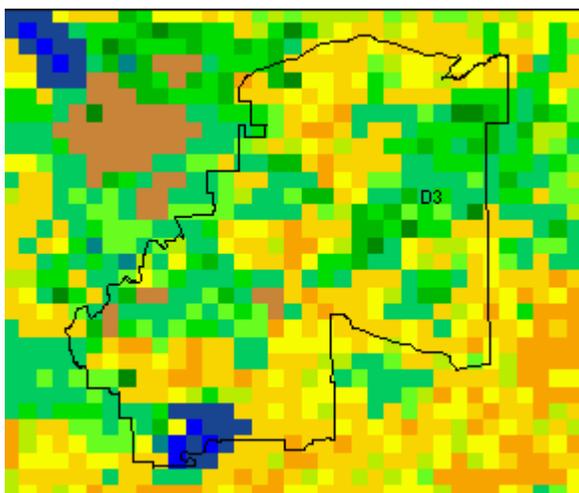


Figure 25. Fort Benning PSN raw product.

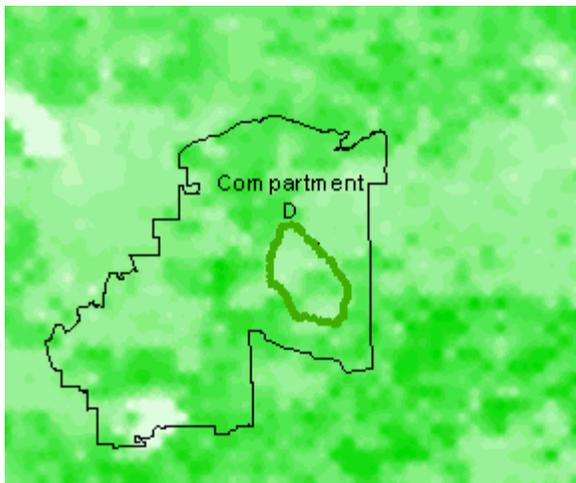


Figure 26. Fort Benning PSN smoothed product showing location of Training Compartment D.

Many SEMP research sites are located in Training Compartment D. Taking a closer look at D and overlaying the major road system in the area, we can see that lower PSN tends to follow the road systems (Figure 27). In this 11- X 13-kilometer window, 90 points were used to generate the surface. There are 443 SEMP sites (Figure 28) within this same area.

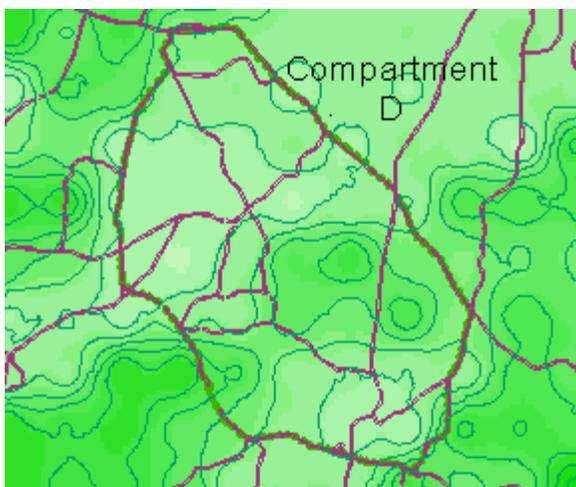


Figure 27. Fort Benning Training Compartment D PSN smoothed and contoured product.

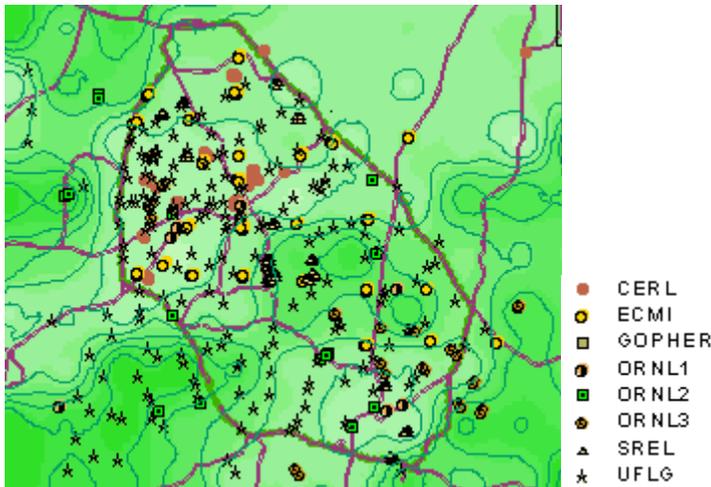


Figure 28. Fort Benning Training Compartment D PSN with SEMP sites.

How do the sites compare by research group? Table 4 shows that the Construction Engineering Research Laboratory (CERL) sites have lower PSN and vary significantly less than others. Oak Ridge National Laboratory, Group 2 (ORNL2) has sites that are highly productive, followed closely by ORNL3 and SREL. But the Standard Deviations (Figure 29) show that the groups' sites mostly overlap.

Table 4. SEMP sites and PSN contours.

| Project_id | Count | Ave_Contour | Min_Contour | Max_Contour | StdDev_Contour |
|------------|-------|-------------|-------------|-------------|----------------|
| CERL | 61 | 150.8197 | 150 | 200 | 6.4018 |
| ECMI | 68 | 175.7353 | 150 | 300 | 41.871 |
| ORNL1 | 12 | 195.8333 | 150 | 300 | 68.9477 |
| ORNL2 | 18 | 225 | 150 | 350 | 71.2287 |
| ORNL3 | 22 | 211.3636 | 150 | 300 | 59.6255 |
| SREL | 64 | 209.375 | 150 | 300 | 60.3396 |
| UFLG | 192 | 197.6563 | 150 | 350 | 67.3525 |

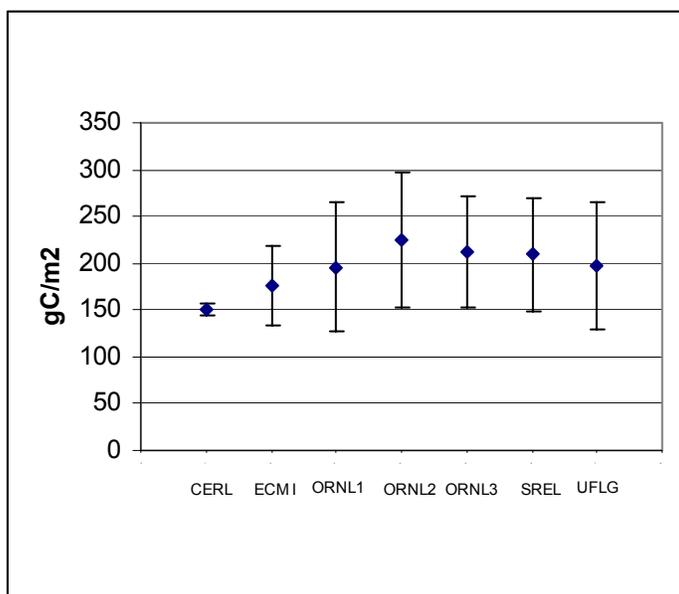


Figure 29. SEMP sites versus PSN contours with standard deviations.

The question is, “Is the difference between the CERL and ORNL2 sites significant?” (It needs to be recognized that this discussion is aimed at illustrating how to use the MODIS products. It does not imply that there was any intent to pick sites based on these criteria or that the results imply a better or poorer choice of research sites.) We test this using a student t-test on the original data in Compartment D3. This results in a value of .000376. Thus, the probability that they are the same distribution is $P < 0.001$, indicating there is a real difference between the two sets of data. In terms of net photosynthesis, in Compartment D, CERL sites are truly not representative of the variety. (In fact, doing the same analysis with the ECMI sites, those seemingly most similar to the CERL sites, the resulting value is even less {0.00000072} so the CERL sites are truly different. Comparing the ECMI sites to the ORNL2 sites result in $P = 0.01$; the two sets are different but much less so.)

Using seasonal comparisons to search for potential encroachment issues

Since these NASA products are generated on a regular basis, the question might be asked, “Can we use changes in the MODIS products to identify potential emerging encroachment issues?” As a test of this issue, we downloaded additional MOD15 FPAR (Figure 30) and LAI (Figure 31) product for the beginning of September 2001, a 6-month time lapse since the March product. In the Fort

Benning area the March 2001 data represents mid spring while the September products represent late summer. What significant changes have occurred?

As one might expect, the FPAR absorbed by vegetation was much greater in September than March, reflecting the seasonal increase in vegetation activity. [Figure 32 contains the legend for the March (left) and September (center) panels in Figures 30 and 31.] The third panel in Figure 30 shows the difference; greens show increases in FPAR and reds show decreases. The difference map is dominated by greens as would be expected. However, the lower right corner shows significant decreases (in the range of 1 to 3 standard deviations negative), and some of those red pixels appear to be connected. Overlaying a roads map shows that the more connected pixels follow a portion of State Highways 41 and 30. Evidently in this area, significant activity associated with the roads occurred during the intervening summer. According to the IBGP land cover map, almost all of these very high negative changes along Highways 41 and 30 occurred in cropland areas.

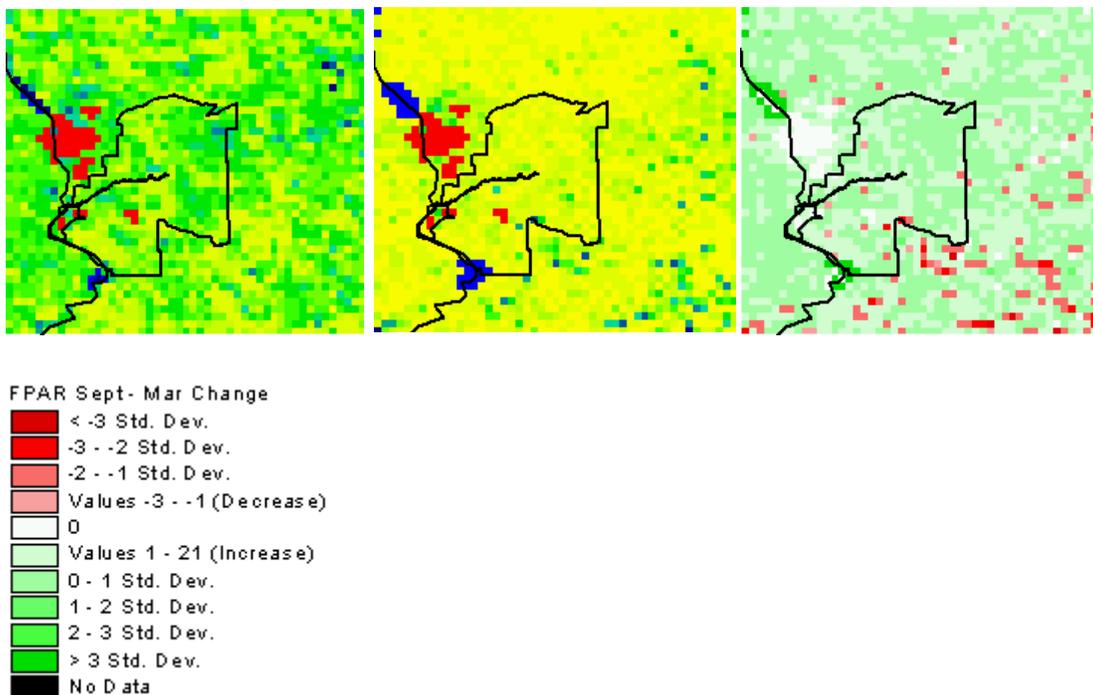


Figure 30. FPAR March (left), FPAR September (center) and FPAR Difference (right, September minus March, with legend at bottom).

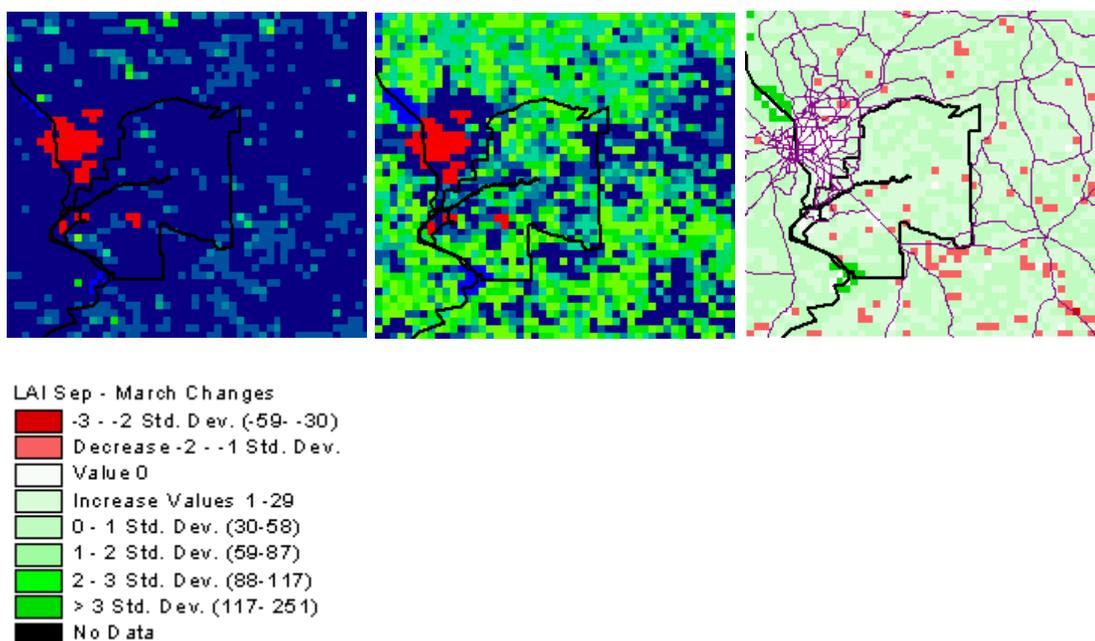


Figure 31. LAI March (left), LAI September (center), and LAI Difference (right, September minus March, with legend at bottom).

Using the legend in Figure 32, the March LAI (left panel in Figure 31) presents index values at a much lower relative level compared to the FPAR in the left panel of Figure 30 (i.e., the leaf area is very low). By September it increases but is still at a lower level relative to the FPAR (middle panels Figures 30 and 31). When the difference is taken (right panel, Figure 31) we are presented with a pattern similar to the FPAR difference (right panel Figure 30), particularly for the large negative changes between March and September. The roads have been overlaid in the right panel of Figure 31 to show their coincidence with the very negative LAI changes.

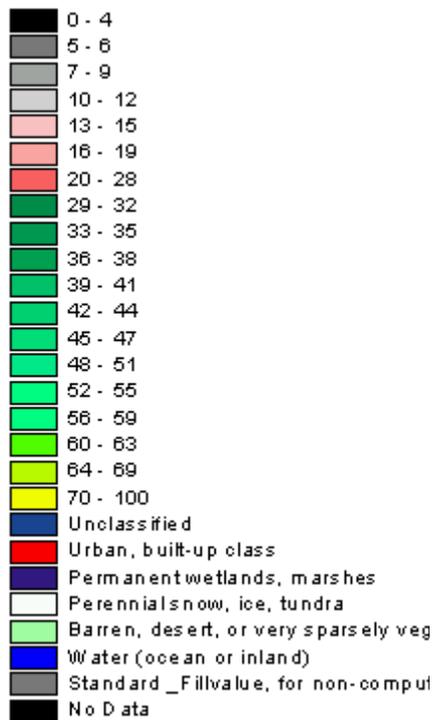


Figure 32. Common legend for FPAR and LAI for March and September (the left and center panels in Figures 30 and 31).

Presented with products like these, a military trainer might be interested in knowing what is causing the large decrease in FPAR and LAI directly to the south of Fort Benning (in Figure 31, the red circled area between State Highway 26 and US Highway 280) and will that causative agent have an encroachment effect on the training mission assigned to Training Compartments G and H in that area? Early “red flagging” of potential issues to the military training mission can help avoid a situation growing significantly worse.

6 Summary and Recommendations

Summary

The military has focused much time and effort observing conditions for installation lands. Generally, however, obtaining data to understand and monitor the character of the ecosystems within which the installation is a component has been costly, time consuming, and not within the installation land manager's mission. However, with the current increased emphasis on regional ecosystem management and particularly the problems of human development near installations that can restrict the carrying out the military mission. Further, the need to understand and monitor the condition of the nearby regions has increased dramatically. As AR 200-3 states "The Army recognizes that natural ecosystems play a vital role in maintaining a healthy environment." To manage ecosystems, we must monitor them. The NASA EOS program provides products that are useful in fulfilling this management requirement.

The NASA EOS Terra satellite launched in 1999 generates numerous digital products, some of which are useful to installation land managers. This report has focused on several products generated from the MODIS sensor. Here, we have described the currently available provisional products, their intended use, and how they might be used for military land management. In addition, we have accessed the products, translated them to standard GIS format and illustrated some initial uses. Products discussed are:

- MOD12 Land cover/Land cover change
- MOD13 Gridded vegetation indices (Max NDVI and Integrated EVI)
- MOD15 Leaf area index and FPAR
- MOD17 Net Photosynthesis and Primary productivity
- MOD44 Vegetation cover conversion

Examples of these products are illustrated. The actual files are available in the SEMP data repository under the "Land Status" (<http://206.166.205.173>) topic area.

The suite of EOS instruments and products present a new and unique set of opportunities to the military land managers. From no other source in the world

are remote sensing products provided, at no cost, to the users that have already been corrected for critically important variables (atmospheric, directional sensing, and seasonal effects among others). From no other source is the data available at such high temporal resolution, and sometimes even at high spatial resolution when compared to other sources.

Recommendations

Because this report illustrates an initial data set for land managers, it also leads toward obvious next steps. The MODIS products are just becoming available. More will appear as production moves toward the yearly products, which will often be of the most interest to land managers. Therefore it is recommended to:

- Continue collecting these products as they become available; document and present their usefulness to managers.
- Assess other dates so comparisons can be made.
- Use this data set to analyze characteristics (e.g., run spatially based indicator evaluations such as EPA's ATtILA [Analytical Tools Interface for Landscape Assessments] or fragmentation analyses on the data available in the repository.)
- Incorporate these products into landscape scale analyses for installations (e.g., carbon budget cycling from derived PSN or vegetation indices NDUI and EVI).
- Use additional data to monitor condition over time. While developing this work, it was noted that EVI was significantly different inside the installation boundaries compared to outside. This was not reflected in the better-known, standard but less scientifically refined NDVI.
- Evaluate the usefulness of other products (NASA or otherwise generated) as they become available. For example, MOD44 Vegetation cover conversion has yet to appear. MOD44B will provide additional vegetation concerns. Another application (Figure 33) that is available is called Rapid Response (<http://rapidresponse.umd.edu/>). It is not a NASA product, but uses MODIS data to fill a user need that emerged since the EOS series was designed. The Rapid Response product is generated independently of NASA for specific purposes. In Figure 33 (11 August 2002) the active fires (red) and resulting smoke (grey plumes) in Oregon (above black line) and California (below) was pulled off the Internet less than 12 hours after the satellite image was acquired.
- Investigate the applications of other products, particularly ASTER and MISR.

- Cooperate more closely with NASA on military, particularly SEMP sites, as validation locations. It is likely there is mutual benefit to be had from such cooperation.

For monitoring purposes AR 200-3 relies heavily on the Land Condition Trend Analysis (LTCA) method. Since that regulation was written, new technologies, such as illustrated by these MODIS products, have become available. It might be useful to revise the current monitoring methods to reflect a better, faster, cheaper philosophy where appropriate.



Figure 33. The Rapid Response system uses MODIS data to show occurrences (e.g., fires, hurricanes) in near-real time (~4 hours from acquisition).

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Appendix: Procedure to Translate MODIS HDF Products to GIS Format

The following is the general procedure used to develop the data themes for the Fort Benning region as described in this paper. Depending on the MODIS product and your particular resource configuration, these steps may vary.

Though many different packages for the display and manipulation of the data are available, it took several attempts to develop a successful configuration to derive the data in standard GIS format. In general, the online web descriptions do not always describe the limitations of a software product. For example, one NASA contractor software package was described as doing exactly what Task 4.c. required. Only after downloading and implementing did it become apparent that it was designed for another (atmospheric sensing) instrument on Terra and did not have the capabilities to deal with MODIS data. However, it should be noted that in the 6 months during which the data for this report was generated, it was evident that access and delivery of software was gradually improving.

Most NASA software is developed on a UNIX platform, and then ported to Microsoft NT. Running under MS Windows 2000 (NASA had not tested the software to see if Windows 2000 worked exactly like NT) meant having to port the data files between the two operating systems. For the very large MOD13 product files this was very slow. A computer partitioned between LINUX and MS Windows would be a desirable configuration.

Many of the quality assessment files use a bit-position code. When translating the QC files to ASCII and flat binary as was done in this report, values for the pixels will not initially match the description in the ATBD. Though the software translated the HDF file without problem, the ASCII values will not coordinate with the published keys and cannot be interpreted. Additional steps must be carried out.

From the initial translation described above, you will get the decimal version of the 8- (or 16-) bit value (depending on the product in question). Translate the decimal (base 10) to the binary (base 2) representation. To find the fields, the resulting string will be read from right to left, but the individual value within

each field is read from left to right. This procedure will then allow interpretation based on the ATBD descriptions. The several software packages from NASA do not overcome this issue for purposes of manipulation into GIS format.

Procedure

1. Go to the MODIS Land Data Products web page:

http://eosdatainfo.gsfc.nasa.gov/eosdata/terra/modis/modland_dataproduct.html

Follow the procedure to order the desired product. The researcher requested products be delivered via “ftp pull.” Availability of the orders ranged from 1 hour to 3 days.

2. Once you have the product or granule, you have to translate it from the NASA standard EOS HDF to an ASCII grid format. The primary researcher used a program called EOSGIS DATA TRANSLATOR now available from: <http://heineken.gsfc.nasa.gov/eosgis/eghome.html>.

On a UNIX platform, the DATA TRANSLATOR would generate ASCII Grid outputs for each theme in the HDF file. The files contain a short georeferencing header, but the extension “.asc” had to be added to each so that the ESRI software would recognize the file. (Note – So that the ESRI software would recognize the file, it is best to truncate the very long default file names and remove any spaces.) A “.prj” file is generated with each ASCII file.

3. Within ESRI ArcView, make sure you have the “Spatial Analyst Extension”. From the file menu choose “Import data source”, “ASCII Raster”, “Add to view”. Make or load a legend “.avl” file. The file is in the NASA standard, SINUSOIDAL projection. For this project, we wanted the data in UTM Zone 16. In ArcView make a window with sinusoidal View properties (i.e., set the “View” parameters from the appropriate .prj file to:

```

Projection  SINUSOIDAL
Zunits     NO
Units      METERS
Spheroid   CLARKE1866
Xshift     0.0000000000
Yshift     0.0000000000

Parameters
6371007.181000
0 0 -0.000
0.000000

```

0.000000

4. Set “Analysis Properties” to **Intersection** of data, cell size to **minimum**.
5. To do the reprojection, the researcher used the “Reproject Grids Extension”, an Arcscript written by William Huber and available from:
<http://gis.esri.com/arcscripsts/index.cfm?action=details&CFGRIDKEY=941245028>
6. Use reproject to go from sinusoidal to UTM

Make a window with UTM 16 Properties

Projection - UTM

Zone - 16

Units - meters

Datum - NAD83

Spheroid - GRS1980

Set Analysis Properties in source (sinusoidal view) to properties of file.

Set Analysis Properties in target window (UTM) to minimum & Intersection of inputs

Choose Theme to be reprojected.

Use Reproject on the theme menu and follow the instructions.

When complete, from the UTM View, for the reprojected theme, “save data” and from the Theme Properties add the new name, e.g.: Net Photosynthesis 8-Day 2001-03-14 KgC/m².

7. Clip data to Benning Region.

Acronyms and Abbreviations

| | |
|---------|--|
| APAR | Absorbed Photosynthetically Active Radiation |
| AR | Army Regulation |
| ARVI | atmospherically resistant vegetation index |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| ASCII | American Standard Code for Information Interchange |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| ATBD | Algorithm Theoretical Basis Document – the complete, official description of the EOS product |
| ATtILA | Analytical Tools Interface for Landscape Assessments |
| AVHRR | Advanced Very High Resolution Radiometer |
| BRDF | Bidirectional Reflectance Distribution Function |
| CERL | Construction Engineering Research Laboratory |
| CN | Installations Division |
| CN-N | Ecological Processes Branch |
| CV-MVC | Constrained View Maximum Value Composite |
| DAO | Data Assimilation Office |
| DEM | digital elevation model |
| DoD | Department of Defense |
| DOE | Department of Energy |
| ECMI | Ecosystem Characterization and Monitoring Initiative |
| EPA | Environmental Protection Agency |
| EOS | Earth Observing System |
| ESDT | Earth Science Data Type |
| ESE | Earth Science Enterprise |
| ESRI | a company name – founded as Environmental Systems Research Institute |
| EVI | Enhanced Vegetation Index |
| ERDC | U.S. Army Engineer Research and Development Center |
| fPAR or | |
| FPAR or | |
| FAPAR | Fraction-of-Photosynthetically Active Radiation |
| FY | Fiscal Year |
| GAP | fragmentation analysis (not an abbreviation) |
| GIS | Geographic Information System |
| GRS | Grid Reference System |
| HDF | Hierarchical Data Format |
| http | Hypertext transfer Protocol |
| IGBP | International Geosphere-biosphere Programme |

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| ISIN | Integerized Sinusoidal grid (a projection that allows for uninterrupted global projections) |
| LAI | Leaf Area Index |
| LTCA | Land Condition Trend Analysis |
| MIR | Millimeter-wave Imaging Radiometer |
| MISR | Multi-angle Imaging SpectroRadiometer |
| MODAGTEX | MODIS Aggregated Texture Product |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MS | MicroSoft |
| MSS | Multispectral Scanner |
| NAD | North American Datum |
| NASA | National Aeronautics and Space Administration |
| NBAR | Nadir BRDF-Adjusted Reflectance |
| NDVI | Normalized Difference Vegetation Index |
| NIR | Near Infrared |
| NOAA | National Oceanic and Atmospheric Administration |
| NPP | Net Primary Production |
| NPV | nonphotosynthetic vegetation |
| ORNL | Oak Ridge National Laboratory |
| PSN | Net Photosynthesis |
| QA | quality assurance |
| QC | Quality Control |
| SEMP | SERDP Ecosystem Management Project |
| SERDP | Strategic Environmental Research and Development Program |
| SREL | Savannah River Ecology Laboratory |
| TAC | Technical Advisory Committee |
| TES | Threatened and Endangered Species |
| TM | Thematic Mapper |
| UMD | University of Maryland |
| URL | Universal Resource Locator |
| UTM | Universal Transverse Mercator |
| VI | Vegetation Index |
| WWW | World Wide Web |

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11/02

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

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|--|------------------------------------|-------------------------------------|-----------------------------------|---|--|
| 1. REPORT DATE (DD-MM-YYYY) 11-2002 | | 2. REPORT TYPE Final | | 3. DATES COVERED (From - To) | |
| 4. TITLE AND SUBTITLE NASA MODIS Products for Military Land Monitoring and Management | | | | 5a. CONTRACT NUMBER | |
| | | | | 5b. GRANT NUMBER | |
| | | | | 5c. PROGRAM ELEMENT NUMBER | |
| 6. AUTHOR(S) Robert C. Lozar and Harold E. Balbach | | | | 5d. PROJECT NUMBER SERDP | |
| | | | | 5e. TASK NUMBER CS-1114 | |
| | | | | 5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center (ERDC) Construction Engineering Research Laboratory (CERL) PO Box 9005 Champaign, IL 61826-9005 | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CERL TR-02-31 | |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research and Development Program 901 N. Stuart St., Suite 303 Arlington, VA 22203-1821 | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) Program Manager | |
| | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. | | | | | |
| 13. SUPPLEMENTARY NOTES Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. | | | | | |
| 14. ABSTRACT Land managers have a need for products derived from remote sensing instruments on satellites. In 1999 NASA launched the first of its Earth Science Enterprise (ESE) satellites, Terra. Terra is the first satellite whose instruments were designed to complement each other in producing digital products that corrected for atmospheric clarity, surface reflectance, seasonal changes, sun angle, and cloudiness to mention only a few concerns. Though its purpose is to study climatic change issues, many of these products have potential use to military land managers. The Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Project (SEMP) sponsored a preliminary investigation to access and manipulate several example products generated from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument for storage in the SEMP data repository. The MODIS products include land cover, vegetation indices, leaf area index, net photosynthesis, fraction-of-photosynthetically active radiation, and vegetation cover conversion. This report describes those products, how they were processed, what they look like, and how they can be used for military land monitoring and management. | | | | | |
| 15. SUBJECT TERMS ecosystem management, military installations, Strategic Environmental Research and Development Program (SERDP), land management, Moderate Resolution Imaging Spectroradiometer (MODIS), SEMP | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON Harold Balbach |
| a. REPORT Unclassified | b. ABSTRACT Unclassified | c. THIS PAGE Unclassified | | | SAR |