Global validation of EOS land products, lessons learned and future challenges: A MODIS case study

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Abstract – The Moderate Resolution Imaging Spectro-radiometer (MODIS) sensors currently provide an 8-year suite of land products essential to Earth system science. The goal of the MODIS land validation group, in conjunction with the Land Product Validation (LPV) sub-group of the Committee on Earth Observing Satellites (CEOS) Working Group on Calibration and Validation (WGCV), is to foster the quantitative evaluation of geophysical products and convey validation data to users. MODIS land products are validated using various techniques to develop uncertainty information including: direct comparisons with in-situ field data collected at Earth Observing System (EOS) core sites and scientific observation networks (e.g. FLUXNET, AERONET); comparisons with data and products from higher spatial resolution sensors (e.g. Landsat); as well as inter-comparison of trends derived from independently-obtained reference data and derived products. The MODIS validation effort contributes to international activities by helping to establish standards and protocols for satellite land product validation.

Keywords: Validation, MODIS, Land products, CEOS WGCV LPV sub-group

1. INTRODUCTION

Global satellite observations of land surface properties are increasingly essential to Earth system science and global change research. The Moderate Resolution Imaging Spectro-radiometer (MODIS) sensor, launched in December 1999, currently provides an 8-year suite of land products spanning radiation budget and biophysical variables to landcover characteristics at a range of temporal (daily, 8-day, monthly, annual) and spatial (250m, 500m, 1km and gridded 1degree) resolutions. The value of these products for science applications and research is dependent on the known accuracy of the data. NASA's EOS program included 'validation' as an explicit responsibility of the investigators to assess the accuracy of their products, augmented by supplementary independent validation activities (Justice et al. 2000). MODIS Land (MODLAND) product quality is ensured by calibration, quality assurance and validation. The MODIS land validation team facilitates this by promoting and assisting with the coordination of quantitative product evaluation. The validation datasets and results are made available to users, to facilitate independent assessments of product accuracy and enable quantitative product inter-comparisons. This paper presents a brief overview of the main data and methods employed to validate the MODLAND products. Requirements for ongoing validation efforts are highlighted as well as the contribution that the CEOS WGCV LPV sub-group lends to maintaining and supporting global validation activities.

Validation is the process of assessing, by independent means, the accuracy of the data products derived from system outputs (Justice et al. 2000). Common approaches involve the collection of independent in-situ, aircraft and satellite sensor data. Given the ambiguity associated with determining if a product is "validated", a hierarchical approach to classify validation stages was adopted by CEOS through consensus of the LPV community (Morisette et al. 2006). The three levels are defined as: **Stage 1**, Product accuracy has been estimated using a small number of independent measurements obtained from selected locations and time periods and ground-truth/field program efforts; **Stage 2**, Product accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts and; **Stage 3**, Product accuracy has been assessed, and the uncertainties in the product well-established via independent measurements made in a systematic and statistically robust way that represents global conditions.

1.1 MODIS Land Product Validation Status

There are 11 MODIS land product types produced operationally by the land discipline team, each with varying levels of maturity (years of production) and validation status, table A. MODLAND product developers as well as independent product users have conducted a considerable number of validation studies over the last decade. The IEEE TGARS special issue on Global Land Product Validation (2006) presents a number of significant MODIS research papers summarizing techniques and datasets utilized for MODLAND product validation activities. The product evaluations and accuracy assessments have contributed to algorithm refinement. Currently MODLAND products have been through three reprocessing efforts and a fourth is planned.

The MODIS global land products are well characterized across North America, Figure 1. Most products are validated at Stage 2, however, the more recent products (Burned Area and Phenology) are currently at Stage 1, Table A. The goal for all products is to achieve Stage 3 validation, which involves assessing product accuracy via independent measurements representing global conditions. Validation at this level is often limited by several factors including costs associated with field data collection, global representation, as well as coordinating international collaborative efforts with the purpose of data sharing. The validation methods employed and datasets utilized for the MODLAND products over the last 10 years provides us with the opportunity to define community needs for sustained and globally integrated satellite validation approaches.

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Table A. MODLAND products, validation stage and main validation data and method utilized.

Product		Stage	Key Data	Method
MOD09	- Surface Reflectance	- 2	Aeronet, Field Landsat ETM	Scaling
MOD10 / 29	- Snow - Sea Ice	- 2 - 2	Volunteer, AWS Landsat ETM, ASTER	Scaling
MOD11	- LST - Emissivity	- 2	Field	Direct
MOD12	- Landcover - Phenology	- 2 - 1	- Landsat ETM - Volunteer field data	- Scaling - Direct
MOD13	- NDVI - EVI	- 2 - 2	Landsat ETM, ASTER, SPOT Aeronet, Fluxnet, Field	Scaling
MOD14	- Active Fire	- 2	Landsat ETM, ASTER	Scaling
MOD15	- LAI - *f*PAR	- 2 - 1	Landsat ETM, SPOT, IKONOS, AVIRIS Fluxnet, field / campaigns	Scaling / Direct
MOD17	- GPP - NPP	- 2 - 2	Landsat ETM Fluxnet, field / campaigns	Scaling / Direct
MCD43	- BRDF/ Albedo	- 1	Landsat ETM, ASTER, IKONOS BSRN, Aeronet, Fluxnet, AWS	Scaling
MOD44	- VCF - VCC	- 1	Landsat ETM, IKONOS, Quickbird Field	Scaling
MCD45	- Burned Area	- 1	Landsat ETM, ASTER	Scaling

2. VALIDATION METHODS AND DATA

Land product validation can be divided into two main categories, absolute and relative validation. Absolute validation involves comparison of the product variable directly with field data, operational scientific network data, or higher resolution airborne and satellite imagery. Relative validation involves comparison of product variables with independently derived satellite products or ecosystem model output of known or lesser accuracy. Figure 1 highlights field locations where both direct and relative validation has been conducted for most products. Site data were not available for MOD10/29 and MOD12 landcover products. Due to the dynamic nature of fire, validation of MOD14 and MCD45 is dependent upon opportunistic sampling and therefore long-term monitoring sites are not used. The following section will provide an overview of the absolute and relative validation techniques and datasets utilized for MODLAND validation activities.

2.1. Absolute Validation

Two commonly applied absolute validation approaches for MODLAND products are utilized. The first involves a *direct* comparison of field or site-level data to the corresponding MODIS pixel, or a window averaged (i.e. 3x3, 7x7) pixel value. This approach has been utilized for MOD11, MOD12 phenology, MOD15, MOD17 and MCD43 validation related studies, Table A. The second, and most common approach utilized for all MODLAND products, involves *scaling* field measurements of the desired variable to produce validated high-resolution reference maps. Higher resolution data such as Landsat ETM+ (Enhanced Thematic Mapper plus) or Quickbird are utilized and aggregated to the MODIS pixel resolution for comparison, Table A.

EOS core sites, field data and coordinated field campaigns - Key to the direct (or absolute) validation of a satellite-derived product is the collection of field measurements under a range of environmental conditions in addition to coincident airborne and satellite measurements (Cihlar et al. 1997).

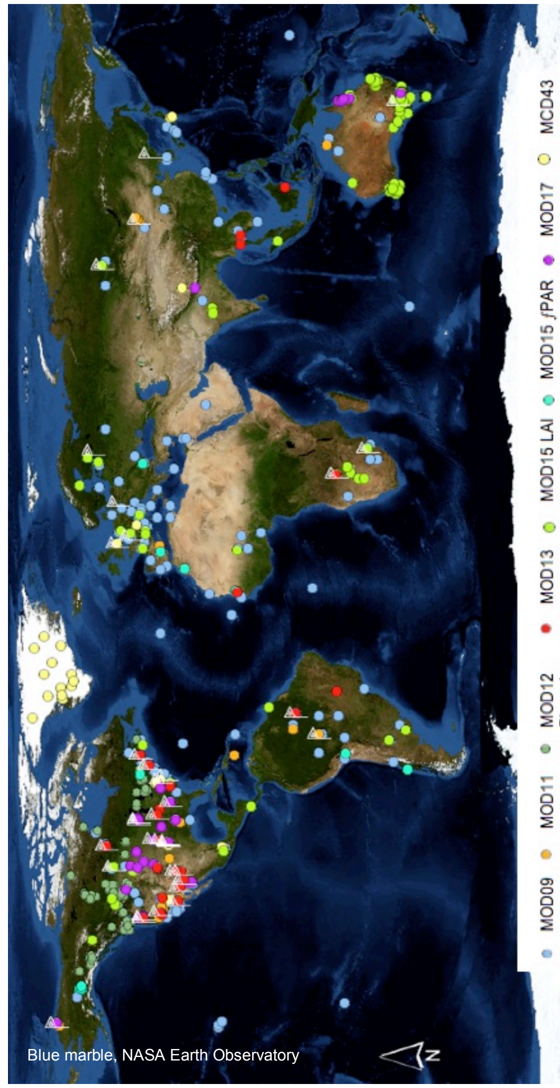

Figure 1. Sites of validation activities for products with available data at time of publication. MOD10/29, 12 landcover, 14 and 44 as well as MCD45 locations were not provided. Core sites are shown by the white flags. The majority of MODLAND validation activities occur in North America, though operational scientific networks such as BSRN, Aeronet and Fluxnet, in addition to satellite-product inter-comparisons, promote global validation.

The selection of set of 'core' validation sites was based on criteria ensuring they were easily accessible, had existing research facilities, a heritage of scientific studies, significant homogenous landcover and represented globally extensive or important biomes (Justice et al. 2000, Morisette et al. 2002). There are currently 34 EOS validation core sites, indicated by the white flag in figure 1. These sites continue to provide the EOS user community with ground, aircraft, and satellite data for science and validation investigations.

MODLAND product validation also relies on field data collected via volunteer networks, automatic weather stations (AWS) and field campaign efforts. The snow and sea ice products (MOD10/29) product utilized the GLOBE (Global Learning and Observations to Benefit the Environment) dataset mainly focusing on data from North America. The phenology product (MOD12) relies heavily on national plant observer networks such as the Canadian Plantwatch program (www.plantwatch.ca).

Prompted by the requirement to validate MODIS land products, several international field campaigns were conducted including, BigFoot (Cohen et al. 1999) and SAVE (South African Validation

of EOS) from which SAFARI (Southern African Regional Science Initiative) 2000 developed (Privette et al. 2002). Other coordinated field validation site networks have also been established including VALERI (www.avignon.infra.fr/valeri). Given the variability of global conditions, efforts have also been made through the international Global Observation of Forest Cover / Global Observations of Landcover Dynamics (GOFC/GOLD) program to engage regional networks of scientists in land product validation.

Operational science data networks - FLUXNET is a global network of micrometeorological tower sites that use eddy covariance methods to measure the fluxes of carbon and energy between the terrestrial ecosystem and atmosphere. Over 500 tower sites are currently operating and at the majority of these sites, information on landcover, vegetation assemblage, soil, hydrologic, and meteorological characteristics are also collected. Data from these sites have, and continue to be, essential for validating a number of MODLAND products including, GPP, VI, LAI, fPAR as well as Albedo (e.g. Turner et al. 2006).

The AERONET (AErosol RObotic NETwork) program provides globally distributed observations of spectral aerosol optical depth in diverse aerosol regimes. This program is critical for validation of the surface reflectance product (MOD09) (Vermote et al. 2008). AERONET data are also routinely used to atmospherically correct Landsat ETM+ imagery to produce reference maps for Albedo and VI validation. Similarly, the Baseline Surface Radiation Network (BSRN) and the US component (SURFRAD) as well as the Climate Reference Network (CRN) provide continuous measures of radiative fluxes at the Earth's surface. These data are essential for BRDF/Albedo product (MCD43) validation activities.

Higher-resolution satellite and airborne imagery - Landsat ETM+ (30m) and ASTER (15m VNIR, 30m SWIR) imagery are both extremely important for MODLAND product validation. Numerous studies have utilized these data to derive high-resolution validated parameter reference maps as an intermediate step between field data and the MODIS resolution pixels (e.g. Gao et al. 2003). SPOT (Systeme Pour I'Observation de la Terre)-Vegetation, IKONOS and Quickbird are also frequently utilized for this scaling purpose. Airborne datasets are less often used in MODLAND validation activities. AVIRIS is the most acquisitioned airborne data, primarily for validation of VI and LAI products. These data are provided through the core site validation activity.

2.2. Relative Validation

With the increase in number of sensors providing frequent coarse-resolution observations, global land products have proliferated. In many cases, multiple products are derived from one sensor and similar products are derived from different sensors (Morisette et al. 2006). Table B outlines satellite sensors that are used to create products similar to those derived from MODIS. Direct validation is both time and resource intensive, and often, existing validation datasets are not representative of the global and seasonal variability of vegetation. Inter-comparison of products from different sensors offers a simple way to evaluate the temporal and spatial consistency between products (Garrigues et al. 2008). Several product inter-comparison studies have been conducted all assessing the performance of MODIS in relation to other sensor-derived products. These studies include for example, the LAI (Garrigues et al. 2008), gross primary productivity (Coops et al. 2009) and albedo products (Schaaf et al. 2008). Product inter-comparisons, whether between satellite-derived or ecosystem model-derived land products show where parameter estimates both agree within suitable bounds or clearly disagree. This provides a unique opportunity to evaluate underlying model assumptions through sensitivity analyses, the need for additional data collection and highlights where perhaps more detailed validation studies are warranted (Coops et al. 2009).

Table B. Satellites producing similar land products to MODIS.

Product	Satellites producing equivalent products
LAI	MISR, SPOT-Veg, ATSR, POLDER, ADEOS, MSG-SEVIRI, MERIS, AVHRR
Vegetation Indices	AVHRR, SPOT-Veg, MISR, MSG-SEVRI MERIS, POLDER
Landcover/Phenology	AVHRR, MERIS
Productivity	SPOT-Veg, AVHRR
Surface Reflectance	AVHRR, ASTER, MERIS, POLDER
BRDF/Albedo	CERES, METEOSAT MISR, MSG SEVIRI, POLDER, MERIS
Fire	L3JRC, SPOT-Veg, ATSR, TRMM, MSG, GOES
Snow	GOES, AVHRR, MSG

3. VALIDATION LIMITATIONS AND REQUIREMENTS

3.1. Data limitations

Validation of global moderate-resolution land products is a challenging endeavor for several reasons. Field data are critical, however, gathering high quality, globally representative and temporally explicit reference data is both time consuming and resource intensive. Maintaining long-term field and airborne imagery acquisition is required at more sites than the current activities at EOS core sites. Operational scientific networks such as FLUXNET and AERONET provide the continuous and globally representative data collection necessary to assess spatial and temporal variability of satellite datasets. FLUXNET is an extremely valuable, yet relatively under-utilized resource for global land product validation. Although these sites could provide a wealth of data for validation of the majority of existing MODLAND products, these site datasets remain unprocessed or unobtainable for such studies. In some cases, FLUXNET site personnel have provided processed data, however, this is not a reliable source of continuous information. There is a consensus need for integrated FLUXNET site data processing, however, logistical challenges constrain this sizeable task.

Collection of high-resolution satellite and airborne imagery, co-incident with field campaigns, is important for EOS validation studies. However, regardless of planning efforts, the actual acquisition of these data near or during the time of a field campaign has been less than 50% successful. This is usually due to the presence of clouds or competing satellite resources during overpass opportunities. The recent release of free Landsat ETM+ data relieves some of the associated cost associated with obtaining cloud-free imagery. The high cost of airborne data acquisitions, limited temporal and spatial coverage, weather dependency and pre-processing requirements (atmospheric correction and geolocation), limit the extent to which airborne data have been used for validation.

3.2. Methodological limitations

Direct field to pixel analysis is the fastest and easiest way to compare field measurements to satellite data and provides a

'quick-look' at relative product behavior. However, it is not recommended due to scale-mismatch, geolocation errors and vegetation heterogeneity within often mixed moderate resolution image pixels. Aggregated and averaged pixel window values may not be representative of landcover surrounding the scientific network or field site. FLUXNET data are representative of a $1km^2$ area surrounding the tower, yet the actual footprint is dependent upon the fetch defined by local meteorology and topography. In addition, field data may only be collected for a few sample points within a pixel area or along a transect line. Such field data will not represent the spatial heterogeneity of the comparison pixel.

To counter the problems associated with direct field to pixel analyses, scaling approaches using intermediate higher-resolution imagery, such as Landsat ETM+ have been developed (Turner et al. 2006). When aggregated to the MODIS resolution, these maps serve as the 'ground-truth'. The approach to produce high-resolution reference maps employs several steps. Firstly, the imagery must be georeferenced and atmospherically corrected. Often this step employs aerosol data from field networks such as AERONET. Reference maps are produced using transfer functions that convert the variable of interest from ground measurements to high-resolution imagery (Yang et al. 2006). Disadvantages to this approach are that it is labor intensive and dependent on manual data interpretation. Differences in spectral properties between the reference data and MODIS are common as well as spatial footprint deformation by off-nadir viewing (Gao et al. 2003).

Product inter-comparisons provide spatially and temporally rigorous analysis of differences between satellite-derived or ecosystem model produced land variables. However, agreement between two products does not equate to establishing product accuracy, especially if both estimates do not match actual physical measurements. These analyses allow general spatial and temporal variability to be assessed and underlying model assumptions must be taken into account. Most importantly, product inter-comparisons indicate regions where more intensive product validation studies are required.

4. 'LESSONS LEARNED' AND FUTURE

The last decade has seen a profusion of validation studies targeted at defining the accuracy of MODIS land products. These have brought to light key 'lessons learned' with regard to validation data requirements, methodology and dissemination of data and results. Firstly, satellite land product accuracy requirements are still not well defined. This is a challenging task and dependent on the end use of the product. Validation results are primarily used in the algorithm improvement process. Yet the question remains, when can a product be considered good enough? MODIS validation studies have highlighted the significance of good quality, spatially and temporally representative, field and operational scientific network datasets. While the majority of MODIS validation activities have been conducted within North America, EOS core sites, operational network data and product inter-comparison activities have facilitated a more global aspect to validation. It is essential to leverage existing scientific networks (FLUXNET and AERONET) and provide processed, quality assured data for EOS validation. Investment of time and resources into strengthening existing networks is critical for validation of the MODLAND products and will continue to be important for future EOS land products stemming from Decadal Survey missions, e.g. HyspIRI, as well as those from operational sensors e.g. VIIRS. Scaling field measurements to produce high-resolution image reference maps is a fundamental approach for validating moderate resolution global satellite land products. Product inter-comparisons offer evaluation of the temporal and spatial consistency between products by representing the global distribution of landcover types over complete vegetation cycles. With the increase in land products and data users, development of international validation standards and method protocols for satellite land product validation is necessary. The CEOS WGCV land validation sub-group provides an international mechanism for coordinating such global validation activities. The goal of this group and the MODLAND validation team is to foster quantitative and collaborative evaluation of higher-level geophysical products. This group has the scientific expertise to develop the validation standards and protocols and convey validation data and results so they are available and relevant to users (http://lpvs.gsfc.nasa.gov/).

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