1. ESDR Name

Land Cover / Land Cover Change

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3. Science Rationale

Land cover, defined as the assemblage of biotic and abiotic components on the Earth's surface, is one of the most crucial properties of the Earth system. In terms of global change we can recognize three fundamental ways in which it is important (Turner II et al. 1994). The first lies in the interaction of land cover with the atmosphere, which leads to regulation of the hydrologic cycle and energy budget, and as such is needed both for weather and climate prediction (DeFries et al., 2002). For example, most climate models are now coupled with Land Surface Parameterizations (LSPs) which use digital land cover data to produce databases of albedo, surface roughness, evapotranspiration and respiration. Second, land cover plays a major role in the carbon cycle acting as both sources and sinks of carbon. In particular, rates of deforestation, afforestation, and regrowth play a significant role in the release and sequestering of carbon and consequently affect atmospheric CO_2 concentration and the strength of the greenhouse effect (IPCC, 2000; Janetos and Justice, 2000; Houghton, 1999). Finally, land cover also reflects the availability of food, fuel, timber, fiber, and shelter resources for human populations, and serves as a critical indicator of other ecosystem services such as biodiversity. Information on land cover is fundamental to many national/global applications including watershed management and agricultural productivity. Thus the need to monitor land cover is derived from multiple intersecting drivers, including the physical climate, ecosystem health, and societal needs.

Economic development and population growth have triggered rapid changes to Earth's land cover over the last two centuries, and there is every indication that the pace of these changes will accelerate in the future. These rapid changes are superposed on long-term dynamics associated with climate variability. Land cover change can affect the ability of the land to sustain human activities through the provision of multiple ecosystem services and because the resultant economic activities cause feedbacks affecting climate and other facets of global change. Accordingly, systematic assessments of Earth's land cover must be repeated, at a frequency that permits monitoring of both long-term trends as well as interannual variability, and at a level of spatial detail to allow the study of human-induced changes.

Scientific requirements for land cover have long been articulated especially at the international level by IGBP and also by WCRP within its GEWEX activity. Profound changes are occurring in the strategic direction of global environmental research over the next decade and there is to be more emphasis on issues of societal concern, more emphasis on regional scales, emphasis not only on climate change but on many other aspects of global change such as human induced land cover and land use change and a scientific focus on coupled human environmental systems. Reliable and consistent land cover products will be needed for the Global Land Project, and the revised Land Ocean Interactions in the Coastal Zone and ILEAPS, whose goal is to provide understanding of how interacting physical, chemical and biological processes transport and transform energy and matter through the land-atmosphere interface.

Within the NASA Science Strategy, land cover and land cover change are baseline measurements necessary for the Carbon Cycle and Ecosystems (CC&E) and Water and Energy Cycle (W&EC) Focus Areas. In fact, assessing "land cover change at fine resolution" is stated explicitly as a major goal of the CC&E Focus Area. These requirements flow from the Strategic Plan for the U.S. Climate Change Science Program which calls for a coordinated research program addressing issues of land use and land cover change. While future remote sensing measurement suites, such as vegetation structure or plant physiology may complement the role of land cover within the CC&E Focus Area, it is likely that land cover will remain a baseline requirement for global change modeling activities for many years to come.

Although global land cover has been a standard science product from the EOS MODIS mission, and is slated to be an Environmental Data Record (EDR) from NPOESS VIIRS, there has been little effort to date to:

- produce a single record of global land cover across three decades of various satellite observations;
- harmonize land cover measurements across a range of measurement scales (eg. 30-meter Landsat to 8km AVHRR);
- reconcile global assessments of land cover with rates of change measured at fine resolution.
- compare continuous fields representations with traditional thematic maps of land cover.

More fundamentally, since the conclusion of the NASA Landsat Pathfinder project in the early-1990's, there has not been a funded program to systematically assess global rates of land-cover change from high-resolution satellite data. This measurement gap severely limits NASA's ability to address the Earth Science questions listed above.

In order to address these issues, this White Paper provides community input on the requirements and approach for a land cover / land-cover change Earth System Data Record (ESDR). Instead of traditional, mission-specific land cover products, this document focuses on an ***integrated suite*** of land cover measurements that bridges sensor attributes and mission lifetimes. The overall purpose of the land-cover/land-cover change ESDR is to provide baseline information for global climate, biogeochemical, and hydrologic modeling and information useful for assessing and forecasting global ecological status. It should also be noted that a single land cover ESDR will not satisfy all applications – custom analyses of land cover will still play an important role for specific user communities and research topics. The proposed suite is divided into four elements, discussed individually below:

- Global, 1km annual land cover type – required for global climate, hydrologic, and biogeochemical modeling, and as an input for other biophysical products.
- Global, 30m decadal land cover type – required for mesoscale climate and ecological studies, and to examine land use and the "human footprint".
- High-resolution 30m interannual land cover change – required for assessing ecological changes in response to climate variability and human activities, and for quantifying changes in carbon stocks.
- Continuous Fields representations – required for more accurate land surface parameterizations at subpixel scales, and for examining long-term changes in vegetation components.

4.0. Requirements and Approach for ESDR Components

4.1. Global, 1-km Annual Land Cover Type

Requirements:

The key requirement for a moderate spatial resolution global land cover ESDR/ESDR is that it provide sufficient quality to support key science objectives; namely support for global and regional modeling, assessment of local resource and ecological assessments, and realistic representation of significant land cover change at annual time scales. Specific requirements include:

1. A robust and repeatable classification algorithm that can be applied in a uniform fashion across all regions of the Earth.

2. The highest spatial resolution that is feasible given available data sources. Retrospective creation of global land cover maps from AVHRR dictates a spatial resolution of 1 km; the MODIS global land cover product is currently produced at 1-km, but will be available at 500-m in collection 5. In the future, global land cover products from the VIIRS instrument on NPOESS will be produced at a spatial resolution of 1-km for continuity with the AVHRR and MODIS data sets.

3. An annual update, acknowledging the challenge of producing maps at this time scale. For such an approach to be effective, however, any changes in land cover observed from year to year must be a result of *actual* change in the landscape and not algorithm errors or changes in training. Because the classification error rate in moderate resolution land cover maps is significantly higher than the annual rate of global land cover change, this points to the critical need for an internally consistent, repeatable and potentially automated classification approach that can be applied in a homogeneous fashion to a consistently generated input data stream.

4. The highest possible classification accuracy given constraints imposed by data, algorithms, and the final classification scheme. Currently, the upper bound is about 80 percent correctly classified. Accuracies associated with specific classes should not be less than 65 percent correctly classified. Also, classification accuracies should not vary widely as a function of location (map quality should be geographically uniform).

5. A statistically robust and defensible strategy for validation, assessing both the overall classification accuracy, as well as the class-specific accuracies.

Technical Approach:

- While there has been some success in using unsupervised classification approaches for global land cover products, the need for repeatable global classifications at annual time scales dictates a supervised classification approach. Decision tree classification algorithms have been successfully used with AVHRR data and are currently being used to produce the MODIS global land cover product, but other strategies could also be considered. The key requirement is that the algorithm produce the maximum accuracy and that it be technically feasible. Note that practical considerations such as the presence of missing and noisy data require the use of algorithms capable of handling such data.
- Current algorithms for AVHRR, MODIS and VIIRS all use different input data for classification. Irrespective of the classification algorithm and/or the types of input data used, the input data need to be processed so as to minimize between and within sensor variations.
- In support of supervised classifications, high-resolution training data sets are required that are transparent and open to the community. Compilation of these data sets requires specific protocols for geographic and ecological sampling, minimum patch size, quality assessment, and procedures for detecting land cover change in any given patch.
- The classification scheme should adopt the FAO Land Cover Classification System (LCCS) (Di Gregorio and Jansen, 2000). The LCCS is becoming widely adopted as an international standard, is hierarchical, and is therefore more easily "harmonized" with other classification systems, including high-resolution land cover maps produced at decadal time scales.
- A validation strategy is required that uses a probability-based sample design with adequate samples to estimate overall accuracy and class-specific accuracy at continental, or preferably, sub-continental, scales.

4.2. Global, Decadal, 30m Land Cover Type

Requirements:

The key challenge facing global land cover mapping is the need to provide datasets that are globally consistent yet locally relevant. The general requirements for the global high-resolution land cover classification include the following:

- Based on a flexible and hierarchical land cover classification scheme with categories relevant for assessing a wide range of environmental applications. Particular attention should be devoted to classes poorly represented in coarse-resolution representations, and those classes reflecting human land use (e.g. urban types, agricultural types, impervious surfaces). Consistency with the Land Cover Classification Scheme developed by FAO is desirable.

- Spatial resolution of 30m; temporal updates every 10 years (at most) or every 5 years (preferred).
- Overall and regional accuracies exceeding 90 percent at the highest level of aggregation.
- Validated based on the use of a probability-based sampling strategy and accuracy results with at least a continental resolution. Harmonized with contemporary global, 1-km land cover classification (e.g. most probable 1km value should match modal type at 30m resolution).

Technical Approach

The emerging states-of-the-art in large-area land cover mapping currently follows two very different strategies. First, manual image interpretation is being used for national land cover mapping in many parts of the world. This labor intensive approach results in high quality land cover maps. A second strategy is the use of classification decision tree approaches in with automated non-parametric techniques can be use used to map land cover using multi-source data sets consisting of multi-temporal imagery and other ancillary land variables. This approach is cost-effective over large areas but the quality of results is directly related to the availability of suitable input data sets.

While there is ample evidence that manual interpretation of high-resolution imagery provides accurate and locally-relevant land cover data, it is a slow labor intensive method and will be costly to implement at a global scale. In addition, without detailed protocols and training, creating globally consistent data will be challenging. Because of this, the only viable, cost-effective approach is to use computer-assisted methods. The quality of results from current decision tree approaches suggests that this methodology is closest to meeting the climate data record requirement.

Validation must be statistically robust and geographically relevant. Ideally, understanding accuracies at sub-continental accuracies is highly desirable. Unfortunately, for every additional geographic subdivision, there is an incremental increase in the amount of required validation data. Suitable sources of validation are also problematic. While costly, very high resolution satellite imagery and aerial photography may be necessary, supplemented with fusion of higher-resolution satellite datasets (e.g. lidar, radar, hyperspectral) as they become available.

4.3. Global Continuous Fields

Requirements:

A global moderate spatial resolution vegetation continuous field (VCF) ESDR must meet the following requirements:

1. The use of explicit physiognomic-structural definition sets that enable the derivation of a mutually exclusive and exhaustive land cover classification.
2. Vegetation trait definitions that allow for their direct incorporation into global, continental and regional scale biogeochemical, hydrological and other natural resource and ecological modeling exercises.

3. A repeatable, transparent methodology that allows for the use of VCF layers in monitoring applications.
4. An algorithm that yields the highest accuracy possible.
5. Annual or finer temporal scale production schedule of those VCF layers appropriate for change monitoring, including tree, bare ground, and other vegetation covers. Five year intervals for layers not likely to exhibit change, for example tree leaf type and longevity, are required.
6. A spatial resolution of a minimum of 500 meters to enable large area monitoring of key vegetation change dynamics such as deforestation.
7. Quality assessment indicators per observation/pixel to enhance user understanding of data potentials/limitations to applications.
8. Availability of all data inputs for VCF production to the user community.
9. Validation protocols for both VCF layers and derived change products.

Technical Approach:

Production of VCF layers should incorporate the following technical aspects:

1. A supervised algorithm to ensure repeatability. Of available supervised approaches, distribution-free methods are necessary to account for the complex spectral distributions of global, continental and regional vegetative traits. This ensures the highest accuracy possible. Of the distribution-free methods, the most transparent are tree-based models. As such, tree-based algorithms meet the key requirements of repeatability, transparency and high accuracy.
2. Inputs must be multi-temporal spectral imagery including time-sequential composite and annual time-integrated metrics. These inputs must be made available to users.
3. Training data derived from high-resolution data sets (5-50 meters) for calibrating the algorithm. These data must be made available to users.
4. The use of vegetation trait definitions that are easily incorporated into the FAO Land Cover Classification System (see above).
5. Probability-based sample designs for assessing product accuracy that are based on the direct observation or measurement of the respective vegetation trait. The leveraging of existing networks of vegetation inventorying should be used without compromising sampling protocols.

4.4. Interannual Land Cover Change and Disturbance

Requirements:

- Numerous studies have demonstrated that high resolution data, with a resolution less than ~50 meters, are required to accurately map the area of land cover conversion and many forms of ecosystem disturbance (Townshend and Justice, 1988). This is particularly true of human induced changes which typically occur on scales of a few hectares or less.

- Two separate temporal resolutions are required for the land cover change ESDR. Assessing long-term trends in land-cover change requires updates on intervals of five years or less, to avoid “missing” change that may be camouflaged by later vegetation recovery. However, deforestation and regrowth also show major annual variations at the regional scale, which strongly affect the strength of sinks and sources of carbon (Houghton, 2000). For this reason, annual updates are required for specific regions.
- Thematically, a land cover change ESDR should record information on (1) *conversion* of land-cover from one type to another; (2) ecosystem *disturbance* events (ie. significant changes in vegetation structure or composition without a change in land cover type); and (3) quantitative information on *changes in vegetation cover or canopy cover* resulting from land cover conversion, disturbance, recovery, or long-term ecological trends. We also acknowledge that in some cases distinguishing between (1) and (2) may not be possible until successional patterns become clear in later years.

Technical Approach:

Given the cost associated with analyzing global high-resolution (Landsat-type) satellite data, the initial implementation of the land cover change ESDR should focus on specific geographic areas. First, hotspots of change should be flagged each year by coarse-resolution sensors (AVHRR, MODIS, VIIRS). These areas should be supplemented with known areas where change occurs at scales too fine to be detected by coarse-resolution sensors (e.g. timber harvest, urbanization, etc). This set of regions should be targeted for annual analysis. Other vegetated areas (intact forests, shrublands, grasslands) should be targeted for analysis one every 5 years, to capture ecological long-term trends. The current Landsat GeoCover data products and planned Mid-decadal Global Land Survey (MDGLS) provide a first opportunity to quantify global land cover changes during the 2000-2005 period.

Numerous algorithms for mapping land cover change from satellite data have been used over the last three decades. Most suffer from the fact that they cannot be automatically extended across large regions and multiple ecosystems without human intervention. To remedy this, algorithms should explicitly account for atmospheric and seasonal variability among images. One promising approach is the use of global MODIS products to provide inter-scene normalization. Atmospheric correction to surface reflectance can also reduce atmospheric variability, and provide a physical basis for further analyses.

For assessing changes in canopy cover or fractional vegetation cover, spectral unmixing algorithms have proven effective, providing that adequate training data (ie. spectral endmembers) exist (Asner, 2005). Direct comparisons between satellite radiometry and results from canopy reflectance models are also being explored. Mapping land-cover conversion requires algorithms that use direct radiometric comparison across time. Multi-date supervised classification has proven effective, as have tasseled-cap based difference products and change-vector analysis. Again, training data are required.

Rather than implement a single, global algorithm for all land cover change, it may be desirable to distribute the task, with different algorithms focusing on particular processes, regions, or parameters. For example, tropical deforestation, urban growth, temperate forest disturbance/recovery, and changes in irrigated agriculture could conceivably be mapped using different algorithms. Advances in automated processing of Landsat-type data can be harnessed to facilitate this model.

5. Data Sources

1. Coarse-resolution optical sensors: AVHRR (1982-2000); MODIS (2000 – 2010+); VIIRS (~2010 -).
2. Fine-resolution optical sensors: Landsat/LDCM (1972-2010+); ASTER (2000-2010+);
3. Limited Hyperspatial (<5m resolution) and in-situ data for training and validation.

6. Necessary Supporting Activities

The ability to generate a land cover ESDR depends on several supporting data sets and activities:

1. Provision of a radiometrically and geometrically high quality data stream of surface reflectance measurements with sufficient atmospheric correction and cloud screening, at both coarse- and fine-resolution. Data availability and quality from optical sensors at high latitudes and in the tropics remains a challenge. The surest way to improve classification accuracy is to use multi-temporal data that represent the landscape's phenological variability. While some parts of the globe are adequately imaged, in many areas, the seasonal coverage is often inadequate due to a variety of environmental and technical reasons. Methods and algorithms that integrate optical data with data from active sensors have the potential to help resolve this challenge.
2. Reducing cost of multi-temporal high-resolution satellite data. Either free or drastically reduced data prices for Landsat-type data are required to generate the ESDR suite envisioned here. The absence of such data will also compromise the quality of validation for the coarse-resolution products.
3. Access to training/validation data that are consistent over geographic space and time, and linked to in-situ observations. A single set of training/validation imagery should be implemented for the entire ESDR suite, linked to ground observations via regional research networks such as GOFC-GOLD. These images should be carefully classified according to local knowledge, and change over time should be assessed for specific locations. While specific ESDR products may augment this "base" data set, its creation will facilitate intercomparison among products.

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