GOFC-GOLD GLOBAL OBSERVATION OF FOREST AND LAND COVER DYNAMICS

Global Observations of Forest Cover: Coarse Resolution Products Design Strategy, Report of a Workshop

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Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) is a coordinated international effort to ensure a continuous program of space-based and in situ forest and other land cover observations to better understand global change, to support international assessments and environmental treaties and to contribute to natural resources management.

GOFC-GOLD encourages countries to increase their ability to measure and track forest and land cover dynamics by promoting and supporting participation on implementation teams and in regional networks. Through these forums, data users and providers share information to improve understanding of user requirements and product quality.

GOFC-GOLD is a Panel of the Global Terrestrial Observing System (GTOS), sponsored by FAO, UNESCO, WMO, ICSU and UNEP. The GOFC-GOLD Secretariat is hosted by Canada and supported by the Canadian Space Agency and Natural Resources Canada. Other contributing agencies include NASA, ESA, START and JRC. Further information can be obtained at http://www.fao.org/gtos/gofc-gold

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1.0 GOFC Coarse Resolution Products

The Coarse Resolution Products Design Team met in Sioux Falls, SD in July 1998 to develop a strategy for generating a set of Global Observation of Forest Cover (GOFC) coarse resolution data sets. The team, listed in the report Appendix, built on the general specifications that were developed during the 1997 Ottawa GOFC meeting. During the Sioux Falls workshop, we reviewed and prioritized all products identified during the Ottawa meeting. In addition, three additional products were recommended: tree cover density, forest cover change, and active fires. The coarse resolution products, prioritized based on their relevance for science, policy, forest management, and other values, are listed in Table 1.

The discussion of priorities focused on user requirements rather than feasibility. Clearly, land cover products (global land cover, forest density, and forest cover change) and fire products (active fires, burned areas) are the highest priority and have the widest applicability. In addition, the state of processing is sufficiently advanced to permit immediate development of quality products. The other products, such as biomass and PAR, have significant research elements that must be resolved before products with the desired accuracy and precision can be developed. The rankings, therefore, strictly reflect the broader issue of user relevance.

After finalizing and prioritizing the list of GOFC coarse resolution products, the group developed specifications and processing strategies for each product. A brief summary of product characteristics is found in Table 2. The following are descriptions of the nine products recommended to represent the core set of coarse resolution products.

2.0 General Design Considerations

The strategies recommended for the development of the coarse resolution products are based on some fundamental considerations, such as:

- Products should be relevant to as broad an audience as is practical and feasible. It is particularly important that the products be designed to be relevant for carbon assessment and carbon crediting applications. In addition, relevance to national and international forestry organizations is also important.
- Product specifications should be achievable, whenever possible, with current technology (i.e., using data from sensors either currently operational, or scheduled to be operating in the coming year). The specifications, however, should also include definitions of optimal characteristics that may be achievable with advancements in future remote sensing systems.
- Research will be a necessary component in most product development strategies.
- Product specifications should be periodically reviewed and improved so that advances in methods and source data characteristics can be incorporated to improve overall data quality.
- Validation of data products is necessary to evaluate product quality, and also to identify new research priorities.

3.0 Global Land Cover Product Summaries Definitions

Three global land cover products were identified as high priority coarse resolution data sets.

They are: (1) land cover; (2) forest density; and (3) forest cover change. The following sections present the definitions of each of the three land cover products.

3.1 Land Cover

The global land cover product should have two components: (1) a detailed thematic map of land cover; and (2) forest canopy density. While they are defined separately in this document, they should be viewed as linked products. The density data layer is considered to be a key part of the land cover product and it can provide information that will improve the consistency of the thematic map definitions, and will contribute directly to both scientific and international forestry applications.

The land cover product should be produced every five years, with completion of the product 12-24 months following the end of the baseline period. A separate annual forest cover change product is needed for monitoring global forest change. The highest possible spatial resolution is desirable. While global land cover with 250m to 500m resolution will have the highest applications value, in the near term a 1000m resolution data set is most practical and feasible. However, it is important to recognize the long-term requirement for higher resolution global land cover products.

The global land cover product must cover the entire global land surface and be relevant for carbon studies. The level of thematic detail should be greatest for woody vegetation (i.e., trees, shrubs) and only general land cover types are necessary for the other landscapes. This means that there will be uneven categorical detail, with 40-50 classes representing woody vegetation, and approximately 5-10 additional categories representing all other cover types. A draft land cover legend is presented for discussion in Table 3. However, before a land cover legend is adopted, it will be necessary to conduct a thorough review of user requirements. The following is a set of guiding principles that can be used in the land cover legend development process:

- The classes mapped must be relevant to carbon studies.
- Cover is based on actual rather than potential land cover.
- Compatibility with exiting legends is desirable, especially those used by national and international forestry organizations.
- A hierarchical system is desirable.
- The system must be sufficiently flexible to permit generation of forest cover products based on different canopy closure criteria.
- Mapping units must consider physiognomic characteristics. Floristic elements are less important, and biome types may be used to imply possible community composition.
- Compatibility with definitions used for the GOFC fine resolution products is necessary.

The development, testing, and evaluation of the actual land cover legend is an appropriate pilot project activity. It is necessary to test legends in an applications context in order to ensure that the product has the highest possible utility.

The methods used to develop the product are perhaps less of an issue than is the issue of source remotely sensed data. While several training procedures and classifiers have recently been used to develop global land cover data sets (i.e., Defries, et al., 1995; Loveland, et al., submitted), there is currently no clear evidence to suggest that one approach is superior to another. The selection of a methodology must therefore be based on applications issues, including degree of required flexibility and tailoring of the GOFC global land cover product, frequency of updates, and implementation considerations.

An understanding of the advantages and disadvantages of a centralized versus decentralized global land cover production model is needed before the operational strategy of the GOFC coarse resolution data set generation activity is finalized. The centralized production model, in which one organization developed the product, has advantages for scientific applications, offers greater chances of global consistency, can likely be completed at a lower cost, and may be completed in a shorter period of time. The decentralized approach is more relevant for policy applications in which it is essential that local to regional landscape conditions are most reliably represented. It also may lead to greater local and regional acceptance of GOFC coarse resolution products. However, is could be less efficient. When considering the intended applications of the global land cover product, it may be appropriate to consider implementation based on the decentralized strategy. However, this issue requires debate within a larger GOFC forum.

The decentralized strategy could consist of a series of mapping organizations with responsibility for mapping a particular continent (i.e., Africa, Asia, Australia, Europe, North America, and South America), and a strong central office with coordination, quality control, validation, data management, and other functions. The mapping organizations must be able to provide long-term operational continuity.

Because of the decentralized model, it is necessary to standardize inputs, and definitions of results. Rather than rigidly standardize methods, the group concluded that it was more realistic to establish a set of criteria that any method used in the land cover classification must meet. It will also be necessary to identify validation strategies that deal with the different error structures associated with each regional data set.

The accuracy requirements for the product must be established based on the state-of-the- practice in global land cover mapping. While past global land cover mapping initiatives such as the IGBP DISCover activity (Loveland and Belward, 1997) call for 85% accuracy, this figure is not practical for the GOFC global land cover product. The results of accuracy assessments of global land cover data sets that will be completed later in 1998 should provide an indication of reasonable accuracy targets. Regardless of the target accuracy statements, validation results should include overall and per class statements of accuracy as well as regional area estimates for each category.

3.2 Forest Density

An integral part of the global land cover product is a forest canopy density product that provides estimates of percent tree canopy for each pixel. The density would be described in terms of percent forest cover within the pixel, varying from 0 in locations with no woody cover to 100 for locations with full canopy cover. The resolution of this product should be the same as that used in the global land cover product. This data set can also be produced in a decentralized structure, but the arguments are less compelling. Regardless, this data set must be based on a standardized methodology. This data set should be produced every five years, but will be needed within 3 months following the end of the baseline period so that it can be used in the global land cover classification process.

The land cover classification will provide information about forest type stratified according to threshold values for canopy closure. Additional information on forest density will allow comparison with other classification systems using alternate definitions and thresholds for canopy cover. A forest density layer will also allow the identification of locations undergoing changes in forest density that would not be detectable if only considering the land cover type. This information is required to monitor changes in canopy density and to assess the condition of forests. From the point of view of the scientific user, this information permits the modeling of carbon and other biospheric properties that would not be possible with the land cover layer alone.

Processing of the forest density layer, though requiring alternate algorithms, would be done in parallel to the generation of the land cover map with a 5 year frequency. Processing for the forest density layer would be done for those pixels classified as woody vegetation in the land cover map. We recommend a pilot project to compare methods for generating a forest density layer and to carry out validation of pilot products.

Several algorithms have been developed and applied to generate forest density maps on regional and global scales. These methods generally fall into three categories:

- Endmember linear unmixing. In this approach the proportion of vegetation types are deconvolved based on the assumption that the spectral signature is a linear combination of reflectances from the components within the pixel. Implementation of this method requires knowledge of reflectances of "pure pixels" from spectral libraries, field measurements, or high resolution data. This approach has been applied at regional and global scales (i.e., Adams et al., 1995; Bierwirth, 1990; DeFries et al., submitted; Pech et al., 1986; Quarmby et al., 1992; Settle and Drake, 1993). Recently methods have been applied to incorporate nonlinear mixtures (Foody et al., 1997) and multiple endmembers (Roberts et al., in press).

- Spectral regressions. This approach is based on empirical relationships derived from coregistration between fine resolution (e.g., Landsat TM) and coarse resolution (e.g. AVHRR) data. The empirical relationships are then extrapolated over larger regions to estimate percent forest density (DeFries et al., 1997; Iverson et al., 1989; Iverson et al., 1994; Zhu and Evans, 1992; Zhu and Evans, 1994).

- Calibration of areal estimates from spatial aggregation of classifications derived from coarse resolution data. These methods can be used to derive areal estimates of forest cover based on classification of coarse resolution data. The method adjusts the areal estimates taking into account the spatial arrangement of land covers at fine resolution (Mayaux and Lambin, 1995; Moody, 1998).

These methods have all been successfully applied. A comparison of these methods for selected area needs to be carried out to determine which is the most feasible in an operational context.

The forest density product should be produced in parallel to the land cover map product. Coregistration with the fine resolution product will be needed to assure consistency in results. The post-launch MODIS product generating continuous fields of vegetation characteristics provides an additional link that might useful in the implementation of GOFC.

The forest density product requires validation to provide information on the reliability of the continuum of density values. The validation of the density product may be done using methods similar to those used for the biophysical products. The forest density validation could use high resolution data and ground studies to assure accuracy. This should be carried out for a small number of selected locations.

A pilot project to test existing algorithms for deriving a forest density layer is needed to determine the methodology that provides the most accurate results and is most feasible for operational implementation. This pilot project would select a few globally distributed regions where high resolution data are available for testing.

3.3 Forest Cover Change

The forest cover change product would identify on an annual basis locations where changes in forest condition are occurring. This product would be linked with the fine resolution product so that more in-depth analysis at higher resolution could be carried out for these locations. The forest cover change product would serve as a flag for detecting change in forest cover.

A forest cover change product is needed for monitoring changes in forest extent and condition to support implementation of emission inventories related to climate convention agreements. This information is also critical for NGOs and other institutions assessing biodiversity and identifying "hot spots". From the science user perspective, the identification of areas undergoing harvesting, deforestation, and burning are critical for assessing the carbon budget. A separate forest cover change product is needed, as opposed to comparison of classification products, because: 1) change detection methods that do not rely on successive comparison of land cover classifications are known to be more accurate; and 2) changes in forest cover need to be detected on a more frequent basis than the five years recommended for the global land cover classification product.

We recommend that the forest cover change product be generated at a spatial resolution of 250m, the resolution necessary to detect clearings and modifications of forests by human activities (Townshend and Justice, 1988). The product would be produced annually and would be compared to a baseline extent of forest cover as well as to the previous 5 years. We propose that a standardized method for deriving this product, including source data and methodology, be established by a coordinating group and that the product be generated on a continental or regional basis by various organizations. Strong oversight is required to assure a consistent product both though time and between regions. The coordinating group would be responsible for disseminating the results.

Many methods have been used for change detection based on satellite data. Analysis of radiometric differences between dates generally provides more accurate results than analysis of difference between classification results because the latter compounds inaccuracies in the classification products. Radiometric analysis includes band differencing, band ratioing, transformed band differencing, principal component analysis, and multispectral or multitemporal change vector analysis (Singh (1989) provides a review of these methods). A key requirement for a methodology to be operational in GOFC is that the process be automated as much as possible with realistic computing resources.

A coordinating group is needed to develop a standardized method for deriving this product. The method would be implemented on a continental or regional basis by various institutions. In the initial phases of GOFC, we recommend that the change detection product focus on changes in forest extent. In the future, this would be expanded to cover other types of land cover conversion such as agricultural expansion.

The forest cover change product would be strongly linked to the fine resolution products. Identification of areas undergoing change would be flagged for more in-depth analysis with finer resolution data. It will also require linkages with the land cover map and fire scar product to assure consistency. The MODIS 250m and 1km land cover change products might serve as a useful linkage for GOFC.

A strong verification process will need to be an integral component of the method. This will involve high resolution data and a sampling strategy on the ground.

A pilot project should be carried out to select from existing change detection methods that can be operationally applied in the context of GOFC. Criteria for selecting a method include accuracy, feasibility to automate the process, and feasibility of implementing with realistic computing resources. The pilot project would be carried out in sample areas where changes are known to occur and where satellite data are available. The pilot project would establish confidence intervals that could be obtained with change detectable algorithms. During the first year, the focus should be on the selection of the most feasible algorithms. In the second year, this would be applied to sample areas where satellite data are available and changes are known to have occurred.

4.0 Active Fire Products

The recommended GOFC coarse resolution products include the development of a global fire monitoring and fire mapping system. Two capabilities are needed. First, the system would provide the capabilities to automatically detect fires on a daily basis using 1 km (250 m to 1 km in the future) resolution satellite data. Second, 1 km (250m in the future) data would also be used to map large (> 200 ha) fire burn boundaries on a seasonal basis.

Wildfires and biomass burning are significant agents of change in forest ecosystems, can cause major perturbations of atmospheric chemistry, often result in economic upsets, and some even result in the loss of human life. There are three main contributors to global fire:

- Land use change where forests are burned to convert forests to cleared land for agricultural crops or for pasture.
- Shifting agriculture or savanna burning where grasslands are burned to improve the soil for agricultural crops or for animal forage.
- Wildfires in woodlands (e.g., temperate forests, savannas, grasslands and shrub lands, conifer plantations, and eucalypt forests) around the world.

This product should benefit countries that do not have fire detection resources or countries that have fires that occur in remote areas. It will also benefit countries that cannot mount traditional forms of fire detection using aircraft or fire towers. The product will greatly shorten the time required to map large forest fires and it will provide a mechanism for inventorying fires on an international scale.

This type of information is also required by many countries for strategic fire management planning. Fire monitoring and end-of-season fire maps would also support updating of national and regional forest inventories, annual fire statistics reporting, criteria and indicators for monitoring sustainable forest management, and fire and global change research. In addition, the data have scientific value in studies on the interaction of climate change and forest fire trends. Information on fires and related emissions is the key to address this critical issue and will have a significant impact on forest policy.

Several initiatives have demonstrated algorithms to detect active fires and reject false alarms using AVHRR satellite data (1 km resolution) as input. Algorithms have been developed by: 1)

NASA/GSFC, by a team of researchers collaborating under the IGBP (Kaufman, et al., 1997), 2) Space Applications Institute of JRC (Pereira, 1998); and 3) Canada Centre for Remote Sensing (Li et al.,1997a, b, and c). With several proven fire detection algorithms that are considered to be robust and that provide similar results when applied to the same satellite data, it is possible to use more than one methodology. However, for purposes of consistency, a single methodology should be used. Rather than suggest a method, selection criteria should be developed. Then the group should consult with members of the IGBP-DIS fire project for assistance in defining this product.

Detailed post-fire burn boundary mapping would also use coarse resolution satellite data but finer resolution data sources could be used as dictated by requirements and budgets. This could be accomplished through close cooperation with the GOFC fine resolution products team.

Global, daily processing of AVHRR data is an enormous task, therefore a decentralized regional model may be appropriate for the development of these products. Considering current capabilities, the on-board recorders of the AVHRR sensor cannot store the data required to obtain global daily coverage at 1 km resolution. In order to acquire global coverage at 1 km resolution, AVHRR data would have to be captured by a network of ground stations. The JRC Fire Web project calls for various regional centers using the same software to extract active fire locations from real-time AVHRR data. In addition, the IGBP-DIS global 1 km AVHRR project currently uses a network of over 30 AVHRR ground stations (Eidenshink and Faundeen, 1994). The IGBP-DIS network, however, does not deliver data in real-time. A co-ordinated global network of real-time receiving stations is required. Each receiving station would have to be able to run the fire detection algorithm on site in order to reduce the amount of data that needs to be transferred to assemble the global fire product.

It is important to recognize that another CEOS initiative, the Disaster Management Support Project, has the primary concern for detection of active forest fires. In addition, there are several other organizations working toward operational fire products, including the IGBP, NASA's Earth Science Enterprise, and the European Commission Joint Research Centre's Space Applications Institute. Close collaboration with these organizations is essential. Even with the activities already underway, there are still several important development issues that need to be resolved, including:

- Development of technology needed to produce operational active fire products on a daily basis. For operational fire management programs, satellite data received as late as 3:00 pm must be analyzed to produce active fire hotspots 9:00 a.m. the following day. These data must be available internationally within 2-3 days of the regional analysis.
- Development and testing of automated algorithms for burned area classification must continue.
- Evaluation of fire mapping accuracy using finer satellite data and field observations. During the pilot phase, specific fire management organizations could provide support for verification assessments.
- Refinement of fire detection algorithms based on the results of the evaluation.
- Methods for using the data in key applications, such as producing daily fuel consumption and fire emissions products.

- Development of Internet processes and security procedures to manage and distribute products to test-clients through a world wide web.

The coarse resolution fire product must be closely linked to the land cover and biomass products. Both land cover and biomass mapping must be able to account for losses of forest cover and transitional changes (vegetation recovery) in biomass following disturbance. Although this strategy proposes to deal with fire detection, monitoring and mapping using coarse resolution satellite data, it will not be practical or desirable to completely separate coarse resolution products from fine resolution products.

As stated in the Implementation Strategy, fine resolution products may be required as a means of validating the coarse resolution mapping. Validation of the fire products has an advantage over validating other GOFC products (land cover, biomass, etc.) because most countries that experience wildfires also have agencies that have a clear mandate to manage fire. Validation will require the cooperation of these national and sub-national fire management agencies. Inconsistencies between the data and regional fire management agency statistics will have to be mitigated by a program of random data checks.

Three to four pilot projects should be undertaken. These pilot studies should include areas where there is a keen international interest such as South America and Indonesia. Natural Resources Canada (the Canadian Forest Service with the Canada Centre for Remote Sensing) is about to undertake a pilot project for monitoring and mapping fires in Canada over the next two years. Australia could be a candidate for a pilot project because the fire season there is often associated with large high pressure systems that are associated with clear skies over much of the country. Another candidate for a pilot project is the USA where some effort has already been expended on this problem at home and internationally. The USA has the advantage of mounting considerable resources to address this issue and they possess one of the most advanced telecommunication networks in the world.

5.0 Biophysical Product Summaries

A suite of related biophysical products, namely Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation (FPAR), Photosynthetically Active Radiation (PAR), and Net Primary Productivity (NPP) are needed to collectively provide estimates of annual forest ecosystem dynamics and productivity. An additional product, biomass, is needed to provide an indication of overall forest carbon stocks and sequestration potential, as well as provide land use implications.

The general strategy for LAI, FPAR, PAR, and NPP is similar, as these products are all related and needed to produce NPP. Because the MODIS product generation plans will become operational during the early years of GOFC, it is logical that they be used. However, it was also recognized that there are a variety of methods being used (e.g., model inversion, look-up tables, vegetation index- based), and other potential data sources (e.g., AVHRR, VEGETATION, GLI, MISR, MERIS, POLDER) so it is practical that other approaches be monitored and investigated.

5.1 Leaf Area Index

LAI is the basic input to process-based models of net primary productivity and carbon budget. Spatially explicit LAI data can also be used to improve other models, which involve land surface processes and parameterizations (Bonan et al., 1993). It is feasible to derive LAI from satellite imagery with a reasonable accuracy (Badhwar et al., 1986; Peterson et al., 1987; Nemani et al., 1994; Spanner et al., 1994; Chen and Cihlar, 1996), and thus this parameter is the critical step toward operational remote sensing applications in areas related to weather, climate and land surface processes, as well as modeling net primary productivity.

We recommend that the functional definition of LAI used to product GOFC coarse resolution products is "one half of the total leaf area per unit flat ground surface area (m^2/m^2)". The use of one half the total leaf area rather than the projected leaf area can unify the effects of different leaf shapes on optical measurements of LAI. The ground area should be projected to the horizontal surface to consider topographical effects on the detection of LAI it nadir and other angles. The LAI product should have a resolution of 1000m. The products are needed for weekly periods and should be available within a week following the production period.

The state of LAI estimation research suggests that LAI be derived from optical data. Methods used for LAI retrieval from multi-spectral optical imagery include: (1) model inversion; (2) look-up table (LUT); and (3) algorithms based on vegetation indices (VI). Model inversion approaches can be quite accurate if detailed radiative transfer processes are considered. However, the computation demand is much higher than other methods. There is also a tradeoff between model complexity and invertibility that makes operational use of this method difficult. The LUT strategy is regarded as a simplified form of model inversion, and may be most desirable for both efficiency and accuracy of computation. VI-based approaches are empirical but can also be efficient and accurate, provided sufficient data for validation are available. All these methods depend on land cover maps with the same projection and resolution. Thus, the land cover product must include classes needed for LAI estimation.

Ground-based measurements of LAI in various biomes in different locations are needed for validation. There are several techniques of measuring LAI on the ground: destructive sampling, allometry and optical instruments. Destructive sampling is labor intensive and time consuming, and is obviously not suitable for collecting data for a large number of sites. Allometry is often species and location specific (Gower, et al., 1997). It is also difficult to establish a suitable set of allometry of a large range of site conditions. Optical instruments hold the best promise for fast and accurate measurements of LAI and are recommended taking measurements needed for LAI validation.

Pilot projects should be conducted for a least one area in each forest biome. Possible sites include: (1) Smithsonian test sites in South America and Southeast Asia could represent the tropical biome; (2) U.S. Long Term Ecological Research (LTER) sites be considered for the temperate biome; and (3) the LAI/FPAR validation program in Canada led by Canada Centre for Remote Sensing be a candidate for boreal biome validation work. This is the minimum set of validation requirement, and multiple test sites for the same biome would be beneficial.

5.2 Fraction of Photosynthetically Active Radiation

FPAR is defined as the fraction of incident photosynthetic radiation (PAR) absorbed by green leaves in plant canopies. It is non-dimensional, and it excludes the fraction of PAR reflected back to space and the fraction absorbed by the underlying surface and non-green materials in the canopy. There is a difference between instantaneous FPAR and daily FPAR (Goward and Huemmrich, 1992). FPAR times incident PAR gives the absorbed PAR (APAR), and APAR is useful for many semi-empirical models of net primary productivity, although in process-based models, FPAR can be calculated from LAI on a cover type basis (Liu, et al., 1997). We suggest that daily FPAR be produced as standard product for the convenience of obtaining daily total PAR absorbed by plant canopies. FPAR products should correspond to weekly baseline periods and should be available within a week following production. The estimates should be 5-10% of actual PAR.

FPAR can be retrieved from multi-spectral optical imagery using the same methods listed for LAI estimation. The accuracy in retrieving FPAR is potentially higher than that in retrieving LAI because FPAR can be more accurately measured on the ground and has more direct effects on remote sensing signals than LAI. FPAR products therefore have advantages in modeling applications, although many process models prefer LAI over FPAR as input.

Consistent FPAR data sets from different biomes are needed for validation purposes. Field estimates can be obtained for a variety of portable instruments and mobile sensors. Pilot validation projects should be carried out in conjunction with LAI validation projects discussed .

5.3 Photosynthetically Active Radiation

The PAR product is also needed to calculate NPP. It is the total photosynthetic active radiation incident on a horizontal surface on the top of a plant canopy. It is in unit of either micromol/m^2/s or W/m^2. Solar radiation is the main driving force affecting all biological and physical processes in plant canopies. PAR is the main control on photosynthesis of plants. NPP is basically proportional to PAR (Monteith and Unsworth, 1990), although temperature, moisture, nutrients, etc. can considerably modify the proportionality. It is therefore crucial to improve the accuracy of this product. PAR products are to be used with FPAR products to obtain APAR (absorbed PAR), i.e. APAR=FPAR*PAR. For regional and global NPP estimation, daily total PAR is the recommended product. The spatial resolution can be considerably coarser than the associated LAI and NPP products; 0.5-1.0 degree resolution may be adequate. The products should be available within a week following the production period. The estimates should be 2-5% of actual PAR.

Spatial distribution of PAR, either instantaneous or daily total, can be obtained from either satellite measurements or from weather prediction models. Geostationary satellites provide frequent PAR measurements for low and middle latitudes (Gu and Smith 1997), and polar orbiting satellites are useful for high latitudes but need temporal scaling methods to obtain the daily total of PAR (Li et al., 1993). Satellite-based products are generally more accurate than gridded weather forecast or reanalysis data, but programs for operational production of daily PAR at the global or continental scale have not been identified. The short-term solution would be pilot projects to validate gridded weather data using satellite imagery for selected areas and seasons.

Both satellite derived and gridded weather data need validation using ground measurements. Surface measurement data sets have been assembled and analysed by the International Satellite Cloud Climatology Project, and these could be used by GOFC. Efforts are needed to have operational production of PAR products using satellite measurements so that the current reliance on weather prediction data can be phased out. Pilot projects could be established to achieve this goal.

5.4 Net Primary Production

Net primary productivity (NPP) is defined as the new carbon stored in vegetation (leaves, stems and roots) per unit space and time. It is the difference between gross photosynthesis and autotrophic respiration. Annual total NPP is usually reported in unit of $gC/m^2/yr$ or tC/ha/yr. NPP provides a highly synthesized measure for ecosystem performance. It is useful for both sustainable forest management and biotic carbon budget estimation. NPP is an important component in the global carbon cycle, affecting not only the carbon stored in vegetation but also the heterotrophic respiration since most of the new carbon is turned over to soils in a short time period. To understand the role of vegetation in global carbon budget and the impact of climate changes as well as vegetation feedback to the climate system, NPP is urgently needed at regional and global scales.

Both weekly and annual estimates of NPP are needed, with the products corresponding to weekly baseline periods, available within a week following this period, and having 1000m resolution. Daily calculation steps should be apparent in the products. At this point, both empirical and process- based models should be considered.

Process-based model estimation of NPP is potentially most accurate, provided satellite and ancillary data are available. Satellite imagery provides the critical spatial distributions of land cover and LAI (Running et al., 1994). Ancillary data required are soil texture (for available water holding capacity), meteorological variables (radiation, temperature, precipitation and humidity), and above- ground and below-ground biomass. The preferred data interval is daily for NPP estimation (Hunt and Running, 1992, Liu et al., 1997). Process-models use either LAI or FPAR as input, but corresponding land cover map at the same projection and resolution as the LAI or FPAR is always needed. LAI and FPAR can be converted from each other for the same land cover types. Semi-empirical methods usually relate NPP to absorbed PAR (APAR) in plant canopies, estimated as the product of FPAR and PAR. Other variables are used to modify to relationship between APAR and NPP (Prince and Goward, 1995). Autotrophic respiration in forest stands usually consumes more than 50% of the gross photosynthesis (Ryan, 1991) and is sensitive to both temperature and biomass. Biomass is therefore an important input to NPP models. As accurate biomass maps derived using remote sensing techniques are not yet available for large areas, a short term solution is to estimate biomass from land cover types with density classes.

The ideal strategy for NPP validation is to have coincident NPP measurements with LAI/FPAR measurements. In this way, not only NPP results but also NPP models can be validated. However, NPP data available for validation are sparse, especially for forest ecosystems. Published measurements for various biomes and different time scales are very limited. NPP also vary considerably between years. Global NPP distributions from various models are often very different (Potter et al., 1993; Melillo et al., 1993; Foley, 1994; Woodward et al., 1995). In recent years, efforts have been made to obtain these measurements on small and large scales.

5.5 Biomass

The forest biomass product has a strong research component and should be viewed as evolutionary. Biomass is defined as total amount of organic matters existing in a unit area at one instance, and described by a weight of organic matters in dry condition. The unit of biomass is, therefore, g/m^2, kg/m^2 or ton/ha. Vegetation biomass includes leaf, stem, root, fruit and flower. However, the product would be limited to providing total above-ground biomass.

Biomass is one of the most important biophysical parameters which defines the carbon budget in a terrestrial ecosystem. Basically, biomass is a parameter defined at the ground level, and is measured only at the ground by cutting trees or grasses and by measuring their dry weight. Satellite observation data cannot provide direct measurement of biomass but can provide indirect estimation based on in-situ field data and on models. Biomass estimation by satellite observation is still in the research phase and the biomass product in this project has a strong research component. It is, therefore, strongly recommended that CEOS promotes parallel research initiatives to develop in-situ observation methods and to develop models relating biomass with remotely sensed data. It should be also noted that this product would be linked with high resolution products on land cover classification and vegetation density.

There have been two potential methods to estimate biomass from satellite data:

- Vegetation classification based method: In this approach biomass is estimated based on vegetation type classification and on the unit biomass value predetermined for each vegetation type which is basically obtained from the ground observation. Multiplication between the area extent of each vegetation type and the predetermined unit biomass for each type would give the estimate of total biomass. Information on vegetation age or height and vegetation density would increase estimation accuracy. High resolution SAR data may provide the parameters for each vegetation type.
- Direct observation of leaf and stem density (fresh biomass): Many investigations have indicated that there is a correlation between microwave backscattering coefficients derived from SAR data and biomass (fresh biomass) in leaves and stems of vegetation. However, correlation is usually vegetation types specific, and we need to investigate the relation between them for all of the vegetation types. The spatial scale of this approach is local at the moment and cannot cover country or continental spatial scale.

We recommend that the first approach be used initially to produce the coarse resolution biomass product. In this case biomass product generation is reduced to the generation of coarse resolution land cover product. A unit biomass database for vegetation types should be developed based on the ground observation and high spatial observation from satellite. The second approach can be implemented as a tool to determine a unit biomass for each vegetation type in a local scale. Vegetation density and vegetation height or age may be estimated from high spatial resolution data (multi-polarization and multi-frequency SAR), and be used to increase the accuracy of biomass estimates for each vegetation type. We expect accuracy within10-20%.

The spatial resolution of the product would be 250m-1000m, and cycle interval should be 5 years, which corresponds to the baseline period for global land cover product.

We recommend that CEOS promote ground observation campaigns to investigate biomass estimation models and to establish a unit biomass database for vegetation types. In this campaign in- situ data relevant to biomass, LAI, APAR and NPP are collected together with the high spatial satellite data and their relations are investigated. Validation and verification processes are essential and should be carried out as a part of the ground observation campaign.

The biomass product would be strongly linked with the land cover and the forest density products at both fine and coarse resolutions. Also the basic part of biomass product generation is common with that of NPP, LAI and other relevant products, therefore, they should be linked together. It also requires the linkage between the current on-going projects such as the MODIS project and the GLI project, which are going to produce similar products.

A pilot project, linked with the ground observation campaign, should be carried out at several test sites representing typical vegetation types covering different ages and different vegetation densities. The sites should be selected from the different zones including American continent, Eurasian continent and Europe-African continent. Candidate sites include the BOREAS sites, Smithsonian sites, and LTER sites. The pilot project should be jointly organized with groups on other biophysical products.

A pilot project should be two years in total, and in the first year appropriate sites are selected based on the previous works and available data for the sites are collected. In parallel to it, inventories for biomass are investigated and a biomass database is developed. In the second year biomass estimation models are developed. Also a preliminary biomass map is produced for the selected regions including the test sites.

6.0 Data Format Considerations

Data formats, including metadata, must be both compliant with appropriate national and international standards. Technical elements of data sets, such as projections and datum, must be usable within most commercial image processing and geographic information systems.

With regard to data formats, the coarse resolution design team discussed the issue of map projections for the coarse resolution products. This issue can benefit from the experience of both the Pathfinder products and the plans for MODIS product generation. After considerable discussion, the group determined that projection specialists should be consulted for advice on map projections. While a solution was not reached, several areas of consensus were reached:

- Two or more projections will likely be needed. An archive projection will be needed for product generation and archiving, and "user" projections will be needed for applications.
- The archive projection should have equal-area characteristics with minimal distortions of areas. Ideally, there should be capabilities in commercial-off-the-shelf image processing and geographic information software to reproject from the archive format. The archive projection should also provide for efficient data storage.
- User projections should be conveniently and universally handled by commercial-off-the-shelf image processing and geographic information software.
- There must be some level of compatibility between the fine and coarse resolution product projections.

The MODIS projection and the Pathfinder projections were both recognized as candidates for the archive projection. Data in latitude/longitude grids and the Mercator projection are possible strategies for the user projections. Adequate warning to caution users about the decay in data quality associated with conversions to some projections.

7.0 Other Considerations

In order to successful produce coarse resolution forest products, several critical issues must be addressed. Perhaps the most serious issue affecting the design of the coarse resolution products is the uncertainty of the availability and specifications of monitoring data (i.e., 250-1000m) from earth observations satellites. While there are some excellent candidates for the first 5-10 years, the picture becomes uncertain beyond that time. GOFC should urge CEOS members to work toward a long-term commitment for space-based environmental monitoring data. Because of this, the following recommendations should be posed to CEOS, IGBP, and their supporters:

- Continued collection of daily global AVHRR data and generation of science-quality 1-km composites, for at least two years following the successful launch of MODIS or similar coarse resolution instruments.
- A long-term commitment to 250m and 500m daily global imagery is essential for the operational success of GOFC. There is clearly a need for global data at this resolution. This resolution is especially important when considering the uses of the coarse resolution products for forest management and sustainable forestry applications, but is also central to improving the value of global forest observations for scientific studies.

Finally, to the extent technically possible, both fine and coarse resolution data should be acquired at the same times so that radiometric cross calibration and correction for atmospheric contamination can be done using similar inputs.

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Table 1. Product priorities

Product	Science	Policy	Forest Manage-ment	Other	Overall Rank
Global Land Cover with Canopy Density	High	High	High	High	High
Forest Cover Change	High	High	High	High	High
Active Fires	High	High	High	High	High
Fire Scars	High	High	Medium	Medium	High
Biomass	High	High	High	Low	High
Leaf Area Index	High	High	Medium	Low	Medium
FPAR	High	High	Medium	Low	Medium
PAR	High	High	Medium	Low	Medium
Net Primary Productivity	High	High	Medium	Low	Medium

Table 2. Summary of Product Characteristics

Product	Informatio n Content	Spatial Resolution	Temporal Cycle	Availability after Cycle
Global Land Cover with Canopy Density	40-60 classes of cover, with 50-60 describing forests; canopy density in percent cover	500 m	5 years	1 year
Forest Cover Change	Change, No-Change	250 m	Annual	1 month
Active Fires	Fire, No-Fire	1000 m	Daily	3 Days
Fire Scars	Burned, Not Burned	500 m	Annual	2 months
Biomass	Tons C/ha, g C/M^2	1000 m	5 years	3 years
Leaf Area Index	m^2/m^2 within 0.2-1 of actual	1000 m	Weekly	7 days
FPAR	Within 5-10% of actual	1000 m	Weekly	7 days
PAR	Within 2-5% of actual	>1000 m	Daily	7 days
Net Primary Productivity	Within 20-30% of actual	1000 m	Weekly, Annual	14 days

Table 3. Optimal classification legend for a global land cover product

Canopy Longevity	**Leaf Type**	**Canopy Density**	**Canopy Height**
Evergreen	Needleleaf	Closed	Trees
Evergreen	Broadleaf	Closed	Trees
Deciduous	Needleleaf	Closed	Trees
Deciduous	Broadleaf	Closed	Trees
Mixed		Closed	Trees
Evergreen	Needleleaf	Open	Trees
Evergreen	Broadleaf	Open	Trees
Deciduous	Needleleaf	Open	Trees
Deciduous	Broadleaf	Open	Trees
Mixed		Open	Trees
Evergreen	Needleleaf	Woodland	Trees
Evergreen	Broadleaf	Woodland	Trees
Deciduous	Needleleaf	Woodland	Trees
Deciduous	Broadleaf	Woodland	Trees
Mixed		Woodland	Trees
Evergreen	Needleleaf	Closed	Tall Shrubs
Evergreen	Broadleaf	Closed	Tall Shrubs
Deciduous	Broadleaf	Closed	Tall Shrubs
Mixed		Closed	Tall Shrubs
Evergreen	Needleleaf	Open	Tall Shrubs
Evergreen	Broadleaf	Open	Tall Shrubs
Deciduous	Broadleaf	Open	Tall Shrubs
Mixed		Open	Tall Shrubs
Evergreen	Needleleaf	Closed	Low Shrubs
Evergreen	Broadleaf	Closed	Low Shrubs

Deciduous	Broadleaf	Closed	Low Shrubs
Mixed		Closed	Low Shrubs
Evergreen	Needleleaf	Open	Low Shrubs
Evergreen	Broadleaf	Open	Low Shrubs
Deciduous	Broadleaf	Open	Low Shrubs
Mixed		Open	Low Shrubs
Evergreen	Needleleaf	Closed	Dwarf Shrubs
Evergreen	Broadleaf	Closed	Dwarf Shrubs
Deciduous	Broadleaf	Closed	Dwarf Shrubs
Mixed		Closed	Dwarf Shrubs
Evergreen	Needleleaf	Open	Dwarf Shrubs
Evergreen	Broadleaf	Open	Dwarf Shrubs
Deciduous	Broadleaf	Open	Dwarf Shrubs
Mixed		Open	Dwarf Shrubs
Grasslands			
Croplands			
Built-Up			
Barren or Sparsely Vegetated			
Snow and Ice			
Water			

Appendix 1 – List of Participants in the July 1998 GOFC Coarse Resolution Design Team Workshop

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