Global biomass mapping for an improved understanding of the CO$_2$ balance—the Earth observation mission Carbon-3D

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Abstract

Understanding global climate change and developing strategies for sustainable use of our environmental resources are major scientific and political challenges. In response to an announcement of the German Aerospace Center (DLR) for a national Earth observation (EO) mission, the Friedrich-Schiller University Jena and the JenaOptronik GmbH proposed the EO mission Carbon-3D. The data products of this mission will for the first time accurately estimate aboveground biomass globally, one of the most important parameters of the carbon cycle. Simultaneous acquisition of multiangle optical with Light Detection and Ranging (LIDAR) observations is unprecedented. The optical imager extrapolates the laser-retrieved height profiles to biophysical vegetation maps. This innovative mission will reduce uncertainties about net effects of deforestation and forest regrowth on atmospheric CO$_2$ concentrations and will also provide key biophysical information for biosphere models.

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1. Introduction

In 2003, the Friedrich-Schiller University Jena and the JenaOptronik proposed the Earth observation mission “Carbon-3D” for global biomass mapping combining the LIDAR system Vegetation Canopy Lidar (VCL) with a Bidirectional Reflectance Distribution function (BRDF) imager on one platform. Carbon-3D improves the knowledge about spatiotemporal patterns and magnitudes of major carbon fluxes between land, atmosphere, and oceans, and allows quantifying aboveground stocks. Because land use, land use change, and forestry activities, as well as vegetation response to enhanced levels of atmospheric CO$_2$, are the major influences on greenhouse gas emissions, quantifying carbon stocks and changes is critical (Cihlar et al., 2002; Harris & Battrick, 2001). Aboveground biomass stocks are also a key parameter in assessing the economic, conservation, and biofuel potential of land surfaces. The provision of a sensor that measures these stocks and their change in space and time is therefore paramount. Global data sets like “Global Tree Cover” (Fig. 1) exhibit high uncertainties for forest cover estimates and amount of carbon stored in different types of forest.

The mission is also relevant for contributing key data on the environmental consequences of nonclimatic global change resulting from continued global population growth, economic globalisation, and expanding land use.
The technical innovation of Carbon-3D is the simultaneous operation of a LIDAR (NASA’s Vegetation Canopy Lidar—VCL) with a multiangle imager providing BRDF information (Bidirectional Reflectance Distribution Function). Carbon-3D’s strength is the combined information on both the fine-scale vertical structure of the canopy (through waveform analysis of the vertical laser profile) and biophysical properties of the surface targets (through multi-angular optical observation of vegetation targets with three-dimensional spatial structure). The BRDF information allows extrapolation of the point measurements to complete spatial coverage.

Large-footprint LIDAR remote sensing is a breakthrough technology for the estimation of important forest structure characteristics. The waveform information (Fig. 2) enables direct determination of vegetation height, the vertical structure of intercepted surfaces, and the subcanopy topography. A critical issue and key requirement for accurate parameter assessment is the ability to identify precisely the top of the canopy, as well as the ground reference level. Accurate retrieval of vertical forest parameters is essential as other biophysical forest characteristics, such as biomass, stem diameter, and basal area, are modelled on the base of these measurements. Aboveground biomass is commonly modelled using the height information by performing regression analyses or applying allometric height–biomass relations (Drake et al., 2003). Traditional predictive models require information on stem diameter to estimate biomass and volume. This parameter is a function of tree height and thus could be inferred on the basis of LIDAR data.

Recent studies have proven the high benefit of large-footprint scanning airborne LIDAR; depending on the respective study area, total aboveground biomass as estimated from field data could be predicted from airborne
LIDAR-derived metrics with $R^2$ values of up to 0.96 on biomass levels of 1300 t/ha, which is far exceeding the capabilities of radar (Drake et al., 2002b; Lefsky et al., 1999a). One major limitation of stand-alone LIDAR systems is their capability to retrieve locally sparse information on vertical forest structure only. For spatially consistent biomass assessment, information on horizontal biophysical forest parameters, e.g., phenology and forest type, is essential. To gain such information simultaneously, the proposed Carbon-3D mission will be equipped with the multangle imager in the range of VIS/NIR/SWIR. Driven mainly by the needs of NASA’s MISR and MODIS mission, considerable work was done regarding the development of BRDF model inversion algorithms for vegetation, surface, and climate parameter retrieval (Knyazikhin et al., 1998; Lucht et al., 2000). With the high spatial resolution of Carbon-3D, it will be possible to exploit more complex BRDF models, i.e., physically based approaches, for precise parameter retrieval. In addition, the use of Look-Up Table (LUT) techniques is expected to enable the derivation of the geophysical data products with a high accuracy (Barnsley et al., 2000).

Data provided by the BRDF instrument onboard the Carbon-3D satellite are also required to extrapolate spatially, regionalizing the LIDAR point measurement on vegetation structure between the transects and to regions where no LIDAR data exist. The spatial extrapolation of forest structure, as derived from locally sparse LIDAR data using radiometer measurements, is central to the mission objectives (see Section 5.1).

2. Strategic positioning of Carbon-3D

The role of vegetation in reducing atmospheric levels of CO$_2$ has been recognised in a number of international agreements [e.g., United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol], which specifically require countries to quantify their carbon stocks and changes. Plants store carbon in above- and belowground biomass, 90% of the aboveground carbon is stored in tree stems—which are being reduced through natural (diseases, wildfires, drought/flooding) and anthropogenic impacts (logging, pollution, human-induced fires), or vice versa increased through regeneration or promoted growth associated with elevated CO$_2$ levels in the atmosphere (Wardle et al., 2003).

Currently, the magnitude of the terrestrial carbon sink is considerably reduced by expanding land use. In the 1990s, terrestrial uptake has been estimated to have been 1.6–4.8 billion tons of carbon per year (GtC/year), a notable fraction of the 6.3 GtC/year that have been emitted from fossil fuel burning. However, losses due to land use are estimated to have amounted to 1.4 to 3.0 GtC/year, leaving the net uptake of carbon from the atmosphere by the biosphere to have been about 1.0±0.8 GtC/year (House et al., 2003). This sink is the result of the combined changes in carbon content of vegetation, litter, and soils. Changes in the carbon flux from vegetation into the litter and soil pools can be estimated from the carbon pools in vegetation. The relative magnitudes of these fluxes demonstrate the importance of interactions between atmospheric composition, biospheric biogeochemistry, and land use for determining the rate of climate change.

Carbon-3D will be an essential contribution to carbon cycle investigations by providing crucial and unique data on vegetation biomass, vegetation productivity, and vegetation types and structure. Model-based extensions of these data will also allow estimations of soil carbon stocks and dynamics with unprecedented spatial detail, and hence the land surface carbon balance. Particularly, the spatial heterogeneity of carbon-related vegetation properties, such as the status of regrowth in intensely managed forests, will be quantified.

These products will fill substantial gaps in current continental-scale carbon assessments which are specifically related to problems of spatial heterogeneity and scaling, as well as reliable quantifications of pool sizes. By observing biomass around the globe, the proposed mission will build a much needed bridge between knowledge gained at sites and the spatially poor resolved information from atmospheric inversion studies (Janssens et al., 2003). Biogeochemical process models of vegetation and soil and the associated carbon and water fluxes will benefit from the upscaling and validation data that will be available, and it will be possible to assimilate the observations into these simulations.

Vegetation biomass is the direct result of vegetation productivity, that is, of the net carbon exchange between the atmosphere and the photosynthetically active tissues of plants. Estimates of net primary production will be improved by not only using estimates of absorbed light, as do current satellite-based algorithms, but also the observed vegetation structure in terms of types and age. This will provide a firm basis for the estimation of autotrophic respiration, a critical but highly uncertain component of previous satellite-driven global model estimates of net primary production.

The implications of changes in biomass for the atmospheric greenhouse gas balance and the future evolution of climate change are critical. The temporal and spatial variations in observations of atmospheric CO$_2$ contain a strong biospheric signal. There is substantial evidence from model studies that the current role of the terrestrial biosphere as a net sink for CO$_2$, and therefore a brake on the build-up of anthropogenic CO$_2$ in the atmosphere, could be reversed during this century as a result of climate change.

3. Modelling carbon fluxes—scientific and technological state of the art

An observation system for carbon stocks and fluxes in vegetation consists of both observations and modelling
Observations characterise processes, spatial and temporal patterns of vegetation structure and activity, while modelling allows to infer from such observations a full carbon account of the surfaces viewed by computing the climate-dependent biogeochemical processes that contribute to the overall surface budget, including the dynamics of carbon pools not accessible to observation (e.g., in soils; Nemani et al., 2003; Potter et al., 2003). A side effect of such modelling is that the magnitude of evapotranspiration, and resulting effects upon soil moisture can be estimated at the same time due to the close coupling of the carbon and water cycles in vegetation (Gerten et al., 2004).

### 3.1. In situ biomass and carbon determination

At the tree level, biomass cannot be assessed directly by nondestructive methods but is usually derived from measurements, such as diameter-at-breast-height (dbh), tree height, and wood density using conversion factors. These biomass estimation methods are relatively time consuming and expensive, not uniformly standardised across the world, and are characterized in many regions by undersampling. Uncertainty also arises from insufficiently validated allometric equations. Upscaling of inventory data to the continental scale remains a challenge (Janssens et al., 2003) and is possible only where the sampling density is sufficient (Kauppi et al., 1992; Liski et al., 2003; Nabuurs et al., 2003; Shvidenko & Nilsson, 2002).

About 100 flux towers have been installed around the globe to directly measure net carbon exchanges above canopies (e.g., Lloyd et al., 2002). These measurements of net fluxes do not immediately allow a differentiation between CO₂ exchanges through vegetation and CO₂ exchanged by soils. An extrapolation of the obtained data to the continental scale (Papale & Valentini, 2003) remains uncertain, but they provide valuable process understanding. Direct measurements of atmospheric CO₂ concentrations are undertaken at a network of stations. Their spatial differences can be inverted by taking into account wind and emission patterns, as well as the effect of the oceans to deduce source-sink distributions for very large regions (Bousquet et al., 1999). The results suffer from a lack of regional pattern and insufficient sampling but are very valuable as the only currently available independent information on large-scale net fluxes.

The above methods are coordinated in observing networks, such as CARBOEUROFLUX, AMERIFLUX, FLUXNET, and LTER (FAO, 2003), and the Terrestrial Ecosystem Monitoring Sites (TEMS) managed by the Global Terrestrial Observing System GTOS.

### 3.2. Simulation of Biomass and NPP in biosphere models

Carbon fluxes between atmosphere and biosphere can be estimated using a range of global biosphere models that simulate the magnitude and geographical distribution of biomass and NPP (Cramer et al., 1999). These models range from simple carbon cycle models to complex ecosystem models that include dynamic vegetation models.

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**Fig. 3.** Role of Carbon-3D in the observation and modelling strategy of the carbon cycle.
in complexity from regressions between climatic variables and one or more estimates of biospheric trace gas fluxes to quasi-mechanistic models that simulate the biophysical and ecophysiological processes. Several different classification systems and descriptions of biosphere models exist in the literature (e.g., Beringer et al., 2002; Cramer et al., 1999, 2001; Peng, 2000; Prentice et al., 2000). The simplest differentiation is that into Static (Equilibrium) and Dynamic Vegetation Models (SVMs and DVMs). SVMs are time-independent and assume equilibrium conditions in climate and terrestrial vegetation to simulate the global distribution of potential vegetation by relating the geographic distribution of climatic parameters to vegetation. DVMs are time-dependent process-based models that simulate the carbon balance of ecosystems under climatically induced changes to ecosystem structure and composition (Peng, 2000). The great strength of DVMs is their generality and predictive capability. By accurately representing the biophysical processes involved, they allow calculations of the long-term behaviour of vegetation systems under changing climate (Cramer et al., 1999; Foley et al., 1996; Peng, 2000; Prentice et al., 2000; Sitch et al., 2003). To achieve this, they use generalised plant functional types (PFTs) to represent the state of vegetation in each grid cell and to simulate plant succession processes like establishment, tree growth, competition, and mortality.

Fire occurrence is modelled based on natural probabilities as a joint function of vegetation and litter state and climate. The majority of models addresses the potential natural state of vegetation, although increasingly human processes are being incorporated, most notably agriculture. In mechanistic models, biogeochemical fluxes in the vegetation–soil system are computed on the basis of soil type, climate, and atmospheric carbon dioxide concentration without additional reference to external data. Exchanges of water and carbon through the stomates of leaves are simulated as physiologically coupled water and carbon balances. Hydrological processes taken into consideration include percolation, evaporation, and runoff, interception by vegetation, snowfall and permafrost. Carbon assimilation is calculated from numerical simulations of photosynthesis. The carbon gained is used for plant respiration, growth, and reproduction following allometric relationships that ensure functional and structural coherence. Carbon fluxes into the litter and soil are estimated from vegetation parameters. Computations of climatically dependent soil decomposition are used to calculate the net carbon balance of the vegetation–soil system as the difference between vegetation net uptake and carbon release from soils and through fire. Vegetation models have been shown to be able to reproduce a wide range of observed data from seasonal cycles of atmospheric carbon dioxide concentrations and growth rates to runoff and soil moisture, global vegetation patterns, and satellite-observed trends in vegetation greenness (Gerten et al., 2004; Kucharik et al., 2000; Lucht et al., 2002; McGuire et al., 2001; Sitch et al., 2003; Wagner et al., 2003b). Due to their generalised nature, however, they are not fully capable of producing the full spatial and temporal detail of the real world, nor can human alterations of the land surface be inherently formulated as mechanistic processes.

Recently, a new type of regional vegetation models, which aim at combining process-based descriptions and available knowledge on individual landscapes in the form of a multilayer Geo Information System (GIS), has been proposed (Nilsson et al., 2003; Shvidenko & Nilsson, 2002).

3.3. Biomass determination by remote sensing

Dong et al. (2003) and Myneni et al. (2001) provide examples of using optical remote sensing data to determine biomass with high spatial resolution at the continental scale using NDVI. Their method of correlating seasonally integrated measures of satellite-observed vegetation greenness with ground-based inventory data amounts to a spatial interpolation and extrapolation of the inventory data. While pioneering, the work is indirect in that direct space-based measurements of biomass are not available. The upscaling used relies on the unknown degree to which the sample of inventories used is representative of the whole of a continental area.

Correlations of Synthetic Aperture Radar (SAR) data to biomass have been proven at low frequencies L- and P-band (Eriksson et al., 2003; Le Toan, 1992; Ranson et al., 1997; Rowland et al., 2002) and at C-band using ERS-1/2 repeat-pass interferometry (Santoro et al., 2002) and combining ERS tandem interferometric coherence and JERS backscatter (Balzter et al., 2002; Wagner et al., 2003a). Multipolarimetric SAR data allow interpretation of the canopy structure up to 200 t/ha aboveground biomass at P-band and 100 t/ha at L-band (Dobson et al., 1992). Recently developed PolInSAR techniques, combining polarimetry and interferometry (Cloude & Papathanassiou, 1998; Papathanassiou & Cloude, 2001) provide better vegetation characterisation and a sensitivity up to 400 t/ha (Mette et al., 2003). No such system is foreseen yet for operational service in space, but the PolInSAR techniques will be tested within the framework of the "Kyoto and Carbon Initiative” with Phased Array type L-band Synthetic Aperture Radar (PALSAR) data from the Advanced Land Observing Satellite (ALOS; Rosenqvist et al., 2001, 2003). ALOS is planned to be launched in 2005.

In contrast to the frequent attempts of using SAR for biomass estimations, only a few airborne light detection and ranging (LIDAR) missions have been developed and validated: the Laser Vegetation Imaging Sensor (LVIS) and the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER). Results of these studies have demonstrated that large-footprint LIDAR instruments show great promise in biomass estimation of tropical as well as temperate forests due to the information about the location of the intercepting surfaces and subcanopy topography (Drake et al., 2002a; Lefsky et al., 1999a,b).
Due to the correlation between light absorption and net carbon uptake by vegetation, a range of diagnostic methods exists for converting optical satellite observations into estimates of net primary production (e.g., Nemani et al., 2003; Potter et al., 2003; Veroustraete et al., 2002). The relationship between these quantities is considerably moderated by effects of temperature and soil moisture, limiting the accuracy of the assessment. The use of satellite data, however, ensures fine spatial and temporal detail. Derivation of biomass from these estimates requires use of a full biogeochemical process model.

4. Description of the mission

Carbon-3D is designed to ensure the overall science-driven goal: global acquisition of a combined, synergistic BRDF-LIDAR data set to continuously map height profiles and reflectance to retrieve biomass (Fig. 4).

Required ground data will be obtained from terrestrial monitoring sites linked to worldwide observation networks and associated regional projects. The scientific project leader is coordinating ESA's Landcover Implementation Office starting in 2004 and will be able to establish close links to global landcover validation activities and the CEOS landcover validation team. If Carbon-3D will be selected for the phase A and B study in 2004 and 2005, the system will be launched in 2009.

4.1. The Carbon-3D BRDF sensor

The BRDF imager is a multispectral pushbroom imager that is sampling the Bidirectional Reflectance Distribution Function of the target scenery (Table 1). The mission design lifetime will be 2 years with an orbit of 390–410 km (with monthly reboost to 410 km using monopropellant hydrazine). The spatial resolution at nadir will be <25 m to match the VCL resolution, allowing for approximately 50 m spatial resolution at the extreme off-nadir angles for BRDF angular acquisitions. The BRDF Imager will consist of two identical Three-Mirror-Anastigmat (TMA) imaging subsystems, a nadir imager and an off-nadir imager.

4.2. The Carbon-3D VCL sensor

The Vegetation Canopy LIDAR (VCL) instrument consists of three near-infrared laser beams (Table 2). The instrument is designed to operate at an orbital altitude of 400 km ±10%. That does require orbital maintenance every few weeks, but higher orbits have a significant impact on the quality of the received laser signal.

Laser altimetry is the only space-based remote sensing technique capable of measuring tree heights in closed canopies. Waveform analyses based on extensive airborne and spaceborne laser altimetry have revealed the need for footprint sizes of about one to two canopy diameters. This

Table 1

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<th>BRDF instrument description</th>
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<tr>
<td>Sensor/FOV</td>
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<tr>
<td>Directional sequence</td>
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<tr>
<td>Spatial resolution</td>
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<tr>
<td>Image swath</td>
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<tr>
<td>Spectral bands</td>
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<td>Radiometric resolution</td>
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<td>SNR</td>
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<tr>
<td>Data rate</td>
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<td>Design lifetime</td>
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Fig. 4. Carbon-3D BRDF imager and VCL data acquisition configuration.
guarantees a resulting reflection from the vertical top of canopies within the sampled area, as well as sufficient intra- and intertree gaps required to image the underlying ground. Sufficient laser output energy and dynamic range in the receiver are required to detect small (~1%) returns from the canopy top and, even in dense canopies, the underlying ground. Smaller footprints underestimate true canopy height (reduced probability of sampling the top of the canopy). Conversely, with larger footprints, similar to those of the ICESat mission (Ice, Cloud, and land Elevation Satellite) with the Geoscience Laser Altimeter System (GLAS; Zwally et al., 2002), the fraction of the total return contributed by the canopy top is greatly reduced, making height measurements inaccurate, especially in mature forests with great height variability (ICESat’s primary scientific objective is to measure changes in elevation of the Greenland and Antarctic ice sheets as part of NASA’s Earth Observing System of satellites).

4.3. Carbon-3D in case of degradation

The proposed BRDF instrument design is generally conceived to minimize technical risks. In the case of degradation of one spectral band, the core products of the Carbon-3D mission could be assessed with reliable accuracy. Additionally, data provided by other sensors, such as MODIS could be used to minimize information loss, whereby errors due to different acquisition times and spatial resolution have to be considered. Concerning the retrieval of LAI, the degradation of the red or NIR channel would be critical. The channel at 2.2 μm is of special interest for the atmospheric correction, and in case of its breakdown, data provided by other missions have to be utilized. Furthermore, the deterioration of the spatial resolution of the optical instrument would be conceivable. As a result, land cover information and vegetation parameters derived by the optical instrument would be less precise (the BRDF instrument onboard of Carbon-3D has a high resolution—25 m at nadir and 50 m at off-nadir). Carbon-3D is designed for vegetation parameter retrieval at global scales. For such applications, a coarser spatial resolution would be admissible, especially when considering that the LIDAR information has to be extrapolated over large areas.

Several studies have been conducted for the VCL instrument that explore the effects of degraded or lost lasers. A minimum science mission of one laser operating for 1 year would provide enough canopy data to provide an order of magnitude increase in our knowledge of global tree heights and thus of biomass. The simulated coverage for

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**Table 2**

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<th>VCL instrument description</th>
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<tr>
<td>Lasers</td>
<td>3 Nd:YAG diode-pumped pulsed lasers at 1064 nm</td>
</tr>
<tr>
<td>Laser pulses</td>
<td>242 pps (land), 10 mJ per pulse (EOL; 15 M, BOL)</td>
</tr>
<tr>
<td>Telescope</td>
<td>0.9 m f/1 parabolic mirror with 20 mrad total FOV and 0.3 mrad IFOV</td>
</tr>
<tr>
<td>Waveform digitisation</td>
<td>250 Mega samples/s</td>
</tr>
<tr>
<td>Resolution</td>
<td>25-m (60 μrad) footprint diameter, 400-km altitude</td>
</tr>
<tr>
<td>Track spacing and swath</td>
<td>4 km (three tracks with 4 km spacing), swath: 8 km</td>
</tr>
<tr>
<td>Elevation accuracy</td>
<td>~1 m in low slope terrain</td>
</tr>
<tr>
<td>Veg. height accuracy</td>
<td>~1 m limited by 100:1 pulse detection dynamic range</td>
</tr>
<tr>
<td>Design lifetime</td>
<td>1 year, goal: 2 years</td>
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![Fraction of 8x8 km cells with at least 100 spots](image.png)

Fig. 5. Simulated coverage for the VCL instrument (for its NASA VCL mission orbital parameters, similar to those of Carbon-3D) for cells of 8x8 km, and assuming 50% loss of data due to cloud obscuration. As can be seen, even under severe degradation, a majority of the Earth’s surface has sufficient LIDAR observations to reliably estimate canopy height at 8x8 km resolution (from Dubayah et al., 2000).
VCL data without fusion with multispectral data is shown in Fig. 5. With fusion of BRDF data, a degraded mission of one laser for 1 year provides far better information on spatial variability.

5. Carbon-3D vegetation parameters and data products

5.1. Carbon-3D LIDAR data extrapolation

Developing ways of using optical data (i.e., the multiangle imager) for spatial extrapolation of forest structure as derived from locally sparse LIDAR data is central to the mission objectives.

The challenge is similar to problems of spatial extrapolation routinely met in other ecological mappings based on sampling. Extrapolating detailed measurements at a restricted number of sites requires an understanding of the spatial structure of the relevant system over larger areas. Monitoring plots in forestry are routinely extrapolated to much larger areas of forest. In agricultural monitoring, yield models for selected sites are extrapolated to the province or country level using Geographic Information Systems (GIS). Estimates of the greenhouse gas exchange of large parts of continents are based on the measurements made by a small number of flux towers that are scaled to the respective cover fractions of the larger area.

In the case of lidar-based samples of vegetation biophysical properties, their extrapolation to larger areas requires a mapping of the spatial distribution of vegetation coverage and type. Classifying pixels of similar spectral and angular characteristics into polygons to which LIDAR-based vegetation properties can be scaled is currently the most feasible and accessible approach, suggesting a combination of a sampling sensor (the LIDAR) with an extrapolation sensor (the optical sensor). Spectral differences allow differentiation of polygons of different vegetation types, while angular information provides some information on the three-dimensional structure of this vegetation (open or a closed canopy). Multispectral, multispectral data also provide an optimal constraint on retrievals of leaf area index. The resultant combination of continuous parameters and categorical polygons can then be associated with the unique information retrieved along the LIDAR scan path.

It is important to realize that in such a scheme, the optical sensor provides a means of extrapolating the LIDAR data, not a means of substituting the information content derived from it. Myneni et al. (2001) use optical data to extrapolate forest inventory data collected on the ground to the whole of the northern hemisphere. Veroustraete et al. (2002) use optical data to extrapolate flux exchange measurements.

Regionalization via data fusion is based on the assumption that there are relationships among vegetation structures and spatially continuous optical data. One strategy is to develop better canopy models that use sparse LIDAR data as model initializations, and then use multispectral imagery to map the model-derived structures (Dubayah et al., 2000). Alternatively, straightforward empirical modelling procedures could be used for data integration purposes (Dubayah et al., 2000).

Hudak et al. (2002) tested five aspatial and spatial approaches to combine LIDAR data with limited coverage in horizontal plane with Landsat data to predict canopy height.

Regression, kriging, cokriging, as well as kriging and cokriging of regression residuals, were used. They conclude (at that time in the context of the upcoming missions ICESat and VCL) that an integrated modelling technique is the most efficient means to assess vegetation parameters at locations unsampled by the LIDAR.

A combined system of LIDAR and an optical sensor sampling the whole globe and extrapolated to complete coverage with matching temporal and spatial characteristics will provide a mapping opportunity for large parts of the earth where ground information from forestry and agriculture is not available nor reliable or consistent.

5.2. Data products

Carbon-3D will provide level 1 (raw data), level 2 (postprocessed data: radiance, reflectance, vertical distribution of interception), and level 3 data (empirical or semi-empirical science algorithms that build the products; Table 3). The combination of the BRDF and the LIDAR information will lead to new and innovative data products [three-dimensional structure of landcover with global coverage, improved landcover and vegetation type mapping, vegetation parameter retrieval (LAI), and life form and physiognomic diversity analysis (compare with Table 3)]. Level 4 products (NPP, forest age) will be the output from the modelling science community.

The following list of applications are anticipated for the Carbon-3D products: global 3-D canopy structure maps,
improved parameterisation of Global Circulation Models (GCM), improved parameterisation of biogeochemical vegetation models (DGVMS), improved forest parameters, and deforestation information for forest inventories, fire susceptibility, fuel accumulation, biodiversity, desertification, shrub encroachment research, detection of habitat features associated with rare or endangered species, and the control of subsidised land use.

6. Relevance to international science-orientated programmes

Since the early 1990s, international organisations have been working towards the establishment of systematic, long-term observation systems. To facilitate progress in the challenge of obtaining and disseminating global carbon cycle observations, space agencies and international research programmes have established a coordination mechanism: the Integrated Observing Strategy Partnership (IGOS-P). IGOS-P established a Terrestrial Carbon Observation theme (TCO) under guidance of GTOS (Harris & Battrick, 2001). Carbon-3D directly serves the IGOS requirements and supplies the missing global biomass map as a solid prerequisite to carbon accounting.

Further international research with respect to the global carbon cycle is organised through the ESA Living Planet Programme, including the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme (EWP), the Orbiting Carbon Observatory (OCO) mission, and the Global Monitoring of Environment and Security (GMES), a joint initiative of the European Commission and the European Space Agency.

Numerous international and national political conventions and multilateral agreements have been adopted targeting global climate change [Kyoto Protocol—United Nations Framework Convention on Climate Change (FCCC); UNFCCC, 2000].

7. Summary

Carbon-3D will be of importance for vegetation and carbon cycle studies, as it provides the first instrument capable of retrieving accurate biomass information from regional to global scales. The presented proposal for an Earth observation mission should also stimulate the research in that field. More work has to be done to integrate LIDAR and radiometer-derived data sets.

Remote sensing only serves to diagnostically analyse the current state of the vegetation. It can neither analyse the actual flux of carbon through the system nor predict the future development and changes of vegetation patterns. Therefore, prognostic vegetation models are necessary for a prediction of future sources and sinks of carbon (Lucht et al., 2001).

The multiangle imager provides BRDF data, delivering more comprehensive land surface information in terms of its spectral, directional, spatial, and temporal characteristics than data acquired from monodirectional observations (Asner, 2000; Barnsley et al., 1997; Diner et al., 1999; Verstraete et al., 1996). The determination of the chemical and physical structure of land surfaces improves biophysical modelling. Second, these data products improve existing vegetation parameters, such as LAI, fAPAR, and NPP (Knyazikhin et al., 1998; Roberts, 2001). Furthermore, a reliable computation of albedo is granted improving climate modelling. These data can only be achieved from a multiangle instrument as on-board Carbon-3D.

Acknowledgement

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