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The BIOMASS mission: Mapping global forest biomass to better understand the terrestrial carbon cycle

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A B S T R A C T

In response to the urgent need for improved mapping of global biomass and the lack of any current space systems capable of addressing this need, the BIOMASS mission was proposed to the European Space Agency for the third cycle of Earth Explorer Core missions and was selected for Feasibility Study (Phase A) in March 2009. The objectives of the mission are 1) to quantify the magnitude and distribution of forest biomass globally to improve resource assessment, carbon accounting and carbon models, and 2) to monitor and quantify changes in terrestrial forest biomass globally, on an annual basis or better, leading to improved estimates of terrestrial carbon sources (primarily from deforestation); and terrestrial carbon sinks due to forest regrowth and afforestation. These science objectives require the mission to measure above-ground forest biomass from 70° N to 56° S at spatial scale of 100–200 m, with error not exceeding ±20% or ±10 t ha^{-1} and forest height with error of ±4 m. To meet the measurement requirements, the mission will carry a P-Band polarimetric SAR (centre frequency 435 MHz with 6 MHz bandwidth) with interferometric capability, operating in a dawn-dusk orbit with a constant incidence angle (in the range of 25°–35°) and a 25–45 day repeat cycle. During its 5-year lifetime, the mission will be capable of providing both direct measurements of biomass derived from intensity data and measurements of forest height derived from polarimetric interferometry. The design of the BIOMASS mission spins together two main observational strands: (1) the long heritage of airborne observations in tropical, temperate and boreal forest that have demonstrated the capabilities of P-band SAR for measuring forest biomass; (2) new developments in recovery of forest structure including forest height from Pol-InSAR, and, crucially, the resistance of P-band to temporal decorrelation, which makes this frequency uniquely suitable for biomass measurements with a single repeat-pass satellite. These two complementary measurement approaches are combined in the single BIOMASS sensor, and have the satisfying property that increasing biomass reduces the sensitivity of the former approach while increasing the sensitivity of the latter. This paper surveys the body of evidence built up over the last decade, from a wide range of airborne experiments, which illustrates the ability of such a sensor to provide the required measurements.

At present, the BIOMASS P-band radar appears to be the only sensor capable of providing the necessary global knowledge about the world's forest biomass and its changes. In addition, this first chance to explore the Earth's environment with a long wavelength satellite SAR is expected to make yield new information in a range of geoscience areas, including subsurface structure in arid lands and polar ice, and forest inundation dynamics.

1. Introduction—Biomass and the global carbon cycle

One of the most unequivocal indications of man's effect on our planet is the continual and accelerating growth of carbon dioxide

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(CO_2) in the atmosphere. A central concern is the climate-change implication of increasing atmospheric CO_2. The principal contribution to this growth is emissions from fossil fuel burning. However, the rate of growth is substantially less and much more variable than these emissions because of a net flux of CO_2 from the atmosphere to the Earth's surface. This net flux can be partitioned into atmosphere-ocean and atmosphere-land components, whose mean values for the 1990s are 2.2 ± 0.4 GtC yr^{-1} and 1.0 ± 0.6 GtC yr^{-1} respectively (International Panel on Climate Change (IPCC), 2007). As in most carbon cycle calculations, CO_2 fluxes are reported in this paper in terms of carbon units; 1 GtC = 1 Pg or 10^{15} g of carbon.

This simple description of the overall carbon balance conceals some major scientific issues, which we illustrate by Fig. 1:

1. Although fossil fuel emissions, the atmospheric CO_2 increase and the net atmosphere-ocean flux are well constrained by measurements (IPCC, 2007), this is not true of the atmosphere-land flux. Its value is estimated simply as the residual needed to close the carbon budget after subtracting the atmospheric growth in CO_2 and the net amount transferred into the oceans from the emissions. Hence its variance is determined indirectly as the sum of the variances of the other fluxes.
2. Fossil fuel burning forms only part of the total anthropogenic CO_2 loading of the atmosphere, with another major contribution coming from land use change. The size of this flux is poorly known, and is reported in IPCC (2007) simply as a range, shown in Fig. 1 as a low and high value about a central value of 1.6 GtC yr^{-1}. (It is worth noting that the lastest value put it to 1.4 GtC yr^{-1} (Le Quéré et al., 2009)).
3. In order to balance the carbon budget, any value of land-use-change flux must have an associated land uptake flux, indicated in Fig. 1 as a "residual" flux, since its value is derived purely as a difference of other terms.

Marked on Fig. 1 are the uncertainties in the well-constrained terms; it can be seen that the uncertainties in both emissions and uptake by the land dominate the overall error budget. Fundamental to better quantification of these land fluxes is accurate knowledge about the magnitude, spatial distribution and change of forest biomass.

More than 98% of the land-use-change flux is caused by tropical deforestation (IPCC, 2007), which converts carbon stored as woody biomass (which is approximately 50% carbon) into emissions. The most basic methods of calculating this flux simply multiply the area

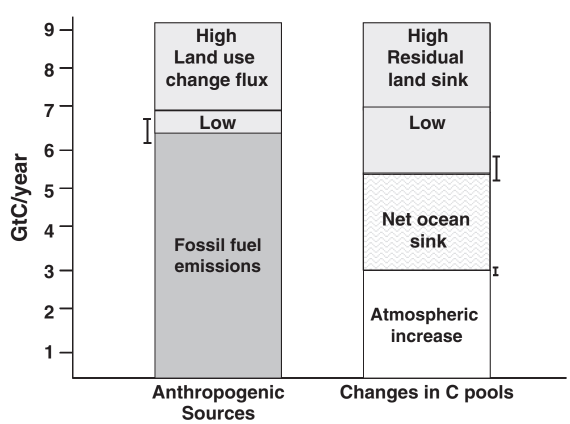

Fig. 1. Bar chart showing the anthropogenic carbon sources and the associated annual net fluxes to the carbon pools for the 1990s, with units given as GtC yr^{-1}. The uncertainties in the well-constrained terms (fossil fuel emissions, the atmospheric increase in CO_2 and the net ocean sink) are indicated by the error bars. The land use change flux is poorly constrained and the chart indicates the range of estimates, from low to high, of this quantity. In order to achieve carbon balance, there must be take-up of CO_2 by the land surface, and the corresponding low and high estimates of this "residual land sink" are indicated. The data for this figure are taken from IPCC (2007).

deforested (derived from national statistics or remote sensing) by the average biomass of the deforested area, expressed in carbon units (IPCC, 2003). More complete methods of carbon accounting would include carbon fluxes from the soil, differential decay rates of carbon depending on how the biomass is used, and regrowth fluxes (DeFries et al., 2002; Houghton, 2003a, 2003b). However, both approaches are severely compromised by lack of reliable information on the levels of biomass actually being lost in deforestation. This uncertainty alone accounts for a spread of values of about 1 GtC yr^{-1} in different estimates of carbon emissions due to tropical deforestation (Houghton, 2005).

The residual land flux is of major significance for climate, since it reduces the build-up of CO_2 in the atmosphere. If we assume a land use change flux of 1.6 GtC yr^{-1}, the total anthropogenic flux to the atmosphere in the 1990s was 8 GtC yr^{-1}. Of this, around 32.5% was absorbed by the land (see Fig. 1), but this value has very large uncertainties arising from the uncertainties in the land use change flux. The uptake is highly variable from year to year, for reasons that are poorly understood. Similar trends are seen since 2000 (Canadell et al., 2007). A key question is how much of this residual sink is due to fixing of carbon in forest biomass.

As a result, biomass is identified by the United Nations Framework Convention on Climate Change (UNFCCC) as an Essential Climate Variable (ECV) needed to reduce uncertainties in our knowledge of the climate system (GCOS, 2003; Sessa & Dolman, 2008). Further strong impetus to improve methods for measuring global biomass comes from the Reduction of Emissions due to Deforestation and Forest Degradation (REDD) mechanism, which was introduced in the UNFCCC Committee of the Parties (COP-13) Bali Action Plan. Its implementation relies fundamentally on systems to monitor carbon emissions due to loss of biomass from deforestation and forest degradation.

Concerns about climate change provide a compelling reason for acquiring improved information on biomass, but biomass is also profoundly important as a source of energy and materials for human use. It is a major energy source in subsistence economies, contributing around 9–13% of the global supply of energy (i.e. $35–55 \times 10^{18}$ J yr^{-1}; Haberl & Erb, 2006). The FAO provides the most widely used information source on biomass harvest (FAO, 2001, 2006), but other studies differ from the FAO estimates of the wood-fuel harvest and forest energy potential by a factor 2 or more (Krausmann et al., 2008; Smeets & Faaij, 2007; Whiteman et al., 2002). Reducing these large uncertainties requires frequently updated information on woody biomass stocks and their change over time, to be combined with other data on human populations and socio-economic indicators.

Biomass and biomass change also act as indicators of other ecosystem services. Field studies have shown how large-scale and rapid change in the dynamics and biomass of tropical forests lead to forest fragmentation and increase in the vulnerability of plants and animals to fires (Malhi & Phillips, 2004). Bunker et al. (2005) also showed that above-ground biomass was strongly related to biodiversity. Regional to global information on human impacts on biodiversity therefore requires accurate determination of forest structure and forest degradation, especially in areas of fragmented forest cover. This is also fundamental for ecological conservation. The provision of regular, consistent, high-resolution mapping of biomass and its changes would be a major step towards meeting this information need.

Despite the obvious need for biomass information, and in contrast with most of the other terrestrial ECVs for which programmes are advanced or evolving, there is currently no global observation programme for biomass (Herold et al., 2007). Until now, the only sources of gridded global biomass (i.e. typically above-ground biomass, which is the dry weight of woody and foliar tree elements) are maps at very coarse spatial resolutions (1/2 to 1°) based largely on ground data of unknown accuracy (Kindermann et al., 2008; Olson et al., 1983, 2001). At regional scale, various approaches have been used to produce biomass maps. Houghton et al. (2003) compared seven biomass maps of