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Coverage of high biomass forests by the ESA BIOMASS mission under defense restrictions

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ABSTRACT

The magnitude of the global terrestrial carbon pool and related fluxes to and from the atmosphere are still poorly known. The European Space Agency P-band radar BIOMASS mission will help to reduce this uncertainty by providing unprecedented information on the distribution of forest above-ground biomass (AGB), particularly in the tropics where the gaps are greatest and knowledge is most needed. Mission selection was made in full knowledge of coverage restrictions over Europe, North and Central America imposed by the US Department of Defense Space Objects Tracking Radar (SOTR) stations. Under these restrictions, only 3% of AGB carbon stock coverage is lost in the tropical forest biome, with this biome representing 66% of global AGB carbon stocks in 2005. The loss is more significant in the temperate (72%), boreal (37%) and subtropical (29%) biomes, with these accounting for approximately 12%, 15% and 7%, respectively, of the global forest AGB carbon stocks. In terms of global carbon cycle modelling, there is minimal impact in areas of high AGB density, since mainly lower biomass forests in cooler climates are affected. In addition, most areas affected by the SOTR stations are located in industrialized countries with well-developed national forest inventories, so that extensive information on AGB is already available. Hence the main scientific objectives of the BIOMASS mission are not seriously compromised. Furthermore, several space sensors that can estimate AGB in lower biomass forests are in orbit or planned for launch between now and the launch of BIOMASS in 2021, which will help to fill the gaps in mission coverage.

1. Introduction

The magnitude of the terrestrial carbon (C) pool is still poorly known, with estimates of the size of the global forest C reservoir at 861 ± 66 Pg C in 2007, with 363 ± 28 Pg C (~40%) stored in living biomass, of which 262 Pg C (~70%) is in the tropics (Pan et al., 2011). Estimates of C fluxes between the atmosphere and the terrestrial biosphere also vary greatly. The (tropical) land-use change source and land sink flux components from global forested areas accounted for 1.3 ± 0.7 Pg C yr^{-1} and 2.4 ± 0.4 Pg C yr^{-1}, respectively, in the 1990–2007 period, based on long-term ground data at decadal time-steps (Pan et al., 2011). The corresponding values from the Global Carbon Project (http://www.globalcarbonproject.org/) using the bookkeeping method are 1.3 ± 0.5 Pg C yr^{-1} and 2.5 ± 0.8 Pg C yr^{-1}, updated to 1.0 ± 0.5 Pg C yr^{-1} and 3.1 ± 0.9 Pg C yr^{-1}, respectively, for the last decade (2006–2015) (Le Quéré et al., 2016). Note that in this case the net land sink was estimated as the residual of all other terms in the global C budget. However, bottom-up estimates of global net carbon exchange based on best available data have shown that the mismatch between the mean global carbon uptake and the atmospheric CO_2 growth rate can be up to 10 Pg C yr^{-1} (Zscheischler et al., 2016). Furthermore, regional scale estimates from different methods can diverge markedly, e.g., in Valentini et al. (2014), the estimates of the net biome production of Africa from inventory data, ecosystem fluxes, DGVMs and atmospheric inversions are −0.74 ± 1.19 Pg C yr^{-1}, −1.34 ± 1.32 Pg C yr^{-1} (1982–2008), −0.41 ± 0.31 Pg C yr^{-1} (1990–2010) and 0.05 ± 0.28 Pg C yr^{-1} (1996–2004) respectively. These different studies emphasize the current limitations in bridging bottom-up/top-down estimates of the C cycle at global and regional scales.

Biomass values are deeply embedded in flux estimates obtained from inventory data, since they are derived from estimates of changing

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areas (i.e., deforestation, afforestation, logging, shifting agriculture, regeneration) together with values for the mean biomass density in these areas before and after change. The urgent need to reduce these uncertainties has motivated major efforts to estimate the spatial distribution of above-ground biomass (AGB) from a range of data sources, including remote sensing instruments designed for other applications. For example, pan-tropical maps of the C stored in AGB have been produced using spaceborne remote sensing data at 1 km scale for the early 2000s (Saatchi et al., 2011) and at 500 m scale for 2007 (Baccini et al., 2012), while similar maps were produced for the temperate and boreal regions of the northern hemisphere in 2010 (Thurner et al., 2014). The two pan-tropical AGB maps (Baccini et al., 2012; Saatchi et al., 2011) used similar input data layers, and are principally based on canopy height data derived from the LiDAR dataset acquired between 2003 and 2009 by the Geoscience Laser Altimeter System (GLAS) sensor onboard the National Aeronautics and Space Administration (NASA) Ice, Cloud and Elevation Satellite (ICESat). However, these studies differ in the methods used to derive height from the GLAS data, the ground datasets used for calibration and the spatial modelling methodology; as a result, there are significant regional differences between them, especially across the tropical rainforests (central Amazon, Congo basin, Papua New Guinea), savanna woodlands in Africa (i.e., Miombo) and dry forests and savannas of South America (Mitchard et al., 2013). These disagreements tend to decrease when aggregating to country or biome scale (Mitchard et al., 2013), thus generating estimates of AGB stocks of 203 Pg C (Saatchi et al., 2011) and 228 Pg C (Baccini et al., 2012) in the pan-tropics. A forest growing stock volume map for the temperate and boreal regions of the northern hemisphere derived from the European Space Agency (ESA) Environmental Satellite (Envisat) C-band Advanced Synthetic Aperture Radar (ASAR) data (Santoro et al., 2011) was combined with allometric relations to generate total (above- and below-ground biomass) C maps, leading to an estimate of 80 ± 30 Pg C of biomass stored in that region (Thurner et al., 2014). However, the associated relative root mean square error is 48–96% at 100 m scale and 34–48% at 1 km, so that considerable spatial averaging is needed to reduce the error to acceptable levels.

It was against this background that BIOMASS was selected in 2013 as the 7th European Space Agency (ESA) Earth Explorer mission, with the aim of providing accurate estimates of the distribution of AGB in the world's forests at a spatial scale of ~200 m. The Report for Selection (ESA, 2012) showed clearly that the mission had to be based on a P-band Synthetic Aperture Radar (SAR), for which permission had been granted by the International Telecommunication Union (ITU) as a secondary allocation in the 432–438 MHz frequency band at the World Radiocommunication Conference in 2003 (ITU, 2004). Furthermore, the science case on which BIOMASS was selected was especially built on its ability to measure AGB within dense tropical forests, which, despite having the highest total forest C stock values (and mean forest AGB density), have minimal coverage by ground data, in contrast to the extensive ground data existing for temperate and boreal latitudes (driven largely by the needs of commercial forestry) (Schimel et al., 2015). In addition, the AGB uncertainty in the tropics is much greater than in all other forest biomes (Phillips and Lewis, 2014), hence introducing great uncertainty into the land-use change flux, most of which is concentrated in the tropics (Pan et al., 2011). Therefore, tropical forests are the focus of current forest conservation and management programmes and initiatives driven by the United Nations Framework Convention on Climate Change (UNFCCC), such as UN-REDD, the Forest Carbon Partnership Facility and the Global Forest Observations Initiative.

BIOMASS, to be launched in 2021 with an expected 5 year mission lifetime, will deliver three primary geophysical products every six months: maps of forest AGB density and forest height at 200 m spatial resolution, and maps of severe forest disturbances at 50 m spatial resolution (Le Toan et al., 2011). In addition to the primary mission objectives, the mission will provide data for new scientific applications, including topographic mapping below forests, mapping ice sheets, glacier flow and structure analysis and mapping of subsurface geological features in arid areas (ESA, 2012; Paillou et al., 2011). To achieve the mission objectives, the BIOMASS sensor will consist of a single satellite with a P-band SAR (432–438 MHz) payload in side-looking geometry with full polarimetric and interferometric capabilities (Le Toan et al., 2011).

Although the mission is capable of providing global coverage, International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) Regulations dictate that the use of this frequency band by active space sensors must be in accordance with the technical and operational constraints established in Recommendation ITU-R RS.1260-1 (ITU-R, 2003) in order to ensure protection of existing services allocated to the band. In particular, SAR sensors using this frequency cannot be operated within line of sight of registered P-band ground stations (ITU-R, 2003). These stations are located in North America and Europe, and together form the network of Space Objects Tracking Radars (SOTR) under the control of the United States Department of Defense (DoD).

The initial selection of BIOMASS by ESA was made in full knowledge of the SOTR restrictions, which prevent imaging of Europe, North and Central America. This reflects the fact that the loss of coverage is principally for countries which already have very extensive biomass information or whose forest activities have relatively small impact on the global carbon cycle. However, these restrictions have little effect on observing the tropical belt, where the information is most needed, and which is the primary focus of BIOMASS. ESA's commitment to BIOMASS was confirmed in a meeting of the Programme Board on Earth Observation (PBEO) in February 2015, and the contract to build the satellite was placed with a consortium led by Airbus in April 2016.

The main objective of the analysis presented here is to quantify the impact of the SOTR stations on BIOMASS objectives in terms of loss of forest coverage and how representative the unaffected regions are as regards AGB C stocks, both in terms of major ecological regions and affected developing tropical countries. Additionally, the impact on large scale C cycle and Earth System Models (ESMs) is evaluated by representing forest AGB in climate space and quantifying changes due to SOTR operations. Furthermore, we discuss the options currently available at the country scale to mitigate the impact of loss of coverage due to the SOTR network.

2. Data and methods

The impact of SOTR operations on BIOMASS objectives will be evaluated by combining the information about the location and area of influence of SOTR stations with that representing the extent of global forest cover and corresponding AGB C stocks. The areas affected and unaffected by these stations will be reported at global, ecological and country scale. Additionally, the impact of the SOTR network in terms of loss of representativeness of AGB information for large-scale ESM modelling will be assessed by identifying the magnitude and location of the occluded areas in a climate space defined by precipitation and temperature. We provide below a critical description of the datasets used for this purpose, including additional information about some methodological steps that are specific to these datasets.

2.1. Location and coverage of SOTR stations

The registered SOTR stations discussed in this study are located in North America and Europe (see Supplementary Table S1). Currently, BIOMASS will not be allowed to operate within line of sight of the stations making up the SOTR network; this occludes the area shown in Fig. 1, which depicts its impact in terms of global ecological zones (FAO, 2012).

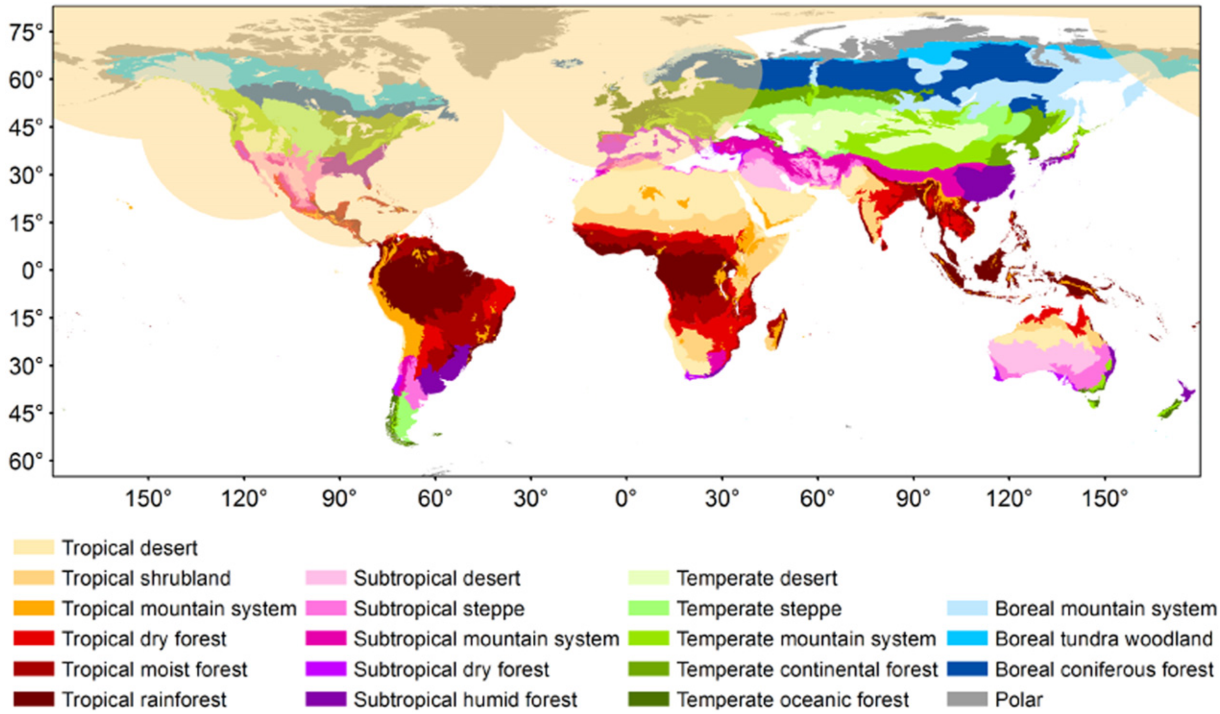

Fig. 1. Global ecological regions of the world (FAO, 2012) with the area affected by Space Objects Tracking Radar (SOTR) stations highlighted in yellow. Only land areas between 65° South and 85° North are represented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Global ecological zones

In order to calculate loss of coverage of forest and corresponding C stocks with respect to different ecological zones we use the classification applied in the 2015 FAO Global Forest Resources Assessment (FAO GFRA) (FAO, 2012) (Fig. 1). Ecological zones are defined as regions encompassing similar natural vegetation, agreeing approximately with the map of Köppen-Trewartha climatic types (Trewartha, 1968), based on temperature and rainfall; the exceptions are mountain systems, which are highly variable in terms of vegetation and climate due to topography (Simons, 2001).

2.3. Forest cover and annual deforestation rates

To assess the effect of SOTR stations on coverage of forest areas, the most up-to-date and detailed global tree cover map (Hansen et al., 2013) was used. This exploits worldwide coverage by 30-m spatial resolution Landsat sensor data to create a baseline map of tree cover for the year 2000 and forest loss and forest gain between 2001 and 2012. Forest loss is disaggregated by year but forest gain is only reported for the whole 2001–2012 period. A forest loss of 2.3×10^6 km^2 and a gain of 0.8×10^6 km^2 were estimated globally over this period (Hansen et al., 2013); 32% of global forest loss was from tropical rainforests, of which half occurred in South America, and tropical areas displayed a statistically significant trend in forest loss of 2101 km^2 per year.

To support our analysis, forest cover maps for 2005 and 2010 were generated from the baseline tree cover map of 2000 using the yearly loss information. Forest gain in Hansen et al. (2013) was not considered as separation at annual time steps is not currently possible. These two reference years were chosen because: i) the global AGB map used in this study (Saatchi et al., unpublished results) is representative of AGB density around 2005; ii) one of the most recent FAO GFRA (FAO, 2010) contemporaneous with the tree cover dataset of Hansen et al. (2013) is from 2010. We followed a conservative approach in defining forest: only land with tree cover not <25% was considered as forest, whereas FAO's GFRA uses a threshold of 10%. The full resolution (30 m) tree cover dataset from 2000 was first converted into a forest/non-forest map using the 25% tree cover threshold and then updated to 2005 and 2010 using the data on yearly loss. These two forest/non-forest maps were subsequently spatially averaged to 3 km spatial resolution and form the basis for the analysis presented here. The percentage annual change rate over the 2005–2010 period, r (in % yr^{-1}), was estimated with the compound annual growth rate equation used in FAO's GFRA.

2.4. Above-ground biomass (AGB)

Two pan-tropical AGB maps (Baccini et al., 2012; Saatchi et al., 2011) have recently been developed at grid scales of 1 km and 500 m respectively. Both use similar input data layers, and are principally driven by the same (though re-analyzed) spaceborne LiDAR dataset acquired by ICESat GLAS between 2003 and 2009. However, they use different ground datasets for calibration and different spatial modelling methodologies. As a result, there are significant regional differences between them, which tend to decrease when AGB estimates are aggregated to country or biome scale (Mitchard et al., 2013). The AGB and C calculations in this paper are based on an updated global version of the Saatchi et al. (2011) map (Saatchi et al., unpublished results). The global map is developed by making use of the ICESat GLAS measurements globally and existing regional algorithms for the global ecological zones (Fig. 1) from a literature review (Asner and Mascaro, 2014; Margolis et al., 2015; Mitchard et al., 2012; Montesano et al., 2014; Neigh et al., 2013; Wu et al., 2009; Yu and Saatchi, 2016). The map was developed originally at 100 m spatial resolution using Landsat, ALOS PALSAR, SRTM and texture measures representing the AGB variations and forest disturbance patterns ca. 2005. It was validated at the regional scale using a large number of ground plots acquired from national forest inventory data from northern temperate and boreal regions and a suite of research plots in tropical and sub-tropical regions. The below-ground woody biomass (BGB) was estimated using allometric models developed from root-to-shoot ratios for different forests types as recommended by the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006; Mokany et al., 2006). We added

AGB and BGB values and aggregated the biomass map to 1 km in order to reduce the uncertainty at finer spatial resolution. A factor of 0.47 was used to convert forest woody biomass to C content (McGroddy et al., 2004). The 1-km global data set is currently available from the JPL Carbon Monitoring System website (https://cmsun.jpl.nasa.gov).

2.5. Climate datasets

A different perspective on the effect of loss of coverage due to SOTR operations, particularly relevant to large scale C cycle calculations and ESMs, is given by examining how forest biomass is distributed in climate space and how this distribution changes when the area affected by SOTR operations is removed. In this analysis we used the sum of AGB and below-ground biomass (BGB) estimates from Saatchi et al. (unpublished results) to obtain the mean vegetation C (cVeg) for all 0.5° land grid cells having a minimum tree cover of 25% (Hansen et al., 2013) and cVeg >5 Mg C ha^{-1}. The air temperature and rainfall data at 0.5° spatial resolution for the period 1982–2005 (Carvalhais et al., 2014) were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis products (Dee et al., 2011), which have been bias-corrected (Beer et al., 2014).

2.6. Developing countries

Many developing countries are currently engaged in forest conservation programmes. Perhaps the most important of these is the "Reduced Emissions from Deforestation and forest Degradation in developing countries, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries" (REDD+) mechanism, though it is not yet fully implemented by the UNFCCC. Henceforth, the term "REDD+ countries" refers both to i) developing countries receiving funding from programmes aimed at supporting REDD+ national readiness efforts, and ii) developing countries with potential for REDD+ activities. Those initiatives include the UN-REDD programme, the Forest Carbon Partnership Facility, the Forest Investment Programme, and other multi- and bilateral agreements (e.g., Amazon Fund, Congo Basin Forest Fund, Norway's International Climate and Forest Initiative). In order to assess the impact of SOTR stations on the coverage of forest and AGB stocks in developing countries a list of current and potential REDD+ countries affected by these stations can be found as Supplementary Table S2; in addition, a list of all developed countries affected by the SOTR stations is given in Supplementary Table S3. Country limits were obtained from the Global Administrative Areas (GADM) database (v 2.8; http://gadm.org/).

3. Results

In this section we analyse the effect of SOTR stations on the ability of BIOMASS to provide information on forest coverage and AGB C stocks. The analysis is comprehensive, but places special emphasis on high biomass tropical forests, which are the key areas for the BIOMASS mission.

3.1. Loss of forest coverage

The loss of coverage of forest area in the different ecological zones due to the SOTR stations is given in Table 1. The global forest area of 39,531 × 10^3 km^2 in 2010 derived from the analysis of 30 m spatial resolution Landsat time-series data (Hansen et al., 2013) is comparable with the 38,526 × 10^3 km^2 estimated with L-band Synthetic Aperture Radar (SAR) data from 2010 at 25 m spatial resolution (Shimada et al., 2014). For 2010, the FAO GFRA (FAO, 2010) reports 40,331 × 10^3 km^2, but this is based on a less stringent definition of forest, requiring tree cover of only 10%. The loss of coverage by the SOTR stations is most significant in the temperate (68.7%), boreal (43.2%) and subtropical (35.2%) ecological regions. Forests in the temperate, boreal and subtropical zones account for 14.1%, 26.9% and 7.8%, respectively, of the global forested area in 2010. Such a large proportion of the subtropical forests is affected because most of them (subtropical dry forest, subtropical humid forest, subtropical mountain systems) occur in the Mediterranean basin and Central and North America (Mexico, California, Florida) (Fig. 1). The impact on tropical forests is much smaller, with only 4.0% occluded by the SOTR stations.

Table 1
Global values of forest area in 2010 (10^3 km^2) (Hansen et al., 2013) by FAO global ecological zone (FAO, 2012) and in 2005 by above-ground biomass (AGB) class (from Saatchi et al., unpublished results) and corresponding loss of coverage due to the Space Objects Tracking Radar (SOTR) restrictions; forest is defined as areas having tree cover not <25% (Hansen et al., 2013); Tropical = Tropical rainforest + Tropical moist forest + Tropical dry forest + Tropical mountain systems; Subtropical = Subtropical humid forest + Subtropical dry forest + Subtropical mountain systems; Temperate = Temperate oceanic forest + Temperate continental forest + Temperate mountain systems; Boreal = Boreal coniferous forest + Boreal tundra woodland + Boreal mountain systems.

	Forest area (10^3 km^2)		
	SOTR	Global	Loss of coverage (%)
Ecological zone			2010
Tropical	808	20,245	4.0
Subtropical	1081	3070	35.2
Temperate	3843	5593	68.7
Boreal	4588	10,623	43.2
Total	10,320	39,531	26.1
AGB class (Mg ha^{-1})			2005
<20	1243	5583	22.3
20–100	6760	18,292	37.0
100–200	2180	8650	25.2
>200	435	7890	5.5
Total	10,618	40,415	26.3

3.2. Loss of above-ground biomass representativeness

The effect of the SOTR stations on forest coverage in terms of four AGB classes: <20 Mg ha^{-1}, 20–100 Mg ha^{-1}, 100–200 Mg ha^{-1} and >200 Mg ha^{-1} is shown in Table 1. The SOTR stations cause a loss of coverage of 25.2% and 5.5% of forest regions in the 100–200 Mg ha^{-1} and >200 Mg ha^{-1} AGB classes respectively. These effects are illustrated spatially in Fig. 2A for forest areas with AGB density exceeding 100 Mg ha^{-1}. In the tropics, the only high biomass forest regions affected by the SOTR stations are in Central America (mainly Mexico) (Fig. 2B); tropical forests in South America, Africa and Asia, which are the main objective of the BIOMASS mission, are not affected at all.

The distribution of forest AGB density values in each ecological zone (Fig. 3) indicates that both the tropical dry and moist forests in the areas affected by the SOTR stations have an AGB density median value that is 1.6 times greater than the global distribution in these forest types. In contrast, the distribution of AGB density in the tropical rainforest region that is occluded by the SOTR stations is shifted towards lower values when compared with the global distribution. In the subtropical, temperate and boreal ecological zones the global distribution of AGB density is similar to the areas impacted by SOTR stations.

In Table 2 the occluded forest areas in 2005 are combined with the corresponding AGB density values from Saatchi et al. (unpublished results) to estimate forest AGB C stocks in those areas, both by ecological zone and by biomass class. The loss of coverage of C stocks is very substantial in the temperate (72.0%), boreal (36.7%) and subtropical (28.6%) zones; however, these forests represent only 12.3%, 14.7% and 7.2% of the global forest AGB C stocks. The impact is much less in the tropical forest zone, with 2.9% affected by SOTR stations, while this biome represents 65.8% of the global forest AGB C stocks. In terms of impact by forest AGB class, only 5.8% of the AGB C stocks in the highest AGB class (>200 Mg ha^{-1}) are occluded under the SOTR stations, with this class accounting for 48.0% of the global forest AGB C stocks.

Globally, the area of tropical forest in 2005 with AGB density ≥ 200 Mg ha^{-1} (see Supplementary Fig. S1) represented an area of 7086 × 10^3 km^2 and C stocks of 88 Pg C, corresponding to 34% of the

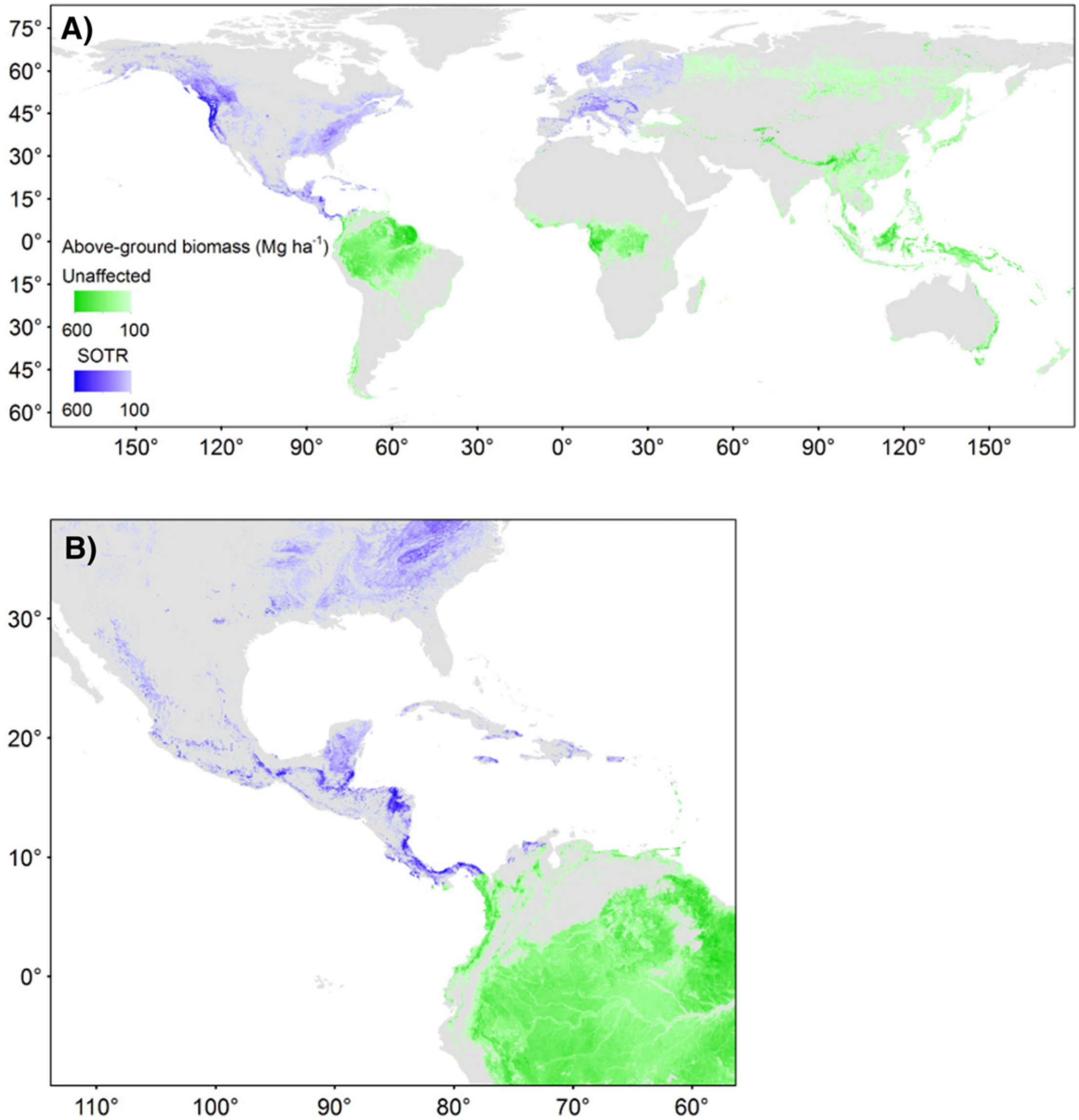

Fig. 2. A) Spatial distribution of above-ground biomass (Saatchi et al., unpublished results) between 65° S and 85° N in forested areas (Hansen et al., 2013) with tree cover not <25% and AGB density over 100 Mg ha^{-1}. The green palette shows the regions unaffected by the Space Objects Tracking Radar (SOTR) stations while the blue palette shows those that are affected; B) enlarged representation over Central America. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

total tropical forest area and 65% of the AGB C stocks; tropical rainforests account for over 90% both in terms of cover and C stocks in tropical regions with AGB density ≥ 200 Mg ha^{-1}. The tropical forest area with AGB density ≥ 200 Mg ha^{-1} affected by SOTR stations represents ~1% in terms of area (81×10^3 km^2) and C stocks (1 Pg C). The main loss of information is for areas with forest AGB density below 200 Mg ha^{-1} (see Supplementary Fig. S2), hence the vast majority of forests with AGB density exceeding 200 Mg ha^{-1} will still be observed by the BIOMASS instrument.

3.3. Impact on deforestation estimates and forest conservation programmes

Although the current patterns of global deforestation may not be a good guide to the situation when BIOMASS launches in 2021, Table 3 quantifies how the SOTR stations would affect measurement of rates of forest area loss if they were similar to those between 2005 and 2010. The major impact is over subtropical forests, with 35.2% not being covered (Table 2). In the occluded areas, the average deforestation rate of 1.13% yr^{-1} was considerably larger than the corresponding global rate of 0.70% yr^{-1} for such forests.

The impact of SOTR stations in terms of loss of coverage of forest area and AGB C stocks by developing country is given in Supplementary Tables S4 and S5, respectively. Several developing countries in the Americas are affected: Bahamas, Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua and Mexico will be fully occluded, but only 2% of the large areas of tropical forests in Colombia will be affected. Of these, only Mexico has significant forest C stocks in global terms. Coverage of forested areas in Algeria, Morocco and Tunisia in North Africa will also be strongly affected.

3.4. Impact on biomass-climate representativeness for global carbon cycle studies

In this section we assess whether the information loss caused by the SOTR stations will hinder analysis of climate-biomass relationships and exploration of the processes leading to the spatial distribution of biomass (e.g. by using land surface models or ESMs). In Fig. 4A the position of each 0.5° forest grid-cell, globally, is located in climate space (defined by air temperature and rainfall). The total biomass (cVeg = above- + below-ground biomass) in grid-cells outside the exclusion zone is

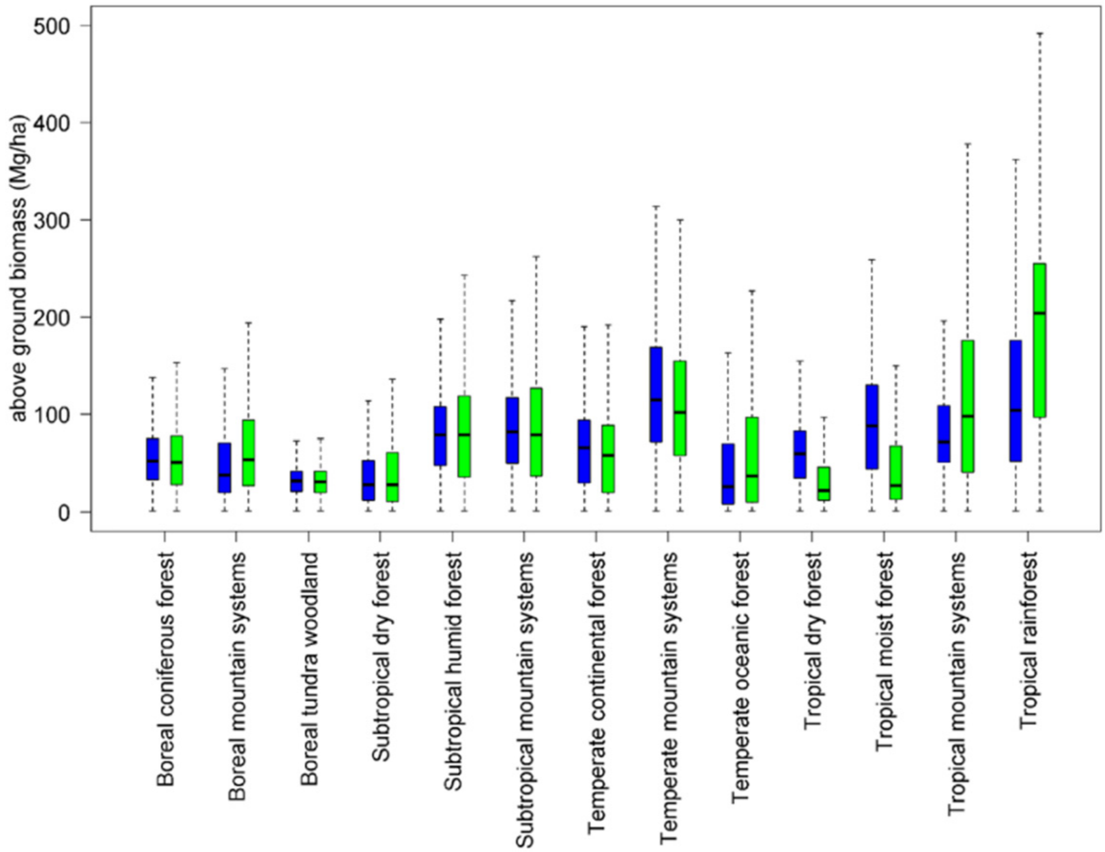

Fig. 3. Distribution of above-ground biomass (AGB) values (from Saatchi et al., unpublished results) by ecological zone (FAO, 2012), with the areas covered by Space Objects Tracking Radar stations represented in blue and the global distribution of AGB values in green. The information given at each boxplot is (from bottom to top): max(min(AGB), Q1 - 1.5IQR), Q1, median, Q3, min(max(AGB), Q3 + 1.5IQR), where max refers to the maximum, min the minimum, Q1 the first quartile, Q3 the third quartile and IQR the inter-quartile range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicated by the colour-bar, while occluded grid-cells are marked as grey. In areas with high temperatures and rainfall, which are mainly located in the tropics and correspond to high forest biomass, the SOTR stations have limited effect, since in most cases >75% of the pixels remain unaffected (Fig. 4B, for higher temperature and rainfall regimes). We used two measures to quantify these effects. Firstly, we calculated the percentage of forest biomass range left in each climate space bin after SOTR exclusion, with this estimated as the difference between percentiles 99.5 and 0.5 of the data inside each climate bin, preserving 99% of the data and eliminating some potential outliers (Fig. 5A). Comparison with Fig. 4A indicates that significant reduction in the range only occurs for lower biomass forests in cooler climates (with air temperature between 0 °C and 10 °C and rainfall above 500 mm yr^{-1}); regions above 15 °C are only slightly affected. Secondly, we used the Kolmogorov-Smirnoff test (which makes no assumption about normality of data) to measure whether the biomass distributions in each climate bin were different before and after removing the data affected by the SOTR stations. Those climate bins where the difference is significant at

Table 2
Forest above-ground biomass (AGB) carbon (C) stocks (Pg C) in ~2005 (from Saatchi et al., unpublished results) per FAO global ecological zone (FAO, 2012) and by AGB class (Mg ha^{-1}) and corresponding loss of coverage due to Space Objects Tracking Radar (SOTR) restrictions; forest is defined as areas having tree cover not <25% (Hansen et al., 2013); Tropical = Tropical rainforest + Tropical moist forest + Tropical dry forest + Tropical mountain systems; Subtropical = Subtropical humid forest + Subtropical dry forest + Subtropical mountain systems; Temperate = Temperate oceanic forest + Temperate continental forest + Temperate mountain systems; Boreal = Boreal coniferous forest + Boreal tundra woodland + Boreal mountain systems.

	Forest AGB C stocks (Pg C)		
	SOTR	Global	Loss of coverage (%)
Ecological zone			
Tropical[1]	3.9	135.1	2.9
Subtropical[2]	4.2	14.8	28.6
Temperate[3]	18.2	25.3	72.0
Boreal[4]	11.1	30.2	36.7
Total	37.4	205.4	18.2
AGB class (Mg ha^{-1})			
<20	0.6	2.7	23.3
20–100	17.6	46.2	38.0
100–200	13.5	57.8	23.3
>200	5.7	98.7	5.8
Total	37.4	205.4	18.2

Table 3
Forest area (10^3 km^2) and deforestation rates (% yr^{-1}) in the 2005–2010 period by global ecological zone (FAO, 2012) and corresponding values in terms of the areas affected by Space Objects Tracking Radar (SOTR) restrictions; forest is defined as areas having tree cover not <25% (Hansen et al., 2013); Tropical = Tropical rainforest + Tropical moist forest + Tropical dry forest + Tropical mountain systems; Subtropical = Subtropical humid forest + Subtropical dry forest + Subtropical mountain systems; Temperate = Temperate oceanic forest + Temperate continental forest + Temperate mountain systems; Boreal = Boreal coniferous forest + Boreal tundra woodland + Boreal mountain systems.

	Forest area (10^3 km^2)				Deforestation rates (% yr^{-1})	
	SOTR		Global			
Ecological zone	2005	2010	2005	2010	SOTR	Global
Tropical	832	808	20,692	20,245	0.58	0.44
Subtropical	1144	1081	3179	3070	1.13	0.70
Temperate	3942	3843	5710	5593	0.51	0.41
Boreal	4700	4588	10,834	10,623	0.48	0.39
Total	10,618	10,320	40,415	39,531	0.57	0.44

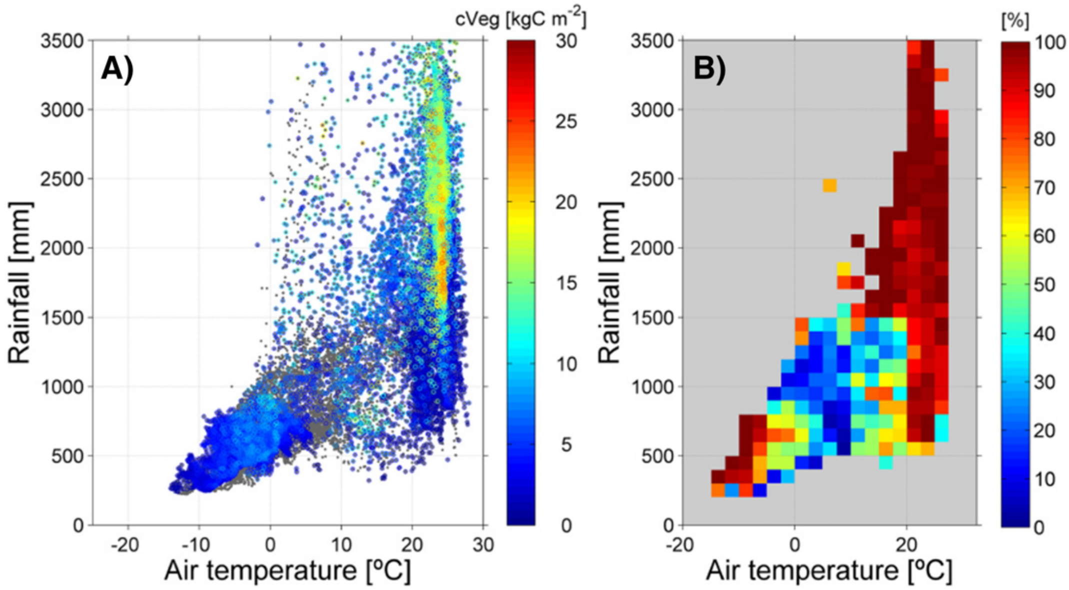

Fig. 4. Distribution of 0.5° grid-cell forest in climate space defined by air temperature (°C) and rainfall (mm yr^{-1}). A) Coloured points represent total biomass (cVeg = above-ground biomass + below-ground biomass, kg C m^{-2}; 1 kg C m^{-2} = 10 Mg C ha^{-1}) (from Saatchi et al., unpublished results) in grid-cells unaffected by Space Objects Tracking Radar (SOTR) operations, while grey points indicate affected grid-cells. B) Percentage of data in each climate bin (2.5 °C air temperature and 100 mm yr^{-1} rainfall) after removing regions occluded by SOTR stations. Grid-cells with <25% tree cover (Hansen et al., 2013) or <0.5 kg C m^{-2} (from Saatchi et al., unpublished results) were excluded from the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the 5% level are marked in red in Fig. 5B. Both measures indicate that in the critical high forest biomass regions, the statistical distribution of biomass in each climate space bin is largely unaffected.

Hence, from a biomass-climate combination standpoint the SOTR exclusion zone has a minor impact in terms of loss in information content. The impact is most significant in regions that already benefit from intense regional observation networks (e.g. North America and Europe), and thus should not hinder future research on ecological or ESM parameterization.

4. Discussion

The impact of the SOTR stations on the BIOMASS mission in terms of forest area and AGB C stocks is summarized in Tables 1 and 2 respectively. The major loss of forest coverage is over the temperate and boreal forests across North America and Europe (Table 1). In 2010 these forests represented over 40% of the world's forests in terms of area and over 80% of the total forest area not covered due to SOTR restrictions. They lie in industrialized countries (see Supplementary Table S3) with well-

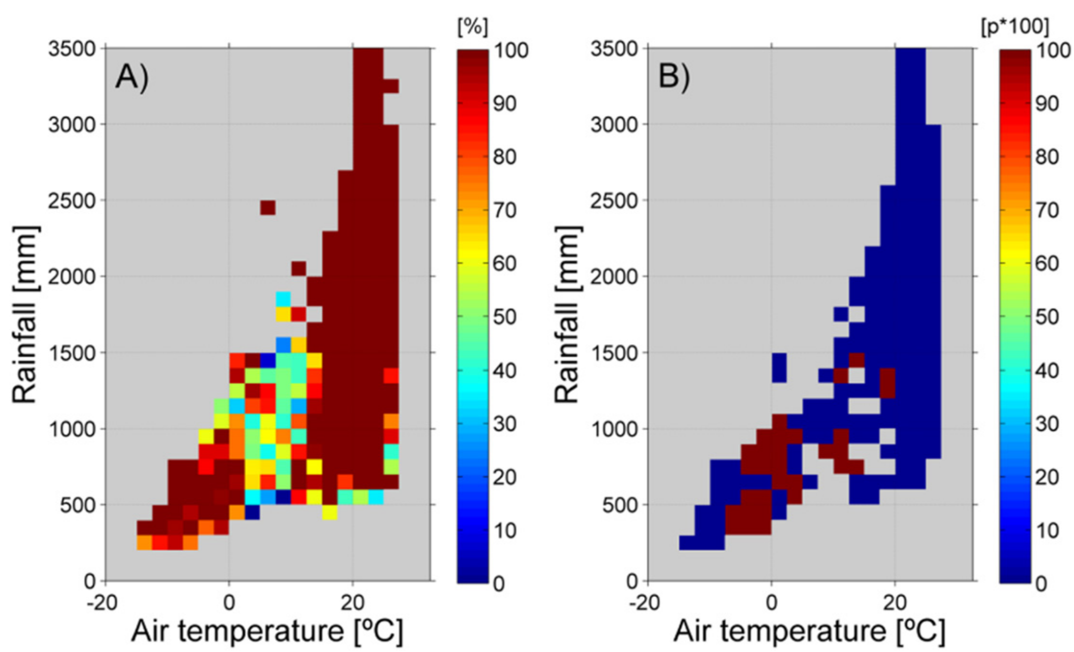

Fig. 5. A) Biomass range (%) maintained in each climate bin (2.5 °C air temperature and 100 mm yr^{-1} rainfall) after removing regions occluded by Space Objects Tracking Radar (SOTR) stations; B) Kolmogorov-Smirnoff *p*-values indicating the similarity between biomass distributions in each climate bin with and without the effect of SOTR stations: red indicates a significant difference at 5% level between the distributions, blue indicates that they are not significantly different; grey areas do not contain enough data for a powerful test. Grid-cells with <25% tree cover (Hansen et al., 2013) or <0.5 kg C m^{-2} (from Saatchi et al., unpublished results) were excluded from the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

developed national forest inventory (NFI) and C accounting systems, which greatly mitigates the loss of coverage. For example, the uncertainty in global forest C stocks and changes in forest C stocks (based mainly on NFI data) is considerably lower in temperate and boreal biomes than in tropical regions (Pan et al., 2011), where forest inventory data are scarce (Schimel et al., 2015). In boreal and temperate regions in 2007, the standard error in forest C stocks represents ~8% and ~5% of the total C stocks, respectively, whereas in tropical regions its value is ~20% (Pan et al., 2011).

For North America, both the United States and Canada have been developing approaches to map forest AGB based on empirical relationships between forest inventory measurements and remote sensing data. The Woods Hole Research Centre recently generated the National Biomass and Carbon Dataset for the year 2000 (NBCD2000), a 30 m resolution baseline estimate of basal area-weighted canopy height, aboveground live dry biomass and standing carbon stock for the conterminous United States (Kellndorfer et al., 2012). The production of this dataset was based on empirical modelling that combined US Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) data with high-resolution Interferometric SAR data acquired from the 2000 Shuttle Radar Topography Mission (SRTM) and optical remote sensing data acquired from the Landsat Enhanced Thematic Mapper (ETM+) sensor. Regional mapping approaches are also being developed across Canada, relying on empirical methods to combine hundreds of NFI measurements with airborne and orbital Light Detection And Ranging (LiDAR) data to generate a map of forest AGB for the Canadian province of Québec in the early 2000s (Boudreau et al., 2008).

Almost all European countries will suffer from complete or nearly complete loss of coverage due to restrictions imposed by the Fylingdales SOTR station in the UK. The European Union, having ratified the Kyoto Protocol in 2002 is responsible for submitting annually to the UNFCCC a compilation of the National Inventory Reports of greenhouse gas emissions and removals from its 28 member states. This includes the contribution of the land-use, land-use change and forestry (LULUCF) sector, and forest AGB values are included in those estimates. According to the latest submission (EEA, 2015) all 28 member states reported using country-specific data (Tier 2 or 3) in this sector in terms of the living biomass pool, with the majority using information from NFIs. Although not included in C reporting some European countries already rely on remote sensing data to produce wall-to-wall maps of forest AGB. For example, in Finland and Sweden country-scale maps of growing stock volume (and other forest variables) have been routinely produced since the 1990s using NFI and remote sensing data (Tomppo et al., 2008).

The impact over Russia will be minor (see Supplementary Table S3), with only 15% of its territory (mainly in Western Russia) not in view of the BIOMASS instrument. The vast majority of boreal and temperate forests in Central and Eastern Russian will be unaffected (Fig. 1 and Fig. 2). The standard error in estimating total forest C stocks represents ~12% for European and Asian Russia in 2007 (Pan et al., 2011).

Higher biomass forests are of particular importance since they are the primary target for the BIOMASS mission; the P-band wavelength was chosen specifically because it provides sensitivity to high AGB density, unlike shorter wavelengths. However, other sensors, like the Advanced Land Observing Satellite (ALOS) Phased Array L-band SAR (PALSAR) (Rosenqvist et al., 2007) and ALOS-2 PALSAR-2 are sensitive to lower values of biomass (Carreiras et al., 2013; Lucas et al., 2010; Mermoz et al., 2014; Mitchard et al., 2011). SAR sensors operating in this frequency are unaffected by SOTR restrictions, so could be used to mitigate loss of coverage of forest areas in regions with AGB <100 Mg ha^{-1}.

The impact over subtropical forests (Figs. 1 and 2) is substantial, with loss of coverage of 35.2% and 28.6% in terms of forest area and AGB C stocks, respectively (Tables 1 and 2). However, this ecological region accounts for only 8% and 7% in terms of global forest area and AGB C stocks respectively. Most of the affected area in this biome is located in Central America and Europe (Fig. 1). In terms of developing countries affected by SOTR operations (see Supplementary Table S2), Mexico contains the vast majority of this biome (88% and 96% in terms of area and C stocks respectively) and will be fully occluded by SOTR restrictions. However, Mexico has a good NFI, with thousands of permanent plots already in place (CONAFOR, 2012), and has a countrywide AGB map produced from a combination of NFI measurements and remote sensing data (Cartus et al., 2014).

In conclusion, the SOTR restrictions currently imposed by the US DoD do not seriously compromise the main scientific objective of the BIOMASS mission, which is to provide biomass information in the tropics where the gaps are greatest and knowledge is most needed. Even in the SOTR exclusion zone, there are options to mitigate the loss of coverage. These include the use of NFI data in developed countries (North America and Europe), either alone or in combination with satellite data, to provide estimates of forest AGB. In particular, L-band radar is sensitive to AGB density, though saturates at biomass density values of ~80–100 Mg ha^{-1}. Currently, the only L-band radar in orbit is ALOS-2 PALSAR-2 (Rosenqvist et al., 2014); this provides dual-polarization mode (HH + HV) global acquisitions at least twice a year over all land masses (dual-season). However, in 2017 and 2018, Argentina is expected to launch two L-band SAR systems onboard the "Satélite Argentino de Observación Con Microondas" (SAOCOM 1A and 1B) (D'Aria et al., 2008). The German Space Agency (DLR) is also currently assessing an L-band SAR tandem mission (TanDEM-L) (Moreira et al., 2011) with an expectation of launch by 2021. A partnership between NASA and the Indian Space Research Organisation (ISRO) has led to the NISAR mission, which aims to place in orbit a dual L- and S-band SAR around 2020, which in terms of C studies will attempt to retrieve AGB and its dynamics globally at 100 m spatial resolution with an accuracy of at least 20 Mg ha^{-1} over no <80% of areas with AGB density < 100 Mg ha^{-1} (Rosen et al., 2015). Additionally, NASA has selected the Global Ecosystem Dynamics Investigation (GEDI) LiDAR mission to be deployed on the International Space Station in 2019; this will be the first LiDAR instrument in space specifically dedicated to estimating forest AGB and change at high spatial resolutions. These missions, alone and in combination, can provide additional coverage in areas lost to the BIOMASS mission due to SOTR restrictions. Finally, there are continuing efforts to establish whether the exclusion zone could be reduced, but currently with little sign of progress.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rse.2017.05.003.

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