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DEFRA: Review of UK applicability of worldwide forest carbon measurement techniques

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Centre for Carbon Measurement

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ABSTRACT

This report provides an overview and case studies for the three approaches to forest carbon measurement: in situ, airborne and satellite-based measurement. The advantages and disadvantages of methods currently applied to estimate forest biomass worldwide are discussed, with a combined approach recommended for a UK-based forest assessment. Effective resource management for timber stocks and deforestation in the UK requires accurate forest-non-forest mapping to monitor tree cover before biomass can be calculated.

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GLOSSARY

DEFRA	Department for Environment, Food & Rural Affairs
ESA	European Space Agency
EUTR	European Union Timber Regulation
FAA	Federal Aviation Association
FAO	Food and Agriculture Organisation
FRA	Forest Resource Assessment
FSC	Forest Stewardship Council
GLAS	Geoscience Laser Altimeter System
GOFC-GOLD	Global Observation for Forest and Land Dynamics
GPS	Global Positioning System
ICESat	Ice, Cloud, and Land Elevation Satellite
IPCC	Intergovernmental Panel on Climate Change
Landsat TM	Landsat Thematic Mapper
LiDAR	Light Detection And Ranging
MODIS	MODerate resolution Imaging Spectro-radiometer
NASA	National Aeronautic and Space Administration
NMO	National Measurement Office (UK)
NOAA	National Oceanic and Atmospheric Agency (US)
PEFC	Programme for the Endorsement of Forest Certification
Radar	RAdio Detection And Ranging
REDD+	Reducing Emissions from Deforestation and forest Degradation
SAR	Synthetic Aperture Radar
UAV	Unmanned Aerial Vehicle
UKWAS	UK Woodland Assurance Standard
UNFCCC	United Nations Framework Convention on Climate change

EXECUTIVE SUMMARY

Forests cover about 30% of the global land area and play a significant role in the delivery of ecosystem services including biodiversity richness, climate regulation, carbon storage and water supplies. Climate change has driven the need for a globally applicable technique to monitor afforestation, natural expansion, deforestation and natural disasters, which control the net change in forest area.

Monitoring and reporting on forest cover and carbon stock is done for two main reasons:

- **Compliance with timber regulations** – the EU Timber Regulation addresses illegal logging activities by placing obligations on operators who place timber on the market. The enforcement of regulations relies on the ability to track trade and monitor logging activities.
- **Supply chain reporting** – reporting is reliant on the traceability of forest resources and products, however companies have varying degrees of traceability. Paper trails following documents of assurance or certification are subject to falsification.

According to the Intergovernmental Panel on Climate Change (IPCC), estimations of forest carbon can be achieved with the provision of information about two fundamental variables: (1) carbon stock and (2) forest area. This report focusses on the latter.

There are three main approaches to forest-non-forest mapping: in situ, airborne and satellite-based measurement.

- **In situ measurements** include direct measurement at user-specified times, often with traceable uncertainty. However they can be labour intensive and therefore high cost, and due to the small plot size may not be representative of the forest as a whole. Additionally direct measurement of forest parameters such as biomass would require destructive monitoring, or alternatively rely on its relationship with other measurable parameters (i.e. use allometric equations). Uncertainty can be increased due to the use of allometric equations, subjective data collection techniques, variation in data collection across individuals and the inaccessibility of certain areas of forest.
- **Airborne measurements**, made from Unmanned Aerial Vehicles (UAVs) have high spatial and radiometric resolution, the ability to monitor inaccessible areas and to avoid issues of cloud cover (low flight altitude plus flights at user-specified times when there is no cloud). Limitations include small swath due to short flight time (due to battery life), weight of instruments the UAV can carry, the need to obtain flight permissions, and the difficulty of navigating in steep environments or those where existence of obstacles is unknown.
- **Satellite-based measurement, or remote sensing**, can cover a large swath, including inaccessible areas, in a short time period. Global databases of satellite data exist enabling global land-use change comparisons and access to archived satellite data for time-series assessment. Disadvantages include that whilst low resolution data can be freely available, high spatial resolution datasets can be both costly and have low temporal resolution. Use of this data requires complex processing techniques (and therefore specialised software and expertise) and there is often no traceability of uncertainties in the raw data or processing chain.

The report has been funded by and produced for Defra, but may also be of interest to the wider climate sector and those with interest in stock management and tackling illegal logging.

1 INTRODUCTION

Forests cover about 30% of the global land area and play a significant role in the delivery of ecosystem services including biodiversity richness, climate regulation, carbon storage and water supplies. According to the Food and Agriculture Organization of the United Nations, forests perform three principal roles with regards to climate change (FAO, 2012):

- Forests contribute about one-sixth of global carbon emissions through clearing, overusing or degrading forests;
- Forests provide wood fuels as an alternative to fossil fuels when managed sustainably;
- Forest biomass, soils and products are a carbon sink - they are able to absorb about one-tenth of global carbon emissions projected for the first half of this century.

Climate change has driven the need for a globally applicable technique to monitor afforestation, natural expansion, deforestation and natural disasters, which control the net change in forest area.

It is estimated that there has been a net loss of approximately 5.2 million hectares of forest per year from 2000 to 2010. In total over this period, this equates to the loss of 13% of the 3.9 billion hectares of global forest area; an area approximately the size of Costa Rica (FAO, 2010). Appropriate forest management requires accurate land cover mapping to track forest resources and in turn calculate forest carbon content. A detailed review of forest carbon and biomass estimation from optical and radar (RAdio Detection And Ranging) satellites is provided within Quegan et al (2012).

The determination of carbon content from forest biomass first requires the extent of forest resources to be mapped via a forest-non-forest map. This is currently achieved through either in situ forest area assessments, or the practice of due diligence to identify the removal of forest products as well as their trade. Unfortunately, due to the size of forests it is a labour intensive task to monitor forest resources and prevent illegal logging (Horcher & Visser, 2004). In situ, airborne and spaceborne land cover mapping techniques support due diligence and traceability activities under the EU Timber Regulation (EUTR), in addition to providers of measurement, monitoring and validation services on an international basis.

In the UK, the Forestry Commission control felling and are responsible for supplying felling licenses, whilst forest management standards are set by Forest Stewardship Council UK (FSC). In order to protect UK forests by tracking forest activities, alternative remote techniques are required to complement ground-based forest assessment.

1.1 BACKGROUND TO THIS REPORT

This report was funded by and produced for the Department for Environment Food & Rural Affairs (Defra) by NPL to review approaches to monitoring forest area and forest change using in situ, airborne and spaceborne capabilities. The range of techniques available to monitor national forests has been assessed. This high level overview of techniques is intended for relevant UK government departments, but also the wider climate sector and those with interest in stock management and tackling illegal logging.

A set of recommendations is laid out on how these monitoring techniques could support current due diligence practices and next steps towards their implementation are suggested.

2 WHY MONITOR FORESTS?

2.1 COMPLIANCE WITH THE EU TIMBER REGULATION

The purpose of this report is to identify forest measurement techniques which can help monitor / track forest stock in the UK to support the EU Timber Regulation[1].

The timber industry represents a good case study of how forest monitoring techniques can support the due diligence processes due to the size of the market. An Interpol report (2012) estimates illegal logging to be worth between £19 billion to £64 billion[2], or 10–30% of the global timber trade. According to WWF (2012), the UK illegally imported a total of 1.5 million cubic meters of timber in 2010 from outside Europe, representing 10% of total imports and with a value of approximately £650 million.

The EU Timber Regulation (EUTR) was introduced to address illegal logging activities as of March 2013. It outlines the obligations of operators who place timber and timber products on the market. The EUTR is enforced by the 'Timber and Timber Products (Placing on the Market) Regulations 2013' in the UK, which gives the National Measurement Office (NMO) enforcement powers to impose appropriate penalties.

The EUTR addresses the trade of illegally harvested timber and timber products through three obligations:

1) It prohibits illegally harvested timber (and products derived from such timber) to be placed on the EU market;
2) It requires EU traders who place timber products on the EU market to exercise 'due diligence';
3) Economic operators (or traders) are required to keep records of their suppliers and customers to facilitate the traceability of timber products, which once on the market can be sold-on or transformed before reaching their final consumer.

Article 6 of the EUTR regulation sets out the due diligence principles required from operators (i.e. those initially placing timber products onto the EU market):

- Access to information (see FSC Implementation Guide, 2013 for a list of required information);
- Risk assessment procedures to evaluate the risk of placing illegal products on the market;
- Adequate risk mitigation procedures to minimise the risk of placing illegal products on the market.

Combining the EUTR with forest area and biomass data can provide a way to not only track trade appropriately, but also ensure logging activities on the ground are monitored.

2.2 SUPPLY CHAIN REPORTING

Supply-chain reporting includes well known certification schemes such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) systems, but also voluntary stakeholder reporting mechanisms such as those under CDP (formerly the Carbon Disclosure Project), next to the now mandatory EUTR and its US counterpart, the 2008 US Lacey Act. The commonality amongst these is that they all require traceability of their resources and products, i.e. documentation that acts as a proxy and assurance as to ascertain that the relevant products do not stem from illegal deforestation activities.

The UK Government Timber Procurement Policy (Defra, 2013) states that the specified public sector procurers must buy all timber and wood-derived products from verifiable legal and sustainable sources (with evidence from Category A or B to classify it as such), or timber with a Forest Law Enforcement, Governance and Trade (FLEGT) license.

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[1] Regulation (EU) No 995/2010
[2] Based on US$ 30-100 billion using the 2013 exchange rate

Category A – Documentary evidence which includes a full chain of custody from the forest to the end user. Forests are certified under the UK Woodland Assurance Standard (UKWAS) i.e. the two credible, international forest certification schemes: (1) Forest Stewardship Council (FSC) and (2) Programme for the Endorsement of Forest Certification (PEFC).

Category B – All evidence other than certification schemes; this is assessed on a case-by-case basis using the *'Framework for evaluating category B evidence'* (see CPET, 2010). Logging is not certified but is legal under Category B.

A 2013 information request by CDP[3] found companies had varying degrees of traceability of their products. *"Companies trying to map their supply chain, particularly retrospectively, are finding the exercise difficult if there are multiple tiers of suppliers upstream. It means that these companies may often find it difficult to meet the information requirements under the EUTR."* Katie McCoy, Head of Forests Program at CDP.

Could the aggregation of in situ, airborne and spaceborne remote sensing data improve the reporting efforts of timber companies, and support compliance with government regulations?

The current, widely applied method for tracking land use change such as deforestation is based on certification and a paper trail. Supplier engagement from multinational companies for reporting purposes, documentation for local clearing activities and governments' sole reliance upon documentation is susceptible to corruption and falsification. A more practical approach to monitoring forests and tracking timber could be the combination of physical measurement methodologies outlined above with reported, due diligence data. This would provide companies and governments a certain level of validation of reported data with land use change – whether it is a confirmation of legal activity or identification of illegal deforestation.

Legal logging activities in the UK are recorded within the Register of Grant Schemes and Felling (Forestry Commission, 2014). This register enables the verification of legal logging as it identifies whether an activity complies with the UK Forestry Standard (UKFS) and the national felling license legislation.

Combining efforts could allow reported data under EUTR in the UK to be cross-referenced against the Register of Grant Schemes and Felling or other national equivalent records, and compared with physical measurements of relevant logging areas. Comparing reported and recorded data with physical measurement could highlight discrepancies between areas which were cleared for logging and those which were not, thus identifying illegal activities. In turn, this could form the basis for further investigation and create market drivers in which governments and timber buyers work together to combat illegal trade. As outlined in Section 3.2.2, physical measurement techniques could also provide visual evidence for convictions around illegal logging.

Supply chain reporting aims to address the vast illegal timber trade (reportedly worth between £19 billion and £64 billion[4] (WWF (2012)), and the EUTR is the latest formalisation of this in legal terms. However there will be limitations in addressing this large issue in isolation with supply chain reporting. Measurement approaches of monitoring forest area and change using in situ, airborne and spaceborne capabilities will provide critical support in validating reported data and put forward critical evidence in legal action.

[3] - CDP received responses from almost 140 companies with market capitalisation in excess of US $3 trillion regarding companies' management of deforestation risk in their operations and supply chains
[4] Based on 2013 exchange rate from US$ 30-100 billion

3 METHODS FOR FOREST MAPPING

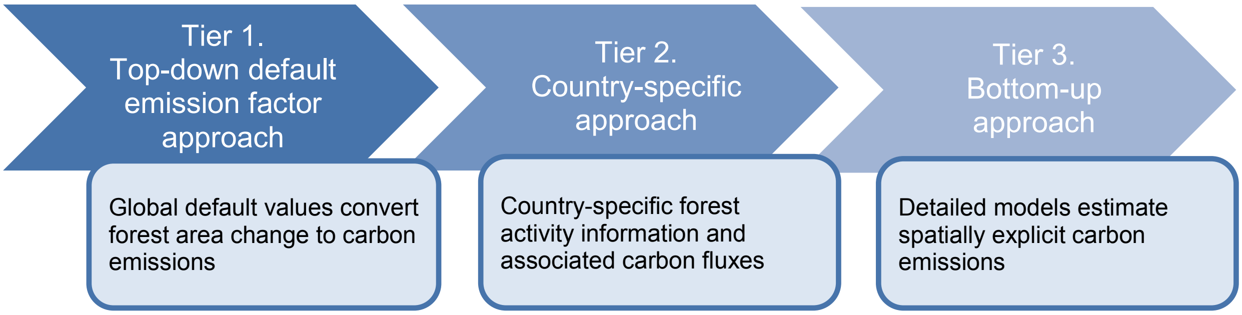
According to the IPCC Good Practice Guidance (2003) estimations of forest carbon can be achieved with the provision of information about two fundamental variables: (1) carbon stock and (2) forest area.

Carbon flux within forests is considered within Section 3.1 Carbon Estimation. This is discussed in more detail within Quegan et al (2012). Accurate emission factors are yet to be developed for the conversion of forest area to carbon flux per unit area. This report therefore has a greater focus on forest area mapping (Section 3.2 Forest Extent mapping).

Traditionally, forest mapping has involved the arduous task of systematically carrying out in situ measurements. Forest inventories have been based on data collected from limited sample plots. Recent technological developments have led to advances in forest mapping using airborne and spaceborne resources. These techniques have the capacity to inform and potentially reduce the need for conventional time-consuming and labour intensive in situ measurements as well as provide extensive information about previously inaccessible and remote areas. Different data sources can produce different results when assessing forest cover change.

3.1 CARBON ESTIMATION

There is a three-tier approach to convert forest activity to country-level estimations of carbon fluxes. Data needs to be acquired for a variety of forests over time and space to progress through the tiers:



Tier 1 is the simplest approach in the estimation of carbon fluxes as it is based on the assumption that all above-ground biomass is converted to carbon emissions. A default factor for biomass is used to determine carbon flux:

$$CE = A \times B \times EF$$

Where:

CE = the carbon flux over a given time period

A = the change in forest area over a given time period

B = the average above-ground biomass of the area

EF = an efficiency factor to convert available carbon content in biomass to carbon emissions

Tier 2 would require in situ data collection from a network of sample sites to produce country-specific values which would enable classification of forest cover into different types or ages.

The most comprehensive approach to estimate carbon flux is Tier 3, based on a local-level model. Modelling will enable modifications to carbon pools caused by forest activity to be inferred (e.g. carbon uptake from forest regrowth) over both long and short timescales (IPCC, 2003; 2006). This approach would also require discrimination between tree species as discussed within Origo et al (2014) in order to account for the variation in different species impact on the carbon cycle.

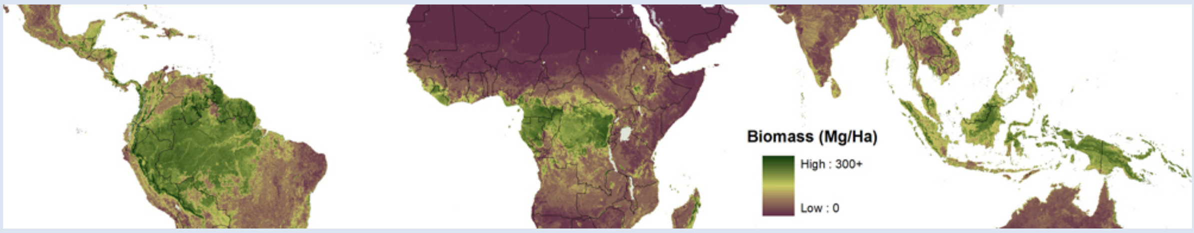
CASE STUDY – Pan-Tropical Forest Carbon map, WHRC

Woods Hole Research Centre embarked on tropical biomass mapping of the Amazon forest in South America and later extended this to continental scale mapping within this three-year project. The project gathers data on forest cover and carbon stocks through measurement of canopy structure and height using MODerate resolution Imaging Spectro-radiometer (MODIS) and the LiDAR sensor on-board ICESat (now defunct) called Geoscience Laser Altimeter System (GLAS).

The project combined ground measurements with satellite data taken under a range of conditions and spread across the region. In situ measurements such as stem diameter at breast height (DBH) were carried out to estimate tree biomass density from allometric equations (see Section 3.2.1) and then a statistical relationship with the LiDAR data (GLAS) was assessed.

The spatial coverage of the dataset was extended by the 500m spatial resolution MODIS data, though the atmospheric conditions, and ground surface slope and roughness limited the quality of this satellite data. The satellite data was calibrated by the ground-based measurements so that important information could be extracted from the imagery, including changes over time as a result of anthropogenic events e.g. illegal logging (Baccini et al, 2008; Saatchi et al, 2011; Lefsky, 2005).

The development of a statistical model enabled the MODIS reflectance data to be related to GLAS estimated biomass. The outcome of this project was the first (baseline) pan-tropical map of carbon stored in aboveground woody biomass, shown below:



(For more information visit: www.whrc.org)

3.2 FOREST EXTENT MAPPING

This section analyses current methods for quantifying forest area and change. Land use change is reported against baseline land cover classification and assessed over 2 to 5 year periods. Change detection can be based on in situ data collection within inventories or from image-based change detection. Ground-based inventories, and mapping from airborne and spaceborne instruments are discussed.

The three main approaches to forest measurement and data collection are identified in Figure 1:

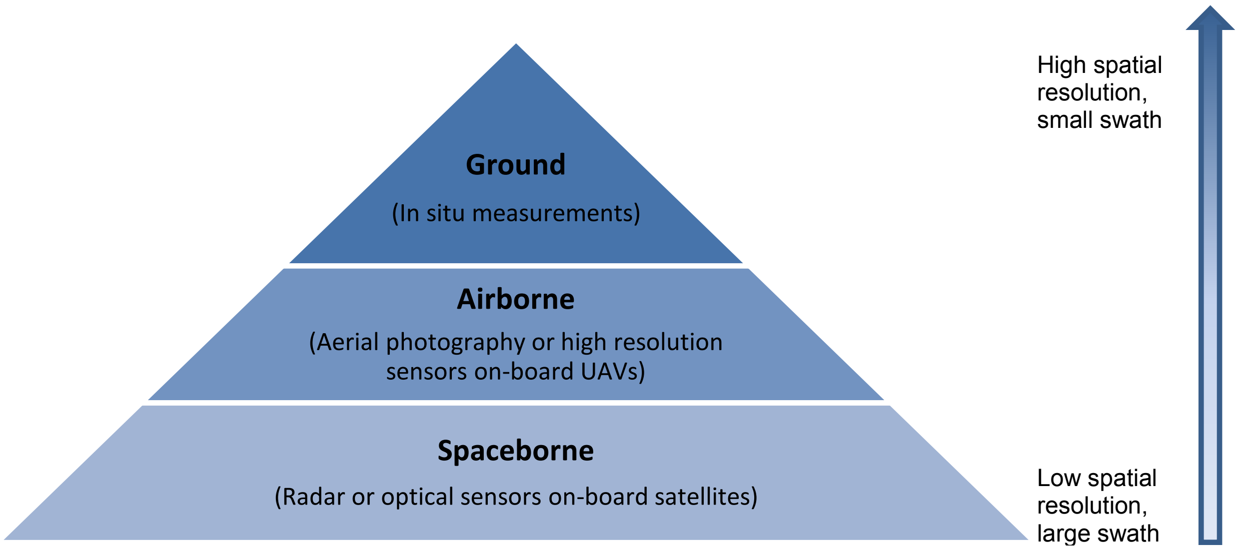


Figure 1 Hierarchy of data assimilation for forest mapping

The data collection approach implemented is dependent on project specifics such as: the parameter to be calculated; the size and location of the study site; and the timing of the data required (acquisition date). Airborne and spaceborne platforms are equipped with various sensors that remotely measure forest parameters such as canopy height, coverage and species. Although these techniques show great potential in providing a higher spatial and temporal resolution of data in comparison to ground-based measurements, weaknesses within these remote methods (outlined in Table 1) need to be considered before an approach is selected.

Table 1 Summary of advantages and disadvantages of data collection approaches

Advantages	Disadvantages
1. In situ measurements (GTOS, 2009; GOFC-GOLD, 2013)	
• Direct measurement of forest characteristics • Non-destructive • Often small, traceable uncertainty associated with equipment • Low capital cost • User specified timing (temporal resolution)	• Time and labour intensive • High on-going monitoring costs (largely labour costs) • Sometimes destructive methods are employed • Sampling bias (may not be a representative sample) • Cannot sample inaccessible areas • Allometric equations (see Section 3.2.1) (often with high associated uncertainty) are required to calculate some forest characteristics e.g. biomass, to avoid destructive monitoring • Subjective data collection techniques and variation in data gathering team
2. Airborne remote sensing from UAVs (Hardin & Hardin, 2010; CielMap, 2012; Horcher & Visser, 2004)	
• High spatial resolution • High radiometric resolution • User-specified temporal resolution (increases probability of cloud-free image) – on demand, near real-time monitoring • Can produce a time-series • Low cost operation • Covers inaccessible areas • Video capabilities • Low flight altitude – not impacted by cloud cover • Easy to transport • Rotor-wing UAVs can hover enabling repeated measurements of the same area	• Limited flight time (dependent on battery life) • Limited by weight of instruments that can be carried by a UAV (manned planes allow heavier sensor payloads) • Flight permissions – limited by government aviation regulations • Affected by weather e.g. wind speed and direction (when controlling UAV manually) and rain • Small swath (large number of scenes required) • Time-consuming and computer intensive processing e.g. orthorectification of data to mosaic images • Potential difficulty in defining clear ground control points within images to accurately mosaic images • Difficult to operate in steep environments • Can have high upfront equipment costs – UAVs tend to range from $500 (close range UAVs) to $123 million (endurance UAVs) • No Sense-and-Avoid system currently exists with adequate performance and reliability– inaccurate flight path coordinates are used to allow for a margin of safety around objects

3. Spaceborne remote sensing from satellite platforms (Koch, no date; Rogan & Chen, 2004)	
• Large swath – full coverage of area in short time period and fewer image tiles required • Reduced sampling intensity • Global databases of satellite data exist enabling global land-use change comparisons • More harmonized national land cover assessment • Some freely available, existing (low resolution) data • Access to archived satellite data for time-series assessment • Geospatial data • Covers inaccessible areas • Visual documentation of land cover changes	• Lower spatial resolution as high resolution data is very costly • High spatial resolution datasets tend to have low temporal resolution – data availability for specified time-period • Data availability for a specified location • Requires use of a proxy i.e. need to identify suitable vegetation indices and other parameters • High reproduction cost of data (though data acquisition costs have reduced) • Cost of image processing software • Complex processing techniques • Training of personnel to use data processing software • No traceability of uncertainty • Forest-non-forest classification difficulties
Optical remote sensing • Identification of target objects using unique spectral signatures	• Data processing – atmospheric, radiometric and geometric correction as well as bidirectional reflectance distribution function (BRDF) normalisation • Limited by weather/atmospheric conditions e.g. cloud cover
Radar remote sensing • Not affected by atmospheric conditions – transmits through clouds • Produce their own incident radiation for illumination of target feature so that acquisitions can be obtained at any time of the day and no BRDF effects • Longer wavelengths more suitable for estimation biomass	• Complex processing techniques – geocoding, radiometric calibration, speckle filtering • Radiometric and geometric limitations in steep terrain – impact of shadow and incidence angle (the latter impacts backscatter intensity) • Backscatter-biomass relationship saturates at high biomass levels • Currently there is a lack of suitable radar sensors (the spatial resolution is not suitable or the wavelength is too short)

3.2.1 Ground-based

Conventional timber inventories are based on in situ measurements. Ground-based measurement has traditionally been used to quantify and map biomass and assess the vegetation structure at site-scale. This method is time-consuming and expensive as it requires in situ data collection and a representative sample size; a systematic sampling method is often employed to select plots within a forest stand. Inaccuracies arise from sampling bias, lack of precision in the measurements, or variation in the user.

Allometric equations allow the determination of forest characteristics such as biomass, which would otherwise require destructive monitoring. An allometric equation enables one characteristic of a tree to be inferred from a statistical relationship with other known characteristics (Chave et al, 2005). Tree allometry uses statistical relationships between tree dimensions such as the height, basal area and number of branches to infer other forest characteristics such as above-ground biomass. Tree characteristics can be measured using instruments as simple as a tape measure or using laser rangefinders depending on the parameter. Unfortunately, allometric equations are based on a limited sample of trees (and in the case of forest biomass, via destructive sampling) thus the accuracy of results can be highly variable depending on a number of factors, most notably the tree species.

Future technological advancements could capitalize on the widespread use of smartphones. A phone application could be developed as a new method of in situ monitoring. It could for example measure tree height which can then be converted into biomass via an allometric equation. Large-scale coordinated mapping and assessment efforts could help ground-truth satellite-based forest surveys on a global scale.

CASE STUDY – Monitoring Networks

Monitoring networks provide consistent regional-to-global-scale vegetation characterisation through the standardisation of practices. They aim to accurately quantify biomass and improve understanding of forest responses to change.

Both the Amazon Forest Inventory Network (RAINFOR) and the African Tropical Rainforest Observation Network (AfriTRON) have developed a framework for long-term, systematic monitoring of rainforests. Data is collected in situ from permanent sample plots (with high frequency monitoring of a subset of plots). The compilation of ground-based measurements produces a regional-scale dataset and has enabled the comparison of data from different plots across Amazonia within RAINFOR and across Africa within AfriTRON - results can also be compared between networks.

ForestPlots is a web-accessible database for forest inventories based on sample plots, and includes data from both the RAINFOR and AfriTRON networks enabling them to view, edit and upload data.

(For more information visit: www.rainfor.org ; www.afritron.org ; www.forestplots.net)

CASE STUDY – GEO-Wiki Project

The Geo-Wiki Project is a crowd-sourcing system which relies on volunteers worldwide to review areas where global land cover maps disagree. Volunteers assess and validate if land cover is correct or incorrect based on GoogleEarth imagery or their local knowledge – they can upload information, in situ measurements or geo-cached photographs to the online database. This enables a mosaic of land cover data to be produced from data at the global- to local-level. The aim is a gap analysis, cross-product validation, harmonization and product development (Geo-Wiki team, 2009; Schepaschenko et al, 2012).

(For more information visit: www.geo-wiki.org)

3.2.2 Airborne Remote Sensing

Airborne data collection has traditionally been retrieved from large airborne systems such as blimps and manned planes. Manned planes allow for heavy sensor payloads; however they require greater skill and higher altitudes, causing problems for air space restrictions. Advances in drones for military purposes in the past 10 years have provided modern airborne systems for civil and scientific purposes, including for the monitoring of illegal resource extraction (Van Blyenburgh, 2011).

Unmanned aerial vehicles (known as UAVs or drones) are aircraft that can be controlled remotely from ground control stations or are fully autonomous owing to an on-board computer (CielMap, 2012). It is possible to generate near real-time geo-referenced land use and land cover maps from UAVs which can help resource management efforts. UAVs can be equipped with various instruments for land cover mapping; cameras, multi- or hyperspectral imaging sensors (from visible to thermal spectrum), passive microwave, active microwave (radar) and Light Detection And Ranging (LiDAR).

The application of UAVs is governed by local aviation regulation like the Civil Aviation Authority (CAA) in the UK who limit aircraft to within a remote pilot's line of sight (usually a maximum distance of 500 m horizontally and 400 ft vertically) (CAA, 2014). Low altitude systems (<200m) tend to be employed for agricultural and forest research purposes (Everaerts, 2008).

Generally UAVs have a spatial resolution of less than 1 m; a typical UAV tends to have a spatial resolution of around 6 cm at an altitude just above 200 m (Rango & Laliberte, 2010). High resolution image tiles are mosaicked to cover a larger spatial area – mosaicking is a complex task as control points are difficult to locate within the images.

UAVs are capable of remotely retrieving information on forest parameters such as vegetation species, health, coverage and size class; they are capable of monitoring crop growth, detecting disease, and identifying vegetation stress due to water shortage. UAV application within forestry also supports law enforcement as they have the capability to map forest boundaries and use automatic land cover recognition systems to identify where land use change has occurred, i.e. gaps caused by logging or forest degradation. Once located, logging activities can be verified against legal logging within the Register of Grant Schemes and Felling (Forestry Commission, 2014).

CASE STUDY – Unmanned Aerial Vehicles in the Amazon, Brazil

In 2009 the São Paulo Environmental Police employed fourteen UAVs to regularly monitor the Amazonian forest. The basic drone system by AGX Tecnologia costs about US$35,000 including training and programming (Barnes, 2011). The Named Arara (Parrot) and Tiriba (Little Parrot) drones produce geo-tagged images to locate illegal logging and mining operations as well as track poachers, providing visual evidence for convictions (Coren, 2011).

The Climate Policy Initiative claims that more stringent policy to protect forests has led to improved monitoring such as the use of UAVs which consequently halved the deforestation rate, saving approximately 6 million hectares of the Amazon between the years 2005 and 2009 (CPI, 2012).

Although increasingly reliable and flexible in terms of operating hours, airborne remote sensing can be costly and global datasets do not exist as the technique is not widely used in developing countries. There is a trade-off between greater coverage and lower spatial resolution. Using high spatial resolution data is usually too expensive as the small swath means a large volume of image tiles to cover an area and more processing is required. The smaller spatial coverage of airborne data in comparison to spaceborne data therefore makes it less appropriate for large-scale forest assessment on its own, and more suitable for smaller scale projects, unless it is being used for validation.

The survey area of UAVs is defined by the operator, however the battery life is a major controlling factor on flight-time and consequently determines the size of the area covered; flight times range from minutes to days. Fixed-wing low altitude aircrafts tend to be used for longer flight durations as they cover a greater distance – these are used in agriculture (CropCam, 2014) and multipurpose monitoring (Aerosonde, 2014). Forest mapping requires endurance UAVs as they are capable of travelling faster to cover an area of over 200km.

However another trade-off exists between system resolution and UAV size (Horcher & Visser, 2004). Higher altitude systems weigh more and tend to have a lower spatial resolution as they fly at higher altitudes (Lucintel, 2011; Koh & Wich, 2012; CielMap, 2012). They do however produce longer-term datasets, although this causes data acquisition and processing to take days or weeks rather than hours. These high altitude aircrafts are consequently better for the identification of seasonal variation or wider change over time.

3.2.3 Spaceborne Remote Sensing

Since the emergence of earth observation from space in 1972 with the launch of the first Earth Resource Satellites (ERS), satellite remote sensing has been accelerated by the European Space Agency (ESA), the National Aeronautic and Space Administration (NASA), the National Oceanic and Atmospheric Agency (NOAA) and other space agencies throughout the world. Remote sensing provides an efficient method to collect information on forest area change at a global, biome and regional scale. Today, satellite-based remote sensing techniques are employed to map and monitor land use change such as forest clearance.

Spaceborne remote sensing is however currently disadvantaged by the technical, methodological and political complexities in its application. Spatial and temporal resolutions tend to be the biggest barrier to the use of remote sensing for global vegetation monitoring as these conflict with the need for timely and cost-effective global data provision. High spatial and temporal resolution data results in large datasets which are more difficult to process and analyse; sub-meter resolution data is expensive, difficult to acquire for a suitable time-frame and still requires ground-truthing image analysis. Meanwhile a high temporal resolution (satellite repetition rate) is important due to the impact of weather conditions i.e. cloud coverage, especially in forested areas (Koch, no date; Freeman & Fox, 1994). Alternatively low spatial and temporal resolution data can produce inaccurate datasets. The large image tiles and infrequency of satellite overpass over the target area can result in inaccurate image classification, whilst differences in satellite configurations and data processing also cause difficulties.

Trade-offs in the use of satellite imagery results from its four characteristic factors which affect image quality, quantity and timeliness (Rogan & Chen, 2004):

- Spatial resolution – smallest detail identified within an image (pixel size)
- Radiometric resolution – ability to detect differences in reflected energy (bit size)
- Spectral resolution – sensitivity of sensor to a frequency range (number of spectral bands the reflected energy can be measured in)
- Temporal resolution – rate of satellite revisit/scheduled overpass over the same area (repetition rate)

The interpretation of imagery to map forest-non-forest area can be based on categorical image classification as there are clear boundaries between the two classes. Land cover change however requires a continuous classification approach to measure the change in forest cover over time (Rogan & Chen, 2004). Image classification can be cost intensive and subjective due to the unclear delineation of the forest boundary. Alternatively learning algorithms can be applied to objectively classify pixels. For further information on methods for monitoring forest cover or carbon stock, refer to Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) REDD Sourcebook (2013) and FAO Global Forest Resources Assessment (2010).

Although spaceborne remote sensing will allow large-scale environmental assessment through the detection of vegetation change from space, ground-based measurements are still required to interpret the spectral signatures of different land uses, i.e. vegetated and non-vegetated land. The quantification of forest area from earth observation requires calibration and validation; ground-truthing to verify and adjust remotely sensed data. A global spectral database therefore needs to be developed based on a significant sample of in situ measurements.

Whilst optical remote sensing is likely to become a more prevalent technique for forest-non-forest cover mapping, radar (also known as active microwave) data is unlikely to be extensively integrated within monitoring methods due to its limitations within mountainous environments, the complex steps of data processing and the lack of a long time-series of earth observation radar satellite data (Koch, no date).

OPTICAL DATASET

CASE STUDY – Near Real-Time Deforestation Detection System (DETER), INPE

The National Institute for Space Research (INPE) began surveying the Amazon forest in 2004 in an attempt to detect land cover change within Brazil's Amazon forest. The DETER system uses remote sensing to map areas of clear-cut forest generating bi-monthly or monthly results to inform law enforcement activities of 'hotspot' areas as part of a government plan to control deforestation.

Imagery is acquired at a periodicity of less than three days from the MODIS sensor on-board NASA's Terra and Aqua satellites; this data is calibrated using Landsat-5 TM data at a 30 m spatial resolution. The optical dataset is limited by cloud cover – deforestation may not be identifiable within the satellite imagery and consequently alerts would not be issued to allocate monitoring personnel to the forest area (Assunção et al, 2013; Shimabukuro et al, 2004).

The high geometric accuracy sensors in DETER are capable of detecting deforestation 'hotspot' areas larger than 250 m^2. DETER contributed to a vast drop in deforestation as law enforcement agencies could locate and control burning and deforestation; in 2010 the Brazilian government recorded the nation's annual rate of deforestation as its lowest since 1988. Unfortunately, although large-scale illegal logging has been deterred, it has more recently led to the deforestation of small, dispersed swaths of land undetected by medium resolution satellite data; higher resolution imagery is available but repeat flyover rates are longer and the datasets are more expensive (Anderson et al, 2005; ECI, 2014).

According to Assunção et al (2013) DETER contributed to the prevention of the clearance of an estimated 59,500 km^2 of Amazon forest from 2007 to 2011.

(For more information visit: www.obt.inpe.br/deter)

RADAR DATASET

CASE STUDY – GSE Forest Monitoring Project

Multi-temporal radar imagery was used to map forest in French Guiana as part of the GSE Forest Monitoring project by ESA. Two C-band SAR datasets were assessed in their ability to classify and estimate forest and non-forest land via wall-to-wall mapping; ERS-1 and ASAR data. Image mosaics of Landsat-5 and Landsat ETM+ data were used to validate the SAR classifications due to the lack of available ground-based measurements.

SAR data went through a number of processing steps including; co-registration of stacked images, geometric and radiometric correction and orthorectification. Temporal filtering (i.e. stacking several scenes covering the same area) was also able to reduce the effect of weather conditions and speckle noise.

Poor forest and non-forest contrast made classification difficult, as did distinguishing between forest cover and different vegetation. A greater percentage of land cover was classified as forest in the SAR data in comparison to the visually interpreted Landsat data due to the mistaken classification of mangroves as forest.

The signal intensity contrast between forest and non-forest was greater in the ASAR dataset by comparison with the ERS data. This was partly due to the higher incidence angle of the ASAR data affecting the backscatter intensity and maximising this difference. Accuracy of forest area mapping was visually assessed using control points within Landsat scenes; ERS data (1992-1993) was 90% accurate in classifying forest-non-forest, whilst classification using ASAR (2003-2004) was 94% accurate. This high forest area mapping accuracy is largely due to the high forest cover in the area investigated, reducing the difficulties found in classification at the forest edge (Rauste et al, 2007; Häme et al, 2004).

(For more information visit: www.gmes-forest.info)

CASE STUDY – BIOMASS Earth Explorer mission 2020

The European Space Agency (ESA) is set to launch Earth Explorer 7, the 'Biomass mission' in 2020. This satellite aims to measure 'forest biomass to assess terrestrial carbon stocks and fluxes' to improve our understanding of forests role in the carbon cycle and in climate change. In addition to this it will provide further information on ice-sheet thickness, subsurface geology in deserts, soil moisture, and permafrost and sea-surface salinity.

The sun-synchronous satellite is equipped with synthetic aperture radar (SAR) operating at P-band. Forest biomass and forest height will be mapped at a spatial resolution of 200m.

(For more information visit: www.esa.int)

3.2.4 *Light Detection And Ranging (LiDAR)*

Recent developments have seen terrestrial scanners such as Light Detection And Ranging (LiDAR) help overcome limitations of ground-based statistical sampling and improve the efficiency of ground-based measurements, allowing faster data collection on forest structure (tree volume and height) and tree quality. The main drawback is a continued high cost.

LiDAR is an optical remote sensing technology that illuminates an object of interest and measures the light signal reflected back to the sensor. The time delay between a signal being transmitted, detected and reflected back determines the distance to an object, whilst the intensity of the signal is used for feature detection; previous studies have used LiDAR for the quantification of above-ground forest biomass (see Lu et al, 2012; He et al, 2013; Zhao et al, 2009; Laurin et al, 2014). LiDAR provides sub-meter forest measurements; it creates digital elevation models of tree heights and digital surface models, it captures forest cover, forest structure and vegetation density and generates a canopy profile.

LiDAR systems can be; mounted on UAVs (Asner et al. 2007, 2012b; Stephens et al. 2012; Montaghi et al. 2013); stationary ground-based (Watt and Donoghue 2005; McDaniel et al. 2012); below-canopy (Jaakkola et al. 2010; Wallace et al. 2012); or on-board satellites – for example the LiDAR sensor (GLAS) on the Ice, Cloud, and Land Elevation Satellite (ICESat) (Lefsky, 2005).

CASE STUDY – LiDAR mapping within CANOPOR project, Carbomap

Paracou, a forest area in French Guiana was mapped within the CANOPOR project (funded by Labex CEBA) using a high-density laser scanner purpose built for use on UAV's, YellowScan by l'Avion Jaune, and optical an infrared imaging systems with 7 cm resolution, mounted on a helicopter which replicated the flight characteristics of a fixed-wing UAV.

Carbomap are a UK-based company who are world leaders in mapping forests using LiDAR, conducted the data processing for this 'first of a kind' project. Carbomap extracted a canopy height model from the LiDAR data, by developing an algorithm which detected the ground points and used this to generate a bare earth digital terrain model (DTM). The canopy height model was calculated by determining the height of each point above the ground level; this was subsequently used to determine other structural parameters of the rainforest.

"UAV-LiDAR is ideal for economically mapping rainforests on the landscape scale, in Three Dimensions" Professor Iain Woodhouse, CEO of Carbomap.

Following on from this, where a time-series of datasets are available, change in forest cover can be mapped by detecting changes over time,

(For more information visit: www.carbomap.com)

3.3 ENSEMBLE OF DATA AND APPROACHES FOR FOREST MAPPING

A geo-referenced multi-temporal database is required to integrate data from all data collection methods (ground-based, airborne and spaceborne data). Citizen science (also known as crowdsourcing), i.e. scientific research conducted by non-professionals, is an effective way to ground-truth spaceborne datasets and prevent the need for intensive ground-based measurements. This integration of data can be achieved within geographic information systems (GIS). GIS is a tool for mapping and analysing spatial datasets. Its application can include the mapping of global phenomena such as forest clearance, and it is useful for combining and displaying forestry data derived from different sources.

CASE STUDY – 'Our Ecosystem' by Ecometrica

'Our Ecosystem' (OE) is a cloud-based platform that enables spatial data to be curated, shared and analysed on the fly at local, regional or global scales. University of Edinburgh is using OE to compare different forest carbon maps produced from organisations such as NASA, Woods Hole Research Centre and others. ESA is using OE to support performance assessment of DFID, DECC and Defra forest conservation projects under the International Climate Fund (ICF).

"OE is a great way to share and build data assets for conservation purposes, REDD+ projects, and forestry departments." Dr Richard Tipper, Chairman of Ecometrica.

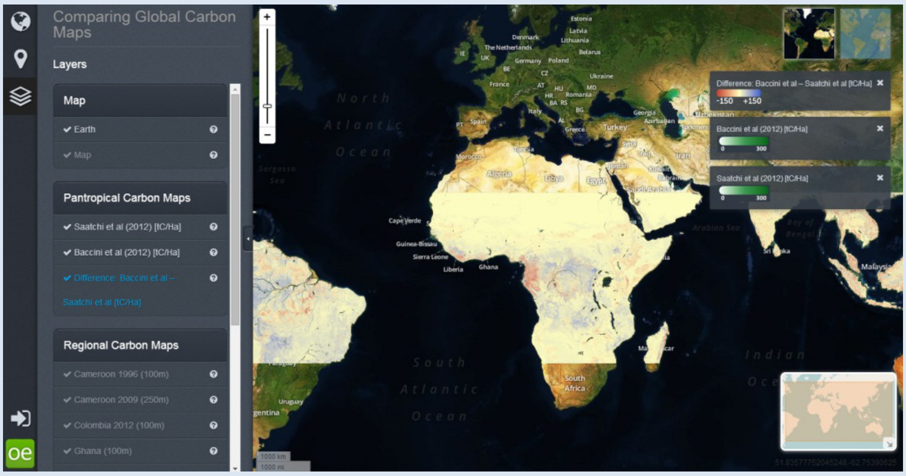


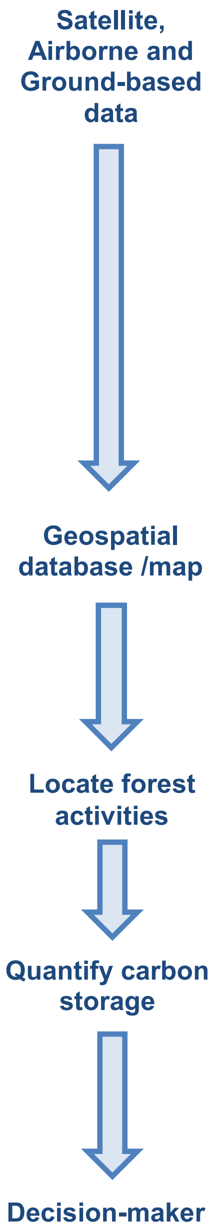
Figure 2 Comparison of Pan-Tropical carbon maps (tC/ha) based on optical and LiDAR spaceborne data and ground-based measurements - difference between a 500 m resolution carbon map (Baccini et al, 2012) and a 1 km resolution map (Saatchi et al, 2011)

Source: Ecometrica (2014)

(For more information visit: www.ecometrica.com/products/our-ecosystem/)

4 RECOMMENDATIONS

The initial step towards effective forest resource management in the UK involves forest-non-forest mapping. A consistent, long-term global forest monitoring system is required to identify and control tree cover and forest land use changes. This requires a number of steps as recommended below.



A geospatial product such as a forest land cover map for the UK should use a combined approach utilizing spaceborne remote sensing data to complement sample in situ measurements and supported by high resolution airborne data. This integration of data to produce a forest inventory will allow for a global 'wall-to-wall' dataset (i.e. complete coverage) to be produced; high resolution ground-based measurements in combination with less time-consuming airborne datasets will overlay and validate large-scale satellite datasets.

Satellite remote sensing provides global coverage, systematic observations, and standardized approaches for the classification of land cover (FRA, 2009). The satellite data acquired should be predominantly an optical dataset, whilst radar data can be acquired to 'fill-in-the-gaps' of optical data where cloud cover is prevalent. Satellite remote sensing is constantly benefiting from improvements in sensor technology and data quality, and this will continue in the future (Rogan & Chen, 2004). However, UAVs should be considered an apt approach to collect high resolution data to supplement ground-based measurements.

A web-based platform/portal can act as a strategic tool to combine datasets of different spatial resolutions to map the distribution of forests and monitor forest clearance. GIS enables access to data for international cooperation and provides an enhanced capacity, especially in developing countries, for monitoring, assessing and reporting forest area and change (FAO, 2010). Mapping software should be used for data management and analysis. GIS can be used as a decision-making tool for programme coordination/natural resource management.

Mapping the spatial distribution of forests will help to locate illegal activities enabling the UK government to enforce regulations and impose penalties, as well as improve environmental assessment (Freeman & Fox, 1994). However further work is needed to see if mapping forest-non-forest areas can support companies to track stocks in conjunction with documentation to report forestry activities.

In addition to tracking the timber trade, it would be beneficial to develop an accurate carbon map that quantifies forests for climate policy purposes (see Section 2). Above-ground biomass is currently the key indicator used as a proxy for forests and their carbon storage. However, forest biomass remains poorly quantified and a strong correlation is yet to be established. Further investigation is required into the correlations between non-destructive measurements of forest characteristics such as canopy height, basal area and number of branches, and the above-ground forest biomass.

Forest data is often provided on a number of scales and at different temporal and spatial resolutions. Identifying the most appropriate dataset to use for different applications can be a daunting task. A set of guidelines needs to be developed to ensure users make educated decisions with regards to which approach and dataset best suits their needs as well as how to use forest mapping data.

As discussed in Section 3.1 Carbon Estimation, the IPCC Good Practice Guidance (2003) states that estimation of forest carbon can be achieved with the provision of information about two fundamental variables: (1) carbon stock and (2) forest area. This report provides an overview on making a forest-non-forest decision.

In future a similar approach to that demonstrated in the flow diagram (above) would be required for carbon flux monitoring. Whilst the three approaches to monitoring forests (in situ, airborne and spaceborne) each rely on measurement, only in situ destructive measurements can directly calculate biomass or accurately estimate carbon content. Techniques currently applied to measure forest parameters such as above-ground biomass in the UK have been discussed within Quegan et al (2012). However the Biomass Mission expected to launch in 2020 aims to measure forest biomass more accurately than currently achieved by spaceborne data, to enable the development of a carbon stock map (see CASE STUDY – BIOMASS Earth Explorer mission 2020). A carbon stock map can inform mechanisms for distributing incentive payments that account for carbon stocks, whether national or subnational, thereby helping to ensure that effective, efficient and equitable mechanisms are in place for reducing carbon emissions from deforestation and forest degradation.

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