Institution: University of Edinburgh

Unit of Assessment: 7

Title of case study: Fusing satellite observations with models to guide and influence tropical forest management and policy

Period when the underpinning research was undertaken: 2005 - 2018

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Matt Williams	Professor of Global Change Ecology	11/2000 - present
Iain Woodhouse	Professor of Applied Earth Observation	07/1999 - present
Casey Ryan	Reader in Ecosystem Services and Global Change	09/2009 - present
Ed Mitchard	Professor of Global Change Mapping	12/2007 - present

Period when the claimed impact occurred: 1 August 2013 – 31 December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

Pioneering fieldwork and radar remote sensing research to map forest biomass has led to improved land use and forest conservation policy and action across the tropics, through supporting NGOs to influence land use policy in multiple countries, and development of forest policy and subsequent implementation to meet international reporting requirements for the United Nations. The team's research has also supported global climate forecast capability, assisting the Brazilian Institute for Space Research to advance its national carbon and forest modelling capability for improved climate forecasts.

Biomass mapping coupled to advanced diagnostic carbon cycle modelling has supported UK industry to develop new spatial products and services for forest sustainability, enhancing the growth of UK environmental businesses through product development, with impact across the globe.

Biomass mapping advances using radar and carbon cycle model diagnostics from the group have influenced space and earth observation strategy and investment decisions. The group's work and advice were major influences on the European Space Agency's decision to allocate GBP 192,000,000 to Airbus UK for satellite construction to monitor forest biomass change.

2. Underpinning research (indicative maximum 500 words)

Forest biomass Carbon (C) change is the major unknown in the terrestrial C cycle and in climate forecasts. Globally leading research at the University of Edinburgh (UoE) has made it possible to map and interpret changes in forest carbon and provide this information to a range of policy makers, SMEs and land managers to support policy development and decision making. The team have done this by advancing the fields of radar remote sensing, data assimilation and carbon cycle modelling. This information is important because forest biomass is a major pool of carbon (C) in the Earth system, is a strong indicator of local biodiversity, and provides timber, fuel and other products that support society and its well-being.

The UoE team has pioneered the use of radar remote sensing techniques to determine above-ground biomass and biomass change. They established and now monitor a network of forest

plots across Southern Africa. They compared radar backscatter-biomass relationships across these plots and at other sites, showing significant similarity in the fit across four different forest-savanna and woodland types **[3.1]**. Based on these consistent relationships they developed the first maps of biomass in African woodlands, quantifying the spatial variability of woody carbon at sub-hectare scales. They used satellite data collected over 4 years to map changes in forest biomass for the first time. This approach showed how radar data can characterise landscapes for forest degradation **[3.2]**, which has been a major unknown in assessments of changes in woody C stocks until now. Building on their proof of concept, the team has quantified the carbon emissions from degradation across all Southern African woodlands, showing that degradation is the principal form of woody carbon loss in this region **[3.3]**. These methods and the modelling advances described below, have also been used to produce a globally repeated, consistent product of global maps of carbon, as part of the European Space Agency (ESA) CCI Biomass programme **[5.5],** and to provide the science case for the ESA Earth Explorer mission BIOMASS **[3.4]**.

To make the best of the new data flowing from the remote sensing methods developed at UoE, the team has also pioneered the use of data assimilation to provide state of the art estimates of ecosystem dynamics that combine the new data sources with carbon cycle modelling. This advance, which leveraged methods from ocean science into carbon cycle science for the first time **[3.5]** allowed the team to show for the first time how repeated biomass data can be used to calibrate and improve terrestrial C models **[3.5].** Data assimilation converted the large volumes of data available from remote sensing into useful information on carbon stocks, flows and emissions **[3.6]**. Bayesian algorithms for fusing satellite observations with models take account of observation error in eg. biomass maps. This means the team could generate a unique probabilistic assessment of the global land C cycle at 1º spatial resolution over multiple years, consistent with local climate, satellite observations of biomass, leaf area index, burned area, and maps of soil C **[3.6]**. The novelty of this research has been to generate a global mapping of residence times of forest C pools at high resolution, a critical determinant of the climate sensitivity of C cycle predictions. The research has allowed development of a capability for continued monitoring of forest change and relevant C cycle diagnostics on an ongoing basis.

This combined expertise in process-based modelling, data assimilation and remote sensing of forests, has helped to generate significant impact with a range of stakeholders who require diagnostic information, clear error quantification and ecological context in their policy development and decision making around for policies on forest carbon management, from local to global scales.

3. References to the research (indicative maximum of six references)

[3.1] Mitchard, E.T.A., Saatchi, S.S., **Woodhouse, I.H.**, Nangendo, G., Ribeiro, N.S., **Williams, M., Ryan, C.M.**, Lewis, S.L., Feldpausch, T.R. & Meir, P. (2009). 'Using satellite radar backscatter to predict above-ground woody biomass: A consistent relationship across four different African landscapes' ***Geophysical Research Letters***, *36* (*23*), L23401. doi: 10.1029/2009GL040692. [178 citations]

[3.2] Ryan, C.M., Hill, T., Woollen, E., Ghee, C., **Mitchard, E.**, Cassells, G., Grace, J.**, Woodhouse, I.H.** & **Williams, M.** (2011). 'Quantifying small-scale deforestation and forest degradation in African woodlands using radar imagery' ***Global Change Biology***, *18*(*1*), 243-257. doi:10.1111/j.1365-2486.2011.02551.x. [94 citations]

[3.3] McNicol, I., **Ryan, C.** & **Mitchard, E.** (2018). 'Carbon losses from deforestation & widespread degradation offset by extensive growth in African woodlands' ***Nature Communications***. doi:10.1038/s41467-018-05386-z. [24 citations]

[3.4] Quegan, S., Le Toan, T., Chave, J., Dall, J., Exbrayat, J.-F., Minh, D.H.T., Lomas, M., D'Alessandro, M.M., Paillou, P., Papathanassiou, K., Rocca, F., Saatchi, S., Scipal, K., Shugart, H., Smallman, T.L., Soja, M.J., Tebaldini, S., Ulander, L., Villard, L., & **Williams, M**. (2019). The European Space Agency BIOMASS mission: Measuring forest above-ground biomass from

space ***Remote Sensing of the Environment****,* 227, 44-60. doi:10.1016/j.rse.2019.03.032. [32 citations]

[3.5] Williams, M., Schwarz, P.A., Law, B.E., Irvine, J. & Kurpius, M. (2005). 'An improved analysis of forest carbon dynamics using data assimilation'. ***Global Change Biology*** *11*, 89-105. doi:10.1111/j.1365-2486.2004.00891.x. [228 citations]

[3.6] Bloom, A.B., Exbrayat, J.-F., van der Velde, I. R., Feng, L. & **Williams, M.** (2016). 'The decadal state of the terrestrial carbon cycle: global retrievals of terrestrial carbon allocation, pools and residence times' ***Proceedings of the National Academy of Sciences*** *113,* 1285-1290. doi:10.1073/pnas.1515160113. [107 citations]

The underpinning research listed was published in highly ranked academic journals (Scopus citations as of December 2020 shown above), and supported by peer-reviewed grants. Examples include:

Co-I, Williams, C. (2014-2021). National Centre for Earth Observation. [pr140015]. NERC/NCEO GBP1,460,812

Co-I, Ryan, C. (2013-2018). ACES: abrupt changes in ecosystem services and wellbeing in Mozambican woodlands. [ne/k010395/1]. *NERC* [GBP1,993,268]

This research also led to MW being awarded the Royal Society Wolfson Merit Award in 2014; winning GBP 500,000 from Newton Fund in 2017 and 2019 for Brazilian collaboration; and winning EURO 155,000 from ESA in 2020 for advancing model-satellite integration. **[3.1]**, **[3.2]**, **[3.3]**, **[3.5]**, & **[3.6]** provided the proof of concept and underpinning methods for a recent NERC Large Grant led by UoE staff (NE/T01279X/1; 5 years; GBP3,700,000) which will improve our understanding of the carbon cycle of the dry tropics.

4. Details of the impact (indicative maximum 750 words)

The team's research has led to impact in 3 main areas, policy, industry and technology:

Policy:
The team's research has underpinned the development and implementation of national policies to reduce carbon emissions from deforestation and forest degradation **[5.1], [5.2], [5.3], [5.4]**. UoE biomass mapping contributed to a USD6,555,000 World Bank project **[5.4]** to develop capabilities and satellite monitoring tools for forest degradation assessment, applicable on a global scale for sustainable forest management and UN REDD+ (Reducing Emissions from Deforestation and Degradation) schemes, particularly across sub-Saharan Africa and Central/South America. The Mozambique government has used this research to inform and implement national policy, where '*these new data sources have been critical to allowing us to monitor carbon stocks and emissions from land use, and this information in turn contributes to our efforts to set ambitious targets as part of the Paris Agreement, and then monitor our progress towards these goals'* **[5.1]**.

The flexibility and accuracy of the methods have supported NGOs working across sub-Saharan Africa, eg Mozambique, Tanzania, Zimbabwe and Rwanda **[5.1] [5.4]**. The team has worked extensively with the Plan Vivo foundation, an Edinburgh-based charity with international scope, which has created a set of requirements for smallholders and communities wishing to manage their land and natural resources more sustainably. Plan Vivo has worked with and supported over 16,000 participating smallholders with over 180,000 ha of land under management in a range of countries, resulting in over 3,500,000 million tonnes of CO_2 emissions reductions **[5.2]**. The methods developed at Edinburgh '*have been instrumental in many community carbon projects generating carbon credits - these cutting-edge methods have been critical for these projects, which would not otherwise have been viable...and.. our collaboration with the University of Edinburgh remains one of our strongest partnerships, which continues to deliver impact through developing an applying innovative approach to carbon mapping, which ultimately benefits thousands of smallholders'* **[5.3]**.

The team have combined biomass data and models to develop new tools to accurately monitor savannas and dry forests, and quantify carbon stock changes and emissions, and build international partnerships to support national agencies reporting and forecasting greenhouse gas budgets required by the UN Paris Climate Agreement **[5.4, 5.6]**. Brazil has the largest tropical forest biomass and coverage of any country in the world. With a UoE-Brazilian partnership built over 20 years, the team's '*world-leading expertise and insights around regional carbon cycles, carbon flows and integrating these fluxes at a regional level'* has been critical to developing the modelling capacity of the Brazilian agency INPE, helping them to meet their institutional goals for carbon and climate. Resulting analyses from INPE are informing and improving the Brazilian national carbon cycle model, which is '*critical to provide a greenhouse gas balance estimate that underpins national reporting'* **[5.6]** to guide mitigation policies and supports the Brazilian Government Working Group on REDD+, as well as contributing to the scientific basis for the deforestation carbon emissions reference levels **[5.4]**.

Industry*:*
A UoE collaboration with Ecometrica resulted in the UK Space Agency funding a GBP14,000,000 project to protect and restore 300,000,000 ha of tropical forests **[5.3]**. This project during 2017-20 led to the development of tools to measure and forecast biomass change and provision of these outputs to customers across the globe; '*the products based on University of Edinburgh Research have proven to have great societal value – informing policy and decision making '* **[5.3]**. The team's research has also been critical to the development of Ecometrica's *Hectares Indicator*. Overseas Development Assistance (ODA) funding provided by the International Climate Fund (ICF) is a key part of the UK's commitment under the Copenhagen Accord to support developing countries to mitigate and adapt to climate change through low carbon growth, reduced deforestation and increased resilience **[5.5]**. ODA funding for forest related programmes is approximately GBP200,000,000 per year, and to ensure this is used effectively and efficiently, ICF resources report against relevant Key Performance Indicators (KPI's). The *Hectares Indicator* is a KPI used by UK government for most forest-related programmes **[5.3]**.

Technology: The team developed and delivered the supporting case for the Earth Explorer BIOMASS satellite mission in 2013, after advising the European Space Agency (ESA) on mission development since 2009. The BIOMASS mission will determine the amount of biomass and carbon stored aboveground in tropical forests over five years (2023-8), at 4 ha (0.04 km^2) resolution, with repeated mapping every 9 months **[5.5]**. BIOMASS is the first satellite mission in space for P-band radar, which is uniquely capable of monitoring the densest tropical forests. UoE research provided a *'critical starting point to the mission design and… the basis of all downstream mission requirements'* **[5.5].** UoE research was instrumental in securing the contract from the European Space Agency (ESA) for Airbus to build the satellite in the UK: UoE '*support in writing the selection document ..and presentation at the selection committee meeting ..led to BIOMASS being selected as an ESA earth explorer over intense competition'* **[5.5]**. The mission, selected in 2013, is the first ever ESA forest-specific monitoring mission, with a budget of EUR420,000,000, including a GBP192,000,000 investment in Airbus UK (currently being built, due to launch in 2023) **[5.5].**

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] a) MRV Unit Coordinator, *FNDS Mozambique*, (testimonial letter 23/11/2020), **b)** Project Manager – Forest 2020, *Kenya Forest Service* (testimonial letter 02/11/2020).

[5.2] a) Plan Vivo project countries and details www.planvivo.org/Pages/Category/projects?Take=24 (accessed 15/12/2020); **b)** Chief Operating Officer, *Plan Vivo foundation* (testimonial letter, 04/11/2020)

[5.3] a) Executive Chairman, *Ecometrica*, (testimonial letter 30/09/2020); **b)** Forests 2020 project website ecometrica.com/forests-2020/ (accessed 15/12/2020); **c)** UK Space Agency case study www.gov.uk/government/case-studies/ecometrica-forest-monitoring-systems (accessed 15/12/2020)

[5.4] a) Senior Forestry Specialist/Task Team Lead, *World Bank Group*, (testimonial letter 10/11/2020); **b)** Satellite Monitoring for Forest Management project details www.smfm-project.com (accessed 15/12/2020); **c)** SMFM project budget www.thegef.org/project/satellite-monitoring-forest-management (accessed 15/12/2020)

[5.5] a) Biomass Mission Manager, *European Space Agency,* (testimonial letter 10/09/2020); **b)** Influencing the European Space Agency selection process for Earth Explorer 7 www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/Future_missions/Biomass (accessed 15/12/2020) ; **c)** Supporting the European Space Agency CCI Biomass project; https://climate.esa.int/en/projects/biomass/about/ (accessed 15/12/2020)

[5.6] a) Head – Centro de Ciencia do Sistema Terrestra, *Brazilian Institute for Space Research,* (testimonial letter,10/09/2020); **b)** Collaboration developed in Newton CSSP Brazil project: www.metoffice.gov.uk/research/approach/collaboration/newton/cssp-brazil/index (accessed 15/12/2020)