Institution: University College London

Unit of Assessment: 14 – Geography and Environmental Studies

Title of case study: New measurements of trees and forests: improving global observations for climate and carbon studies and extending public understanding

Period when the underpinning research was undertaken: 2016-2019

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:
Prof. Mathias Disney	Professor of Remote Sensing	2005-present
Prof. Philip Lewis	Professor of Remote Sensing	1992-present
Dr. Phil Wilkes	Research Associate	2016-present
Dr. Andrew Burt	Research Associate	2017-present

Period when the claimed impact occurred: 2017-2020

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

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

Disney's research generates new 3D measurements of trees to improve measurement of forest carbon stocks and validate new space-based observations from NASA and the European Space Agency. Disney's work has: 1) improved the way international space agencies are conducting measurements of forest carbon; 2) changed UN-led policy recommendations for national greenhouse gas inventory reporting, to help meet the COP21 (Conference of Parties) Paris Agreement targets; 3) provided new ways to assess and communicate the value of forests benefitting charities, including Friends of the Earth and Trees for Cities, forest management practitioners, and a public audience of [Text redacted for publication] through television programmes, inclusion in an exhibition at the Victoria and Albert Museum, and related media coverage.

2. Underpinning research (indicative maximum 500 words)

Disney's research seeks to better understand and model how radiation interacts with vegetation in order to quantify and understand changes in the carbon cycle in response to changing climate and human actions. Since 2014, he has used ground-based terrestrial laser scanning (TLS) to provide unique 3D measurements of forest structure and biomass. Under the COP21 Paris Agreement, forests are earmarked to provide 25% of planned greenhouse gas emissions reductions. Monitoring and verification of forest carbon uptake relies on accurate and timely estimation of forest carbon stocks from ground and space. Yet significant uncertainty around the response of trees and forests to climate and disturbance arises due to the difficulty of accurately and reliably measuring the size and mass of trees, particularly in the tropics. The best global maps of forest biomass – stored carbon (C) – rely on extrapolating a very small sample of trees that have been harvested and weighed, a few thousand at most across the whole tropics, to the estimated pan-tropical total of 3 trillion trees.

Disney's expertise in observational methods, models and ecological applications led to his development of a new approach to 'weighing' trees, using TLS. This provides very detailed 3D measurements of tree size, mass and structure **[R1/R2]** and is changing the way forest C is measured from the ground and from satellites This approach provides critical improvements over existing methods in several respects: it is non-destructive, can be applied to many more trees than is feasible (or desirable) to harvest, and its use is independent of tree size **[R2]**. Disney's work with Calders et al. **[R4]** was the first to show that TLS measurements align very closely with destructive harvest measurements, subsequently confirmed by work with large tropical trees **[R2/R5]**. Crucially, TLS measurements suggest that the mass of larger trees is generally underestimated, by more than 35% in some situations **[R2/R5]**. Given their disproportionately large contribution to forest C stocks, this has important implications for assessing the relationship between forests and climate, particularly from new satellite observations **[R3]**. The intact value of tropical forests for climate mitigation may potentially be greater than previously thought; conversely, the loss of these areas would release more C than current estimates suggests.

This result underlines the critical importance of tropical forest protection and 'avoided deforestation' to climate policy.

Disney has extended this new approach to urban forests. This has become a critical area of interest for policy and one where estimating tree size and canopy cover is even more important than in the tropics because the value of urban forests is underestimated. Disney's work provides a new way to assess the state and quality of urban forests leading to the unexpected conclusion, for example, that pockets of urban forest can store as much carbon per hectare as rainforests in places **[R6]**. More generally, the ecosystem services provided by e.g. London's trees – that is, the benefits residents gain from the environment's natural processes – were recently valued at GBP130,000,000 a year, less than GBP20 a year per tree. However Disney's work suggests that even the carbon uptake potential may be worth nearly double this **[R6]**.

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

R1. Disney, M. I. (2018). Terrestrial LiDAR: a 3D revolution in how we look at trees, New Phytologist, doi:10.1111/nph.15517. *One of the top 10% of articles downloaded from New Phytologist in 2018-19.*

R2. Disney, M. I. et al. (2018). Weighing trees with lasers: advances, challenges and opportunities, Royal Society Interface Focus 8 (2), doi:10.1098/rsfs.2017.0048. *Work funded via* (IV)*; special issue arising from Royal Society-funded meeting 'The terrestrial laser scanning revolution in forest ecology', co-led by Disney.*

R3. Disney, M. I. et al. (2019). Innovations in ground and airborne technologies as reference and for training and validation: Terrestrial Laser Scanning (TLS), Surveys in Geophysics vol 71: Forest Biomass and Structure from Space, eds. K. Scipal. R. Dubyah, T. Le Toan, S. Quegan, A. Cazenave and T. Lopez, doi:10.1007/s10712-019-09527-x. *Invited contribution to edited volume summarising state-of-the art on forest measurement, arising from meeting organised by International Space Science Institute (ISSI).*

R4. Calders, K., **Disney, M. I**. et al. (2014). Non-destructive estimates of above-ground biomass using terrestrial laser scanning, Methods in Ecol. and Evolution, doi:10.1111/2041-210X.12301. *The first demonstration of TLS as an accurate indirect measurement of tree volume and biomass; won the British Ecological Society Robert May Prize for Early Career Research*.

R5. Gonzalez de Tanago, J., **Disney, M. I.** et al. (2017). Estimation of above-ground biomass of large tropical trees with Terrestrial LiDAR, Methods in Ecology and Evolution, doi:10.1111/2041-210X.12904. *First demonstration of TLS for assessing tree biomass in the tropics.*

R6. Wilkes, P., **Disney, M. I.** et al. (2018). Estimating urban Above Ground Biomass with multi-scale LiDAR, Carbon Balance and Management 2018, 13:10, doi:10.1186/s13021-018-0098-0.

All outputs were peer reviewed.

Funding

i. 2021: ESA ForestSCAN: new measurements of tropical forests (EUR500,000, PI);

ii. 2018 EU Horizon 20:20: FODEX: Tropical Forest Degradation Experiment, proposal 757526: (EUR244,000 of EUR1,900,000 total, PI, lead RO Edinburgh);

iii. 2017 NASA ROSES Carbon Monitoring System (CMS): Future Mission Fusion for High Biomass Forest Carbon Accounting (USD30,000, collaborator);

iv. 2015 NERC Standard Grant: Weighing Trees with Lasers: reducing uncertainty in tropical forest biomass and allometry: NE/N00373X/1 (GBP630,000, PI).

v. 2015 EU FP7: METEOC2: Metrology for Earth Observation and Climate: II (EUR5,000,000 total led by National Physical Laboratory, UCL component GBP300,000) co-I.

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

Accurate measurement of the carbon stored in global forests is crucial in understanding and responding to the climate crisis since forests are key to reducing greenhouse gas emissions. Disney developed a new and more accurate method for measuring carbon in trees which enabled space agencies to validate their satellite estimates of carbon stocks. Disney's approach has been recommended by the United Nations Intergovernmental Panel on Climate Change as their preferred method for estimating carbon stocks in forests. Charities have used Disney's evidence of the value of urban forests in their campaigns, and Disney's evidence has reached a large public audience of [Text redacted for publication] and an exhibition at the V&A.

Improving new spaceborne measurements of forest carbon

Disney has pioneered terrestrial laser scanning (TLS) methods for measuring forest structure and biomass **[R2/R3/R4]**. These methods are being used by NASA and European Space Agency (ESA) space missions to improve satellite estimates of carbon stocks. Prior to this approach, remote sensing estimates relied on simple relationships between tree size and mass, known as allometric equations, to extrapolate from small numbers of harvested trees to entire regions. These equations are necessary for all space-based estimates, but have large uncertainties. Disney was funded by NASA [iii] to collect validation measurements in high biomass forests in the US and Gabon across climate and environmental gradients for use in the Global Ecosystem Dynamics Investigation (GEDI) mission, launched in 2018. GEDI measures the height and structure of forests, helping quantify their role in global climate and global biodiversity. A lead scientist from the NASA GEDI Science Team, writes, "Research outputs by Prof. Disney and collaborators have been central to […] delivering the plot scale measurements and models needed for explicit linking of in situ measurements of forest structure with high resolution observations from spaceborne instruments such as GEDI and NISAR [NASA-ISRO Synthetic Aperture Radar]" **[A]**. This has improved the methodology used by the space agencies by allowing them to validate their satellite measurements: "TLS methods pioneered by Disney and colleagues provide a means to benchmark and improve the in situ measurements and models used by all space agency missions" **[A]**. Disney leads an ESA-funded consortium [i] providing critical calibration information for the 2022 BIOMASS mission, in French Guiana, Gabon and Borneo. The mission will provide height and density data specifically on tropical forests, how they are changing, and their role in the carbon cycle. NASA GEDI Science Team's lead scientist confirms: "[Disney's] TLS measurements and models from these campaigns have been used by NASA GEDI to validate vertical foliage profile estimates […] Without this work, GEDI would have to rely on [less accurate] generic allometric models for some of the tallest and highest biomass forests on Earth" **[A]**. Disney's measurements provide improved tree height-to-mass relationships, enabling more accurate maps of forest C stocks to be produced.

NASA's Committee on Earth Observation Satellites (CEOS) is an international consortium of approximately 60 agencies established to ensure coordination of civilian earth observation programs, and promote best practice. Disney co-chairs the CEOS sub-panel on calibration and validation of satellite biomass and the 2020 CEOS protocol cites Disney's work on TLS measurement of tree biomass as the recommended 'gold standard' approach for national reporting of biomass validation **[B]**, ensuring this can be done much more accurately and consistently than at present. The protocol was ratified in March 2021 and then publicly released. NASA GEDI Science Team's lead scientist explains: "TLS is now established as a disruptive technology that is requiring us to rethink vegetation surveys for quantifying ecosystem structure and function" and its application "has far reaching implications for reducing the uncertainty of satellite-derived estimates of aboveground biomass maps being generated by the NASA GEDI and NISAR missions over the next 5 years" **[A]**. Accurate biomass maps are critical to enhance understanding of and responses to climate change, as well as elucidating the functioning and biodiversity of forests more generally.

Changing international guidance on climate change

Disney's work has changed international policy guidelines for national greenhouse gas inventory (NGHGI) reporting, provided by the United Nations Intergovernmental Panel on Climate Change (IPCC). The most recent 2019 IPCC Good Practice Guidelines (GPG) for NGHGIs emphasises

that adoption of transparent and reliable forest biomass estimation is key to effective forest carbon accounting and hence a vital part of implementing COP21 Paris Agreement policy. Disney's work is cited by the IPCC GPG as a transformative approach: "Terrestrial laser scanning provides non-destructive and highly detailed measurements independent of the size and shape of a tree that are otherwise only available from destructive Disney et al., 2018 **[R2]**" **[C1]**. The IPCC GHG reporting guidelines must be adopted by all 195 signatories for the COP21 agreement. A lead author of the 2019 IPCC GPGs, confirms that Disney's "ground-breaking work to develop a new, non-destructive approach" to carbon estimation "is being used to underpin satellite and ground-based estimates of carbon stocks in an integrated manner and leads to more precise and open data on tropical forest biomass" **[C2]**. Disney's work has led to this direct change in IPCC GPG policy recommendations: "The revised inventory guidances have recognised and cited the work of M. Disney as a suitable approach for more consistent and accurate GHG reporting – so the approach is ready to be used by countries for their national estimation and reporting" **[C2]**.

Demonstrating the value of forests to a public audience and providing data for use in campaigns by charities and practitioners

While the importance of urban forests for climate resilience, health and wellbeing is clear, Disney's work shows that urban forests are likely to be undervalued by policymakers and practitioners involved in urban planning and development, particularly in terms of their carbon uptake potential **[R6]**. Disney's new way to capture and express the benefits of urban forest is particularly important for communicating these benefits to practitioners and the public as we develop more climate-resilient and sustainable cities. Practitioners have recognised the value of Disney's research in raising awareness of the value of urban forests. In 2018 the (then) Chair of the Forestry Commission, said: "This **[R6]** is exciting work. The trees in our cities are important. They matter because they are close to people and a key component of our urban environment providing beauty, shade and homes for myriad species as well as absorbing carbon and pollutants. [Disney's] work is adding colour and detail to this understanding" **[D]**. This research complements the work of agencies such as Forest Research whose role is, in part, to estimate the value of urban trees. The Head of the Forest Research's Urban Forest Research Group observed that "we should expect our urban trees to also be providing us with an important carbon sink, helping to combat the global trend of increasing carbon dioxide in the atmosphere. This new work by UCL **[R6]** is a welcome development in advancing this understanding" **[D]**. A Camden Councillor and Cabinet Member for Improving Camden's Environment explained that Disney's research: "unlock[s] the benefits of trees not just for our own residents but for people's benefit round the world" **[D]**. Disney has developed tools to help UK charity Trees for Cities (TfC), who fund and deliver tree planting projects in under-served urban areas in the UK and internationally, track the success of their planting projects. Due to the challenges of visiting planting sites, TfC had been unable to systematically review the health of 20 woodlands they had planted in London since 1999 until working with Disney in 2019. TfC's Impact Coordinator said: "This work has enabled us to gain an indication of the status of our larger planted woodlands in London after 20 years of growth, without the need to visit them all individually. Disney's work […] has provided us with […] quantitative data that allows us to speak with greater confidence about the impact we are having, to both internal and external stakeholders" **[E]**. While most sites were healthy, some were less so and identifying those using TLS: "allow[ed] us to target follow-up maintenance activities to maximise our impact". In addition, Disney's team's use of open source software and data, plus the provision of a detailed workflow, has built TfC capacity so that "TfC are able to replicate the processes developed during the project as more data becomes available" **[E]**. TfC are now better able to monitor these sites.

Disney's research has reached a large public audience, raising awareness of the value of trees through television programmes, press coverage, and a major design exhibition. He has also provided data for charities and policymakers to use within a UK-wide campaign to demonstrate the value of trees. In 2019, Disney was invited to participate in Friends of the Earth's campaign 'More Trees Please'. Responding to the government's public consultation on its England Tree Strategy, 'More Trees Please' seeks to restore England's forests and elicit a government commitment to double the amount of trees in England to tackle the climate emergency **[F]**.

Disney's film with Dan Snow in which he explains the role of trees in absorbing fossil fuel equivalents, and their environmental and wellbeing benefits, has been viewed over 55,000 times and Friends of the Earth's petition to double England's tree cover has been signed by 173,113 people (their target is 175,000). In the 2018 BBC documentary 'Dame Judi Dench: My Passion for Trees', Disney measured Dench's favourite tree using TLS and discussed the significance of the tree with her in the context of global climate. The programme has been seen by an estimated [Text redacted for publication]. One viewer commented: "A revelation beautifully filmed, giving such a valuable insight into their hidden lives" and another "I thought I knew everything about trees! How wrong I was!" **[G]**. Press coverage of **[R3]** and **[R5]** in outlets from The Metro to The Financial Times has reached an audience of 105,000,000 **[G]**. Disney's research also featured as a video installation (a 3D visualisation of a Brazilian rainforest, which played on a loop on a display screen) in a major 2018 exhibition at the Victoria and Albert Museum (V&A) in London, 'The Future Starts Here'. The exhibition ran from 12 May 2018 to 4 November 2018, received over 110,000 paying visitors, and due to its popularity, was commissioned to tour other locations including Sweden (ArkDes, 21 March 2019 - 4 August 2019). The curator explained that Disney's work changed their approach to the exhibition in places, shifting their focus "from 'solutions' in the technocratic sense – tools or technologies for reducing emissions […] to show how a deeper understanding of the natural environment can have vast consequences. We wanted to show our visitors that by changing the way forests are measured, can change their value, and may ultimately contribute to their preservation. In short, how a laser scan of a tree could help save the world" **[H]**.

Disney's development of new ways to measure trees and forests has achieved demonstrable impact in key ways via improving space-based observations, influencing policy recommendation on greenhouse gas reporting and influencing perceptions of trees and forests among forest professionals and the wider public.

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

A. Testimonial statement from NASA GEDI lead scientist
B. Committee on Earth Observation Satellites (CEOS) sub-panel on calibration and validation of satellite biomass (https://go.nasa.gov/3qtshPL)
C. IPCC Evidence: (1) Good Practice Guidelines to National Greenhouse Gas reporting IPCC https://bit.ly/2OaTJVm (See Box 2.0c on p. 2.17); (2)Testimony from IPCC GHG guide lead author
D. Testimonial statements attesting to the value of Disney's work from former head of Forest Research and the Chair of the Forestry Commission; Head of the Urban Forest Research Group, Forest Research; and Councillor and Cabinet Member for Improving Camden's Environment
E. Testimonial statement from Impact Coordinator, Trees for Cities
F. Friends of the Earth "More Trees Please" campaign 2019: https://bit.ly/3ekm6eA (55,000 views on Twitter alone as of 11/2019, after release 9/2019, pers. comm. Shaunna Rushton, former Marketing Manager, FotE: https://bit.ly/3eiDosk).
G. Press coverage: BTScienceNews, The Conversation, Earth.com, Engineering & Technology, The Herald, IFLS, The Metro, MongaBay, MyScience, Phys.org, Financial Times, viewer comments on 'Dame Judi Dench: My Passion for Trees'. See pp. 43-44 for viewer comments
H. Testimonial statement from co-curator of V&A exhibition 'The Future Starts Here'; attendance figures provided by Exhibitions Assistant, V&A