Institution: University of Southampton		
Unit of Assessment: 14 Geography and Environmental Studies		
Title of case study: 14-04 Strengthening space-based terrestrial vegetation monitoring capability with the European Space Agency.		
Period when the underpinning research was undertaken: 2002 – 2020		
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:**
Jadu Dash	Professor in Remote Sensing	October 2005 – present
Sir Paul Curran	Professor of Physical Geography	October 1993 – August 2005
Francesco Vuolo	Research Fellow	May 2009 – January 2011
Booker Ogutu	Lecturer in Remote Sensing	January 2015 – present
Period when the claimed impact occurred: October 2016 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research at the University of Southampton has enhanced the European Space Agency (ESA) and European Commission's (EC) capability to monitor global vegetation from space. Specifically, Southampton's algorithm underpinned ESA's development of the only global satellite data product estimating terrestrial chlorophyll content in vegetation in near real-time. Distribution of this data through the ESA and EC's flagship Copernicus programme has generated major benefits for agricultural and environmental service providers, including timely and targeted response to poor harvests or plant disease outbreaks. Southampton have also developed validation data and protocols that are essential to support quality assurance of satellite-derived vegetation products and ensure their suitability for numerous operational applications, ranging from monitoring biodiversity to drought surveillance.

2. Underpinning research

Chlorophyll content and concentration within a vegetation canopy control the condition and productivity of vegetation. Reliable estimation of vegetation chlorophyll content is vital for those forest and agricultural service providers who monitor crop yields, plant health, seasonality, carbon fluxes and carbon sequestration. Therefore, accurate and near-real-time vegetation chlorophyll content estimation enables timely response to poor harvests or plant disease outbreaks, whilst global chlorophyll content estimates enable improvements in carbon flux modelling and evaluation of vegetation response to climate change.

The European Space Agency's (ESA's) Medium Resolution Imaging Spectrometer (MERIS) satellite sensor was launched in March 2002, aiming primarily at improving our understanding of ocean productivity via measurement of water colour. In 2004, **Curran** led the development of the **algorithm** [**3.1**] to exploit MERIS imagery for the estimation of vegetation chlorophyll content. The algorithm uses a specific feature called the 'red edge', which is proportional to the vegetation chlorophyll content and can be detected by MERIS. The resultant index, the MERIS Terrestrial Chlorophyll Index (MTCI), can be derived automatically from MERIS imagery and this led to establishment of **MTCI as a dedicated 'land' product** from the MERIS sensor.

MERIS sensor operation ended suddenly in 2012 following unexpected loss of satellite contact, ending generation of the MTCI product. ESA identified a continued need to provide similar quantitative information on vegetation canopy chlorophyll content to the user community through subsequent satellite missions. Based on the foundation of the MTCI algorithm and requirements from many users, **Dash** led research (Grant B) to develop and validate a **second vegetation chlorophyll content product, OTCI** [**3.2**] from ESA's Sentinel-3A optical sensor, launched in 2016. Sentinel-3A is an ocean and land observation satellite that forms part of the European Union's Copernicus programme, one of the largest and most ambitious space programmes globally. This is the first time the ESA has produced a dedicated operational global vegetation product.

Subsequent research at Southampton and elsewhere demonstrated the superiority of MTCI over alternative satellite-derived products in estimating vegetation chlorophyll content and monitoring vegetation condition. For example, **Dash** and **Ogutu** developed a new **MTCI-GPP** model to estimate terrestrial vegetation primary productivity using estimates of vegetation chlorophyll content derived from the MERIS sensor's MTCI product [**3.3**]. Further independent research demonstrated the MTCI's suitability in quantifying vegetation processes such as phenology and productivity. For example, among over **700** papers citing Southampton's algorithm [**3.1**] is the Copernicus Institute of Sustainable Development, which used MTCI to map forest canopy nitrogen across the Mediterranean region (Loozen *et al.*, 2018).

To be fit for purpose for specific applications, it is essential for satellite-derived products to undergo rigorous validation to assess data accuracy and measurement uncertainty. Through research funded by ESA in 2009 (Grant A), **Dash** established a new procedure for validation of satellite-derived vegetation chlorophyll content products at various sites [**3.4**]. This procedure is crucial to measuring the accuracy of ESA's operational vegetation chlorophyll content products, and is delivered to users through the Copernicus programme. Building upon the validation work, **Dash, Ogutu** and PhD student Luke Brown developed new techniques to analyse time series data and assess the accuracy of satellite-derived land products [**3.5**]. This included: (i) systematic estimation and propagation of ***uncertainty of in-situ measurements*** (Grant C) and (ii) establishing for the first time a framework for operational validation of Copernicus land products [**3.6**].

3. References to the research

3.1 Dash, J. and Curran, P. J., 2004, The MERIS Terrestrial Chlorophyll Index. *International Journal of Remote Sensing*, 25, pp-5003-5013. https://doi.org/10.1080/0143116042000274015

3.2 Vuolo, F., Dash, J., Curran, P.J., Lajas, D., & Kwiatkowska, E. (2012). Methodologies and uncertainties in the use of the terrestrial chlorophyll index for the sentinel-3 mission. *Remote Sensing*, 4, 1112-1133. https://doi.org/10.3390/rs4051112

3.3 Ogutu, B., Dash, J. & Dawson, T.P. (2013). Developing a diagnostic model for estimating terrestrial vegetation gross primary productivity using the photosynthetic quantum yield and Earth Observation data. *Global Change Biology*, 19, 2878–2892. https://doi.org/10.1111/gcb.12261

3.4 Dash, J., Curran, P., Tallis, M.J., Llewellyn, G., Taylor, G., & Snoeij, P. (2010). Validating the MERIS Terrestrial Chlorophyll Index (MTCI) with ground chlorophyll content data at MERIS spatial resolution. *International Journal of Remote Sensing*, 31, 5513-5532. https://doi.org/10.1080/01431160903376340

3.5 Brown, L.A., Dash, J., Ogutu, B.O. and Richardson, A.D. (2017). On the relationship between continuous measures of canopy greenness derived using near-surface remote sensing and satellite-derived vegetation products. *Agricultural and Forest Meteorology*, 247, pp.280-292. https://doi.org/10.1016/j.agrformet.2017.08.012

3.6. Brown, L.A., Dash, J., Morris, H.,Pastor-Guzman,J., Lerebourg, C., Lamquin, M., Bai, G., Gobron, N.,Lanconelli, C., and Clerici, M. (2020), Direct validation of global leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (FAPAR) products using the Copernicus Ground Based Observations for Validation (GBOV) dataset, *Remote Sensing of Environment*, 247, 111935. https://doi.org/10.1016/j.rse.2020.111935

Underpinning Funding:

Grant A: 2009-2012, PI Dash, MERIS extended validation and exploratory approach for high resolution optical sensors, ESA, £210,000

Grant B: 2015-2019, UoS PI Dash, Land product calibration and validation for Sentinel 3 Mission performance centre, ESA, £258,000

Grand C: 2017-2021, UoS PI Dash, Ground-based observations for validation (GBOV) of Copernicus global land products, European Commission, £210,000

Reference documenting context to impact – work on MTCI beyond University of Southampton:

Loozen, Y., Rebel, K.T., Karssenberg, D., Wassen, M.J., Sardans, J., Peñuelas, J., De Jong, S.M., 2018. Remote sensing of canopy nitrogen at regional scale in Mediterranean forests using

the spaceborne MERIS terrestrial chlorophyll index. *Biogeosciences* 15, 2723–2742. https://doi.org/10.5194/bg-15-2723-2018

4. Details of the impact

Research at the University of Southampton made a key contribution to the European Copernicus programme's capability to monitor global vegetation by (i) providing near real-time data on global vegetation chlorophyll content that are routinely distributed to users by the ESA, and (ii) establishing an operational validation procedure for vegetation monitoring products. Both of these contributions are vital to meeting the objectives of the Copernicus land monitoring services programme to provide geographical information on the status of vegetation cover to a broad range of users in the field of terrestrial environmental applications, including those in agriculture, food security and forest management.

ESA used Dash's algorithm to develop a new vegetation data product, the **OLCI Terrestrial Chlorophyll Index (OTCI)**. OTCI is based on the Sentinel-3 satellite's Ocean and Land Imaging spectrometer (OLCI) instrument, and replaced MTCI after MERIS ceased operation in 2012. User demand for a replacement product, coupled with evidence of the Southampton algorithm's robustness, led ESA to include the 'red edge' detection capability offered by OTCI within the mission requirements document for the Copernicus Sentinel-3 satellite programme. Since Sentinel 3 was launched in October 2016, ESA has used OTCI as a near real-time, global data product on vegetation chlorophyll content. Dash's group authored the user guide and algorithm description [**5.2**]. The OTCI is currently (February 2021) the only near-real time, global operational product estimating terrestrial vegetation chlorophyll content. An operational data product is one that ESA has committed to deliver long-term and in near-real time, guaranteeing users its continued and timely production. It is distributed to users free of charge through the Copernicus programme. As ESA states *'the unique capability of the OTCI algorithm to exploit the red edge position, thus providing accurate information on very high level of chlorophyll contents which cannot be performed by other sensors, put Europe and the European Space Agency and Copernicus Programme in a unique and leading position for monitoring the state of vegetation all over the world*" [**5.1**].

During 2017 alone, 2.44 pebibytes (> 1000 terabytes) of Sentinel 3 OTCI data were downloaded from Copernicus' dissemination system [**5.3**]. Copernicus programme users have deployed OTCI to monitor and manage terrestrial ecosystems, including estimating forest and crop health. As ESA stated "*The innovative product (OTCI) that was developed by Dash's team now contributes to an overall observation system that allows us to better understand how our planet is evolving and how it is responding to climate change and at the same time allows us to better understand climate change itself*" [**5.1**].

To ensure the quality of their operational data products meets the expected user requirements, in 2016 the European Commission established a new service called the Ground-Based Observations for Validation (GBOV). Southampton's research on the ground-based validation of satellite-derived vegetation data products [**3.3**, **3.4**] led to **Dash**'s group writing an Algorithm Theoretical Basis Document for the European Commission specifying validation procedures for three other vegetation products – leaf area index, **LAI**; fraction of vegetation cover, **FVC**; and fraction of absorbed photosynthetically active radiation, **FAPAR** [**5.4**]. **Dash**'s group led the validation of the vegetation component [**5.5**] and from 2017, conducted one of the largest and most comprehensive ground validation exercises globally, processing ground data across the world to determine the products' accuracy as part of ESA's Sentinel-3 Validation Team. In 2017, ESA noted *'Feedback from the Sentinel-3 Validation Team meeting provided essential information to ESA and EUMETSAT to progress with the evolution and improvement of Sentinel-3's core data products'* [**5.5**]. The validation data are now being routinely used by the European Commission (EC) to ensure the operational products meet user requirements. The EC has noted that they '…*reproduce well the changes due to drought and wet conditions in Europe, as well as the realism of the temporal variation over specific events around the globe'* [**5.6**]. Since 2017, the EC has delivered these three products – LAI, FVC, FAPAR – through the Copernicus programme to users worldwide. They are used by more than 6,000 organisations and users worldwide for a wide range of applications ranging from monitoring biodiversity to drought surveillance [**5.7**]. For example, the EC's Joint Research Centre uses Copernicus FAPAR and

LAI product as key inputs to the Europe-wide Monitoring Agriculture ResourceS (MARS) crop early warning programme [**5.8**], which supports the Common Agricultural Policy and food security assessments worldwide.

In addition to ensuring the quality of the three satellite-based vegetation products [**5.4**], the Copernicus programme has distributed the ground-based GBOV validation data set produced by **Dash**'s group since October 2018. The GBOV data are the largest ground data set for in-depth quality assessment of any satellite-derived vegetation product. Since their release in 2019, they have been downloaded by more than 300 users worldwide [**5.9**]. Through such downloads, users have applied Southampton's ground data to accuracy assessment of other satellite-derived vegetation data products (e.g. those from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensor) alongside the data products distributed through the Copernicus programme [**5.10**].

Meanwhile, users have also benefitted significantly from implementing Dash's chlorophyll algorithms independently of ESA. For example, in 2018 the World Bank reviewed the performance of algorithms for their prediction of crop yields from satellite data and recommend use of MTCI for countrywide maize crop yield estimates in Uganda, noting *'the superior performance of MTCI is noteworthy'* [p. 17] and *'The large boost in performance when using MTCI with Sentinel2 therefore more than outweighed any loss in accuracy from using coarser resolution'* [**5.11**].

The MTCI and OTCI algorithms developed at the University of Southampton thus formed the basis for innovative and robust data products for global vegetation monitoring which help the European Commission to deliver part of its flagship Copernicus programme. These data products provide accurate and timely information for users to monitor and manage both crops and our terrestrial biosphere.

5. Sources to corroborate the impact

5.1 Testimonial from Head of Sensor Performance, Products and Algorithms, ESA

5.2 Sentinel-3 OLCI online user guide, ESA: https://earth.esa.int/web/sentinel/user-guides/sentinel-3-olci/product-types/level-2-land

5.3 SERCO (2018): *Sentinel 3 Data Access 2017 Annual Report.* ESA report COPE-SERCO-RP-17-0186 (see page 30, figure 38 for Sentinel-3 download statistics): https://scihub.copernicus.eu/twiki/pub/SciHubWebPortal/AnnualReport2017/COPE-SERCO-RP-17-0186_-_Sentinel_Data_Access_Annual_Report_2017-Final_v1.4.1.pdf

5.4 Brown L and Dash J (2018): *Ground-Based Observations for Validation (GBOV) of Copernicus Global Land Products.Algorithm Theoretical Basis Document - Vegetation Products LP3 (LAI), LP4 (FAPAR), and LP5 (FCOVER)*. Copernicus Programme https://gbov.acri.fr/public/docs/products/GBOV-ATBD-LP3-LP4-LP5_v1.2-Vegetation.pdf

5.5 ESA: *Sentinel-3 Validation Team forge ahead with satellite data*, March 2017 (PDF supplied)

5.6 Sanchez-Zapero J., Perez, L, and Fuster, B.: *Copernicus Global Land Operations Vegetation and Energy: Scientific Quality Evaluation – LAI, FAPAR, FCOVER Collection*. Copernicus programme report no. CGLOPS1_SQE2018_LAI300m_V1 (PDF supplied, see page 14).

5.7 Copernicus global land service – product user statistics: https://land.copernicus.eu/global (see 'in the picture', bottom of page)

5.8 Copernicus programme (2019): *Copernicus Global Land Service Use Case – Crop monitoring in Europe*. https://land.copernicus.eu/global/sites/cgls.vito.be/files/use-cases/CGLOPS_UC_JRC-MARS_I1.00_1.pdf

5.9 Ground-Based Observations for Validation (GBOV) of Copernicus Global Land Products [download statistics]: https://land.copernicus.eu/global/gbov/statistics

5.10 Testimonial from Director of Copernicus land services, EC, on the use of GBOV.

5.11 Lobell, D., Azzari G., Burke, M., Gourlay, S., Jin, Z., Kilic, T., Murray, S. (2018): Eyes in the Sky, Boots on the ground: assessing satellite and ground-based approaches to crop yield measurement and analysis in Uganda. *World Bank Policy Research Working Paper* 8374 http://documents.worldbank.org/curated/en/556261522069698373/pdf/WPS8374.pdf