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| **Institution:** King's College London | | |
| **Unit of Assessment:** 14 Geography | | |
| **Title of case study:** King's earth observation research enables use of satellite data to reduce the negative impacts of global wildfires on landscapes, infrastructure and health | | |
| **Period when the underpinning research was undertaken:** 2002 – 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:** |
| Martin Wooster | Professor of Earth Observation Science | From 01/01/1998 |
| **Period when the claimed impact occurred:** 2014 – July 2020 | | |
| **Is this case study continued from a case study submitted in 2014?** N | | |

## 1. Summary of the impact

Landscape fires are an increasing problem in many areas worldwide. On average, an area as large as India is burned every year. Whilst some fires are seen as an ecological necessity, others put lives, homes and infrastructure at risk, lead to ecological damage, and release smoke whose particulate matter greatly degrades air quality and leads to hundreds of thousands of early deaths annually in fire-affected regions – mostly in developing nations. King's research on Fire Radiative Power (FRP) has enabled space agencies to adjust and develop satellites and instruments to better measure fires worldwide. This has greatly improved scientists' capacity to monitor, map and quantify the nature, trajectory and impact of wildfire activity and other forms of landscape burning in real-time and at a global scale. As a result, fire response agencies, landscape managers, public utilities and citizens across the globe are provided with improved information and situational awareness to support decision-making.

## 2. Underpinning research

Landscape fires perturb a greater area over a wider variety of biomes than any other natural disturbance agent. Moreover, it has been estimated that hundreds of thousands of people around the world die an early death each year as a result of air quality reductions coming from landscape fires. However, the large-scale, sporadic and highly dynamic nature of fires makes their identification and quantification difficult.

Taking leading roles within the Natural Environment Research Council's National Centre for Earth Observation (NCEO), King's researchers have contributed to significant advances in monitoring the changing state of our planet through use of satellite instrumentation. King's research underpins a number of Active Fire Radiative Power (FRP) products which measure the emitted heat signal of active fires to provide information in real-time as a fire is burning. This enables satellite data to be converted to actionable information, capable in some cases of supporting real-time monitoring, decision-making and early warning systems, including for air quality forecasting.

King's research has:

**(i) Linked FRP to biomass burning and emissions.** Based on numerous small-scale experimental fires conducted in a combustion chamber, King's researchers and their collaborators were the first group worldwide to show that the FRP released by burning vegetation fires can be related directly to vegetation fire fuel consumption and the emission rate of trace gases and particulates released in the smoke [1].

**(ii) Delivered FRP products for satellites to better detect fires.** King's research has improved detection of FRP from both geostationary and orbiting satellites. The King's team were the first to deliver the former capability, which is advantageous because of the far higher observation frequency of these systems, while the latter have a higher spatial resolution.

Based on assessment of FRP, King's researchers developed a new approach to estimate biomass burning rates from Europe's geostationary Meteosat Second Generation series of satellites [2]. This was able to detect and quantify fires in near-real-time close to 100 times per day, an advantage over existing methods which estimated fire emissions based on the observed burned area – a method which only works after a fire has happened and has relatively low temporal resolution. Compared with the latter approach, the FRP method was also able to detect much smaller fires without increasing the number of false detections. Based on the algorithms developed in [2], King's researchers also developed a new algorithm to detect and characterise active fires within the imaging footprint of the US Geostationary Operational Environmental satellites (GOES) [3], thus ensuring geostationary FRP coverage of the entire Western hemisphere. Results were validated against the active fire data collected by the Moderate Resolution Imaging Spectrometer (MODIS) onboard NASA's orbiting Terra and Aqua satellites which, between them, view the entire earth every day [3,4].

King's researchers developed algorithms to detect actively-burning fires and retrieve FRP from the Sea and Land Surface Temperature Radiometer (SLSTR), a new Earth Observation instrument launched on the EU's orbiting Sentinel-3 satellites in 2016 and 2018 [5]. King's research made use of the SLSTR's measurements in the visible and infrared spectral regions to identify the location and quantify the radiative power of any hotspot present on the land or ocean that radiates a heating signal within a pixel size of $1km^2$. All threatening hotspots comprising more than 0.01 to 0.1% of a pixel, e.g. agricultural burning, wildfires, deforestation, tropical peatland fires, industrial gas flares, and volcanoes, are identified and characterised within three hours of the SLSTR observation [5]. In common with the Meteosat and GOES systems, the SLSTR uses a two-part approach to identify active fire pixels; first using a set of relatively basic tests to detect potential active fire pixels and then testing each of these pixels against more demanding criteria to confirm (or reject) them as a true fire pixel [5]. Available both in near-real-time, and in archive format using an even more sophisticated algorithm, the SLSTR active fire product built on King's algorithms and testing and now available from the European Space Agency supports both operational applications (e.g. atmospheric monitoring and forecasting) and earth system science (e.g. assessment of the contribution of biomass burning to the carbon cycle).

**(iii) Enabled use of FRP to assess air quality.** King's researchers were the first to research and publish an approach to relate the emission rates of health-impacting particulates directly to the FRP measures derived from the continuous observations of fires provided by geostationary satellites [6]. Using the case study of a 2007 'mega-fire' event in the Peloponnese region of Greece, King's researchers and collaborators demonstrated that models based on geostationary FRP data were highly effective in capturing the sub-daily variability in smoke plume parameters that benefitted air quality forecasting [4]. They were thus the first to demonstrate the value of these geostationary fire emissions data for the particulate matter/aerosol optical-depth forecasts produced by the EU's Copernicus Atmosphere Monitoring Service [4].

## 3. References to the research

[1] Freeborn, P.H., Wooster, M.J., Hao, W.M., Ryan, C.A., Nordgren, B.L., Baker, S.P. and Ichoku, C. (2008). Relationships between energy release, fuel mass loss, and trace gas and aerosol emissions during laboratory biomass fires. *Journal of Geophysical Research: Atmospheres*, 113(D1). DOI: 10.1029/2007JD008679

[2] Wooster, M.J., Roberts, G., Freeborn, P.H., Govaerts, Y., Beeby, R., He, J., Lattanzia, A. and Mullen, R. (2015) LSA SAF Meteosat FRP products – Part 1: Algorithms, product contents, and analysis. *Atmospheric Chemistry and Physics*, 15(22), 13217–13239. DOI:10.5194/acp-15-13217-2015

[3] Xu, W., Wooster, M.J., Roberts, G. and Freeborn, P. (2010) New GOES imager algorithms for cloud and active fire detection and fire radiative power assessment across North, South and Central America. *Remote Sensing of Environment*, 114(9), 1876–1895. DOI: 10.1016/j.rse.2010.03.012

[4] Roberts, G., Wooster, M. J., Xu, W., Freeborn, P. H., Morcrette, J.-J., Jones, L., Benedetti, A., Jiangping, H., Fisher, D. and Kaiser, J. W. (2015) LSA SAF Meteosat FRP products – Part 2:

Evaluation and demonstration for use in the Copernicus Atmosphere Monitoring Service (CAMS). *Atmospheric Chemistry and Physics*, 15(22), 13241–13267. DOI: 10.5194/acp-15-13241-2015

[5] Wooster, M.J., Xu, W. and Nightingale, T. (2012) Sentinel-3 SLSTR active fire detection and FRP product: Pre-launch algorithm development and performance evaluation using MODIS and ASTER datasets. *Remote Sensing of Environment*, 120, 236–254. DOI: 10.1016/j.rse.2011.09.033

[6] Mota, B. and Wooster, M.J. (2018) A new top-down approach for directly estimating biomass burning emissions and fuel consumption rates and totals from geostationary satellite fire radiative power (FRP). *Remote Sensing of Environment*, 206, 45–62. DOI: 10.1016/j.rse.2017.12.016

## 4. Details of the impact

With wildfires posing an increasing threat to both our climate and human life, agencies around the world have come to understand the societal importance of having good information about the occurrence and scale of burning. Carried out in close collaboration with satellite developers around the world, King's research enabling improved assessment of Fire Radiative Power (FRP) has had major impacts on the specification and design of space-based instruments. This, in turn, has enhanced the capacity of international operational agencies to use satellite data to map, quantify and monitor global wildfires in near-real-time for better wildfire management and response.

**A. Influencing the specification and design of space-based instruments**

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is an intergovernmental organisation of 30 member states established to maintain and exploit European operational meteorological satellite systems. EUMETSAT is responsible for the commissioning and operation of these satellites and for delivering the satellite data and derived products to end-users. King's researchers have worked closely with EUMETSAT's Land Surface Analysis Satellite Application Facility (LSA SAF) which is responsible for developing and implementing algorithms that allow operational use of data from EUMETSAT's second generation Meteosat satellites. According to Dr Isobel Trigo, the LSA SAF Project Manager, King's research has had a *"very significant, indeed vital, impact on the fire products issued by the LSA SAF"* [A]. This includes the 'FRP-Pixel' product, based on [2] and [4], which records information on the location, timing and FRP output of landscape fires detected in almost real-time across much of the Earth [B]. King's research [4] has further informed the design and development of the new third generation Meteosat satellite, by specifying the saturation temperature of its Middle Infrared band which will enable it to better detect smaller (lower-temperature) fires while still capturing larger fire events [A]. This satellite is currently in the test stages and due to be launched in 2022.

Furthermore, King's researchers have been part of the Sentinel-3 Mission Performance Team of the European Space Agency (ESA). Here, their fundamental research [5] and recommendations have had significant impact on the specifications of the SLSTR instrument onboard Europe's Sentinel-3 satellites, which detect and quantify the FRP of fires burning across the entire earth [C]. Based on [5], King's researchers were also responsible for designing the algorithm that continually processes SLSTR data at ESA and is used to provide the final publicly available fire information. Dr Steffen Dransfeld, the ESA Sentinel-3 Optical Data Quality Manager, explains that the algorithm description and prototype software developed by King's researchers was "*used by ESA and its contractors to develop the fully operational software which now runs 24/7 in the Sentinel-3 Instrument Processing Facility and which processes the 'raw' data collected by SLSTR into global information on active fire location and FRP…. Without this code the satellite would not provide any information useful for this fire application [FRP]*" [C].

Working with the Canadian Forest Service, King's researchers have also influenced the development of WildFireSat, the world's first dedicated and operational wildfire monitoring satellite. Dr Joshua Johnston, Forest Fire Research Scientist at the Canadian Forest Service, explains that the Mission Requirements Document [D], "*upon which the mission is being designed, has been overwhelmingly influenced by [King's] research*" [E]. Specifically, the WildFireSat spectral band requirements were influenced by King's work on detection and characterisation [2,3,5], while several of the fire products developed by King's [2,5,6] supported the overall viability of satellite wildfire monitoring for emergency management [E]. Uniquely, WildFireSat has been designed specifically to monitor wildfires, with the intention of delivering near-real-time tactical intelligence to emergency responders. Given the high costs of wildfires to the economy in terms of smoke-based health impacts, economic shutdowns, evacuations, and the cost of suppression, Dr Johnston reports that WildFireSat is expected to "*save our economy about CAD5.2 billion over its 5-year mission life*" [E].

**B. Facilitating operational use of satellite fire data**

The significance of King's research in making high resolution fire data available in a more timely and easily accessible fashion is illustrated by operational use of the data to detect fire risk, monitor wildfire activity and enable air quality warning systems.

**(i) Creating fire risk detection products**

Dr Isobel Trigo, the LSA SAF Project Manager highlighted that *"the geostationary FRP products are vital inputs into the LSA SAF Fire Risk product, which for Southern Europe and North Africa provides an index of fire risk based on combined use of meteorological observations, weather forecast model outputs and remote sensing data. This Fire Risk product is used currently by agencies across southern Europe, including the Portuguese National Civil Protection Authority, to forewarn of periods and locations experiencing conditions of extreme landscape vulnerability to fire*" [A].

**(ii) Improving fire monitoring and response operations**

King's research has been pivotal to the development of the Canadian Forest Service's monitoring of wildfires. In Canada, wildfires burn on average 17,000km$^2$ of forest annually, impacting humans through both poor air quality and damage to infrastructure. Taking appropriate action used to be difficult as the official active fire products produced by the GOES-16 satellite operated by the US National Oceanic and Atmospheric Administration (NOAA) were considered "*unusable operationally due to the extreme numbers of false positives (i.e. false alarms that are not real fires)"* [E]. However, by writing geostationary active fire algorithms that were applied to the GOES-16 satellite data stream, King's research [2,3] led to a "*dramatic improvement*" in the quality of fire detections [E]. As noted by Dr Johnston, Forest Fire Research Scientist, "*your innovative approach to the GOES-16 algorithm has unlocked the use of this state-of-the-art system for scientific and emergency management in Canada"* [E]. The GOES-16 satellite now delivers real-time data for use in the Consolidated Fire Detection and Monitoring System of the Canadian Forest Service, providing rapid response fire locations for fire management and fire response services [E]. Critically, the higher-quality data obtained by applying the King's algorithms also allows monitoring of wildfire activity throughout the burn period at lower latitudes where most citizens live [E].

**(iii) Enabling early warning systems for poor air quality**

Fully operational since 2015, the EU's Copernicus Atmosphere Monitoring Service (CAMS) provides the public and decision-makers with global monitoring of atmospheric composition as well as detailed air quality forecasts [C]. To do this, CAMS operates a Global Fire Assimilation System (GFAS), the development of which is now led by King's researchers [F,H]. Built on the FRP approach and its relationship to fuel consumption and fire emissions [1], GFAS provides an estimate of smoke emissions from all satellite-detected wildfires burning around the planet [C,F]. Dr Mark Parrington, Senior Scientist at CAMS explains that GFAS is key to enabling users to integrate hourly (rather than daily) information about fire emissions into air quality early warning systems, a critical feature given that fires show strong diurnal cycles with emissions varying significantly over the day [H].

By 2019, CAMS GFAS data had 956 global users, with 369 from non-research entities, who were using GFAS outputs directly to bring fire emissions into their own air quality early warning systems [H]. One significant user is the Association of Southeast Asian Nations (ASEAN) Specialised Meteorological Centre (ASMC), who provide monitoring and early warning of smoke pollution coming from peat, forest and agricultural burning across Southeast Asia to the ten ASEAN nation states [H]. Dr Parrington explains that, "*by having early warning of forthcoming poor air quality, the nations are able to take action to try to minimise the exposure of their populations to the severe air pollution that can result from the fires, for example closing schools, delaying or stopping sporting events, and arranging flights at airports so they do not operate in very low visibility conditions*" [H].

The CAMS global and European forecasts now reach, directly or indirectly, a global audience of hundreds of millions of people. For example, leading news media such as Euronews and CNN International, and apps such as windy.com (with more than 3,500,000 unique users worldwide since June 2019 [G]), use CAMS data to provide the public with air quality information, enabling those with pre-existing health conditions such as asthma to take precautionary actions at times of forecast poor air quality [H].

## 5. Sources to corroborate the impact

[A] Testimonial from: Dr Isabel F. Trigo, Coordinator of the Earth Observation Unit of the *Instituto Português do Mar e Atmosfera* (IPMA) and LSA-SAF Project Manager, 20th January 2021.

[B] Fire Radiative Power (FRP) product webpage from the Satellite Application Facility on Land Surface Analysis (LSA SAF) distributed by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). Detailing the FRPPixel product used within Copernicus Atmosphere Monitoring Service.

[C] Testimonial from: Dr Steffen Dransfeld, Sentinel-3 Optical Data Quality Manager, EOP-GMQ, ESA/ESRIN, European Space Agency, 12th January 2021.

[D] Johnston, J. et al (2020) “Development of the User Requirements for the Canadian WildFireSat Satellite Mission”.

[E] Testimonial from: Dr Joshua Johnston, Forest Fire Research Scientist, Natural Resources Canada, Canadian Forest Service, 12th January 2021.

[F] European Centre for Medium-Range Weather Forecasts (ECMWF) Documentation on the development of the Global Fire Assimilation System for Copernicus Atmosphere Monitoring Service (CAMS) providing an FRP monitoring system.

[G] Copernicus Atmosphere Monitoring webpage. “A look back at monitoring the atmosphere in 2020: How CAMS data are used”, 21st December 2020.

[H] Testimonial from: Dr Mark Parrington, Senior Scientist, Copernicus Atmosphere Monitoring Service (CAMS)/ECMWF, 12th January 2021.