

<b>Institution:</b> University of Oxford		
<b>Unit of Assessment:</b> 5 – Biological Sciences		
<b>Title of case study:</b> BRAHMS: advancing global plant biosecurity and conservation with a worldwide data management system		
<b>Period when the underpinning research was undertaken:</b> 2005 – 2020		
<b>Details of staff conducting the underpinning research from the submitting unit:</b>		
<b>Name(s):</b>	<b>Role(s) (e.g. job title):</b>	<b>Period(s) employed by submitting HEI:</b>
Dr Denis Filer	Senior Research Associate	1985 – present
Prof Stephen Harris	Druce Curator (Herbaria), Associate Professor in Plant Science	1993 – present
<b>Period when the claimed impact occurred:</b> August 2013 to December 2020		
<b>Is this case study continued from a case study submitted in 2014?</b> N		
<b>1. Summary of the impact</b>		
<p>BRAHMS is a platform developed as part of research projects at the University of Oxford, to help understand, manage and conserve plant diversity by managing large amounts of data such as plant name records; botanical and plant taxonomic information; and herbaria specimen records. It has now mobilised and integrated data from over 12,000,000 specimens across national and international biodiversity networks.</p> <p>During the REF2021 period, data managed through BRAHMS have contributed to biodiversity policy and its monitoring in at least 60 countries. It has enabled 34 areas of high conservation value to be identified in Malaysia and Brazil. BRAHMS has been adopted by organisations such as the Millennium Seed Bank Partnership and Kew Gardens, to manage legal commitments associated with the international movement of plants, to underpin the systematic collection of new samples, and to enable consistent and systematic naming. BRAHMS has also enabled herbaria in South Africa and Malawi to undertake threatened species assessment and to meet commitments in conservation. There are 23 licensees of a fully-supported version worldwide, including in the USA, New Zealand, Malaysia, Africa and Europe.</p>		
<b>2. Underpinning research</b>		
<p>BRAHMS (Botanical Research And Herbarium Management System) was first developed at the University of Oxford in the 1990s to manage data from internal forestry and agro-forestry research projects on multi-purpose tree species in Central America and Africa. These species are widely used for human and animal food, soil enrichment and stabilization, fuelwood and fencing. The University of Oxford researchers collaborated with partners in many developing countries on these projects, generating and using large volumes of botanical data gathered from museums, field surveys, tree breeding trials, seed banks and libraries. By bringing these data together, BRAHMS enabled researchers, for the first time, to recognise and understand the global, socio-economic potential of tree species such as the African acacias and the so-called Central American 'miracle trees' (<i>Leucaena</i>, <i>Gliricidia</i> and <i>Prosopis</i>).</p> <p>Of these trees, those from the fast-growing, leguminous genus <i>Leucaena</i>, found naturally in Mexico and Central America, proved to have the greatest potential. However, at this time, the various species in <i>Leucaena</i> were poorly defined and described. If <i>Leucaena</i> was to be used globally for agro-forestry and tree breeding programmes, it was essential to name and fully understand the characteristics of each species. To address this issue, the critical challenge was to integrate large amounts of existing, fragmented data, mostly from museums, with new data from field and genetic studies. The <i>Leucaena</i> project, with its broad spectrum of demands,</p>		

demonstrated how BRAHMS could be developed and then used to exploit the full research potential of these data.

*Leucaena* has been domesticated in Central America on many occasions over the last 5,000 years. Early research by the *Leucaena* project clearly showed that where the different species ranges overlapped, natural crossing occurred with the resulting hybrids being selected and domesticated repeatedly by local farmers. A particular research objective was to understand the pattern and extent of the initial stages of this domestication process. To achieve the overall research aims, it was essential to analyse geographic areas where species of *Leucaena* had overlapping distributions, meaning that the prerequisites for this analysis were accurate species identification and precise map references. A study of *Leucaena* in south-central Mexico [1], a collaboration between University of Oxford researchers and a team at New Mexico State University, combined ethnobotanical, genetic, geographical and archaeological data and found that 'backyard hybridization' played a central role in crop domestication, as a result of bringing species together in cultivation.

These research demands led to the development of new components in BRAHMS, especially the ability to analyse and visualize overlapping species distributions at different scales. This in turn reinforced its functionality as a research tool, highlighted its flexibility and underlined its potential to manage and analyse large and complex biodiversity data sets. These developments not only underpinned [1] but then highlighted three high-priority needs that led to the further enhancement of BRAHMS as a research tool:

*Images and identification:* University of Oxford researchers highlighted the difficulties of species identification in many tropical plant families [2]. As a result, the capabilities of BRAHMS were subsequently expanded to use high-resolution image data from field and museum specimens to improve identification accuracy.

*Mapping:* Three Oxford based researchers used data gathered from field surveys across Trinidad and Tobago, together with all known herbarium specimens, to create a comprehensive geo-referenced checklist to the plant biodiversity hotspots on these species-rich islands [3]. These hotspots were objectively identified using BRAHMS by combining data on species rarity and species distribution and introducing a mapping capability.

*Online data access:* Denis Filer contributed his specialist expertise with BRAHMS to a large international team that developed a method to integrate data from the principal South African botanical institutions within a unified BRAHMS framework [4]. Recognising the need to distribute these biodiversity data as widely as possible and beyond the scientific community, the BRAHMS team continued to help to raise South Africa's international profile as a valuable source of biodiversity data by providing the mechanism to present these data online.

### 3. References to the research

(University of Oxford employees in bold)

1. **Hughes C.E.**, Govindarajulu R., Robertson A., **Filer D.L.**, **Harris S.A.**, Bailey C.D. (2007) Serendipitous backyard hybridization and the origin of crops. *Proceedings of the National Academy of Sciences (USA)* 104:14389-14394. DOI: [10.1073/pnas.0702193104](https://doi.org/10.1073/pnas.0702193104)
2. Goodwin Z.A., Harris D.J., **Filer D.L.**, **Wood J.R.I.**, **Scotland R.W.** (2015). Widespread mistaken identity in tropical plant collections. *Current Biology* 25(22): 1066-1067. DOI: [10.1016/j.cub.2015.10.002](https://doi.org/10.1016/j.cub.2015.10.002)
3. Baksh-Comeau Y.S., Maharaj S.S., Adams C.D., **Harris S.A.**, **Filer D.L.**, **Hawthorne W.D.** (2016). An annotated checklist of the vascular plants of Trinidad and Tobago with analysis of vegetation types and botanical 'hotspots'. *Phytotaxa*, 250:1. DOI: [10.11646/phytotaxa.250.1.1](https://doi.org/10.11646/phytotaxa.250.1.1)
4. le Roux M.M., Wilkin P, Balkwill K., Boatwright J.S., Bytebier B., **Filer, D.**, Klak C., Klopper R.R., Koekemoer M., Livermore L., Lubke R., Magee A.R., Manning J.C., Paton A., Pearce T., Slingsby, van Wyk J.B-E., Victor J.E. & von Staden L. (2017). Producing a plant diversity portal for South Africa *TAXON* 66(2):421–431 DOI: [10.12705/662.9](https://doi.org/10.12705/662.9)

**Funding** to the University of Oxford included a Darwin Initiative award from DEFRA, 'A biodiversity monitoring system for Trinidad and Tobago' [3] GBP264,500 (reference 14-004, 2005-09); Leverhulme Trust project grant, 'Exploring ways to Accelerate Taxonomy: Foundation Monographs and the World Flora' [2] GBP243,323 (RPG-309, 2012-2014); NERC grant 'BRAHMS8 - a flexible database management system for botanical researchers and herbaria' with Royal Botanic Gardens Kew, GBP40,000 to Oxford (NE/L013053/1, 2013-2014).

#### 4. Details of the impact

Whilst a preliminary prototype of BRAHMS had existed previously, the research on *Leucaena* [1] drove a step-change enhancement in functionality [2,3,4] that led during the REF2021 impact period to BRAHMS becoming a world-leading data management system for managing complex datasets from natural collections and surveys. BRAHMS database software now manages data from natural history collections, botanic gardens, seed banks, field surveys, taxonomic research and biogeographic study.

BRAHMS facilitates data management and integration, which then enables environmental policy implementation and monitoring. BRAHMS has been adopted by governments, national and international institutions, businesses, NGOs, educators and local peoples to support science-led policy-making on the management and use of biodiversity. At December 2020 it was enabling the management of data resources including more than 12,000,000 botanical records in over 60 countries. This represents about 5% of the total number of botanical records held in herbaria, globally. The most recent major release of the software (version 8) was published in May 2019 with a wide range of features [A]. The previous version remains available without needing a licence, enabling the widest usage.

#### Provision of accurate species names

Effective policy application and monitoring requires accurate species names. The widespread proliferation of different names for the same cultivated plant is increasingly causing confusion for plant breeders, horticultural traders, gardeners and the general public worldwide: it makes it more difficult not only to provide accurate horticultural information but also to enforce plant breeding rights. Furthermore, a standardised approach to plant names is critical to satisfy the increased requirement to document and track the movement of cultivated plants for legal and biosecurity issues. In 2019, BRAHMS enabled researchers at the Royal Horticultural Society (RHS) to develop a new approach to determine cultivated plant names, by ranking the various names a plant may have. In partnership with the RHS, the functionality of BRAHMS was extended to manage data on names, providing a global naming standard promoted throughout the horticultural world, and at October 2020 was being used by the RHS for 358,532 species [C(i)]. Similarly, the National Herbarium of the Netherlands were using BRAHMS to manage 659,878 species names in 2019 [C(ii)].

In 2020, BRAHMS was formally adopted by the RHS for managing their living plant collections, not only through the transfer of taxonomic data, but also the tracing of plant records across their five gardens to help limit the spread of pests and diseases [B]. The Head of Horticultural Information described other benefits soon after licencing the new version:

*"Already we have been able to use BRAHMS to replace a legacy system that was serving information to the RHS website – a move which has sped up the rate at which we are able to add details about new plants and make those available for free to the public to aid gardeners to choose the correct plant for them. This is a significant part of the RHS's charitable remit."* [B(ii)]

#### Securing global seed collections

The Royal Botanic Garden Kew's Millennium Seed Bank Partnership (MSBP) is the largest *ex situ* plant conservation project in the world. This network of 120 seed banks covers 95 countries and is a fundamental resource for the more than 150 active collaborating partners. It set a first target of securing seed collections from 25% of the world's flora by 2020. In 2017, BRAHMS software integrated data from across this network into a single, online resource, the MSBP Data Warehouse [D(i),(ii)]. For the first time, data on native plants conserved in these seed banks were published as a single, globally accessible online resource and provides an opportunity for MSBP partners to

query the status of their seed collections alongside other collections from across the MSBP. Partners frequently compare seed accession location data with known distribution of a species to establish if a new collection is likely to represent new genetic diversity in the collection, while germination test data enables seed bank managers the best insight into the treatments and conditions required to achieve optimal seed germination. Moreover, the MSBP Data Warehouse provides the means to monitor collection targets, thus providing management tools to monitor progress towards the 2020 target [D(ii)]. The MSBP's Africa Programme Coordinator wrote in 2020 that:

*"I have been working with the BRAHMS software for many years and we have made some strong steps in achieving the integration of data from the collection event such as linking the seed collection with the herbarium voucher, or being able to monitor the management of the living plants generated from our seed."*

MSBP Africa Programme Coordinator, RBG Kew [E(i)]

At November 2020, the MSBP's BRAHMS database held records of over 228,000 seed collections from 204 countries and territories and 96 different seed banks, providing information on over 48,800 different species [E(ii)]. The database also held data on 215,700 germination tests and over 9,870 x-ray images. More than half of these records were by then available online [E(ii)].

### **Species identification and conservation planning with integrated data**

Large-scale international and national biodiversity networks have used BRAHMS to gather and integrate primary botanical data from multiple institutions.

Data stored in BRAHMS, from around 2,000,000 specimens across 10 institutions in South Africa, Namibia, Botswana and Malawi contribute directly to the botanical infrastructure of this region. Specimen-level records from the three herbaria at the South African National Biodiversity Institute (SANBI), the National Herbarium in Pretoria, the Compton Herbarium in Cape Town, and the KwaZulu-Natal Herbarium in Durban, have since 2013 been digitised, stored, curated and improved using BRAHMS. This data is used for threatened species assessments, conservation planning, management and policy advice; is disseminated to other international projects; and helps to fulfil commitments under the 2020 targets of the Global Strategy for Plant Conservation [F]. The Deputy Director of Biodiversity Information and Planning at SANBI wrote that

*"BRAHMS is thus crucial for SANBI to be able to fulfil its mandate...BRAHMS helps to raise South Africa's international profile as a valuable source of biodiversity data for our unique flora. This would not be possible without the technical and training support provided by the University of Oxford as well as the extensive source of user documentation ..."* [F]

BRAHMS is used extensively in most regions of Brazil managing data in over 80 academic and non-academic institutions. In 2016, a review by the Central Environmental Resources Institute (CRIA) highlighted the key role of BRAHMS in strengthening the botanical infrastructure across Brazil. Approximately half of CRIA's botanical data (around 3,500,000 records) have been contributed by 82 separate BRAHMS databases. In 2019, approximately 1,500,000 plant and fungi records (including 11,000 images) were accessed daily. These data and images have been used for a wide range of purposes, including improving species identification, monitoring species distribution, and setting conservation priorities [G].

The National Herbarium & Botanic Gardens of Malawi have digitised over 32,000 specimens, recording data in BRAHMS, and report uses including species conservation (Malawi National Redlist Project), relating pollinator biodiversity to agro-ecological interventions, and inventories of threatened, invasive and alien plants [H]. In many of these, BRAHMS' compatibility with the Global Biodiversity Information Facility (GBIF) data standards [I] enabled biodiversity information to be made more accessible.

The National Herbarium of the Netherlands (Naturalis) uses BRAHMS to enable access to botanical data from approximately 7,000,000 specimens collected from Europe, South East Asia, West Africa and South America. Other non-academic institutions, such as the National Museums of Kenya and the New Zealand National Forest Service, use BRAHMS to manage fine-scale botanical data.



**Protecting High Conservation Value areas**

Fine-scale mapping of species' distributions using BRAHMS (e.g. [3]) has enabled areas with high concentrations of rare species to be identified, prioritised and monitored. In 2015, BRAHMS enabled the Forestry Research Institute of Malaysia (FRIM) to assemble evidence to underpin proposals of High Conservation Value Forests (HCVFs). HCVFs are defined by the Forestry Stewardship Council to be of outstanding importance due to their biodiversity, environmental, landscape or socio-economic attributes. To identify HCVFs, it was essential to understand and integrate the distributions and rarity of all plants living in the forests of the Malay Peninsula. Using BRAHMS, FRIM assembled data from herbaria, published literature and unpublished field-records from around the world. Using BRAHMS' high-functionality mapping and analysis tools, areas of Malaysia containing high concentrations of rare species were identified. At least 33 HCVFs for a range of Critically Endangered and Endangered species were approved by the Malaysian government as a result of these data and contribute to the implementation of a Sustainable Forest Management protocol in Malaysia [J].

**Global uptake of commercial licences**

BRAHMS is licensed worldwide through Oxford University Innovation (OUI). A number of users of earlier versions have decided to adopt BRAHMS as a paid and supported product to ensure the longevity of their high-value datasets and management systems, reflecting its importance to their operations. Since 2015, BRAHMS has had 23 paying licensees worldwide, including the USA, New Zealand, Malaysia, Africa and Europe, spanning herbaria, arboreta, botanic gardens and seed banks. Since 2015, 122 organisations have commenced free 60-day trials of BRAHMS, which has facilitated discussions about longer-term usage and customisation [K].

**5. Sources to corroborate the impact**

- A. Feature list of BRAHMS v8, <https://herbaria.plants.ox.ac.uk/bol/brahms/software/v8>
- B. (i) Press release, Royal Horticultural Society (RHS), 10-07-2020. <https://www.rhs.org.uk/press/releases/RHS-Teams-Up-with-University-of-Oxford-to-Develop>  
(ii) Letter from Head of Horticultural Information, RHS Science & Collections, 25-11-2020.
- C. Screenshot of BRAHMS databases giving number of taxa for (i) Royal Horticultural Society, as at October 2020; (ii) National Herbarium of the Netherlands, as at June 2019.
- D. (i) Description of MBSP Data Warehouse, <http://brahmsonline.kew.org/msbp>, snapshot from 28-12-2020 retrieved from <https://web.archive.org/web/20201228090816/http://brahmsonline.kew.org/msbp>  
(ii) Letter from Senior Research Leader, Seed Conservation, Royal Botanic Garden, Kew, 29-01-2020, corroborating usage of BRAHMS for the MSBP.
- E. Samara, the newsletter of the Millennium Seedbank Partnership  
(i) Lead article, MBSP Africa Programme Coordinator, Issue 33 (July 2018), p1-2,  
(ii) 'MBSP Data Warehouse', Issue 36, (November 2020) p.19.  
<https://www.kew.org/science/our-science/publications-and-reports/publications/samara>
- F. Letter from Deputy Director: Information Systems Manager, Biodiversity Information and Planning Directorate, South African National Biodiversity Institute (SANBI), 23-10-2020, corroborating usage of BRAHMS v7 for the Botanical Database of Southern Africa.
- G. Letter from Associate Director, Centro de Referência em Informação Ambiental (CRIA), Brazil, 15-09-2020, corroborating numbers of records using BRAHMS in Brazil's Virtual Herbarium of Plants and Fungi.
- H. Letter from National Herbarium and Botanic Gardens Of Malawi, 30-09-2020, corroborating number of specimens digitized and the projects drawing on BRAHMS data.
- I. Inclusion of BRAHMS on the Global Biodiversity Information Facility (GBIF) website, Nov 2019 <https://www.gbif.org/tool/81413/brahms-management-of-natural-history>
- J. Letter from Director, Forest Biodiversity Division, Forest Research Institute Malaysia (FRIM), 23-12-2020, corroborating establishment of HCVFs.
- K. Statement of BRAHMS licensing since 2015 from Oxford University Innovation.