Institution: Queen Mary University of London		
Unit of Assessment: 5		
Title of case study: Leading the Fight Against Ash Dieback in the UK and Europe		
Period when the underpinning research was undertaken: 21/01/2013 - 31/12/2020		
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:**
1) Richard Buggs	1) Professor of Evolutionary Genomics	1) 01/03/2012 - present
2) Laura Kelly	2) Postdoctoral Research Fellow	2) 01/07/2014 - 30/06/2018
3) Endymion Cooper	3) Postdoctoral Research Fellow	3) 01/07/2015 - 30/06/2017
4) Richard Nichols	4) Professor of Evolutionary Genetics	4) 01/09/1991 - present
Period when the claimed impact occurred: 01/08/2013 - 31/12/2020		
Is this case study continued from a case study submitted in 2014? N		

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

In 2012, a deadly new fungal disease targeting the ash tree arrived in Britain. Since then, ash dieback disease has killed millions of trees, with a predicted cost to the UK economy of GBP15,000,000,000. Combatting ash dieback is a priority for the UK government, and in ground-breaking genetic analysis, Buggs' group at Queen Mary University of London discovered how some ash trees are resistant to the disease. Buggs' research shows how selective breeding of naturally selected resistant trees can mitigate the impact of the disease. This approach, set out by Buggs, has been adopted into UK government policy in Defra. The genetic markers identified by Buggs have also been included in the design of a new custom genotyping array produced by Thermo Fisher Scientific, helping to fight the disease in the UK and across Europe by effectively screening for these resistance markers.

2. Underpinning research (indicative maximum 500 words)

Ash (*Fraxinus excelsior*) is the UK's third most common native woodland, hedgerow and urban tree species, with an estimated population size of more than 100,000,000. Ash plays a major role in the UK's timber industry, biomass production and flood management. It also has an important role in removing carbon dioxide from the atmosphere (carbon sequestration). More than 900 other species in natural environments rely upon ash as a food source, a habitat and for nutrient recycling.

The ash dieback epidemic, caused by the fungus *Hymenoscyphus fraxineus*, has afflicted ash populations since 2012, with a predicted cost to the UK economy of GBP15,000,000,000, including recovery and ecosystem service costs (Hill et al., 2019). Consequently, since 2012, fighting the ash dieback epidemic has been a priority for the UK Government Department for Environment, Food and Rural Affairs (Defra).

Prof. Buggs from Queen Mary has led the UK research effort to identify the basis of ash dieback resistance in ash genomes. In April 2013, Buggs and his Queen Mary PhD student (Sollars) published the first draft ash genome online, funded by a NERC Urgency Grant [EQR.1]. An improved genome assembly and analyses were later published by Buggs, Sollars, Kelly, Cooper and collaborators at the Earlham Institute, Earth Trust, and Universities of York and Exeter in *Nature* in early 2016 [3.1]. In 2017, with direct funding for sequencing from Defra [EQR.3], Buggs, Kelly and his Queen Mary PhD students (Stocks and Metheringham) carried out a genome-wide association study on 1,250 UK ash trees grown in mass screening trials by the organisation Forest Research. The researchers identified 3,149 genetic loci in the ash genome that are associated with natural resistance to ash dieback disease. They then demonstrated how these loci could be used to select ash trees for breeding to improve resistance to ash dieback across the tree population [3.2]. This study was published in *Nature Ecology and Evolution* in 2019 [3.2]. The researchers concluded that a breeding programme for increased resistance to ash dieback is a viable long-term strategy to mitigate the epidemic in Europe, and that breeding

could be accelerated using genetic information. These findings also suggest that natural selection may be effective in enabling the evolution of increased ash dieback resistance in woodlands over a longer period of time [3.3].

In 2019/20, Buggs collaborated with researchers at Wageningen University (The Netherlands) and INRA (France) in the EU Horizon 2020 project "B4EST: Adaptive BREEDING for productive, sustainable and resilient FORESTs under climate change". The researchers designed a genotyping array for ash that incorporates polymorphisms and markers for ash dieback resistance discovered by Buggs' group [3.1, 3.2]. This is being used by tree breeders throughout Europe.

In another line of research, Buggs' group and collaborators (Kent County Council; John Innes Centre and the Faculty of Forestry and Wood Technology; Mendel University, Brno, Czech Republic) have helped to more accurately predict the impact that ash dieback will have on European ash populations. At the outset of the disease in 2012, a mortality rate of more than 95% was widely predicted. In a meta-analysis [3.4] of mortality rates across Europe, Buggs' group and their collaborators showed that the highest mortality rates recorded anywhere so far are 85% in plantations and 69% in woodlands. These revised estimates have informed tree management guidelines published by many organisations, providing a more targeted approach to ash protection.

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

[3.1] Sollars, E. S. A., Harper, A. L., Kelly, L. J., Sambles, C. M., Ramirez-Gonzalez, R. H., Swarbreck, D., Kaithakottil, G., Cooper, E. D., Uauy, C., Havlickova, L., Worswick, G., Studholme, D. J., Zohren, J., Salmon, D. L., Clavijo, B. J., Li, Y., He, Z., Fellgett, A., McKinney, L. V., Nielsen, L. R., Douglas, G. C., Kjær, E. D., Downie, J. A., Boshier, D., Lee, S., Clark, J., Grant, M., Bancroft, I., Caccamo, M. & Buggs, R. J. A. (2016). Genome sequence and genetic diversity of European ash trees. *Nature, 541*, 212-216. https://doi.org/10.1038/nature20786

[3.2] Stocks, J. J., Metheringham, C. L., Plumb, W., Lee, S. J., Kelly, L. J., Nichols, R. A. & Buggs, R. J. A. (2019). Genomic basis of European ash tree resistance to ash dieback fungus. *Nature Ecology & Evolution*, *3*, 1686-1696. https://doi.org/10.1038/s41559-019-1036-6

[3.3] Plumb, W. J., Coker, T. L. R., Stocks, J. J., Woodcock, P., Quine, C. P., Nemesio-Gorriz, M., Douglas, G. C., Kelly, L. J., & Buggs, R.J.A. (2019). The viability of a breeding programme for ash in the British Isles in the face of ash dieback. *Plants People Planet*, *2* (1), 29-40. https://doi.org/10.1002/ppp3.10060

[3.4] Coker, T. L. R., Rozsypálek, J., Edwards, A., Harwood, T. P., Butfoy, L. A. & Buggs, R. J. A. (2018). Estimating mortality rates of European ash (*Fraxinus excelsior*) under the ash dieback (*Hymenoscyphus fraxineus*) epidemic. *Plants People Planet*, *1* (1), 48-58. https://doi.org/10.1002/ppp3.11

[3.5] Woodcock, P., Cottrell, J. E., Buggs, R. J. A. & Quine, C.P. (2017). Mitigating pest and pathogen impacts using resistant trees: a framework and overview to inform development and deployment in Europe and North America. *Forestry: An International Journal of Forest Research*, *91* (1), 1-16. https://doi.org/10.1093/forestry/cpx031

References

Hill, L., Jones, G., Atkinson, N., Hector, A., Hemery, G. & Brown, N. (2019). The £15 billion cost of ash dieback in Britain. *Current Biology*, *29* (9), *PR315-R316*. https://doi.org/10.1016/j.cub.2019.03.033

Evidence of quality of the research:

[EQR.1] Buggs, R. J. A. [PI]. (21/01/2013–21/01/2014). Ash tree genomics: an urgent need [NE/K01112X/1]. *NERC*. Urgency Grant. GBP64,966.

[EQR.2] Buggs, R. J. A. [PI]. Rossiter S. (Queen Mary), Lee, S. (Forest Research), Jepson, P. (Oxford) [Co-investigators]. (01/04/2014-01/12/2017). Identifying genomic resources against pests and pathogens in tree genera: a case study in *Fraxinus* [BB/L012162/1]. *BBSRC*. LWEC tree health and plant biosecurity initiative - Phase 2 Grant. GBP935,982 (Queen Mary: GBP640,038).

[EQR.3] Buggs, R. J. A. [PI]. (2017-2020). Direct grants from Defra for ash dieback research by Buggs' group at Kew. *Defra*. GBP475,000.

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

Since 2012, the fungal disease ash dieback has spread rapidly throughout the UK, killing millions of trees, and potentially inflicting a huge economic cost on the country. The potential loss of this tree species in the UK would increase the risk of flooding, reduce the productivity of commercial forestry, and have a negative impact on ecosystem services and carbon sequestration. It would also change the character of the UK's landscape, representing a significant cultural and social loss. Genetic analysis by Prof. Buggs' group at Queen Mary has shown how selective breeding of naturally resistant trees can mitigate the impact of the disease. This approach has been adopted into UK government policy, enabled breeding of ash dieback-resistant trees across Europe and informed forestry management. It has also informed public understanding of the epidemic, with Buggs' research findings injecting a message of hope for ash trees into the national and international media (including *The Times,* BBC News*,* BBC World Service*, Financial Times, Economist*, *Daily Mail*, *Daily Express*, *Sunday Telegraph*, *Guardian*, and *El Mundo* [5.1]).

Informing UK and Irish Government policy on ash

Genomic research led by Buggs has directly informed UK Government policy on ash and has been reported on in parliament [5.2]. Specifically, Buggs' research has provided the evidence base that prompted Defra to adopt a policy of breeding trees for ash dieback resistance as a long-term solution to the epidemic. In a letter [5.3] describing the impact of Buggs' research on Defra policy, Defra's Chief Plant Health Officer, says: "The work conducted by Prof Buggs has been central to Defra's ability to manage and respond to ash dieback, helping us make policy decisions about the future of ash trees in the UK that are informed by world-class evidence."

The important place of genomics in Defra policy is highlighted in its 2019 *Ash tree research strategy* [5.4]. The Ministerial Forward states: "Good progress has been made in screening for tolerant trees and conserving the genetic diversity of our native ash trees…Genomics will continue to play a key role to understand and identify tolerance." Buggs' research underpins key sections in the strategy relating to existing knowledge and future research, with Defra citing eight of Buggs' papers. In particular, the proposed research theme – to better understand genetic tolerance to ash dieback and to identify tolerant trees (theme 8 of the strategy) – draws extensively on Buggs' work on European ash tree resistance [3.2] and the viability of a breeding programme [3.3].

The policy document also states that the Government intends to open the UK's first archive of trees tolerant to ash dieback in order to support a viable breeding programme. This archive opened in January 2020, and will see organisations including Future Trees Trust, Forest Research, Forestry England, Kew Gardens and Fera collaborating on genomics research. According to Prof. Nicola Spence, the Chief Plant Health Officer at Defra [5.3], "this research has enabled the UK government to formulate and defend a policy aiming to retain UK ash trees in the landscape. If no natural resistance had been found in UK ash trees, we would have instead had to focus entirely on replacing ash with alternative species," and that the Queen Mary team "has been central to the formulation and implementation of Defra's policy aiming to retain native ash trees in the UK landscape via natural selection and a breeding programme."

Buggs' research also influenced the Government of Ireland's decision to combat ash dieback through tree breeding. In December 2020, Ireland's Council for Forest Research and Development recommended ash breeding in a report that cited Buggs' work, taking the success of this approach as evidence to implement such a breeding programme in Ireland [5.5].

Informing the management of existing ash populations in the UK

Buggs' research has directly informed tree management guidelines published by a range of UK public bodies, government departments and conservation charities, including Natural England, the Forestry Commission, The Arboricultural Association, and The Tree Council. Specifically:

(1) Buggs' research has provided more accurate estimates on ash mortality (see Section 2 above and [3.4]), significantly lower than previous estimates, which has encouraged managers not to pre-emptively fell all their ash trees. These statistics, drawn from Buggs' research, are cited by joint advice from Natural England and the Forestry Commission [5.6], The Arboricultural Association's ash dieback guidance [5.7], and The Tree Council's ash dieback action plan toolkit [5.8].

(2) Buggs' evidence that resistance to ash dieback is heritable and highly polygenic, and will therefore respond well to natural selection, means that managers can promote the natural evolution of ash dieback resistance by retaining healthy ash trees and promoting natural regeneration [3.3]. This approach is encouraged in three advisory documents [5.6, 5.8 and 5.9].

Making genotyping commercially available to fight ash dieback across Europe

Buggs' research has been used to produce a new commercially available product – the Applied Biosystems™ Axiom™ custom genotyping array for ash – that enables high-throughput genotyping of ash trees. The product was developed by a group of European institutions (as part of the EUR6,478,662 EU Horizon 2020 project B4EST) and US company Thermo Fisher Scientific. According to Dr. Mohini Patil, Senior Product Manager at Thermo Fisher Scientific, the "microarrays have several advantages over other technologies today" [5.10]. By incorporating thousands of polymorphisms and markers for ash dieback resistance discovered by Buggs' group, the new array provides an "innovative, cost-effective and flexible" way to screen ash populations for genetic markers that indicate resistance to ash dieback on a large scale. Trees that have a natural resistance to the disease can then be selected for breeding, which, combined with "the microarray data [being] easy to analyse…[has] enable[ed] the European Ash breeding community to accelerate their breeding programs" [5.10].

The array is being used by tree breeders across Europe, including in Austria, where Europe's largest ash breeding programme, based on 30,000 trees, is underway [5.11]. Peter Mayer, the Head of the Austrian Federal Research and Training Centre for Forests (BFW) and this programme, confirms: "we specifically implemented and utilised project outcomes and resources that were provided by Queen Mary," into the Austrian Ash breeding programme, which is "to our knowledge – the biggest conservation effort in Europe aiming to safeguard European Ash and to produce ash trees resistant against ash dieback" [5.11].

Exploring tree resistance in other species

Buggs' work on ash has enabled him to promote exploring the resistance of other tree species to pests and pathogens. For example, a consortium of USA federal agencies asked the National Academies USA to consider the use of biotechnology to mitigate threats to the health of the nation's forests [5.12]. Buggs' work, demonstrating the viability of research on tree resistance [3.1, 3.5], contributed to recommendations on new "research to understand the role of resistance in coevolved systems from the perspective of a global host–pest system, where the non-native pathogen or insect originate, would help guide efforts in North America" (p.81) [5.12].

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

[5.1] For example, a *Guardian* article 'British ash trees may resist dieback disease, research reveals' (26 December 2016) was shared 218 times and generated 76 comments (*Guardian* print circulation: 111,953; print readership: 3,600,000; monthly unique online browsers: 25,100,000); an interview with BBC London (1 November 2018) subsequently loaded onto YouTube has been viewed 3,178 times; and a film produced by Kew Gardens about Buggs' research and shared on Facebook was watched 7,300 times and shared 75 times (all figures correct 25/07/20). For a full list of media coverage with links, see Richard Buggs' website: http://richardbuggs.com/media

[5.2] UK Parliament. *Ash Dieback*. House of Lords. 25 June 2019. 798. https://hansard.parliament.uk/Lords/2019-06-25/debates/AF00B422-F419-4A62-8B15-F33855B8F8AD/AshDieback

[5.3] N. Spence. Chief Plant Health Officer. *Defra, UK Government*. (testimonial letter, 26 August 2020). [Corroborator 1]

[5.4] Defra. (2019). *Conserving our ash trees and mitigating the impacts of pests and diseases of ash: A vision and high-level strategy for ash research*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/806872/ash-research-strategy-2019a.pdf

[5.5] Department of Agriculture, Food and the Marine, Government of Ireland. (2020). *COFORD: Sustainable Development and Conservation of Forest Genetic Resources 2020-2030* (pp. 32 & 35). http://www.coford.ie/media/coford/content/publications/2020/35769COFORDbodyreportweb211220.pdf

[5.6] Natural England and Forestry Commission. (2019). *Managing woodland SSSIs with ash dieback (Hymenoscyphus fraxineus). Joint advice from Natural England and the Forestry Commission.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/811166/NE_FC_Ash_dieback_SSSI_management_advice_V2_April_19.pdf

[5.7] The Arboricultural Association. (2019). *Ash Dieback Guidance: For Tree Owners, Managers, Contractors and Consultants.* https://www.trees.org.uk/Trees.org.uk/media/Trees-org.uk/Documents/eBooks/AshDieback-GuidanceNote-web.pdf

[5.8] Tree Council. (2019). *Ash Dieback: An Action Plan Toolkit*. https://treecouncil.org.uk/wp-content/uploads/2019/12/Tree-Council-Ash-Dieback-Toolkit-2.0-2.pdf

[5.9] Forestry Commission. (2019). *Managing Ash Dieback in England*. https://www.forestresearch.gov.uk/documents/7277/7894_New_FC_Chalara_leaflet_dft9.pdf

[5.10] M. Patil. Senior Product Manager. *Thermo Fisher Scientific*. (testimonial letter, 12 January 2021). [Corroborator 2]

[5.11] P. Mayer. Head of the Federal Research and Training Centre for Forests, Austria. *The Federal Research and Training Centre for Forests, Austria*. (testimonial letter, 17 January 2020). [Corroborator 3]

[5.12] National Academies of Sciences, Engineering, and Medicine. (2019*). Forest Health and Biotechnology: Possibilities and Considerations*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25221