Institution: University of Oxford		
Unit of Assessment: 5 – Biological Sciences		
Title of case study: Improved conservation of endangered tree species with genetic approaches to landscapes		
Period when the underpinning research was undertaken: Jan 2000 to 31 July 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:**
Dr David Boshier	Senior Research Associate	1988 – present
Prof Stephen Harris	Druce Curator (Herbaria), Associate Professor in Plant Science	1994 – present
Period when the claimed impact occurred: Aug 2013 to July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research at the University of Oxford into landscape genetics of forest trees has demonstrated the importance of fragmented areas of forest, and trees outside of forests, for the conservation of endangered tree species. The research led to changes in conservation strategy – including by the UN Food and Agriculture Organisation, and in Chile, Canada and the UK – and enhanced practical approaches to the conservation of endangered tree species and native forest patches, in areas with commercial timber plantations and agriculture. Forestry professionals from at least 25 countries have been trained on the importance of trees outside of forests and conservation in agricultural landscapes, through free online teaching material and in-person courses with more than 300 attendees. Strategies from the training have been implemented to enable the development of synergistic relationships between communities, small businesses, and native tree conservation in Chile. These global actions and policy changes are protecting the genetic diversity and viability of tree species threatened by land-use changes and deforestation.

2. Underpinning research

Globally more than 20% of tree species are threatened with extinction, particularly through changes in land use. Research by the University of Oxford's Department of Plant Sciences has provided important insights into the role of fragmented areas of forest in tree conservation.

Gene flow, which is the exchange of genetic material either between populations or between individuals in a population, helps to maintain genetic diversity and thus provides the basis for population viability in response to external challenges. Isolation, which often leads to reduced gene flow, can have detrimental consequences on the evolutionary viability of populations, due to increased levels of inbreeding and a reduction in the ability to combat pathogens and other threats. Habitat destruction, deforestation and changes in land use have fragmented native forests worldwide, and University of Oxford researchers have investigated the extent and patterns of gene flow among spatially isolated individual trees and remnant patches of native forest.

Extent of gene flow in fragmented populations: David Boshier developed and tested hypotheses about gene flow in fragmented populations of different tree species, through extensive field work and genetic analyses. His original concept was investigated in collaboration with researchers from the Scottish Crop Research Institute, in the Punta Ratón region of the Honduran Pacific alluvial coastal plains, where they studied *Swietenia humilis* Zuccarini [1], which is protected by the Convention on International Trade in Endangered Species (CITES) and is one of the three species commonly known as true or American mahogany. By genotyping trees to determine paternity, they were able to quantify pollen movement, and the research demonstrated

pollen flow over distances 10 times greater than previously reported. These results demonstrated that some tropical angiosperm tree species could be much more resilient to habitat destruction and fragmentation than previously considered [1]. This study was the first to use a landscape genetic approach to study community fragmentation within the context of forest sustainability, and is routinely cited in studies of gene flow in fragmented forests.

In the same landscapes, selective felling, deforestation, and destructive agricultural practices have left the once common deciduous tree *Pachira quinata* (syn: *Bombacopsis quinata*) largely restricted to isolated forest remnants. University of Oxford researchers, Stephen Harris and David Boshier, used a novel combination of field and laboratory techniques to show that remnant *P. quinata* trees in pastures significantly contribute to gene flow through pollen movement across the fragmented landscape [2]. However, *P. quinata* has differences in reproductive biology compared to *S. humilis*, resulting in some of the pasture trees showing increased levels of inbreeding. This research showed that to maximise fitness and adaptability and protect investments in planting - *P. quinata* is a valuable source of timber - seed collection should concentrate in larger stands of *P. quinata* [2].

Insect-mediated gene flow: University of Oxford researchers, Stephen Harris and David Boshier, also led studies of insect-mediated gene flow between forest patches and spatially isolated trees, focusing on the endangered Chilean tree species *Gomortega keule,* which is found in the fragmented Central Chile Biodiversity Hotspot, and its insect pollinators (Syrphid flies) [3,4]. Their analyses showed that pollinator-driven gene flow depends strongly on types of land use between habitat fragments, and identified the landscape characteristics that promote gene flow, and those which inhibit it [3]. Specifically, pollination probability was highest through pine plantation, moderate over low-intensity agriculture and native forest, and lowest over clearfells. Changing the proportions of these land uses over 1km altered pollination probability up to 7-fold. These results led to the proposal of the novel "Circe principle", which postulates that pollinators presented with a wealth of resources are likely to move through a habitat slowly or not leave it at all, and that pollinators presented with hostile or resource-poor land uses might not enter, but if they do, they are likely to move through it as quickly as possible [3]. Paternity analysis also showed that *G. keule*'s insect pollinators travel outside of forest patches, over distances of up to 6 km, through plantations and agricultural systems, and into and out of very small populations [4].

Novel conservation concepts: These studies developed understanding of fundamental genetic processes, important for the conservation of tree species in fragmented landscapes, in particular by showing the value of trees in agricultural landscapes and thus the value of 'circa situm' approaches – farmer-based conservation. Firstly, single trees and small sites contribute to the effective breeding population of rare tree species in fragmented landscapes, so no site should be considered too small for protection [1-4]. Secondly, land-use types, landscape features and topography affect the probability of genetic connectivity between individuals and forest patches more than distance *per se* [3,4]. Thirdly, assessment of the viability of endangered tree species in fragmented landscapes requires more nuanced models than simple landscape models contrasting areas as 'habitat' and 'non-habitat' [1-4].

3. References to the research

University of Oxford staff in **bold**; University of Oxford students in italics.
Citation counts from Google Scholar at Dec 2020

1. White G.M., **Boshier D.H.,** Powell W. (2002) Increased pollen flow counteracts fragmentation in a tropical dry forest: an example from *Swietenia humilis* Zuccarini *Proceedings of the National Academy of Sciences* 99, 2038-2042 DOI: 10.1073/pnas.042649999 [406 citations]
2. **Rymer P.D.**, *Sandiford M.*, **Harris S.A.**, *Billingham M.R.*, **Boshier D.H.** (2015; published Aug 2013). Remnant *Pachira quinata* pasture trees have greater opportunities to self and suffer reduced reproductive success due to inbreeding depression. *Heredity* **115**, 115-124. DOI:10.1038/hdy.2013.73 [26 citations]

3. *Lander T.A.*, Bebber D.P., *Choy C.T.L.*, **Harris S.A.**, **Boshier D.H.** (2011) The Circe Principle explains how resource-rich land can waylay pollinators in fragmented landscapes. *Current Biology* **21,** 1302-1307. DOI: 10.1016/j.cub.2011.06.045 [59 citations]

4. *Lander T.A.*, **Boshier D.H., Harris S.A.** (2010) Fragmented but not isolated: contribution of single trees, small patches and long-distance pollen flow to genetic connectivity for *Gomortega keule*, an endangered Chilean tree. *Biological Conservation* **143**, 2583-2590. DOI: 10.1016/j.biocon.2010.06.028 [97 citations]

Funding included **The Darwin Initiative (UK-DEFRA), '**Conservation of Endangered Coastal Biodiversity Hotspots of Central Chile' (Grant 15-023, GBP224,036, 2006-2009);
European Commission FP6 'Seedsource' led by NERC (Grant: 3708, EUR1,699,999 of which EUR206,439 to Oxford, 2005-2010);
DFID (previously ODA) Forestry Research Programme, Genetic diversity and population structure of trees in fragmented dry zone forests of Central America', GBP188,272 (R5729, 1993-1996) and GBP173,919 (R6516, 1996-2000), and 'A study of the reproductive biology and population differentiation of *Bombacopsis quinata*; a threatened Central American dry zone tree with potential for semi-arid zones'. GBP38,900 (R6168, 1994-1997).

4. Details of the impact

Trees are fundamental to terrestrial ecosystems and the lives of people across the planet, contributing to at least 13 of the United Nations' 17 Sustainable Development Goals. It is estimated that 420,000,000ha of forest were lost through conversion to other land uses between 1990 and 2020. Many forests have become fragmented, with nearly 20% of global forest area being in patches less than 1,000ha in size, 9% in fragments with little or no connectivity, and approximately 12,000 tree species at risk of extinction. University of Oxford research showing the importance and relevance of remnant trees in fragmented agroecosystems to conservation, forest management and associated rural livelihoods has led to changes in policy, training, and professional practice internationally.

Influencing national and international conservation policies

UN Food and Agriculture Organisation: Boshier was commissioned to write a chapter ("*Fragmentation, landscape functionalities and connectivity"*) for the UN Food and Agriculture Organisation (FAO) report on the state of the world's forest genetic resources, which drew extensively on the University of Oxford research, including [1,3,4] and was published in 2014 [A]. This report directly informed the FAO's Global Plan of Action on Forest Genetic Resources in 2014 [B], which identified 27 strategic priorities for forest conservation.

Canadian Species at Risk Action Plan: In 2015, the Canadian Species at Risk Action Plan for the endangered cucumber tree (*Magnolia acuminata*) - the only native Magnolia in Canada - was changed, directly influenced by University of Oxford research [4] [C(i)]. The previous Action Plan (since 2007) had specified a minimum of 10 mature trees for a habitat to be considered critical. Citing the research [4], the 2015 Action Plan states *"single trees and small populations contribute to genetic connectivity across the landscape; fragmented sites can play a role as functioning elements of a larger population as 'stepping stones' between sites"*. Under the revised criteria, the number of critical habitat sites increased from 7 to 15. Importantly, a 2019 assessment of Canadian Environmental Sustainability Indicators found the cucumber tree is showing progress towards population and distribution objectives [C(ii)], indicative of success of the Action Plan.

UK Woodland Trust: The Woodland Trust is a major woodland conservation charity, owning more than 1,000 woods in the UK, managing woodlands for conservation, and campaigning to protect woodlands. In 2017, the Woodland Trust adopted a policy to support conservation of single trees and small woods, as part of the wider network of woodland habitat across the UK [D(i)]. According to a Woodland Trust Regional Director [D(ii)], this policy was based on University of Oxford research [3,4] showing the importance of single trees and small woods as 'stepping stones' and habitats. This policy on the importance of single trees and small woods also influenced the Woodland Trust's Emergency Tree Plan campaign and the Woodland Trust and the independent Committee on Climate Change's recommendation to the UK Government to implement "*significant expansion of trees outside woods to achieve net zero carbon*" [D(ii)].

Forest Stewardship Council (FSC), Chile: The FSC is a global organisation setting standards for certification of sustainable forest management and sustainably managed forest products. Forestry companies must conform to FSC requirements (criteria and indicators) to achieve FSC certification, which is increasingly essential for access to international markets, and consequent economic benefits. In 2016, FSC-Chile updated their certification standards, and criteria and indicators for the "*Identification, Management and Monitoring of High Conservation Value forests*", citing University of Oxford research [3,4] with respect to important local conditions, such as temporary habitats and migration sites [E].

Improving conservation training and professional practice

The University of Oxford research has directly shaped training delivered by the researchers and non-governmental organisations to forestry professionals, reaching at least 300 people from more than 25 countries, influencing their learning and practice, and contributing to Strategic Priority 21 of the FAO's Global Plan of Action on Forest Genetic Resources to strengthen training and education [B].

Conservation in disturbed agroecosystems, Chile: In 2015, based on their research showing importance of tree species in fragmented landscapes, particularly the value of trees in agricultural landscapes and thus potential of 'circa situm' conservation approaches, Boshier trained 144 participants - principally Chilean government forestry officials [F]. The Chilean Foundation for Agricultural Innovation provided USD13,140 to support dissemination and adoption of the novel land management approach for conservation in disturbed agroecosystems, including circa situm approaches [F]. The training programme and circa situm methods received media coverage [F], and Chilean organisations (Chilean Forestry Institute (INFOR), Institute of Agricultural Development, BioBio Regional Government) implemented the approach. For example, in 2016, INFOR's Conservation and Genetic Improvement Group reported an apiculture programme, financed by the BioBio Regional Government, to increase the number of available flowers through the restoration and supplementation of floral diversity with emphasis on native forest species. The report showed dual benefits for local businesses and tree conservation, stating:

> "*INFOR promotes use of the circa situm model (conserve through use), popularised by David Boshier of the University of Oxford. This model has been applied in the creation of honey orchards with native species. These orchards, practical conservation banks for forest genetic resources, are established and used by bee-keeper members of BIOMIELAG, to improve availability of nectar and pollen in support of honey production by small and medium scale regional beekeeping enterprises. Thus, the honey orchards are valued and transformed into true ex situ conservation units*" [G] (translated from Spanish)

International online and in-person training on forest genetic resources:

Collaborating with Biodiversity International, Boshier developed free online teaching materials on forest genetic resources, including the importance of trees outside forests (based on [1-4]) published in 2014 [H(i)]. Between Oct 2014 and Oct 2016, the training guides were accessed more than 2,700 times (unique events) with over 2,000 PDF downloads [H(ii)].

The UK Centre for Ecology and Hydrology has used these resources for training in East Africa, including in Tanzania (2018) and Kenya (2019) where there were 50 participants from a wide range of sectors, including forest research, forest policy, forest managers, extension workers, national park staff, and NGO staff [I(i)]. The leader of the training courses stated that these materials have been a "*major help in communicating messages regarding the identification, protection and use of tree genetic resources…trainees are also very appreciative of the fact that you have made all of this [content] available free online"* and that the training was *"very influential"* [I(i)]. From the course in Kenya, 14 attendees (78%) "strongly agreed" and 4 attendees (22%) "agreed" in answer to the statement "*after the course I plan to apply content from the course in my role*" [I(ii)].

Since 2013, Biodiversity International have run 5 forest genetics training courses using the materials influenced by the University of Oxford research. These have taken place in Costa Rica, China, France and Malaysia, with a total of 136 participants from at least 20 countries, of whom at least 67% were from non-academic organisations (including forest and conservation managers, government officials, and non-governmental organisations) [J]. Boshier has delivered additional

training courses in several countries including Cambodia (24 participants, mostly from central and local forestry administration, March 2020) [K] and Brazil (33 participants, 9 from non-academic organisations, August 2019) [L]. According to the Deputy Director of the Institute of Forest and Wildlife Research and Development in Cambodia, a participant said "*it is very useful to have learned the different strategy for conservations, particularly the circa situm which is quite new for me*" [K]. The material is also being adopted by other environmental training organisations: the coordinator of the Environmental Leadership and Training Initiative for the Philippines is quoted by Biodiversity International as saying,

> "*I realized how important forest genetic resources are for restoration. We run training programmes for governmental and civil society organizations and research institutes on using native tree species in restoration, but until now we haven't covered genetic aspects in the training sessions. I can't wait to go back and incorporate in our training programme what I learned about genetic conservation strategies during this course.*" [M].

5. Sources to corroborate the impact

A. UN Food and Agriculture Organisation (FAO) 2014 report on the state of the world's forest genetic resources, citing [1], [3] and [4].

B. UN Food and Agriculture Organisation (FAO) 2014, Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources.

C. Environment Canada polices and reports (i) 2015 Action Plan for the Cucumber Tree (*Magnolia acuminata*) in Canada; (ii) 2019 Species at Risk Population Trends (Canadian Environmental Sustainability Indicators), Table A.1.

D. Woodland Trust, UK: (i) Report: role of trees outside woods in contributing to the ecological connectivity and functioning of landscapes (August 2017), citing University of Oxford research including [3,4]. (ii) Letter from Woodland Trust Regional Director (North England), describing influence of University of Oxford research on policies.

E. FSC-Chile Guidelines for Identification, Management and Monitoring of High Conservation Values. (In Spanish: Pautas para Identificación, Manejo y Monitoreo de ALTOS VALORES DE CONSERVACION de FSC en Chile), 2016, citing [3,4] on p125-126.

F. Report from Chilean Ministry of Agriculture and INFOR, regarding seminars on forest genetic resources, 2015 (in Spanish), including annexes on participation and newspaper articles covering the events.

G. Molina, M.P. Soto, H. Gutiérrez, B. González, J. Koch, L. Ipinza, R. Rojas, P. y Chung, P. (2016) Huertos meliferos con especies forestales nativas una alternativa para apoyar a la agricultura familiar campesina y mejorar el negocio apicola. Ciencia e Investigación Forestal INFOR Chile Vol 22 (3): 53-72 (In Spanish)

H. Biodiversity International online training materials on forest genetic resources: (i) training materials website; (ii) web analytics for online training materials Oct 2014-Oct 2016.

I. Information about UK Centre for Ecology and Hydrology courses in East Africa:
(i) Letter from course leader from Centre for Ecology and Hydrology;
(ii) survey of course participants, Kenya 2019.

J. Letter from Program Leader Tree Biodiversity for Resilient Landscapes, Alliance of Biodiversity International and CIA, describing training courses with D Boshier since 2013, stating countries and numbers of participants.

K. Letter from Deputy Director of the Institute of Forest and Wildlife Research and Development in Cambodia, describing training course on forest genetic resources.

L. Letter from Universidade Estadual do Centro-Oeste (UNICENTRO), Brazil, head of Genetics and Forest Tree Breeding, describing training course on forest genetic resources.

M. Biodiversity International online report on the training course (Nov 2016), describing course in China (Oct 2016) and quoting participants.