Institution: University of Glasgow (UofG)		
Unit of Assessment: UoA 8 (Chemistry)		
Title of case study: Selective breeding of spruce for cellulose orientation improves the timber supply chain in the UK		
Period when the underpinning research was undertaken: 2003−2014		
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 Michael Jarvis	Reader; Honorary Research Fellow	1979−2014; 2014−present
Dr Clemens Altaner	SIRT Research Fellow	2004−2007
Dr Anwesha Fernandes	Research Assistant	2007−2009
Dr Lynne Thomas	Research Assistant	2006−2010
Period when the claimed impact occurred: 1st August 2013–present		
Is this case study continued from a case study submitted in 2014? Yes		

1. Summary of the impact

The timber sector, including forestry and primary wood processing, contributes GBP2.5 billion per year to the UK economy and supports more than 32,000 jobs. UofG research on cellulose nanochemistry demonstrated for the first time that increased timber yield of Sitka spruce trees from the UK's internationally acclaimed breeding programme did not compromise mechanical performance. This knowledge removed the key barrier to the adoption of the genetically improved planting stock by the forestry industry. These trees now account for >90% of new planting in the public and private sectors in the UK and much grant-aided planting in Ireland. In the UK alone the improved stock planted since 2013 has increased the current market value of the national standing timber resource by GBP61 million. The increased yield of these trees will capture an additional 3.7 million net tonnes of CO_2 over their lifetime.

2. Underpinning research

Context

Both the underpinning research and its transformation into impact were carried out within the Scottish Integrated Research in Timber (SIRT) Project. This was a unique collaboration between UofG, Edinburgh Napier University and the Forestry Commission, initiated in 2003 by a strategic grant from SFC and continuing to the present with funding from RCUK, EC (European Commission) and the timber industry. SIRT's objectives are to increase knowledge of the properties of the UK-grown timber and to improve the value of the domestic forest resource. Until 2014 UofG was responsible for the basic science research, while others focussed on structural timber research and the development of other wood products. The primary route for knowledge exchange was through collaborations with the Forestry Commission, commercial sawmills, and forestry industry professionals.

The SIRT project focused on Sitka spruce (*Picea sitchensis*), the principal commercial UK timber species. It was also the model conifer species adopted by UofG to elucidate relationship between the nanostructure of wood and its response to tensile stress. This basic science was directly interleaved with applied PhD projects to disentangle the influences of genetics, environment and forest management on timber yield and quality. The key commercial challenge of SIRT was how to obtain strong, stiff timber for the construction industry from fast-growing, high-yielding trees.

Key Research Findings

Wood is a nanocomposite material based on cellulose fibres (microfibrils) embedded in a matrix of other polymers. UofG research on Sitka spruce led to the nanostructural characterisation of the cellulose microfibrils by spectroscopic, X-ray and neutron and scattering methods [3.1] and their interconnection through disordered interfaces [3.2]. Novel experiments, combining spectroscopy and scattering with tensile mechanical stress, revealed that at the nanoscale, wood deforms by two independent mechanisms. When the cellulose microfibrils are well aligned with the grain in the stiffest and strongest wood, the cellulose chains resist elongation by a novel 'molecular leverage' mechanism involving synergy between covalent and hydrogen bonding [3.3]. When the cellulose microfibrils make a large angle with the grain, the wood is much more flexible and deforms by a slip-stick mechanism (termed 'molecular Velcro') where hydrogen bonds in the disordered interfaces between the microfibrils break and re-form [3.4]. The tensile stiffness of spruce wood varies by a factor of four, within and between trees [3.4, 3.5] according to the cellulose microfibril angle and hence the relative contributions of these two mechanisms [3.6]. The key to growing quality timber for the construction industry is therefore to maximise the proportion of stiff wood with low microfibril angle.

Key Researchers

The underpinning research was carried out by Jarvis, Altaner, Thomas and Fernandes, and translated with extensive support from industry, including visiting researcher Mochan (sabbatical from the Forestry Commission, 2007) and a team of five fully- or co-funded UofG PhD students (2004-2014), including a professional timber buyer.

3. References to the research

3.1 * Fernandes, A.N., Thomas, L.H., Altaner, C.M., Callow, P., Forsyth, V.T., Apperley, D.C., Kennedy, C.J. and **Jarvis, M.C.** Nanostructure of cellulose microfibrils in spruce wood. Proceedings of the National Academy of Sciences of the USA, 108, E1195−E1203 (2011). (doi:10.1073/pnas.1108942108)

3.2 Thomas, L.H., Martel, A., Grillo, I. and **Jarvis, M.C.** Hemicellulose binding and the spacing of cellulose microfibrils in spruce wood. Cellulose, 27(8), 4249−4254 (2020) doi:10.1007/s10570-020-03091-z

3.3 * Altaner, C.M., Thomas, L.H., Fernandes, A.N., & **Jarvis, M.C.** (2014). How cellulose stretches: Synergism between covalent and hydrogen bonding. Biomacromolecules, 15(3), 791−798. (doi:10.1021/bm401616n)

3.4 * Altaner, C. M., and **Jarvis, M.C.** Modelling polymer interactions of the 'molecular Velcro' type in wood under mechanical stress. Journal of Theoretical Biology 253, 434−445 (2008). (doi:10.1016/j.jtbi.2008.03.010)

3.5 Moore, J., Gardiner, B., Ridley-Ellis, D., **Jarvis, M.C.**, Mochan, S., and MacDonald, E., Getting the most out of the United Kingdom's timber resource. Scottish Forestry, 63, 3−8 (2009). [available on request from HEI]

3.6 Guo, F., Altaner, C.M. & **Jarvis, M.C.** Thickness-dependent stiffness of wood: potential mechanisms and implications. Holzforschung 74, 1079−1087 (2020). (doi:10.1515/hf-2019-0311).

*=best indicators of research quality

4. Details of the impact

The forestry sector contributes GBP0.67 billion in gross value added to the UK economy, and directly supports more than 16,000 jobs, with an additional 10,000 in sawmilling and 6,000 jobs in panel mills. The UK harvests >10 million tonnes of timber annually. Sitka Spruce is the predominant commercial species, with 6 million tonnes of logs processed by UK sawmills annually into construction-quality timber. The remainder is used for paper, packaging, chipboard, and biofuel, commanding a lower price than timber for construction [5.1]. The carbon in these latter products is returned to the atmosphere within 1-10 years, compared to 50-100 years for timber used to build houses. Consequently, there are both financial and environmental reasons to channel the maximum possible percentage of UK timber into the construction industry.

UK Building Regulations require timber used in construction to meet, at a minimum, the British Standard C16 in terms of quality, stiffness, and strength. The limiting C16 requirement for Sitka spruce is stiffness. Prior to 2007, the adoption of fast-growing, genetically improved planting stock from the Forestry Commission's breeding programme was blocked because it was assumed that the stiffness of low-density timber from fast-growing trees such as Sitka spruce would be too low to meet the C16 requirement. At that time, timber-frame housing construction was expanding fast, but was based on slow-grown Scandinavian softwoods.

Path to impact

The improved genotypes were the subject of a SIRT (UofG/Forestry Commission) PhD project (J.P. McLean supervised by Dr. Jarvis) showing that cellulose orientation measured by X-ray diffraction changed very little with the fast growth of the improved trees, and that loss of stiffness was therefore negligible when their timber was tested on standard grading equipment in a commercial sawmill [3.6]. This led to the realisation that sawn timber from the improved trees would have the requisite strength and stiffness to meet the C16 specification for construction, removing the key barrier to the adoption of the genetically improved planting stock. These important UofG research findings were disseminated informally to the forest industry in 2006−2007 [5.2a-b], followed by a formal Forestry Commission Information Note in 2008 [5.2c].

Genetically improved trees in the UK

As a result of UofG research and this Information Note [5.2c], forest and nursery managers across the UK have enthusiastically adopted the improved planting stock, to deliver the following impacts:

1. Improved yield as direct result of the improved genotypes
2. Improved productivity in terms of sawlog output
3. Increased carbon capture through increased tree growth.

Across both public and private sectors, 112 million genetically improved trees have been planted since 2013 (200 million since 2008), which means that the genetically improved stock now accounts for >95% of new planting [5.3]. These dramatic changes in planting practice were driven by dissemination of UofG research findings through [5.2]. This, in turn, convinced the forestry and nursery sectors that the new trees would produce construction-grade timber, thereby increasing sawlog output, and increased total wood volume. The current monetary value of these trees and their contribution to carbon capture in the UK and Ireland are explicitly calculated below.

There are inevitable uncertainties in calculating economic benefits when spruce trees typically take 40 years to mature. However, investment in forestry requires long-term planning, and standardised accounting methods are available to assess the Net Present Value (NPV) of standing trees from their predicted revenue at harvest. On that basis, the improved trees planted between 2014 and 2020 are expected to yield 6.3 million m^3 of additional timber [5.4] and a 5.6% price increase due to their extra sawlog proportion, leading to an increase of GBP61 million in the 2020 market value of the UK standing timber resource [5.1].

This economic gain has changed UK perceptions about the value of basic science to forestry, as evidenced by a major BBSRC/Forestry Commission investment in new genomic research on Sitka spruce (https://sitkaspruced.web.ox.ac.uk/).

Sitka spruce plantations as a carbon store in The UK and Ireland

In the UK, the 6.3 million m^3 of additional timber in the improved trees corresponds to the capture of 3.7 million tonnes of CO_2 equivalent during the lifetime of these trees [5.4]. After they are harvested, the additional sawn timber incorporated into buildings will store the equivalent of 4.9 million tonnes of CO_2 for a further 50−100 years [5.4].

Sitka spruce is the dominant species in Irish forestry; one rotation of a Sitka spruce woodland can fix over 200 tonnes of carbon per hectare. Forestry, as an expanding sink for carbon capture, has proven to be of pivotal significance in Ireland reaching its Kyoto target to reduce carbon emissions. A report by Teagasc (Agriculture and Food Development Authority in Ireland) on the comparative productivity of Sitka spruce [5.5] led the Irish Government to approve the use of UK-grown improved Sitka spruce genotypes on its list of "Accepted Tree Species for Grant Aid and Accepted Seed Origins / Provenances" [5.6]. Inclusion on this list is required for grant aid to the Irish forestry sector via the Afforestation Grant and Premium Scheme 2014−2020 [5.7]. This scheme has resulted in an additional 59,600 additional hectares of afforestation in Ireland in this REF period, with a predicted total carbon store of approximately 11.9 million tonnes. None So Hardy Nurseries, which employs 85 people, supply between 80−90% of the plants nationwide to the grant-aided forestry sector through the afforestation programme in Ireland, and "*have been supplying improved (Forestry Commission) Sitka Spruce for over 10 years to our customers as we felt it would improve the quality of timber… would benefit our customers …(and) improve growth rates etc. As we received more and more positive feedback from our customers, we decided to only use improved Sitka*" [5.8; Nursery Manager, None-So-Hardy Nurseries].

5. Sources to corroborate the impact [supplied in PDF format]

5.1. Mapping UK Timber industries. Confederation of Timber Industries Policy Report Oct 2016. https://cti-timber.org/wp-content/uploads/2020/06/CTI_Value_Growth_report.pdf

5.2. Forestry Commission Notes and knowledge exchange which underpin the industry changes that drove the detailed impacts
   a. J.P. McLean, S. Mochan and J Moore. Investigating the effect of tree breeding on the timber properties of Sitka spruce. IUFRO (International Union of Forest Research Organisations) Meeting 2007 Division 5. https://slideplayer.com/slide/4982017/
   b. S. Mochan, S. Lee and B. Gardiner. Benefits of improved Sitka spruce: volume and quality of timber. Forestry Commission Research Note, 2008. https://www.forestresearch.gov.uk/research/benefits-of-improved-sitka-spruce-volume-and-quality-of-timber-2/
   c. S. Lee & G Watt. Choosing Sitka spruce planting stock. Forestry Commission Practice Note, 2012. https://www.forestresearch.gov.uk/research/choosing-sitka-spruce-planting-stock/

5.3. Forestry statistics 2020.

5.4. Discounted yield metric and carbon capture calculations of UK Forestry based on published values

5.5. Teagasc Report 6273. Productivity of Southern provenances of Sitka spruce.

5.6. Teagasc Circular 5 of 2016, 4th April 2016 to all Registered Foresters, Forestry Companies, and other Stakeholders. Accepted Tree Species for Grant Aid and Accepted

Seed Origins / Provenances. The Department of Agriculture, Food and the Marine, Government of Ireland

5.7. a) Afforestation Grant and Premium Scheme 2014−2020, Published by Department of Agriculture, Food and the Marine, Ireland 1 Jan 2015; b) Forest Statistics Ireland 2020, Published by Department of Agriculture, Food and the Marine, Ireland July 2020.

5.8. Statement, Nursery Manager, None-So-Hardy Nurseries.