Institution: University of Portsmouth		
Unit of Assessment: UoA7 - Earth Systems and Environmental Sciences		
Title of case study: Driving innovation in sustainable wood protection		
Period when the underpinning research was undertaken: 2004 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Simon Cragg	**Role(s) (e.g. job title):** Professor of Marine Zoology	**Period(s) employed by submitting HEI:** 01/01/1997 - date
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

Marine wood borers cause huge economic losses by damaging maritime structures. Innovative laboratory methods developed by **Cragg** reduce the duration and cost of testing of wood protection products. **Cragg**'s methods and expertise have been used in commercial product development and process optimisation to deliver new wood protection treatments and inform treatment design. This has opened new markets and improved the profitability and commercial competitiveness of international wood treatment companies. The methods are being incorporated into the European standard for testing of wood and wood protection treatments. Technical data has been incorporated into international guidelines for timber procurement that have supported sustainable global forestry and the development of products with enhanced efficacy and improved environmental profiles.

2. Underpinning research

Over the last 15 years, **Professor Simon Cragg,** has developed internationally recognised expertise in the identification, biology and husbandry of marine wood borers. Research programmes led by **Cragg** have:

(i) provided the basis for standard laboratory tests of wood durability against damage by marine wood borers

Initial research developed quantitative methods for assessing the vulnerability of wood to the crustacean wood borer (*Limnoria*) attack by measuring faecal pellet production rate. Method development determined an optimum study duration of 15 days, optimised environmental and animal-related conditions for *Limnoria* as a test organism and investigated the role of wood surface hardness in conferring resistance to *Limnoria* attack, resulting in the inclusion of a denser, non-durable wood species in routine testing (**R1**). **This Portsmouth protocol provided the first standardised laboratory test for the rapid and consistent assessment of the resistance of timbers to attack by *Limnoria* spp**. In 2009, the Environment Agency (EA) and the Timber Research and Development Association jointly commissioned Portsmouth researchers to use this test to evaluate the marine borer resistance of 18 lesser-utilised species (LUS) of tropical hardwoods (**G1**). These data confirmed that several LUS performed as well as the traditional marine construction hardwood species, ekki and greenheart, which are being over-exploited (**R2**).

Cragg then collaborated with international material testing agencies in Germany (BAM - Bundesanstalt fùr Materialforschung und -prùfung), France (FCBA) and Sweden (RISE) to link laboratory performance data with field assessments. Between 2013 and 2015, **Cragg** worked with RISE and a Norwegian wood technology company, Kebony AS, to use Portsmouth laboratory testing protocols alongside standard marine field tests to evaluate the efficacy of novel wood treatments in reducing attack by marine wood borers (**G2**). These studies obtained statistically robust results from the laboratory tests within four weeks and, most significantly, demonstrated that the laboratory and field findings (the latter from years of testing) were in broad agreement. **This confirmed not only that the Portsmouth laboratory protocols had the potential to replace long term field trials, but also that the laboratory tests could be used with accuracy and speed in performance testing during product development.** New laboratory methods developed during this project yielded similarly robust and rapid demonstrations of the efficacy of wood treatments against attack by wood-boring molluscs (shipworms), which are also economically-significant pests (**R3**).

(ii) improved the understanding of the key mechanisms of wood digestion by marine borers

The challenge of wood digestion lies in the recalcitrance of the polymer complex, lignocellulose, to enzymatic action. Between 2004 and 2013, **Cragg** led a Portsmouth team, which incorporated expertise in gene regulation (Guille, M., UoA 3) and structural biology (McGeehan, J., UoA3), to investigate the key molecular mechanisms of wood digestion in *Limnoria* (**G3**, **G4**, **G5**). Collaborators included the University of York, the US Dept of Energy and an industrial partner, Novozymes. This work identified and characterised key digestive enzymes in *Limnoria* and confirmed that certain respiratory proteins, haemocyanins, in the hindgut of *Limnoria* act to pre-treat wood for subsequent enzymatic degradation (**R4**). **Cragg**'s research with wood scientists and engineers from Scandinavia also demonstrated that resistance of modified wood to shipworm and *Limnoria* attack required modifications at the wood cell wall level that restrict enzyme access to wood polymers (**R5**).

These discoveries led onto the 'Marine wood borer enzyme discovery' research project (2014 - 2019) which was a component of the BBSRC Sustainable Bioenergy Centre (**G6**). This project, led by the University of York with **Cragg**'s team and partners from the University of Cambridge, further characterised the range of proteins involved in wood digestion in *Limnoria* (**R6**) and revealed the complex molecular mechanisms of wood digestion in shipworms (**R7**). **Cragg's detailed understanding of the mechanisms of wood degradation by marine wood borers has been vital for the development of innovative and effective ways of protecting timber in marine environments.**

3. References to the research

3.1 Research outputs

R1. Borges, L. M. S., **Cragg, S. M.** & Busch S. (2009). A laboratory assay for measuring feeding and mortality of the marine wood borer *Limnoria* under forced feeding conditions: A basis for a standard test method. *International Biodeterioration & Biodegradation, 63*(3), 289-296. https://doi.org/10.1016/j.ibiod.2008.10.007

R2. Williams, J. R., Sawyer, G. S., **Cragg, S. M.**, Icely, J. D., Simm, J., Meaden, M., Borges, L. M. S., & Malyon, G. P. (2018). Evaluating less-used timber species for marine construction. *Proceedings of the ICE - Construction Materials*, *171*(4), 134-148. https://doi.org/10.1680/jcoma.15.00065

R3. Slevin, C. R., Westin, M., Lande, S., & **Cragg, S.** (2015). Laboratory and marine trials of resistance of furfurylated wood to marine borers. In M. Hughes, L. Rautkari, T. Uimonen, H. Militz, & B. Junge (Eds.), Proceedings of the eighth European conference on wood modification (pp. 464-471). Aalto University. https://researchportal.port.ac.uk/portal/files/25235079/ECWM8_Slevin_et_al_ms_1_.pdf

R4. King, A., **Cragg, S.**, Li, Y., Dymond, J., Guille, M. J., Bowles, D., Bruce, N., Graham, I., & McQueen-Mason, S. (2010). Molecular insight into lignocellulose digestion by a marine isopod in the absence of gut microbes. *Proceedings of the National Academy of Sciences*, *107*(12), 5345-5350. https://doi.org/10.1073/pnas.0914228107

R5. Klüppel, A., **Cragg, S. M.**, Militz, H., & Mai, C. (2015). Resistance of modified wood to marine borers. *International Biodeterioration & Biodegradation 104,* 8-14. https://doi.org/10.1016/j.ibiod.2015.05.013

R6. Besser, K., et al. (2018). Hemocyanin facilitates lignocellulose digestion by wood-boring marine crustaceans. *Nature Communications*, *2018*(9), [5125]. (23 authors including **Cragg, S.M**). https://doi.org/10.1038/s41467-018-07575-2

R7. Sabbadin, F., Pesante, G., Elias, L., Besser, K., Li, Y., Steele-King, C., Stark, M., Rathbone, D., Dowle, A., Bates, R., Shipway, J. R., **Cragg, S.**, Bruce, N., & McQueen-Mason, S. (2018). Uncovering the molecular mechanisms of lignocellulose digestion in shipworms. *Biotechnology for Biofuels*, *11*(59). https://doi.org/10.1186/s13068-018-1058-3

3.2. Evidence of the quality of the research

Underpinning research was published in high quality, peer-reviewed international journals and funded by competitive, peer-reviewed awards from the Leverhulme Trust, UK Research Councils

(BBSRC) and the Research Council of Norway (with **Cragg** as PI or named CoI). R6 is returned to REF2 with Output ID 13087939.

3.3. Related grants

G1. **Cragg, S. M.** Evaluation of timbers for their potential to replace greenheart in coastal construction. Funded by the Timber Research and Development Association, 02/2008 - 12/2008 (GBP7,500)

G2. **Cragg, S**. Wood-polymer composites for use in marine environments. Funded by the Research Council of Norway, 09/2012 - 09/2015 (NOK4,300,000 (GBP467,931; 10/2012): GBP60,000 to UoP)

G3. Guille, M. (PI) & **Cragg, S**. The Control and Molecular Mechanism of Wood Digestion in *Limnoria*. Funded by the Leverhulme Trust, 10/2004 - 09/2007 (GBP110,040)

G4. **Cragg, S. (PI),** McGeehan, J. E. & Guille, M. New tools for the realization of cost-effective liquid biofuels from plant biomass. Funded by the Biotechnology and Biological Sciences Research Council, 03/2009 - 10/2013 (GBP439,723)

G5. **Cragg, S.** New insights into using lignocellulose degradation mechanisms for biofuel generation gained by sharing expertise in wood-degrading animals and fungi. Funded by the Funded by the Biotechnology and Biological Sciences Research Council, 05/2010 - 10/2013 (GBP33,305)

G6. McQueen-Mason, S. (PI), Bruce, N., Davies, G. J., Dupree, P., **Cragg, S. M. (CoI)**, McGeehan, J. E. & Walton, P. H.. Learning from marine wood borers; enzymes and mechanisms of lignocellulose digestion. Funded by the Biotechnology and Biological Sciences Research Council, 04/2014 - 03/2019 (GBP2,820,183; GBP568,462 to UoP)

G7. **Cragg, S.** Evaluation by Lab and Field Experimentation of Novel Non-Biocidal Wood Protection Methods for use in the Marine Environment. Funded by the Research Council of Norway (Oslofjordfondet), 10/2017 - 05/2022 (GBP36,000).

4. Details of the impact

Degradation of wood by marine wood boring species causes major economic losses world-wide: in the last four years, over USD120,000,000 has been spent on treating timber pilings in Brooklyn Bridge Park and over GBP500,000 to repair damage to Swanage and Yarmouth Piers. The use of tropical hardwoods with natural durability has negative environmental, cultural and social implications and traditional wood preservatives, such as creosote and chromated copper arsenate (CCA), are prohibited or restricted in Europe and the USA. Standard testing of alternative treatments requires long term field exposure testing, which is slow, costly and renders an iterative approach to product or process refinement unfeasible.

Developing innovative treatments with improved efficacy and environmental profiles

The Portsmouth protocols enable 'high throughput' testing of materials or samples and rapid, reliable evaluation of wood protection treatments. They have been incorporated into product development and process optimisation in a commercial context to reduce the duration and cost of testing. Additionally, **Cragg**'s expert knowledge on marine borer behaviour and the mechanisms of wood degradation has been used to inform treatment design. As a result, wood protection companies have developed innovative treatments with improved efficacy and environmental profiles.

Kebony AS (Norway), a globally-leading wood technology company, have used the Portsmouth protocols (*Limnoria* and shipworms) and **Cragg**'s expertise to develop and refine their innovative, award-winning, proprietary process of wood modification, furfurylation. Furfurylation renders wood more durable and resistant to decay. Crucially, by using permeable timbers from managed temperate forests and furfuryl alcohol produced from agricultural crop waste, furfurylation offers sustainable and environmentally-beneficial alternatives to tropical hardwoods and to wood protected with chemical biocides. Initial work conducted between 2013 and 2015 (**G2**), used the Portsmouth laboratory protocols to assess marine durability and indicated that the required performance improvement for marine applications could be achieved by replacing water with alcohol as a solvent in the furfurylation process, but that the choice of solvent had a decisive effect on product performance (**S1**). In 2017, a subsequent project, Alcofur, was initiated to optimise solvent and process conditions for full-scale production of furfurylated wood (**G7**). In this project,

the Portsmouth protocols were used in iterative rounds of process modification and testing to assess product performance as economically-sensitive variations in process parameters and raw materials were introduced. **The accuracy, cost-effectiveness and speed of results obtained using the Portsmouth laboratory tests made this iterative approach to process optimisation feasible.** In addition, **Cragg**'s understanding of the molecular mechanisms of wood degradation by marine borers was used to inform treatment design by interpreting borer behaviour in response to furan polymer formation and changes in the structure and accessibility of wood cells. As a result of this testing programme, Kebony AS has developed furfurylated wood products with improved properties for use in existing markets, such as yachts and decking**. Most significantly, this testing programme has developed a product for marine construction.** This is a major innovation at an international level and represents a significant new market for Kebony; the estimated increase in revenue is GBP10,000,000 over the first five years. Additionally, the Portsmouth protocols confirmed that improved recycling of solvents in the Kebony process did not compromise product performance. The use of alcohol and recycling of solvents in the new process improves process efficiency by 15% and reduces chemical consumption by 20% per unit, offering a potential improvement to the profitability (GBP50,000,000 in the first 5 years) and competitiveness of the company. As the Research Manager of Kebony AS confirms, *'The documented effect and possibilities for further growth of Kebony as a leading wood modification company would not have been possible without the conducted research'* (**S3**).

Similarly, in 2016, [text removed for publication], a Danish company specialising in sustainable wood and wood treatments, adopted the Portsmouth laboratory methods to test the efficacy of a non-biocide treatment against marine organisms. The ability to test multiple, small samples rapidly and at low cost means that smaller companies, such as [text removed for publication], can evaluate potential candidate systems and technologies. '*If the methods developed by Professor Cragg were not available, entry costs to evaluate potential candidate systems would pose a high risk and would probably mean that we would not be able to initiate the work at all. The methods developed make this possible'*. Commercial product development, supported by **Cragg**'s team at the UoP, is underway: successful introduction of this product for marine construction will increase the annual turnover of the company by up to GBP3,000,000 (**S4**).

Revising the European Standard for marine testing

Development of innovative softwood modification processes and treatments is frustrated by the need for long term and costly field exposure testing. The European standard for marine testing durable and treated timbers (EN 275) requires field exposure and annual inspection for a minimum of five years: costs are high (EUR12,000 p.a.) and generation of results is slow. In 2013, in recognition of his expertise in marine wood borer biology and, in particular, of the benefits of the Portsmouth protocols, **Cragg** was invited to join a European Standards Commission (CEN) Task Group (CEN/TC 38) charged with revising EN275. This standard has been in force, unchanged, since 1992 and the scale of revision is considerable: the scope has been extended to include treated, modified and composite wood products and replacements for the now-banned reference preservatives must be identified. **Significantly, in 2015, the Portsmouth protocol for the evaluation of wood resistance to attack by *Limnoria* (R1) was recommended for inclusion in the revised standard as a valid, cost effective alternative to field trials.** Between 2015 and 2018, **Cragg** attended workgroup meetings in Berlin, Florence and Venice and worked with scientists, material testing agencies and industry across Europe to refine and validate the protocol. A meeting of TC38 in November 2018 was devoted to evaluating the method, which was subsequently drafted as a Technical Report in CEN format (**S5**), a vital precursor to incorporation into a standard. In May 2019, TC38 approved a programme of round robin testing in Europe. A round robin test is an interlaboratory programme in which the method is used, independently and repeatedly, to assess its reproducibility. The testing programme, which included laboratory and seasonally-dependent field trials in the UK (UoP), Italy (CNR ISMAR), Sweden (RISE and University of Uppsala) and Germany (Thuenen Institute of Wood Research), was planned for the spring and summer 2020 (**S6**). All participants were to attend training, delivered by **Cragg** at Portsmouth, in April 2020. As a result of the Covid-19 pandemic, both the 2020 training and the round robin testing programme had to be cancelled. To mitigate further delays, **Cragg**'s team have made a film of the *Limnoria* procedures available to the EN275 task group and all participating laboratories, and submitted it to the Journal of Visualised Experiments. Interlaboratory testing will

resume as soon as safe face-to-face collaboration permits (**S6**). The outcomes will be published as a CEN Technical Report for subsequent adoption into the revised standard. Incorporation of the *Limnoria* protocol into EN275 will ensure mandatory, wide scale adoption across the 34 CEN national members and establish a sector-leading methodology, with obvious and significant benefits to the wood preservation industry and the environment.

Supporting sustainable forestry on a global scale

Cragg's research has supported sustainable global forestry by providing technical data and methods to enable the use of a wider range of hardwoods in marine construction. Technical data on the borer resistance of Lesser Used Hardwood Species (LUS) (**R2**) underpinned UK Environment Agency guidance aimed at structural and civil engineers, design consultants, building contractors and asset managers. These data supported changes to the UK Government's timber procurement procedures to include a mandatory requirement to consider LUS in all proposals submitted for marine and freshwater construction, and underpinned a GBP10,000,000 framework contract with two UK-based LUS timber suppliers. Since August 2013 and under this framework contract, Wijma UK Ltd have supplied Forest Stewardship Council (FSC) certified Okan in the replacement of Grafton Head Lock Gates, Oxfordshire (2014) and Basralocus as part of the GBP44,000,000, 17 year programme of replacement of Bournemouth's Groynes (2015-2020) (**S7**). Both Okan and Basralocus performed very well in UoP testing (EA Guidance: Annex 2, p23, 25). In October 2013, **R2** data was incorporated into the 'Guide to Lesser Known Tropical Timber Species', published by the World Wildlife Fund/Global Forest and Trade Network (GTFN) (**S8**). The Guide is designed to inform buyers and decision-makers about the properties of lesser known timber species and links their availability to GFTN producer participants. GTFN participants manage 21,600,000ha of credibly-certified forests and sell 18% of total global forest products (equivalent to USD69,000,000,000 annually). **Cragg** also contributed his expertise in laboratory and marine field testing methods to the European COST Action FP 1303 'Performance of Biobased Building Materials' (**S9**) aimed at policymakers, regulatory bodies, national decision makers and industry stakeholders. To date, this has been accessed 3,517 times on Science Direct and generated USD12,612 of print revenue and USD22,188 for electronic access. (Monetary amounts are supplied here as measures of use of the information rather than as income generation).

5. Sources to corroborate the impact

S1. Polywood Results report: Attachment to the final report for User-driven Innovation Projects (BIP) under the BIA programme, 01/12/2015

S2. Alcofur final report, 02/07/2020

S3. Letter, Research Manager, Kebony AS, confirming that novel testing methodology allowed rapid iterative testing and evaluation of furfurylation process optimisation and resultant improvements in competitiveness to company, 23/02/2021

S4. Email from [text removed for publication], 07/12/2020

S5. Durability of wood and wood-based products – Testing the durability of wood and wood-based materials against the attack by marine organisms. Part 1 Laboratory test for European *Limnoria* species (CEN/TC 38/WG 24 TG EN 275 N 08)

S6. Palanti, S., **Cragg, S.**, & Plarre, R. (2020). Resistance against marine borers: about the revision of EN 275 and the attempt for a new laboratory standard for Limnoria. In Proceedings IRG Annual Meeting [IRG/WP 20-20669] The International Research Group on Wood Protection. https://www.irg-wp.com/search-irg-docs.html

S7. Confirmation of supply of LUS of hardwood by Wijma UK Ltd for construction projects at Grafton Head Lock (11/2013) and Bournemouth Groynes (01/2016)

S8. World Wildlife Fund/Global Forest and Trade Network 'Guide to Lesser Known Tropical Timber Species' (10/2013)

S9. **Cragg, S. M.** (2017). Marine Borers. In D. Jones, & C. Brischke (Eds.), *Performance of Bio-based Building Materials*, Elsevier. Chapter 7, Test methods for bio-based building materials: sub-sections 7.2.3 and 7.3.2. https://doi.org/10.1016/B978-0-08-100982-6.00007-0