Institution: University of Exeter		
Unit of Assessment: UoA 9 Physics		
Title of case study: Banning microplastics: Label-free imaging provides key evidence of accumulation of microplastics in marine organisms		
Period when the underpinning research was undertaken: 2013 - 2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Prof Julian Moger	**Role(s) (e.g. job title):** Chair in Biophotonics	**Period(s) employed by submitting HEI:** 2005 - present
Period when the claimed impact occurred: 2015 – 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Until recently, virtually nothing was known of the fate and potential harm that manufactured microplastics posed on the marine environment. Images acquired using novel microscopy techniques developed by the Moger Group **provided unequivocal evidence** of the ingestion and accumulation of microplastics in marine organisms. The visual impact of these images played a key role in **influencing government policy changes in the UK** to ban the use of microplastics in cosmetics and personal care products. These changes spread across the world, resulting in policy changes in **Europe, US, Canada, UN and the G7 group**. In the UK alone policy changes have led to an annual reduction of some 4000 tonnes of plastic entering marine systems, improving the health of marine organisms and their environments.

2. Underpinning research (indicative maximum 500 words)

Identifying plastic at the microscopic level in living organisms is not straightforward. While conventional light microscopy can be used to visualise particles ingested by marine organisms, it cannot distinguish man-made compounds, such as plastics, from food and other naturally occurring particulates. Fluorescence microscopy is routinely applied to derive chemical specificity based on the attachment of extrinsic fluorescent labels to molecular species of interest. However, this cannot be applied to samples from the environment since they are, by their very nature, unlabelled.

Since 2007, Moger's research has focused on the development and application of nonlinear optical microscopy, which compared to conventional (linear) techniques offers significant advantages for biological applications. The near-IR excitation extends the depth penetration into tissues with minimal photodamage, and the nonlinear signal dependence provides intrinsic 3D optical sectioning. More importantly, with techniques such as coherent Raman scattering (CRS), which utilize the intrinsic nonlinear optical responses of selected molecules, it is possible to derive label-free biochemical contrast in living systems. In particular, Moger has world-leading expertise in applying these techniques to track unlabelled nano- and micro- particles in tissues at the cellular level. This capability has proven vital in many important areas, including the detection and imaging of semiconductor particles, nanomedicines **[3.1; 3.2]**, nanotherapeutics, and microplastics **[3.3 - 3.6]**.

For the impact discussed here, a key development by the Moger Group was the ability, for the first time, to unequivocally detect the presence of microplastics in marine organisms. This was based on the intrinsic chemical signatures of the polymers from which the particles were composed and represented a step change in analytical capability. Between 2013-2017, research was undertaken to apply CRS to detect and visualise the uptake and accumulation of microplastics in a range of marine organisms. CRS was applied to show that microplastics are ingested by, and impact upon, common species of zooplankton found in the northeast Atlantic **[3.4]**. The Group's findings showed that zooplankton had the capacity to ingest microplastic particles, with uptake varying by life-stage and particle-size. They also observed microplastics adhered to the external carapace and appendages of exposed zooplankton. Figure 1 below shows an example image demonstrating the accumulation of microplastics in the digestive tract of a copepod (*temora longicornis*). The image is constructed from the projection of 3D data sets acquired using the non-linear optical molecular responses of microplastics (red) and the surrounding biological tissues (grey).

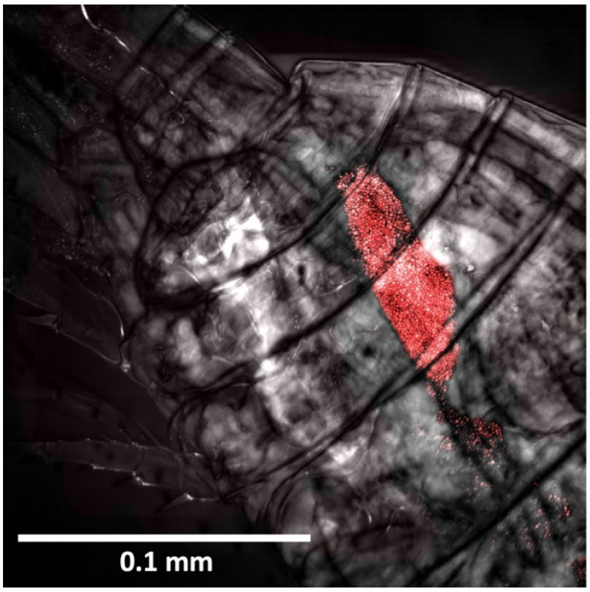

Figure 1: CRS microscopy image showing accumulated microplastics (shown in red) in the digestive tract of a copepod (shown in grey). Adapted from ***[3.4]****.*

Moger later found that the shore crabs (c*arcinus maenas*) uptake microplastics through ingestion of pre-exposed food (i.e. *mussels, Mytilus edulis*) and through inspiration across the gills **[3.5]**. Images showed that ingested particles were retained within the body tissues of the crabs for up to two weeks following ingestion and up to three weeks following inspiration across the gill. Particles were seen to be retained in the foregut and on the gill surface. These were the first results to identify a possible route of uptake and retention of microplastics other than trophic transfer into a common coastal species. Later, Moger's images revealed the distribution of particles across the gill surface and showed that plastic particles inhaled into the gill chamber had a significant effect on respiration, illustrating the extent of the physiological effects of microplastics compared to naturally occurring particles **[3.6]**.

The Group's findings implied that the accumulation of particles has a significant affect on the food chain. These results provided key evidence of the potentially harmful affects of microplastics on the marine environment and formed the basis of the scientific case that led to their ban.

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

[3.1] Garrett NL, Lalatsa A, Begley D, Mihoreanu L, Uchegbu IF, Schätzlein AG, **Moger J**. *"Label-free imaging of polymeric nanomedicines using coherent anti-stokes Raman scattering microscopy"*, Journal of Raman Spectroscopy, 43(5), pages 681-688. (2012) DOI: 10.1002/jrs.3170

[3.2] Garrett NL, Lalatsa A, Uchegbu I, Schätzlein A, **Moger J**. (2012) *"Exploring uptake mechanisms of oral nanomedicines using multimodal nonlinear optical microscopy"*, J Biophotonics, 5(5-6), pages 458-468. DOI: 10.1002/jbio.201200006

[3.3] Galloway TS, Dogra Y, Garrett N, Rowe D, Tyler CR, **Moger J**, Lammer E, Landsiedel R, Sauer UG, Scherer G. *"Ecotoxicological assessment of nanoparticle-containing acrylic copolymer dispersions in fairy shrimp and zebrafish embryos"*, Environmental Science: Nano, 4(10), pages 1981-1997. (2017) DOI: 10.1039/c7en00385d

[3.4] Cole M, Lindeque P, Fileman E, Halsband C, Goodhead R, **Moger J**, Galloway TS. *"Microplastic ingestion by zooplankton"*, Environ Sci Technol, 47(12), pages 6646-6655. (2013) DOI: 10.1021/es400663f

[3.5] Watts, A. J. R., C. Lewis, R. M. Goodhead, S. J. Beckett, **J. Moger**, C. R. Tyler and T. S. Galloway *"Uptake and Retention of Microplastics by the Shore Crab Carcinus maenas"*. Environmental Science & Technology. 48(15), pages 8823–8830. (2014). DOI: 10.1021/es501090e

[3.6] Watts AJR, Urbina MA, Goodhead R, **Moger J**, Lewis C, Galloway TS. *"Effect of Microplastic on the Gills of the Shore Crab Carcinus maenas"*, Environmental Science and Technology, 50(10), pages 5364-5369. (2016) DOI:10.1021/acs.est.6b01187

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

Plastics are being disposed of at an unprecedented rate. However, much of the plastic we create is hidden: for example, in 2013, a typical exfoliating shower gel was found to contain roughly as much microplastic in the cosmetic formulation as was used to make the plastic packaging it comes in **[5.8]**. However, these hidden plastics do not degrade, and when used in cosmetics, easily find their way into marine environments. It has been estimated that microplastics present in our oceans are costing approximately $13Bn per year in environmental damage **[5.8],** and bring unknown damage to our marine ecosystems.

Detecting the presence of microplastics: It is very difficult to accurately determine the total amount and true effect of microplastic particles in the environment, as they can be hard to detect. Work by a cross-disciplinary team at Exeter made a crucial contribution to our understanding of the impact of microplastics on the world's oceans and their potential to cause wide-spread ecological damage. The research has supported the campaigns of numerous non-profit organizations and stimulated huge public interest internationally. It has provided instrumental evidence for government policy changes resulting in a legal UK ban of microbeads in cosmetics and personal care products; and changes to European, North American and UN global policies. Throughout, the label-free microscopy techniques developed by Moger provided the key evidence of the ingestion and accumulation of microplastics in marine organisms, and the visual impact of the images played a vital role in influencing policy change.

Influencing policy changes in the UK: The team's research findings supported a successful effort on behalf of NERC, various academic institutions and non-profit organisations to include microplastics in a UK House of Commons Science and Technology Committee inquiry into water quality. Parliamentarians were informed about the negative effects of microplastics, with the team's research cited in the Government Parliamentary Office of Science and Technology (POST) notes on *Trends in the Environment* in 2015 **[5.1]** and *Marine Microplastic Pollution* in 2016 **[5.2]**, both citing papers with images taken by the Moger Group **[3.4-3.6]**. In June 2016, Exeter's research was presented, including images from the Moger group, to an Environmental Audit Committee hearing on Microbeads in the Marine Environment at the Houses of Parliament. The submission influenced a change in legislation to outlaw microscopic plastics from being added to consumer products, which was announced following the enquiry in August 2016 and came into force in January 2018.

Moger's work, verifying the presence of microplastics in marine organisms, played a crucial role in bringing about these changes to environmental policy and practice. The Chair of the Environmental Audit Committee specifically noted the contribution of the label-free images towards the case for the environmental impact of microplastics, commenting that "*the provocative nature of these striking images made a particular impact as evidence of uptake into the food chain*" **[5.6].**

Influencing international policy changes: The Exeter team's research evidence has also had significant influence on policy decisions beyond the UK. In Canada, a report published by the Canadian Environment Agency '*Microbeads – a Science Summary*' references papers by the team and recommends that, based on the available information, "microbeads be considered toxic under subsection 64(a) of the Environmental Protection Act 1999" **[5.3]**. In the US, the Microbead-Free Waters Act (2015) was informed by NOAA reports **[5.7]** produced as part of their Marine Debris Program which referenced papers with images taken by the Moger Group **[3.4].** In 2019 and 2020 the European Chemicals Agency Committee for Socio-economic Analysis (SEAC) released reports **[5.10]**, again citing papers with images from the Moger Group **[3.4]**, which proposed restrictions on intentionally-added microplastics as an appropriate EU-wide measure.

Political action on microbeads has now expanded worldwide, with the United Nations supporting resolutions to drastically reduce plastic pollution. Moger's work again played a key role: In June

2016 results were presented, including images produced by Moger, to the United Nations *Consultation on the Laws of the Oceans,* held in New York. Evidence was then presented to the UN General Assembly on 13 September 2016 which contained four references to oral evidence provided by the Exeter team. Finally, in December 2017, more than 200 nations represented at the United Nations Environment Assembly resolved to eliminate marine plastic pollution. Parallel to this, the G7 pledged to reduce uncontrolled disposal of waste plastics as one of its strategic development goals, which aims to reduce marine debris and microplastics by encouraging improvements to legislation, waste management and social education.

The UN resolution referenced the UN Environment Programme (UNEP) report '*Marine plastic debris and microplastics - Global lessons and research to inspire action and guide policy change*' **[5.8]**, which itself directly referenced publications from the Moger group **[3.5]**. As a result of Moger's pioneering work, CRS microscopy is now viewed as a benchmark for analysing the effects of plastic pollutants in biological systems. In the UN Environment Programme GESAMP (Group of Experts on the Scientific Aspects of Marine Environmental Policy) advice documents, Moger's research approach was specifically cited as a precedent for how to accurately measure marine microplastics **[5.4; 5.5]**.

Summary statement: The Moger group has developed and used novel microscopy approaches which are capable, for the first time, of quantifying the take-up of plastic pollutants in real biological systems. The striking visual impact of the images played a key role in generating pivotal policy changes banning microplastics in cosmetics and personal care products in the UK, Europe, and across the world. At the time of submission to REF 2021, the governments of 15 major developed countries have banned (or committed to banning) the use microplastics in cosmetics, and many of the world's largest cosmetics brands have pledged to remove microplastics from their products, including Unilever, L'Oréal, Colgate-Palmolive, Beiersdorf, Procter & Gamble, and Johnson & Johnson **[5.9]**. The UK ban alone has resulted in an estimated reduction of 4,000 tonnes per year of microplastics entering our oceans **[5.2],** improving the health of marine organisms and benefiting their environments.

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

5.1 Government Parliamentary Office of Science and Technology (POST) notes on *Trends in the Environment* in 2015.

5.2 Government Parliamentary Office of Science and Technology (POST) notes on *Marine Microplastic Pollution* in 2016.

5.3 Canadian Environment Agency '*Microbeads – a Science Summary*'
Available at
https://web.archive.org/web/20200930213150/http://www.publications.gc.ca/site/fra/9.811686/publication.html

5.4 GESAMP (2015). "Sources, fate and effects of microplastics in the marine environment: a global assessment" (Kershaw, P. J., ed.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 90, 96 p.

5.5 GESAMP (2016). "Sources, fate and effects of microplastics in the marine environment: part two of a global assessment" (Kershaw, P.J., and Rochman, C.M., eds). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 93, 220 p.

5.6 Letter of support from The Chair of the Environmental Audit Committee.

5.7 Report prepared for the National Oceanic and Atmospheric Administration's (NOAA) Marine Debris Program: '*Quantification of Microplastics on National Park Beaches*'.

5.8 United Nations Environment Programme (2016). "Marine plastic debris and microplastics - Global lessons and research to inspire action and guide policy change".

See also:
https://web.archive.org/web/20201026112340/https://news.un.org/en/story/2014/06/471492-plastic-waste-causes-13-billion-annual-damage-marine-ecosystems-says-un-agency

5.9 Beat the Microbead campaign:
https://web.archive.org/web/20210101093739/https://www.beatthemicrobead.org/

5.10 European Chemicals Agency (ECHA) Committee for Risk Assessment (RAC) and the Committee for Socio-economic Analysis (SEAC) commissioned report proposing restrictions on intentionally added microplastics (2019 and 2020).