Institution: University of Southampton		
Unit of Assessment: 05 Biological Sciences		
Title of case study: 05-03 AudioMoth: the first open-source, low-cost, small, power-efficient and smart acoustic sensor for environmental monitoring		
Period when the underpinning research was undertaken: October 2015 – December 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:**
C. Patrick Doncaster	Professor in Ecology	April 1995 – present
Jake Snaddon	Lecturer in Environmental Science	September 2013 – present
Alex Rogers	Professor of Computer Science	July 2003 – September 2015
Period when the claimed impact occurred: December 2017 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research led by the University of Southampton underpinned the development and field testing of an acoustic sensor, 'AudioMoth', for smart detection of environmental sounds. The open-source device met a need for high power efficiency and portability in large-scale and long-term monitoring of wilderness habitats with difficult access. AudioMoth outperformed commercial equivalents by 20× on both size and price. It attracted immediate broad interest from conservation communities, enthusiastically expressed in social media, which resulted in 13,894 sales within 3 years, at an increasing rate. Managing this high demand motivated the creation of a novel generic framework for democratising access to acoustic technology. AudioMoths are now deployed globally by Government agencies, NGOs, consultancies, and research and teaching institutions. The devices are enabling in-situ monitoring of Endangered monkeys, apes, felids and birds, and were crucial to the discovery of three new species of Brazilian insects. Belize's Forest Department is using AudioMoths to monitor gunshots in Tapir Mountain Nature Reserve. In citizen-science projects, AudioMoth is the acoustic sensor for the British Bat Survey, for the CetaKit tool to monitor marine mammals, and for the NASA-funded satellite-observation project Soundscapes to Landscapes.

2. Underpinning research

Tropical forests support two-thirds of Earth's biodiversity, despite covering less than 10% of land surface. Mesoamerica is suffering amongst the worst losses of tropical forests globally, with 72% converted to agriculture. In 2009-2012, Professor Patrick Doncaster at the University of Southampton School of Biological Sciences directed a Defra-Darwin funded project to establish the Central Belize Corridor (CBC), the first forest corridor in Belize, designed to preserve the integrity of the Mesoamerican Biological Corridor. One of the main issues addressed by the CBC is unsustainable hunting by people of game animals that are also the main prey of large felids [**3.1**]. Over-exploitation of natural resources, including wild meat and forest timber, is recognised as a top-five contributor to global biodiversity loss, and yet we have almost no data globally on these cryptic activities in forests. This knowledge gap exists because extraction of meat and wood goes undetected by satellite imagery, and ground-based detectors under-report (camera-traps) or are prohibitively expensive (acoustic detectors) and cannot store the vast quantities of data needed to detect rare events.

In 2014, Doncaster teamed up with forest-biodiversity expert Dr Jake Snaddon and electronics expert Professor Alex Rogers to lead the new *Open Acoustic Devices* team, formed to develop and test a low-cost acoustic detector for environmental monitoring. In December 2017, the team announced the product, 'AudioMoth' with publication of a research paper [**3.2**], describing its design and three field tests of its utility for environmental monitoring. AudioMoth is a low-cost, small, power-efficient and smart acoustic detector of environmental sounds, including insects, amphibians, birds, bats and anthropogenic sources [**3.3**]. It outperforms commercial devices with equivalent detection capabilities by 20× on both unit price, at USD50, and size, at 58×48×4 mm and 10 g without batteries. The cost-saving over commercial equivalents (@ USD1,000 in 2017) is achieved through entirely open-source protocols, solely word-of-mouth advertising, and a new

kind of centralised management framework for group purchase, bulk order, and community-led after-sales care [Policy Perspective **3.4**]. The power efficiency and smart detection of AudioMoth mean that devices can be left operating in the field for over 400 days with a 250-g 6-volt battery [**3.5**]. The AudioMoth team have devised and field-tested new Bayesian methods of analysis, for optimal placement of acoustic sensors to maximise detection of a gunshot, and for localisation of the gunshot [**3.6**]. The probability maps for optimal placement halve the number of devices needed in hilly terrain compared to the previous standard of a hexagonal grid, and they allow probabilistic evaluation of sub-optimal sensor placements imposed by access or cost constraints. The gunshot localisation algorithm uniquely uses whatever data may be available on detection timings or simply detection successes and failures, and allows for inclusion of prior beliefs about the most likely areas of gunshot activity, all within the same principled framework.

3. References to the research

3.1 Foster, R.J., Harmsen, B.J., Macdonald, D.W., Collins, J., Urbina, Y., Garcia, R. and Doncaster, C.P. (2016) Wild meat: a shared resource amongst people and predators. Oryx,50: 63-75. https://doi.org/10.1017/S003060531400060X

3.2 Hill, A.P., Prince, P., Piña Covarrubias, E., Doncaster, C.P., Snaddon, J.L. and Rogers, A. (2018) AudioMoth: Evaluation of a smart open acoustic device for monitoring biodiversity and the environment. *Methods in Ecology & Evolution*, 9: 1199-1211. https://doi.org/10.1111/2041-210X.12955

3.3 Hill, A.P., Prince, P., Snaddon, J.L., Doncaster, C.P. and Rogers, A. (2019) AudioMoth: A low-cost acoustic device for monitoring biodiversity and the environment. *HardwareX*, 6: e00073. https://doi.org/10.1016/j.ohx.2019.e00073

3.4 Hill, A.P., Davies, A., Prince, P., Snaddon, J.L., Doncaster, C.P. and Rogers, A. (2019) Leveraging conservation action with open-source hardware. *Conservation Letters*, 12: e12661. https://doi.org/10.1111/conl.12661

3.5 Prince, P., Hill, A.P., Piña Covarrubias, E., Doncaster, C.P., Snaddon, J.L. and Rogers, A. (2019) Deploying acoustic detection algorithms on low-cost, open-source acoustic sensors for environmental monitoring. *Sensors*, 19: 553. https://doi.org/10.3390/s19030553

3.6 Piña Covarrubias, E., Hill, A.P., Prince, P., Snaddon, J.L., Rogers, A. and Doncaster, C.P. (2019) Optimization of sensor deployment for acoustic detection and localization in terrestrial environments. *Remote Sensing in Ecology and Conservation*, 5: 180-192**.** https://doi.org/10.1002/rse2.97. Accompanying videocast on journal twitter feed: https://twitter.com/RSECJournal/status/1053223689980989440

4. Details of the impact

Global public interest and recognition

AudioMoth is the first device to bring large-scale environmental acoustic detection within the means of conservation organisations and local-scale research projects, achieved with open-source hardware and software [**3.4**]. Its utility was immediately recognised on its launch in December 2017, with a rapid uptake of interest in the devices. The publication of reference [**3.2**] announcing AudioMoth coincided with a talk by University of Southampton PhD student Piña-Covarrubias at the 2017 Meeting of the British Ecological Society (BES), and a BES blogpost on her talk, and subsequently a blogpost by *Sparkfun*, the biggest electronics hobbyist website in America with 100,000 reads per day of their website. AudioMoth has also featured in two articles for the *New Scientist* magazine, and headlined two for *Mongabay*, a non-profit provider of conservation news with 2.5 million visitors per month. University of Southampton PhD students Hill and Prince showcased AudioMoth at the 2018 Conference on Illegal Wildlife Trade held in London, where they attracted interest in the devices from Prince William the Duke of Cambridge, and Jeremy Hunt then Secretary of State for Foreign and Commonwealth Affairs [**5.1**].

AudioMoth has won prizes from community forums, and commendation from the applied-science community [**5.1**]. It was a winning entry for the 2019 TECH HUB programme of the Google-funded WILDLABS web-forum, showcasing its role in tackling illegal trade in wildlife, and a finalist for the Con X Tech Prize, and micro-grant winner from the US-based Conservation X

Labs. Reference **3.2** announcing AudioMoth became 'Highly Cited' in Web of Science (top 1% of field-weighted citations) within 18 months of publication. The Bayesian methods developed by the AudioMoth team, for optimal placement of the devices and localisation of the sound sources they detect, were commended in the editorial 'Making an impact' for the *Remote Sensing in Ecology and Conservation 5-Year Anniversary Collection* (June 2020), which includes reference **3.6** in its collation of the journal's 13 best and most highly cited research articles.

AudioMoth features as a case study in outputs by scientists calling for policy change, and by NGOs and companies involved directly in conservation action [**5.2**]. AudioMoth is a case study in a 2019 call for international leadership and coordination to realise the potential of conservation technology, published in *BioScience*. The call declares that the "*AudioMoth acoustic device is one of the best existing examples of how technologist talent in a small independent team can achieve global scale, supported by service provision within the context of open innovation*". AudioMoth features as a case study in the 2017 WWF Acoustic Monitoring Guide to sensor selection and deployment, and in the 2017 annual report of the WILDLABS web-forum, whose members coordinate large group-orders of AudioMoth. The Puerto Rican company Sieve Analytics Inc., which host the global Automated Remote Biodiversity Monitoring Network, say on their website: "*We highly recommend the AudioMoth recorders. We have had extensive field experience with these recorders, and they produce high quality recordings. Since the recorders cost < $100 (USD), you can greatly increase your sample size*". Founder Mitch Aide "*sees the AudioMoth as a huge boost for acoustics research around the world, especially for developing-world researchers on small budgets*" according to filmmaker Adam Welz reporting for *YaleEnvironment360*.

By April 2019, these diverse routes to global awareness had resulted in AudioMoths being deployed by 687 projects across six continents. Surveyed purchasers included universities (34% of devices), NGOs (23%), businesses (11%), and government agencies (1%), in a wide range of applications including monitoring of individual species and human-wildlife conflicts, marine surveys, ecosystem soundscape analysis, and university-level education. Purchasers were globally distributed, with clusters around the financial hubs of advanced economies, particularly in Europe (63%), North America (23%), and Australia (8%). Purchases made elsewhere included Central and South America (4%), Asia (2%), and Africa (<1%) [**3.4**].

Significance in democratising access

The centralised management alternative to the standard commercial framework dramatically reduces participation costs and technical barriers to acoustic monitoring; it serves conservation organisations, which can adapt the scheme to their specific needs, and individual citizens, who may need only a single device. Within 18 months of its first public announcement, 5,242 AudioMoth units had been sold to individuals and organisations worldwide in six group-purchasing campaigns [**3.4**]. The revenue of USD262,048 from these sales (all at USD49.99) had outstripped the setup investment in development, and manufacture and distribution costs (USD203,859), to generate a pool of funds worth USD58,188 [**3.4**]. The not-for-profit Arribada Initiative [**5.3**] manages these pool-funds, guaranteeing their reinvestment, at about USD10 per device, into further research and development of AudioMoth. For example, Arribada has committed GBP3,500 to a CASE partnership with the UoS NERC-INSPIRE DTP, for a PhD project running from 2019-2023 to test large-scale deployments of AudioMoths in Belize.

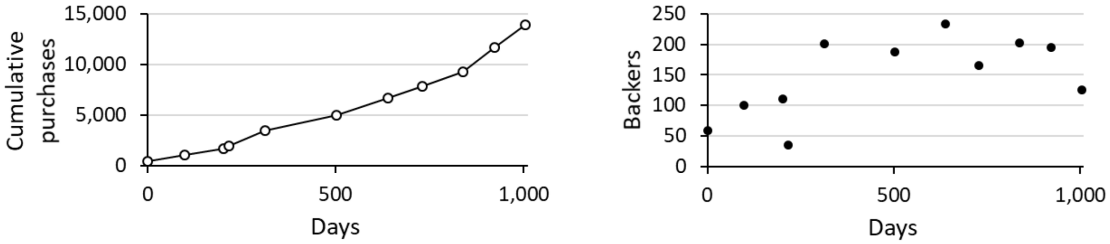

Fig. 1. A rising passion for the devices is demonstrated in average increases of 176 funded units and 11 backers per 100 days since the first campaign in October 2017 [**5.4**].

As of 31 December 2020, the total of funded group purchases stood at 13,894 AudioMoth units (revenue of USD0.7M) distributed to 1,611 campaign backers, following the 11th campaign in July 2020. Googling 'AudioMoth' brings up 12,200 results as of 7 December 2020.

The centralised management framework and open-access architecture have already started to realise their scope for accommodating intermediaries between the designers and users of the product, by individuals and groups [**5.5**]. Independent users have posted on the web two AudioMoth manuals, designs for weather-proof cases, live tuition in scaling up acoustic surveys with AudioMoths (93 participants), and a Facebook page to organise Latin American group purchases (299 members by 7 December 2020). The German commercial organisation LabMaker UG, an assembly service for open-science instruments, now purchases multiple AudioMoths to sell on ready-for-use at a unit price of USD74. The Zoological Society of London has collaborated with the Arribada initiative to adapt the original AudioMoth for fitting to birds in flight. Their creation of 'µMoth', reducing the weight from 30 g to 5 g, is the first community-led and open-source development on the AudioMoth design.

Significance in diversity of conservation impacts

In the survey of AudioMoth applications to April 2019 for reference **3.4**, 14% of the framework's end-users posted on social media about conservation work using AudioMoths, with conservation action occurring largely away from purchase locations. For example, Africa was the source country for only two sales, but the deployment location for 23% of purchases.

AudioMoths have been used to recognise three species of katydid insects (Orthoptera) as new to science [**5.6**]. The Brazilian researchers at the Instituto Latino-Americano de Ciências da Vida e da Natureza, and the Museo de La Plata, identified their unique songs in the UNESCO World Heritage Site of Iguaçu National Park. The naming of two new members of the genus *Xenicola*, containing only two other species, and an 11th member of the genus *Anisophya*, is especially important at a time of unprecedented losses of taxonomic and functional biodiversity, given the 2019 IPBES global assessment of biodiversity finding 1 million animal and plant species facing extinction, and an absence of data on half the world's 8 million species, particularly amongst the insects.

A recently completed large-scale deployment of AudioMoth acoustic sensors across 360 tropical-forest sites is "*crucial to developing conservation priorities for the highly endangered spider monkey (Ateles geoffroyi)*" [**5.7**]. The landscape ecologist at Imperial College London who leads this conservation effort attests that the AudioMoth data "*will allow us to model the threats to this species and design landscape management strategies to mitigate these threats. … The cost-efficient performance of the AudioMoth device, combined with its extremely small size, is a game changer for environmental monitoring. AudioMoth deployments make it possible to collect conservation evidence across vast areas on relatively small budgets, and for the first time to monitor the acoustic landscape of biodiversity on a regional scale in Costa Rica*". Exemplifying AudioMoth's diversity of uses, the same team go on to describe how the devices have enabled them to develop a new adaptable, open-source acoustic bat call detection and classification tool for the Atlantic Forest of Brazil, one of the most threatened biodiversity hotspots, where they have deployed the devices across 50 sites. They further "*highlight the reliability of AudioMoth devices*," with a failure rate of less than 5%, and their subsequent repurposing for post-graduate teaching.

The British Trust for Ornithology (BTO) finds that "*AudioMoth's efficient performance has substantially lowered the barriers for systematic acoustic monitoring at county, national and international levels. … This device is crucial to the world's first end-to-end system for monitoring bats in the UK, currently being implemented in the British Bat Survey by the Bat Conservation Trust and BTO, but its development has much wider implications for international bat monitoring*" [**5.8**]. They post AudioMoths to citizen-science volunteers, who deploy them in their local area with an onboard bat-detection algorithm. The returned secure digital memory cards of acoustic data then add to an emerging online display of bat distributions. The 2019 pilot identified over 2 million bat calls. BTO's Senior Research Ecologist concludes: "*Without this conservation technology and its underpinning research, there would not have been a step change in our*

ability to monitor bat populations in the UK, that is so important for informing future work and policy on bat conservation."

At the invitation of the Belize Forest Department in 2018, the AudioMoth team field-tested the optimal-deployment algorithm described in reference **3.6**, in combination with the onboard gunshot-detection algorithm described in reference **3.5**, across 10 km^2 of Tapir Mountain Nature Reserve. The resulting detection of 139 gunshots over the course of 12 months' uninterrupted monitoring, with 95% detection probability, persuaded the Belize Forest Department that illegal hunting is an ongoing problem in the reserve. Recognising that they lack the workforce of forest rangers to patrol the reserve, they have called upon the University of Southampton AudioMoth team to expand the survey to an optimal configuration of devices across all 25 km^2 of the reserve. This deployment had just begun in January 2020 when all fieldwork was stopped by the coronavirus pandemic. It will restart upon lifting of current restrictions.

Numerous other citizen-science projects, consultancies, governments and NGOs have adopted AudioMoths, with frequently-expressed enthusiasm on Twitter [**5.9**]. AudioMoth is the acoustic sensor for the CetaKit equipment supplied to divers by the Florida-based Cetalingua Project to monitor marine mammal vocalisations. It is likewise the chosen sensor for the NASA-funded Soundscapes to Landscapes project run by a consortium of NGOs and Universities, which combines Earth-observing satellites with ground-based sensors to map bird diversity across Sonoma County California. AudioMoths are one of the recommended devices for the Silent Cities participatory monitoring scheme to test for changes in ambient sounds in response to Covid-19. AudioMoths are used by consultants to government, with for example Bowland Ecology deploying them to survey bats for Blackburn with Darwen Borough Council, resulting in a recommendation for the Council to seek a European Protected Species Licence from Natural England. They are used by governments, with for example Mexican startup Ornitronik developing AudioMoth casings, and logistics for their mass production, for CONABIO, the Mexican government's national commission on knowledge and use of biodiversity. AudioMoths are used by numerous NGOs, including the Shropshire Mammal Group for monitoring local mammalian fauna; the Tropical Biology Association for teaching; Fundação Príncipe Trust for biodiversity assessment on the African island of Principe, particularly seabirds and the Critically Endangered and endemic Principe thrush (*Turdus xanthorhynchus*); the Prusten Project for improving the efficiency of protection for Endangered tigers. Fauna & Flora International (FFI) has bought 20 sensors for monitoring the Critically Endangered cau vit gibbon (*Nomascus nasutus*) in Vietnam. FFI's Technical Advisor says: "*AudioMoth has the capability to revolutionise acoustic monitoring of environments, by making it affordable in principle and feasible logistically to flood large areas of inhospitable ecosystems with sensors*" [**5.10**].

5. Sources to corroborate the impact

5.1 Report – Prizes and recognition for AudioMoth

5.2 Report – AudioMoth as case study

5.3 Arribada Initiative: http://blog.arribada.org/2017/12/28/driving-down-the-cost-of-acoustic-monitoring-with-the-audiomoth/

5.4 Group-purchasing campaigns run by GroupGets: https://groupgets.com/manufacturers/open-acoustic-devices/products/audiomoth

5.5 Report – Independent intermediaries between AudioMoth designers and users

5.6 Paper in the journal *Zootaxa* recognising three new orthopteran species, described using AudioMoths: http://dx.doi.org/10.11646/zootaxa.4652.2.2

5.7 ICL testimonial

5.8 BTO testimonial

5.9 Report – AudioMoth deployments for citizen-science projects, NGOs, consultants, and government

5.10 FFI testimonial