Nature makes sense

Professors Jim Hayward, **Shandelle Henson** and **Jim Cushing** form part of an interdisciplinary group of biologists and mathematicians who focus their studies on the behavioural ecology of marine organisms. Here, they discuss several aspects of their research and how they enable underrepresented groups to become part of it

How did the Seabird Ecology Team form and why did you decide to work together?

JC: Early in my career I worked in fluid dynamics. I began working in the emerging field of mathematical ecology in the 1970s. In those days, mathematical ecology was highly theoretical, consisting of theorems, proofs and generalities, and lacked a solid connection to data. However, in the 1990s I teamed up with two biologists (Robert Costantino and Robert Desharnais) and a statistician/ ecologist (Brian Dennis), and eventually with fellow mathematicians Shandelle Henson and Aaron King.

SH: The Beetle Team, as we were known, developed a mechanistically-based mathematical model of flour beetle (*Tribolium castaneum*) dynamics and gave the first rigorous experimental demonstrations of nonlinear population phenomena, such as bifurcations and chaos, as predicted by a mathematical model. A 'Holy Grail' for us was to move beyond a laboratory setting and demonstrate a similarly rigorous correspondence between models and data in the field.

JH: During this time, I was amassing dense observational time series of seabird behaviours and habitat occupancies in the field – just the kind of data needed to parameterise mathematical models. After meeting Shandelle at a seminar she gave at Andrews University, we began collaborating on mathematical models of seabird behaviour and were soon joined by Jim Cushing.

What different skills and experiences do you each bring to the research?

JH: I've worked on Protection Island in the Strait of Juan de Fuca, Washington, USA, each field season since 1987 and have developed a pretty good sense for how the system works. I also like to collect datasets that are temporally dense in relation to environmental variables; temporally dense datasets allow mathematicians to rigorously connect dynamic models to data.

SH: As a mathematician, I am trained to think in terms of dynamical systems and bifurcation theory. My computer programming skills allow me to connect mathematical models to data using time series analysis, maximum likelihood methods and information theoretic model selection techniques.

JC: My contribution to the team's efforts lies mainly in model development and analysis. I like to challenge biologists – who typically think in terms of the many detailed complexities of life – to hypothesise only a few key mechanisms that drive a phenomenon of interest. Using these key mechanisms, we can construct models that are reasonably tractable to mathematical analysis. An analysis of such models can support – or disprove – hypothesised causes and correlations and make predictions that stimulate further laboratory or field studies.

Could you tell us about some favourite elements of your job?

JH: I enjoy observing animals in their natural environment and becoming acquainted with them as both individuals and groups. Seeing predictable, environmentally-influenced behaviour patterns emerge from the data I collect reaffirms a fundamental scientific presupposition that nature makes sense and that if we try hard enough we can understand how things work. I find this tremendously satisfying.

SH: I am fascinated by finding mathematical expressions that explain and predict deep patterns in the observed world. Much of my research effort is a mental wrestling with complex ideas – trying to understand how to define concepts, clarify relationships and quantify patterns. Another extremely rewarding part of my job is mentoring research students.

JC: I am thrilled when a model – formulated to encapsulate certain biological mechanisms – accurately describes data. Even more exciting is when a counterintuitive prediction from a model is subsequently validated by further laboratory or field studies. An extra delight comes when the derived model presents mathematical challenges because its analysis lies outside available methods and thus requires the development of new mathematical tools or theorems.

How can your approach to the study of seabird ecology be considered new and different?

All: Seabird ecology enjoys a long and venerable history, and several fundamental concepts of behavioural ecology have emerged from data collected on seabird colonies. Seabird biologists typically use statistical analysis to identify behaviours and environmental factors that influence reproductive fitness of colony residents.

Our approach differs in that we view seabird colonies as dynamical systems amenable to the power of mathematical analysis, an approach that serves us well as we investigate the impact of climate change on these colonies.

What is next for the Seabird Ecology Team?

All: The effect of climate change on ecological systems is a big subject. We will continue to study the effects of El Niño climate variability on the seabird colony in an attempt to understand how adaptive processes may respond to long-term increases in temperature. We also will continue to construct and refine mathematical models to test how these processes might affect population dynamics, especially in the context of bifurcations and tipping points.

Finally, could you explain how important it is to you that underrepresented groups (URGs) are thoroughly integrated into your research activities?

JH&SH: Andrews University is the second most ethnically diverse campus and the seventh most internationally diverse campus in the US. We are careful to maintain a research team that reflects the diversity of the larger campus, and we are passionate about involving URGs in STEM research. Students with city backgrounds, who have never spent significant time outdoors, have worked on Protection Island, experiencing almost complete immersion in the natural world for weeks at a time.

One such student recently went on to obtain a PhD in Environmental Science and a professorship. We are committed to co-authoring papers with students, having them present at conferences and networking them into the research community.

JC: The University of Arizona is highly committed to the recruitment and success of URGs. Personally, I have been fortunate, with my research group in the Interdisciplinary Program in Applied Mathematics, to have had a majority of URG students over the years. For example, my current group working on seabird-related projects consists of two women and an African American male postdoc.

On Isla Fernandina in Galápagos, Ecuador, the Seabird Ecology Team used mathematics to identify key environmental variables influencing the behaviour of flightless cormorants, which are among the rarest of seabirds. **Inset**: Student research assistants Andre Moncrieff, Brianna Payne and Libby Megna collect data on the Protection Island gull colony in Washington, USA.

Effects of climate change on animal behaviour

A collaboration between researchers from Andrews University, Michigan, and the University of Arizona has seen the formation of the **Seabird Ecology Team**, which is currently using mathematics to investigate various behaviours of seabirds on the Protection Island National Wildlife Refuge in Washington, USA

THE GOLDEN RATIO is one of the most famous examples of a pattern found in nature that can be studied and modelled mathematically. Indeed, the ratio of 1.618 has been found in leaves, branches, plant stems, the skeletons of animals and, in 2010, researchers discovered that it was even present at the atomic scale. Mathematics is evidently a useful tool for understanding aspects of nature and, more generally, the physical world.

The desire to better understand and explain real-life phenomena through mathematical models was one of the underlying aspirations for a collaboration between biologists and mathematicians from Andrews University and the University of Arizona. The interdisciplinary group uses mathematics to describe, analyse and predict the behavioural ecology of marine organisms at a variety of locations around the world.

Behavioural ecology is the process of finding the evolutionary bases for animal behaviours that have been brought about through ecological pressures. It follows that if there is an observed shift in an organism's behaviour there may be an underlying adaptive explanation.

EL NIÑO EVENTS

One potential problem with studying the effects of long-term climate change is that it must necessarily be conducted over a long period of time. However, El Niño events – specifically, the warm phase of the El Niño Southern Oscillation – often mimic particular features of long-term climate change on manageable timescales, enabling scientists to test various hypotheses regarding their effects.

With that in mind, Professors Jim Hayward, Shandelle Henson and Jim Cushing have been conducting investigations on the Protection Island National Wildlife Refuge in the Strait of Juan de Fuca, Washington, USA, to understand how climate change – and concomitant high sea surface temperature increases – impacts upon marine systems in a variety of interlinked ways. The three collaborators have established the Seabird Ecology Team, with their most recent research focusing on the Island's glaucous-winged gull colony and how the behaviours of colony residents adapt to environmental changes.

Protection Island National Wildlife Refuge is an excellent location for the team to conduct much of their fieldwork. It hosts 70 per cent of the seabirds nesting in Washington's inland waters and the glaucous-winged gulls that nest there are easily observable sentinels of climate change.

"The island's topography facilitates study of the colony at several scales," explains Hayward. "If we want to examine habitat occupancies or large-scale movement patterns, we can observe the entire colony from a steep bluff just to the west. Alternatively, if we need to collect reproductive success data from individual nests or watch the behaviour patterns of individual birds, we have over 1,500 nests and 3,000 birds to sample."

REPRODUCTIVE SYNCHRONY

After the gull colony on Protection Island suffered catastrophically low reproductive success in 2005, the team travelled there to begin collecting data on almost 300 nests. The aim was to understand why some nests were successful while others were not. Interestingly, it soon became apparent that there was a marked increase in egg laying every other day.

From this observation, the researchers began using mathematical methods to ascertain whether or not this synchrony occurred purely by chance. They employed Monte Carlo techniques (repeated random sampling to generate numerical results), and showed that the synchronicity between the gulls' egg laying every other day was not mere coincidence: "We had a number of sample plots in the colony with various nesting densities," recalls Henson. "The degree of synchrony in the plots was correlated with average nest densities, and we've now found this same type of synchrony in a second gull species."

Left: Student research assistant Ashley Reichert monitors egg cannibalism on the Protection Island gull colony.
Below: A glaucous-winged gull cannibal has captured a neighbour's egg.

Having established the type and degree of synchrony, the team hypothesised that it was brought about through a chain of events beginning with the intermittent rise in sea surface temperatures. They reasoned that every-other-day ovulation synchrony is an adaptive response to egg cannibalism – when an egg is laid synchronously with other eggs, there is less chance of any one of them being cannibalised. In turn, egg cannibalism is itself an adaptive response to food shortages associated with El Niño events.

EGG CANNIBALISM

As mentioned, cannibalism – the eating of an individual of the same species – was found to be prevalent in the glaucous-winged gull colony and, although it is a regular, natural occurrence in many different species, has previously been linked to rises in sea surface temperature in the case of polar bears and Peruvian anchovy.

The conjecture is that sea surface temperature increases have a significant impact on marine food webs, affecting each link in the food chain on an ever-increasing scale. Resultant shortages in food resources lead to cannibalism. Indeed, the consumption of a single glaucous-winged gull egg can provide almost half the required daily energy for an adult gull. Cannibalism is therefore an effective means for an individual to survive and, without it, population extinction would be a possibility.

MATHEMATICAL MODELS

Having hypothesised the interactions between sea surface temperatures, reduced environmental food availability, cannibalism and reproductive synchrony, the team is now using general mathematical models to elucidate some of the main factors driving the interactions: "We use discrete-time dynamical systems to study the relationships between the different factors and, because we are interested in climate change effects, we study how changes in model parameters affect the predicted dynamics," explains Cushing. "We also use general linear models such as logistic regression to study how sea surface temperature impacts egg cannibalism and hatching success."

To mathematically probe the implications of their hypotheses at the population level, the team began by building proof-of-concept models constructed to include key mechanisms believed to be the basic causes of the observed phenomena. The next step is to prove theorems and run computer simulations in an attempt to demonstrate that the models predict the patterns the team has observed. "Once we convince ourselves that these basic mechanisms can lead to the observed patterns at the population level, our goal will be to extend the model to include a more realistic description of seabird colonies," Hayward outlines.

BROADENED IMPACT

Over the years, the Seabird Ecology Team's studies have taken the researchers to far-flung places and led to the publication of several papers on a variety of marine organisms, including seabirds, common seals and marine iguanas. In examining El Niño events and how they impact upon the behaviours of different species (both empirically and theoretically, using mathematical models), their work provides tangible evidence of climate change; how it leads to food shortages and the resultant rapidly manifest consequences and related population dynamics.

Natural populations are clearly affected by climate change and the behaviours of individuals respond in delicate, intricate ways. It is hoped that the team's previous, current and future findings will enable careful management of natural populations, ideally bringing into focus the potentially serious consequences of global warming, especially in the context of bifurcations and tipping points.

Entrance to Protection Island National Wildlife Refuge in the Strait of Juan de Fuca, Washington, USA.

SEABIRD ECOLOGY TEAM

OBJECTIVES

- To study the effects of climate change on the life history strategies of seabirds using a gull colony at Protection Island National Wildlife Refuge, USA
- To develop and analyse general mathematical models for exploring the interaction of sea surface temperatures, reduced environmental food availability, cannibalism and reproductive synchrony

KEY COLLABORATORS

Adjunct Professor Gordon J Atkins; **Associate Professor Lynelle M Weldon**, Andrews University, USA • **Professor Joseph G Galusha**, Walla Walla University, USA

PARTNERS

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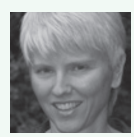
CONTACT

Dr James Hayward
Professor of Biology

Department of Biology
Andrews University
4280 Administration Drive
Berrien Springs, MI 49104-0410
USA

T +1 269 471 3241
E hayward@andrews.edu

JIM HAYWARD, Professor of Biology at Andrews University, earned his PhD in Zoology at Washington State University. His research focuses on how environmental factors influence seabird reproduction. He also studies dinosaur egg fossilisation, an interest fostered by Mount St Helens' eruption which buried and preserved a gull colony he was studying.



SHANDELLE HENSON is Professor and Chair of Mathematics at Andrews University. With a PhD in Mathematics from the University of Tennessee, she uses dynamical systems theory and bifurcation theory to study the effects of climate change on marine organisms.

JIM CUSHING obtained his PhD at the University of Maryland and currently works as Professor in the Department of Mathematics at the University of Arizona. He is a member of the Interdisciplinary Program in Applied Mathematics and his research interests are in dynamical systems and their applications to problems in ecology and evolution.