# Chapter 28
# Island Digital Ecosystem Avatars (IDEA) Consortium: Infrastructure for Democratic Ecological Action

**Neil Davies**

## Introduction: Island Earth

In 1988, Margaret Thatcher – not known as an environmental activist – implored the UN to take action on climate change, warning that "*It is life itself—human life, the innumerable species of our planet—that we wantonly destroy. It is life itself that we must battle to preserve*." She opened her historic address on "the threat to our global environment" recounting to fellow world leaders how – to a young Charles Darwin perched on a Tahitian hillside – the South Pacific island of Moorea resembled "a framed engraving". From Darwin's contribution to coral reef science, she turned to astronomer Fred Hoyle's 1948 prediction that "once a photograph of the earth, taken from the outside is available … a new idea as powerful as any other in history will be let loose". Obscure references for such an important speech it might seem, but Thatcher was onto something: evoking the power of holistic visualization. Technology gives us new perspectives on our place in complex systems. The capacity to see the whole – perceiving the wood despite the trees – reveals interdependencies never quite grasped before. Hoyle was correct. To astronauts perched in outer space, the sight of our planet elicits an "overview effect", a quasi-spiritual awareness of the interconnection of all life and its isolation on Island Earth. Technological advances from missions like Sputnik and Apollo led to breakthroughs that eventually enabled scientists to study the Earth as an integrated whole, observing planetary-scale processes continuously in fine detail over decades. Satellite data has helped explain phenomena we experience on the planet's surface. Indeed, it sometimes

N. Davies (✉)
Gump South Pacific Research Station, University of California, Moorea, French Polynesia

Berkeley Institute for Data Science, Berkeley, CA, USA
e-mail: ndavies@berkeley.edu


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seems easier to model processes playing out – relatively slowly – across the entire Earth than those occurring at much smaller, and noisier, scales.

Remote sensing can get you a long way. Depending on the power of your telescope, you can discern life forms, what they are doing, and what they have built. But remote sensing can only get you so far. Many of the phenomena that make the Earth unique (as far as we know) in the Universe are due to life, and to truly understand life, we need to make observations at the molecular scale too. For the time-being, many scientific observations, especially those relating to biodiversity, can only be made close-up "*in situ*". They literally require access to and physical contact with what we want to measure. For example, we cannot sequence DNA from satellites. Rather, we need to bring the molecules onboard a sensor in to read them. Most often this involves the rather messy process of physically extracting genetic material from cells and tissues. Sometimes this can be done with little impact, but all too often genetic analyses sacrifice the organism. If humanity and the rest of life on earth is to successfully navigate the next few decades, we will need to learn how to integrate *in situ* fieldwork with remotely sensed data, across all domains of scientific research, to develop much greater capacity for social-ecological foresight. We will have to model life on Earth.

## Islands as Model Systems for Sustainability Science

In late 2013, following a series of conferences on Quantum Computing at the UC Gump South Pacific Research Station in French Polynesia, Matthias Troyer – a computational physicist – convened a workshop at ETH Zurich to consider the outlandish proposition of modeling an entire tropical island, from genes to satellites. At that time, large-scale modeling had become capable of measuring changes across continents and even the vast Pacific Ocean. Drawing on increasingly rich data streams, coupled with ecological understanding from experiments, it was possible to make forecasts of local-scale impacts, such as the risk of coral bleaching on a given reef. Troyer and colleagues, including ecologists, oceanographers, anthropologists, and geneticists, aimed to take this much further. Global models help understand processes like climate change and ocean acidification (OA). But how do organisms respond to these changes and feed-back on the Earth system? In OA, for example, how does the calcification process respond to lower pH in different species of coral, or among different genotypes within coral species, or among different coral microbiomes? The answers to such questions at the cellular scale affect the resilience of entire ecological communities. In other words, to really understand ecological change, we must study the Earth 'genome up' and 'planet down' (Fig. 28.1). Developing such a comprehensive view of life on Earth will require integrating diverse data, models, and understanding across vast scales (Purves et al. 2013). Needless to say, it is a massive challenge. Yet science has faced similarly overwhelming complexity before. In biomedical research, for example, great advances have been made in tackling human biology through studies of simpler,


**Fig. 28.1** Scientific challenges: connecting large scale changes to local impact. (Adapted from the presentation "Future Pacific Ocean: Modeling the World's Largest Biome" by Nicolas Gruber & Matthias Münnich (ETH Zürich) in the "Island Avatars: Simulating Social-Ecological Systems Symposium", Berkeley Institute for Data Science, Berkeley, California. 13 April 2016)

more scientifically tractable, 'model organisms', such as the nematode worm *C. Elegans* and the fruit fly *Drosophila melanogaster*. Similarly, intensively studied islands are 'model ecosystems' for ecology (Vitousek 2002) and anthropology (Kirch 1989). In this spirit, the Zurich conference targeted the island of Moorea in French Polynesia as a model system for sustainability science (Cressey 2015).

## *Island Research in French Polynesia*

Befitting its location in the heart of the Pacific, French Polynesia has one of the worlds' largest exclusive economic zones (EEZ) of some 5 million km$^2$. The country's five archipelagos and 118 islands stretch across a gradient of environmental conditions in an area the size of Europe. Most of the the country's 279,554 people live on the Windward Islands of Tahiti, Moorea-Maiao, and Tetiaroa. The cluster of islands represents a gradient in complexity for sustainability science from the small private atoll of Tetiaroa (site of an exclusive eco-resort The Brando), through Moorea (<17,000 people, 134 Km$^2$) to Tahiti (1045 km$^2$, >189,000 people). The Windward Islands also host significant research capacity with local, national (French), and international institutions, which have recently established a formal collaboration under the French Polynesia Research, Higher Education, and Innovation Consortium (RESIPOL), whose founding members include the University of French Polynesia, Institute Louis Malardé, IRD, and IFREMER on Tahiti, and the CNRS (representing its CRIOBE laboratory), and University of California Berkeley (through its Gump Station, see Fig. 28.2) on Moorea. Access to Tetiaroa is provided by Tetiaroa Society, which operates a research station on the atoll.

Moorea is a 'goldilocks' island for sustainability science. Just about the right compromise of sufficient complexity to be representative of the challenges facing coastal communities everywhere, but not too complex to be overwhelming.

**Fig. 28.2** Gump Station. The University of California's Richard B. Gump South Pacific Research Station (Gump Station) on Moorea in French Polynesia supports research on land and sea spanning physical, biological, and social sciences as well as the humanities. For example, it hosts the only coral reef site in the NSF Long-Term Ecological Research (LTER) network of place-based programs collecting highest quality time-series data across different ecosystem types to understand how they respond to human activities and environmental change. Moorea is part of a growing global network of international LTER sites (Mirtl et al. 2018). The Gump Station is located on Polynesian land called Atitia and since 2002 half the property is managed by the Tahitian community-based organization Te Pu Atitia focused on traditional knowledge, culture, and educational programs. The Gump Station and Atitia Center side by side, provide a unique opportunity to explore synergies and mutualistic feedback between local traditional knowledge and global scientific understanding

Scientific progress on biophysical fronts on smaller, privately owned islands, like Tetiaroa, can be made even more rapidly, but this inevitably excludes some of the social-ecological factors that sustainability science must tackle. On the other hand, large metropolitan islands like Tahiti represent the scale of ambition for the complex places we must learn to steward effectively. The model system approach does not ignore the simpler or more complex systems; rather, it seeks to advance at multiple scales simultaneously through an intentional program of research that allocates resources where scientific progress can be made most efficiently.

## Networking Island Research Stations as Innovation Hubs for Biodiversity Science

The development of model organisms for biomedical research was not accidental. They were proposed by visionary scientists like Sydney Brenner for C. elegans in 1963, who then helped build them (Brenner 2009). The approach was formalized in what one might call a systems biology roadmap (Sauer et al. 2007; Raes and Bork 2008). Inspired by this work, in the early 2000s, an international team of researchers, with support of the Gordon & Betty Moore Foundation, set out to develop Moorea as a model system for ecology. Just as Brenner and colleagues had described all the cell lineages and sequenced their worm's genome, the Moorea team proposed to sequence their island from its coral reefs to mountaintops.

## *Moorea Biocode*

The Moorea Biocode Project (Check 2006) produced an unprecedented all-taxon biotic inventory. Applying the DNA barcoding standard first proposed by Paul Hebert (Hebert et al. 2003) the project employed an expert-driven, voucher-based methodology: collecting exemplars (individual organisms) of every species on the island, taking digital photographs, depositing specimens, subsampling tissues, extracting DNA, and sequencing at least one gene, the DNA barcode, from each species. Moorea became perhaps the best-characterized complex ecosystem in the world and served as an important use case for the development of genomic biodiversity data standards and informatics tools. For example, software developed under Moorea Biocode seeded GEOME, the Genomic Observatories Metadatabase (Deck et al. 2017, 2018), a component of the informatics stack for the international genomic observing community and contributed to the development of the internet of samples (iSamples) a national cyberinfrastructure for material samples in natural science (Davies et al. 2021).

In terms of scientific applications, studies demonstrated the value of the Biocode database as a research infrastructure for tracking species across an ecosystem, including targets that had previously been intractable for most ecological investigations: early life stages (eggs or larvae), partial tissues (e.g., legs and leaves), and homogenized mixtures, such as gut contents or environmental samples (Ransome et al. 2017; Andersen et al. 2019; Casey et al. 2019). These studies also served to confirm that the inventory was quite comprehensive, as many sequences observed in the test samples corresponded with a species in the reference database. Unidentified “dark taxa” were generally from lineages of tiny organisms that were not targeted in this phase of the project. While microbes were outside the scope of Moorea Biocode Project, microbial-host interactions were explored through preliminary studies on fungi-plant and fungi-insect associations, and through surveys of endosymbiotic bacteria across terrestrial invertebrates (Ramage et al. 2017).

The project also had impacts beyond biological science. Education and outreach components of Moorea Biocode led to a close collaboration with the Tahitian community-based organization Association Te Pu Atitia in their inventory of traditional knowledge of biodiversity on Moorea (e.g., for medicine and food). As a result, the DNA barcodes in the Biocode database serve as a potential bridge from specimens to both scientific knowledge (via the Latin name) and traditional knowledge (via the Tahitian name). Through this work with local elders (the ‘Ethnocode’ project), Moorea Biocode helped catalyze the Atitia Center, a cultural center located on the Gump Station property operated by Te Pu Atitia that now hosts hundreds of Polynesian school children each year. The community outreach efforts complemented work to develop Access and Benefit Sharing (ABS) policies for large biodiversity genomic studies, with education representing a significant means for sharing benefits. The Biocode ABS agreement (Davies and Hirsch 2010) is a model available to regulators and biodiversity programs worldwide.

## *Genomic Observatories*

The next step in the systems ecology roadmap is to pivot from inventory to observatory. We know surprisingly little about how cells and organisms interact with each other and the environment to shape ecosystems. Yet, powerful biodiversity observation technologies are now more affordable than ever. They include both remote and *in situ* instruments and fall into three main categories: acoustics (e.g., hydrophones, sonar), optics (e.g., satellite imagery, digital photography), and omics (biomolecular sequencing). In addition to new sensors, rapid advances in high performance computing (e.g., machine learning) are also transforming the field of bio-observation. Individually or especially in combination, this technological triumvirate makes it possible to explore vast new realms of the living world. A focus on biodiversity observation then, is at least as much an appeal to seize low hanging fruit as it is about the importance of this dimension for sustainability science.

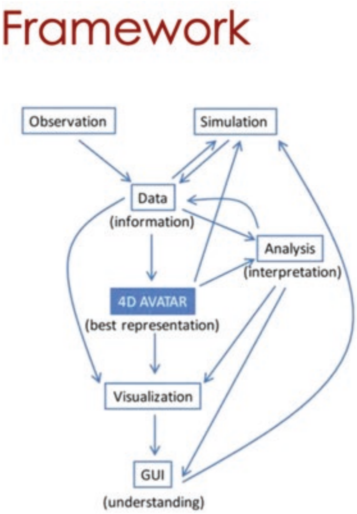
Just considering the molecular level (omic observations) a new age of biodiscovery is emerging. Biodiversity genomics promises to transform ecology and conservation, while providing a source of genetic parts for synthetic biology and the bio-economy. As society enters a new age of genomics (Check 2006; Field and Davies 2015), scientists have powerful new tools to address abundance, distribution, and other properties of species with the goal of developing predictive models (Casey et al. 2019). Research at island field stations will contribute to the mainstreaming of genomics and other 'omics' into sustainability science. Doing so will require global collaboration through efforts like the Genomic Observatories Network (Davies et al. 2012a, b, 2014), a collaboration of the Genomic Standards Consortium (Field et al. 2011) and the Group on Earth Observations (GEO), which demonstrated a de facto global genomic observatory through Ocean Sampling Day (Kopf et al. 2015). Further proof of concept for blending omics into sustained environmental observations has since come from programs such as Autonomous Reef Monitoring Structures (Leray and Knowlton 2015; Ransome et al. 2017; Obst et al. 2020). Island field station networks can contribute to these efforts by fostering shared capabilities for genomic sensing (Makiola et al. 2020) including the tracking of the material samples that underpin genomic research and many other domains of natural science (Davies et al. 2021). While there has been significant progress (Bork et al. 2015; Thompson et al. 2017) much remains to be done to operationalize omic observing (Buttigieg et al. 2018). The new Omic Biodiversity Observation Network (Meyer et al. 2021), stimulated by the union of the Global Omics Observatory Network (Buttigieg et al. 2019) and the Genomic Observatories Network, is one response to foster global collaboration among key networks, such as the UN Ocean Decade Program "Ocean Biomolecular Observing Network" (Leinen et al. 2022).

## Island Digital Ecosystem Avatars

As important as biodiversity genomics and biocomplexity science will be in the coming decades, island research will have to go further. Addressing biodiversity and other grand challenges of environmental sustainability and justice, necessitates integration of the physical, biological and social sciences. Lessons can be learned from "precision medicine" and attempts to move away from treating disease to promoting wellness. As in ecology, the capacity to generate massive datasets using molecular technologies and wireless sensor networks is also transforming medicine (Topol 2012), leading to calls for an approach that is Personalized, Participatory, Predictive and Preventative (Hood and Flores 2012). Networks of island research centers are well placed to coordinate the application of such a "P4 approach" to sustainability through data-intensive, multi-dimensional and longitudinal studies of places (social-ecological systems). Inspired by urban data science initiatives such as ETH's Future Cities Lab in Singapore, the Moorea Island Digital Ecosystem Avatar (IDEA) workshop at ETH Zurich in 2013 laid out such a vision (see Fig. 28.3).

### *IDEA Consortium*

The Moorea IDEA aims to enable holistic use-oriented simulations of entire social-ecological systems, starting with small oceanic islands. A roadmap was published and a consortium founded to pursue the IDEA (Davies et al. 2016). Established in




| WORKING GROUP | TASK |
|---|---|
| **1. Data Science** | Integrating diverse data sources, coupling models, visualizing information |
| **2. Physical Modeling** | Oceanic / atmospheric forcing, physical-chemical properties and fluxes |
| **3. Genes to Ecosystems** | Biodiversity dynamics, evolutionary processes, ecological interactions |
| **4. Social-Ecological Systems** | Coupling past, present, future ecosystems to human activities |
| **5. Simulations, Synthesis, and Service** | Use-oriented avatar for data exploration, scenario-based planning, education |

**Fig. 28.3** A framework for building digital representations of complex social-ecological systems (Davies et al. 2016)

2016, the IDEA Consortium was led by an executive committee of researchers from University of California Berkeley, ETH Zurich, UC Santa Barbara, France's CNRS, and University of Oxford, and involved more than 80 scientists from 20 institutions. Its founding mission was to understand how the island would change depending on human actions, local and global. Specifically: to understand how biodiversity, ecosystem services, and society in a coupled marine-terrestrial system will co-evolve over the next several decades depending upon what actions are taken. Crucially this would involve understanding an island's history, describing its current state in detail (from genes to satellites), and then simulating different scenarios of the future. Three big questions lay behind the initiative: (1) What is the physical, biological, and social state of the island system today? (2) How did it get to this point? (3) What is its future under alternative scenarios of environmental change and human activity, including conservation efforts?

Model systems reduce the overwhelming complexity at the global scale by focusing on small local systems – microcosms of the larger problem where we can concentrate research resources and make scientific headway. It is an inherently empirical approach and goes beyond generating just big data, the key point is to build more "complete data"… ultimately data representing the entire system with an understanding of what all the components contribute to healthy functioning, and which are the most essential components to maintain resilience. The knowledge and tools gained from the island model systems can scale horizontally and help move all places – not just islands – toward greater resilience.

Work by Joachim Claudet, Lauric Thiault, and colleagues on Moorea has demonstrated the potential for integrated approaches and that they are now capable of informing policy and management (Thiault et al. 2020). But there are still many barriers to overcome. Among them, data and model curation remain a significant challenge. Machines, even intelligent ones, are not built with all the answers preloaded. They need to learn too, and just as human brains need books and libraries, machine intelligences need well-described data. Recognizing this, governments around the world seeking to develop Artificial Intelligence as a new industry have been recommending the creation of open data standards and repositories or trusts that provide access for machines to high quality datasets. One of the most influential efforts is known as the FAIR data principles for Findable, Accessible, Interoperable, and Reusable data (Wilkinson et al. 2016), which enhance the ability of machines to find and use data across different domains and sectors. As with many technology-driven trends, however, it is important to consider who benefits and whether the current institutional frameworks are also fair in the sense of equity and justice. Strides are being made to address the ethical, legal, and social aspects of digital data that will be important to ensure predictive modeling and AI is used for good. The CARE principles for Indigenous Data Governance, for example, "are people and purpose-oriented" addressing Collective benefit, Authority to control, Responsibility, and Ethics (Alliance 2019; Carroll et al. 2020). Recent work inspired by the Moorea IDEA is seeking to implement these principles in island settings as a model for how place-based research data should be managed at any site (Robinson et al. 2022).

### *Island Twins?*

We are at an inflection point in our capacity to build digital representations of natural and human systems, and of coupled social-ecological systems. Evidence of this includes an explosion in “digital twin” (El Saddik 2018) initiatives beyond their initial use in manufacturing, such as the European Union’s initiative to build a Digital Twin of Earth (Voosen 2020) and the UK’s National Digital Twin program (Bolton et al. 2018). Typically, digital twins are deterministic and predictive, focusing on systems about which humans have a great deal of knowledge – often because humans built them in the first place. Like other technology-branding concepts, such as Artificial Intelligence (AI) or environmental DNA (eDNA), there is much hype and misunderstanding around what they are exactly. Indeed, the more these terms break through to the public, the more experts question whether they have any meaning at all – beyond a clever marketing campaign. The fact that they do break through, however, indicates that something significant might be happening and that the world beyond Silicon Valley should take some notice. The term twin implies an exact copy, which is clearly an impossible goal if applied to living systems. Such terminology risks disappointing at best and dangerously misleading at worst. There are relatively few studies that address the potential opportunities and risks of applying a digital twin paradigm to sustainable development goals (Tzachor et al. 2022); more will be needed. The term avatar as used by the IDEA Consortium (Davies et al. 2016) might be a useful alternative. Because social-ecological systems can be chaotic and/or the rules of the system are only partially visible, digital avatars are multiple, competing hypotheses that are all incorrect to varying degrees (none is a twin or clone of the entity being represented). The task is to weed out the avatars that are demonstrably wrong – based on observations/evidence – and build on those that cannot be ruled out (i.e., those that are the best approximations). In other words, science.

The choices we make today in designing digital avatar (or twin) programs are not solely scientific, however, and they could have profound impacts on the way decision-support infrastructure evolves. How, where, and when to implement digital twin technologies raises deep issues on the relationship between science and societal decision-making at multiple scales of governance. There is an urgent need to consider ethical, legal and social issues as well as the scientific and technological challenges. Such reflection has been taken on recently by a Swiss initiative, the Geneva Science and Diplomacy Anticipator (GESDA).

## Infrastructure for Democratic Ecological Action

Among the grand challenges humanity faces, tackling biodiversity loss and increasing greenhouse gas concentrations is a prerequisite for social progress. (The reverse might also be true). In a changing environment, science provides ecological foresight, which combined with human values, guides decision-making when the future is uncertain. But science can't tell us what future to aim for. The U.N. Ocean Decade for Sustainable Development, for example, has an eloquent, inclusive, and inspiring goal: "*The science we need for the ocean we want*". If we dig into those words a little, however, nagging questions arise: What type of ocean do we want? Or even: What gives humans the right to make demands of the ocean? And perhaps even more challenging: Who is 'we' and what do we do if some of us disagree? After the techno-optimism of earlier sections, it behooves us to recall Albert Einstein's warning that "we should be on our guard not to overestimate science and scientific methods when it is a question of human problems" and we should "not assume that experts are the only ones who have a right to express themselves on questions affecting the organization of society."

In the Anthropocene, ecological questions of island sustainability are increasingly human collective action problems. How do the people of an island decide what is the best course of action to achieve their collective goals within the ecological boundaries of their island and the planet? To paraphrase the Doughnut Economics Action Lab: "*How can our [island] be a home to thriving people, in a thriving place, whilst respecting the wellbeing of all people, and the health of the whole planet?"* (Raworth 2017a; DEAL 2020*)*. When it comes to making decisions that are in the interest of all, the cognitive diversity of the population is an empirically important resource (Landemore 2017) that is particularly well harnessed by deliberative democratic institutions (OECD 2020). Citizens assemblies, for example, bring together a random sample of the population and give them the time and information needed to address challenging questions. The digital ecosystem avatars as envisaged above, provide a framework for presenting admissible evidence for such citizen assemblies to deliberate over. The result could be an intelligent fabric of humans and machines learning together to better tend social-ecological systems. Yet, if the future is to be human-centered, public participation in science will not be enough to prevent elites dominating the new social-technological infrastructure. Superintelligence, whether wielded by humans or machines, poses well-known risks and one mitigation strategy is to ensure that systems are "*designed to be inherently uncertain about the human preferences they are required to satisfy*" (Russell 2019). Fortunately, it is impossible to be certain which policy preferences humans will prefer in the future, in part because there are an infinite range of possibilities, but also because human preferences can and do change, especially when given the opportunity for dialogue and deliberation (Fishkin 2011). This is important for Social-Ecological Foresight: First, if human preferences cannot be predicted, even by the humans concerned themselves, then future states of a social-ecological system are also impossible to predict. Second, it suggests that the purpose of digital ecosystem avatars is to support democratic deliberation by providing citizens the best-available evidence for predicting the likely consequences of their decisions (impacts on themselves, their society, and their planet) in an intelligible and transparent manner. The actual impacts are reported back through the avatars as sensor networks feed updates on the status of the social-ecological system. The iterative feedback enables society to learn and evolve towards desired future states – progressing towards the "realization of Utopias" as Oscar Wilde put it.

As decision-support tools, digital ecosystems avatars raise important questions for citizens, including: who controls the avatars (the data, code, and knowledge on which they rely), who uses avatars to make decisions, and how is this organized to ensure equity and justice? These questions have both empirical and normative dimensions and provide rich opportunities for scholarly research in political science and diplomacy. Many of the issues revolve around the concept of collective intelligence (Mulgan 2018) and how to build a better democracy (Landemore 2020). While social-ecological governance is usually territorial (place-based), there are also powerful non-territorial actors, including multinational corporations and international institutions. Networks of islands navigating to sustainable futures will share data and models pertaining to social-ecological states at multiple scales. Sharing within and between communities, including across international boundaries will raise political and diplomatic challenges including questions of "cosmopolitan democracy" and the "implementation of a multi-layered and multi-centered democratic society within, among and beyond states" (Besson 2006).

## Conclusions

Navigating the Anthropocene requires much better Social-Ecological Foresight. Island observing systems will need to be better linked and harmonized with respect to the data they gather to feed modeling efforts. Models will need to be coupled with data from island observatories and connected across domains and spatial / temporal scales. In particular, mechanistic ecological, socio-economic, and social-ecological models will need to catch up with the mechanistic sophistication of physical models. As advances in science and technology transform our capacity to sense the world and to process massively diverse data streams, the collective intelligence of people and machines will expand human potential. Individuals and communities will make ever more complex decisions at multiple scales, leveraging integrated digital ecosystem avatars for environmental sustainability. Important impacts will include an enhanced appreciation for the web of life that connects our inner ecosystem (Gilbert et al. 2018) to the people and ecosystems around us, mainstreaming the concept of One Health (Coker et al. 2011; Amuasi et al. 2020) and operationalizing "Predictive, Preventive, Personalized, and Participatory" approaches to personal wellness (Hood et al. 2004) and sustainable development (Raworth 2017b). I began this chapter quoting Margaret Thatcher's 1988 speech to the UN on the threat to our global environment. I will leave the last words to her: "We need our reason to teach us today that we are not, that we must not try to be, the lords of all we survey. We are not the lords, we are the Lord's creatures, the trustees of this planet, charged today with preserving life itself—preserving life with all its mystery and all its wonder. May we all be equal to that task."

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**Neil Davies** graduated in Zoology from the University of Oxford and has a PhD in Genetics from University College London. He has lived in French Polynesia for over 20 years, where he is Director of the University of California's Gump South Pacific Research Station on Moorea, French Polynesia.