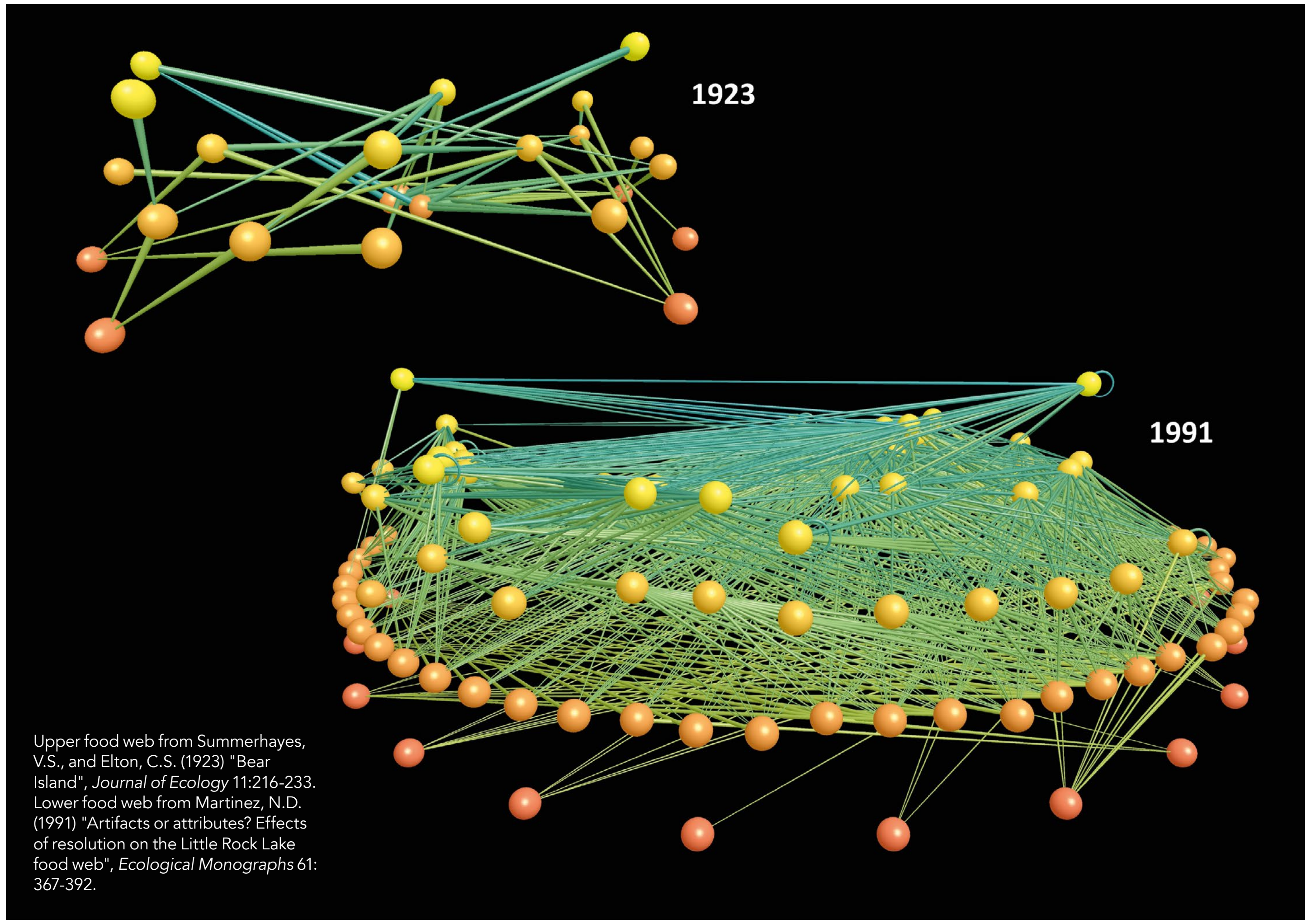
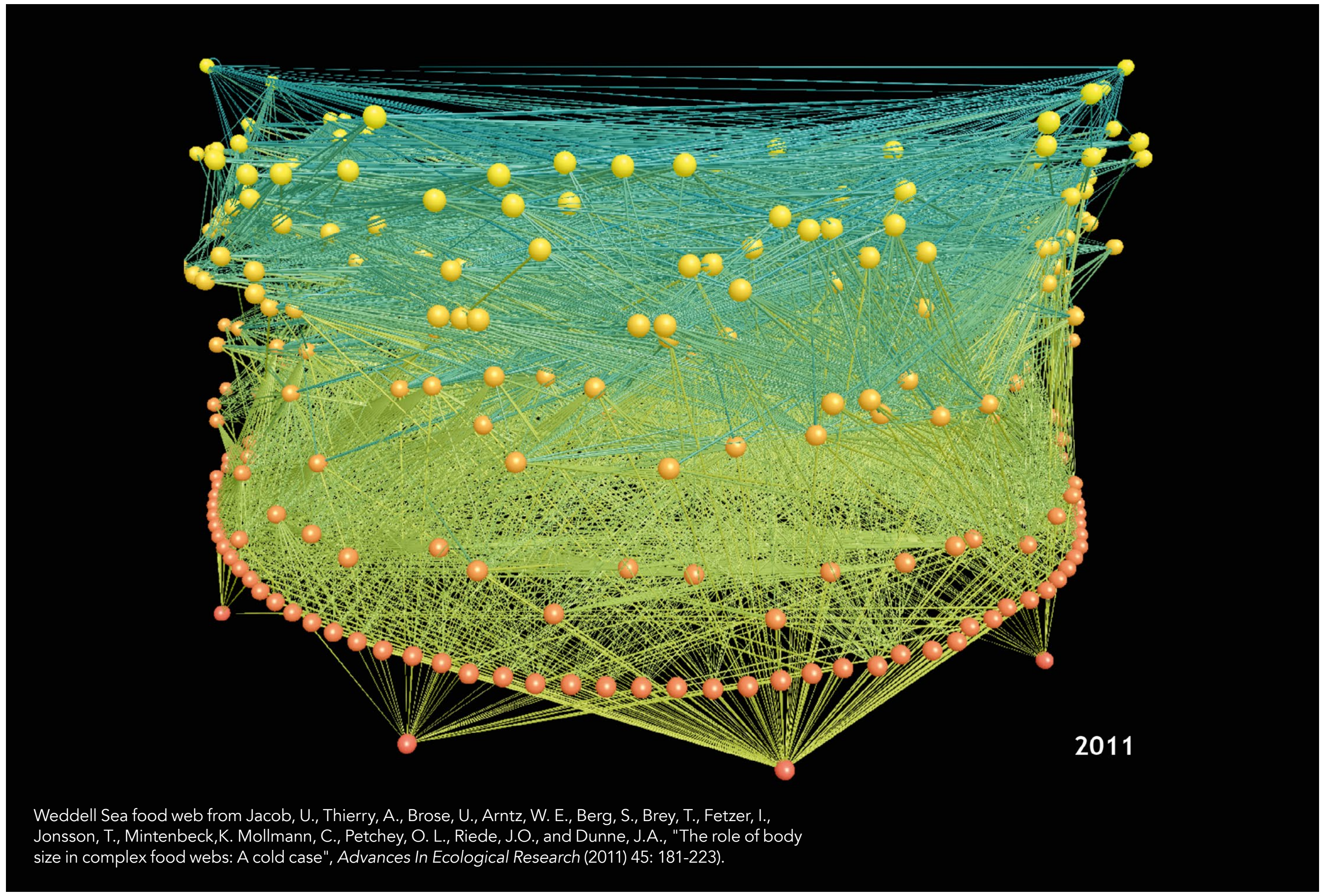


Upper food web from Summerhayes, V.S., and Elton, C.S. (1923) "Bear Island", *Journal of Ecology* 11:216-233. Lower food web from Martinez, N.D. (1991) "Artifacts or attributes? Effects of resolution on the Little Rock Lake food web", *Ecological Monographs* 61: 367-392.



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From field to supercomputer: the evolution of food webs

Over the past three decades, **Dr Neo Martinez** from the University of Arizona has been continuously developing one of the most fundamental concepts of the natural environment: the food web. His research has pushed the boundaries of this field, often revising our understanding of ecological complexity. By leveraging the surge in computational potential to synthesise and analyse field data, he has developed powerful new models and visualisations which advise, educate, and predict ecosystem changes, as well as help elucidate our relationship with the natural world.

Great science always starts by questioning the world around us, and what we've already been told. As a curious undergraduate at Cornell University, Neo questioned his lessons that emphasised the radical differences among ecosystems and species. Instead, his perhaps overly theoretical mind told him something few others believed: that complex ecosystems and species are quite similar in that they obey scientific laws and are therefore simpler and more predictable than ecologists thought. Ecologists had to do what scientists are supposed to do: discover the fundamental laws that their systems obey. He decided to look for those laws by exploring food webs, the networks of interconnected food chains indicating who eats whom in nature. Previous work on food webs bothered him. That work ignored most of the species within those systems and used biased and incomplete food-web data to support its theory. Dr Martinez viewed ecosystems as much more complex yet, at least potentially, much more predictable than ecologists thought. Working from the ground up, Dr Martinez set out to peer through the fogginess surrounding food webs, and in doing so would rewrite the way ecologists view ecosystems.

THE NICHE MODEL

With myriad interactions, variables and influences, nature appears incredibly complex and difficult to predict. However, careful thought, observation, and analysis might enable ecologists to discover the rules and algorithms underlying these systems. Such rules can then be described with mathematical equations that reconstruct the natural world in mathematical and digital form. We call these reconstructions ecological models. Ecologists have many of them which vary in their purpose and complexity.

During the 1990s, together with his colleague Dr Richard Williams, Dr Martinez set out to create a model that could predict the network structure of food webs in all ecosystems. The model randomly assigned each species a position on a line and a segment along the line lower than itself containing all the species that the species fed upon. The only two numbers needed to do this are the number of species, and the 'connectance' value, which represents how many feeding links are in the ecosystem. The model could then predict the structure of any ecosystem's food web based only on the diversity (species number) and complexity (connectance) found in the ecosystem.

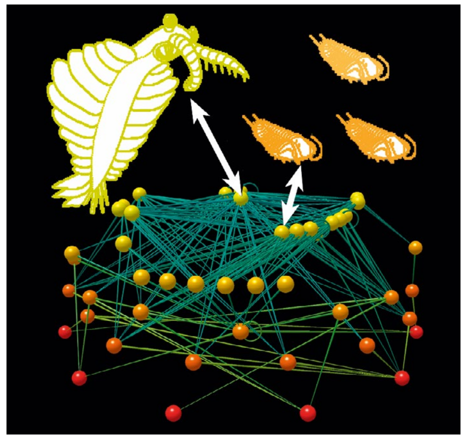
Dr Martinez set out to peer through the fogginess surrounding food webs, and in doing so would rewrite the way ecologists view ecosystems

In addition to this theory, Dr Martinez and his colleagues collected an incredible array of food-web data from real ecosystems, noted to be the most comprehensive to date. These datasets were matched with ones generated in the niche model. Amazingly, the model output was ten times more similar to the real-life ecosystems than any previous model based on only two simple inputs. This meant that the mechanistic rules represented by the niche-model algorithms appeared to be a powerful underlying feature of natural systems.

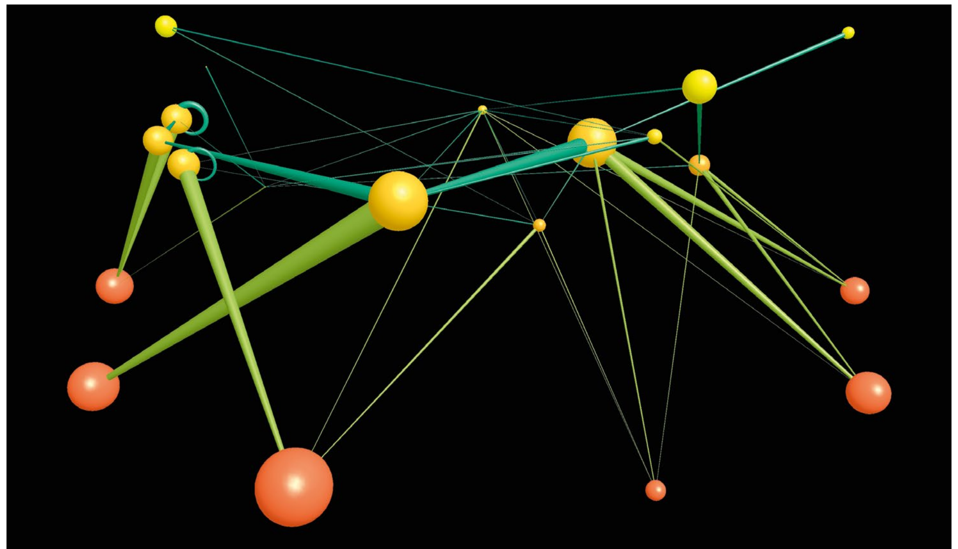
A DYNAMIC SYSTEM

So far, so good. But Dr Martinez knew that a food web model that could be applied to many ecological challenges facing humanity was still a long way off. A key component was now in place that provided remarkably accurate architectural roadmaps of natural food webs. However, if we were to effectively manage ecosystems, we also needed to incorporate that all important factor – time. We know that ecosystems are truly dynamic, so Dr Martinez and his team set about crunching the more specific numbers behind thousands of biotic (life form) and abiotic (physical) interactions. This sort of project requires a monumental amount of data to constantly form and improve each 'branch' of the model. Dr Martinez's wide network of collaborators across the world (along with modern-day connectivity) is crucial to his work – he is quick to point out that without them, his work would not be possible.

Luckily for his team, the growth in research mirrored (and was largely interlinked with) the explosion in technological power. The sheer number of variables required results concerning millions of potential outcomes, which can only be handled by supercomputers. As more data came through, the computers became more powerful. But how could he ensure that these 'virtual ecosystems' would be stable like the ones we see (uninterrupted) in nature? To do this, Dr Martinez began to break down how feeding changed across the trophic levels. The term 'allometric degree distribution' describes how species with larger bodies tend to eat more



Half billion year old Cambrian food web derived from fossils in the Burgess Shale from Dunne, J. A., Williams, R. J., Martinez, N. D., Wood, R. A., & Erwin, D. H. (2008) "Compilation and network analyses of Cambrian food webs", *PLOS Biology*, 6(4), e102.



Snapshot of a Niche Model food web (Williams, R. J., and Martinez, N. D. (2000) "Simple rules yield complex food webs", *Nature* 404:180-183) with dynamically varying species abundances and feeding rates.

species and be eaten by fewer species. This rule is key to providing the dynamic stability seen in nature over a long period of time. When these allometric degree distributions are disturbed – perhaps when an invasive species brings a disease, or a large-bodied predator is removed from the system – then food webs can become unstable, resulting in a cascade of many other species being lost.

Dr Martinez became increasingly interested in what happens when we start losing species – an effect that humans often have on nature. What if we could predict the likely effects of introducing or removing an important species, and the consequential ripple or 'trophic cascade' that would cause? One of his favourite results is his team's successful prediction of this ripple effect on other organisms within a species removal experiment in the field. Expanding such predictive capacities would be hugely beneficial for the implementation of conservation efforts and preventative measures.

FOOD WEBS OF THE FUTURE

Over the past decade, Dr Martinez and his ever-increasing team of collaborators have been refining food web models by better integrating factors such as parasites, evolutionary history, and abiotic pressures. The virtual ecosystem is becoming increasingly precise but we need a place to test these models. Enter the IDEA (Island Digital Ecosystem Avatars) Consortium, and the remarkable Tahitian island of Moorea.

At least since Darwin, islands have long been considered ecological model systems. Their natural boundaries act as a constraint for many biotic and abiotic fluxes which would otherwise be difficult to model. Moorea is possibly the most studied island in the world, with every species over 1mm (including coral) being characterised through physical and genetic means. Dr Martinez and his colleagues have provided an essential role by coupling his models to past and present data. By analysing the way populations of species have changed through time, under the various pressures at those times, the Moorea IDEA can make predictions into the future. Ideally, the model would be constantly refined by continuously testing these predictions against real life data resulting in an ever better tool for understanding and prediction.

One result of the IDEA is a 3D map of the island, not dissimilar from Google Earth, where viewers can 'fly' around and observe species' distributions. Furthermore, they can zoom in to particular locations, simulate environmental changes, apply varying timeframes and view the results. This is ground breaking science for ecology, and for environmental policy.

By accessing the 'Moorea Avatar', local stakeholders will be able to rapidly simulate future plans, how they will affect the environment, and how they will affect their businesses. Before long, the model will be applied to other islands (Crete has already shown an interest), and maybe one day coastal and inland areas.

Beyond Moorea, Dr Martinez is extending his research to three other Pacific islands. He will be investigating human–food web interactions throughout each island's history to extract a robust theory for their differing current environmental makeups. The islands have been chosen strategically according to human sustainability from historically high to horrendously low. By analysing how each island is different, Dr Martinez will once again show how models can be applied to ecosystems elsewhere across the world to better understand ecological and human sustainability.

What is perhaps most remarkable about this work is the underlying framework, the mathematical models and equations which often get hidden behind eye-catching results. At its core, ecology obeys laws, and it takes a special kind of mind to break down natural behaviours and abiotic pressures into manageable equations representing those laws. Dr Martinez and his colleagues appear to have achieved this, and coupled with incredible computer technology, we could be entering a new era for environmental modelling, prediction and understanding.

We could be entering a new era for environmental modelling, prediction and understanding

Q&A

When you were young, were you initially drawn to mathematics, or the natural world?

I was interested more in the natural world. I was interested in math simply because it was a cool puzzle and seemed necessary for science. I was much more interested in computers because they could do so much more math than I could as well as being yet another cool puzzle. As I learned about ecological complexity, my thoughts could go much farther knowing that computers could do the incredibly tedious calculations that the development of more sophisticated mathematical models of ecosystems would require.

How did observing fisheries influence your research?

My most thorough ecological training was in aquatic ecosystems and fish play a huge role in aquatic ecology. People also consume vast amounts of fish giving rise to large fishery industries that count fish as a commodity and a research community that studies fishery ecosystems. Given the rich sources of data and research support created by large scale fisheries combined with the horrific exploitation of animals from cod to tuna to whales and the obvious role of complex ecosystems in sustaining fisheries, fishery ecosystems from lakes to coral reefs have been one of the most powerful conceptual and practical engines of my research. And a love for snorkelling beautiful coral reefs helps me tend that engine rather attentively…

Does the Moorea IDEA incorporate the 'Niche Model'?

The IDEA is mostly just an idea(!) now only beginning to become what we hope it will be. As development progresses, the niche model will be used to fill in where data on food web structure is lacking e.g., in the soils and among invertebrates that are less well known. It will also help generalise results from specific networks we observe in places like Moorea. For example, if our models find that removing herbivorous fish from coral reefs degrades food webs that look specifically like Moorea's food webs, we can use the niche model to generate many other webs that are similar to Moorea's and see if they provide similar results. If they do, we can talk more about reef webs in general instead of just one specific web on a spectacularly beautiful island.

Do you think these models will become limited by field data collection rather than mathematical accuracy in the future?

Both data and math will always be both limiting and empowering. Limitations force us to think more strategically. I think if we had complete knowledge of all the data describing ecosystems from nanosecond to nanosecond, the abstractions needed to understand ecological laws would be harder to imagine. We'd be in a dilemma similar to psychologists. It's hard to come up with a theory of thought when you know all the thoughts you're thinking. Much of the advances of physics, molecular biology and astronomy seem to come from the difficulty of observing their details. Those challenges help us think about generalities because so many specifics are obscured from our view.

How easy is it to apply your models to other ecosystems? Does a lot have to be changed depending on the specific environment? Or are the models for say deserts, similar to those for rainforests?

It's super easy. All you have to do is assume all ecosystems are the same. Of course, such application may be ineffective. We've been continually and pleasantly surprised how far such simplistic assumptions get us. For example, the niche model does quite well for deserts and forests as well as some of the first recognisable ecosystems over half a billion years old. Still, for particular purposes, such as predicting next year's fishery yield, we will probably have to include many more specifics including nuances of the food web structure and the species feeding within that structure.

Detail

RESEARCH OBJECTIVES

Dr Martinez has applied computational methods to food webs in order to explore and understand relationships between species in ecosystems. He focuses on finding general rules in the form of mathematical descriptions of these relationships that can broadly predict ecosystem behaviour.

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Anna Kuparinen, Associate Professor, University of Jyväskylä, Finland
Fernanda Valdovinos, Assistant Professor, University of Michigan

BIO

Dr Martinez gained his BS from Cornell University, followed by an MS at University of Wisconsin. A further MS and PhD in Energy and Resources at University of California confirmed his interest in complex networks. Now Associate Professor at University of Arizona, Dr Martinez continues to explore the world of food webs and other ecological networks.

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