

ECOLOGY

The Forgotten Megafauna

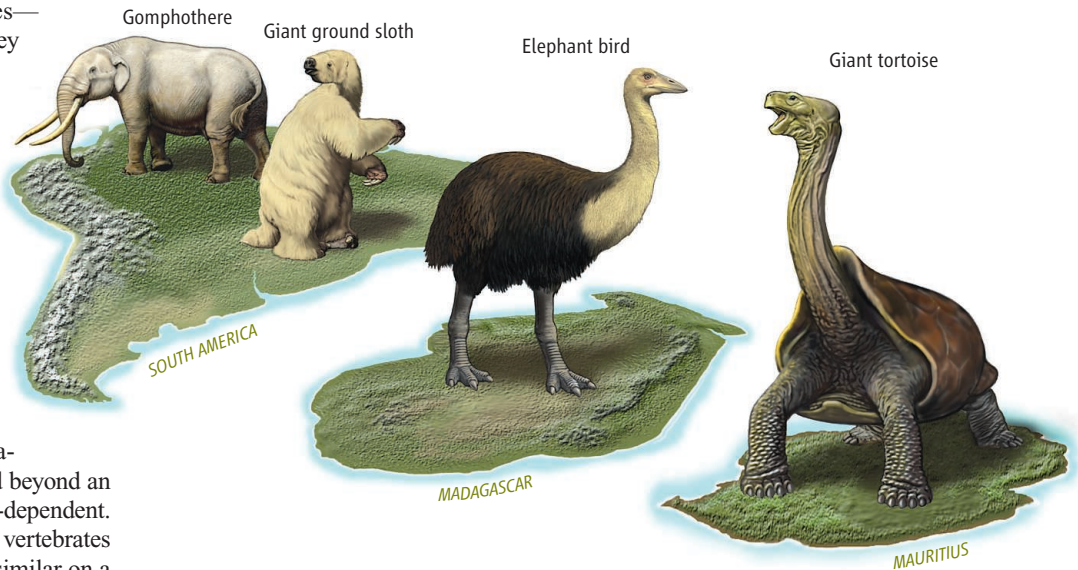
Dennis M. Hansen¹ and Mauro Galetti^{1,2}

Large terrestrial vertebrates—called megafauna—play key roles in ecosystem dynamics by feeding on plants and by maintaining habitat heterogeneity (1). A global wave of megafauna extinctions occurred 50,000 to 10,000 years ago, when many large continental mammals were lost (2–5). Classical definitions of megafauna are based on such continental mammals and are variably given as animals larger than 44 kg (6) or above 1000 kg (7). Here, we argue that the megafauna concept should be extended beyond an absolute animal size to be context-dependent. In any given ecosystem, the largest vertebrates have ecosystem impacts that are similar on a relative scale to those of the largest vertebrates in another ecosystem: One ecosystem's mesofauna is another ecosystem's megafauna.

An ecosystem function that clearly illustrates this argument is animal-mediated seed dispersal. Here, the link between animal body mass and ecosystem function is straightforward: The larger the fruit-eating animal (frugivore), the larger the fruits it can consume. Thus, extinction-mediated “ecological shrinkage”—the loss of species interactions—in community-level seed dispersal roughly scales with frugivore body mass.

Scientists have argued that in continental Central and South America, the extinction of the classic mammalian megafauna—such as giant ground sloths and gomphotheres—caused disruption of seed dispersal for large fruits (4, 5). However, on islands, the extinction of large birds and reptiles in the past two or three millennia has led to similar disruptions (8, 9). In both locations the demographic and genetic consequences of large-vertebrate extinctions for plants are likely similar—for example, disruption of long-distance gene flow or changes in species composition (10, 11). Yet, by the classic definitions, large insular vertebrates would not be considered megafauna.

¹Department of Biology, 371 Serra Mall, Stanford University, Stanford, CA 94305, USA. ²UNESP-São Paulo State University, Department of Ecology, Rio Claro, São Paulo, Brazil 13506-900. E-mail: dmhansen@stanford.edu



Scaling the megafauna. The magnitude of loss of frugivorous megafauna is currently most dramatic on islands, as illustrated by the smaller drawn sizes of the giant ground sloth and the gomphothere from South America, compared with the elephant bird in Madagascar and the giant tortoise of Mauritius. However, many continental regions are poised to catch up.

To illustrate our point, we have examined tropical and subtropical faunas from three kinds of ecosystems: continental, continental islands, and oceanic islands. For each fauna, we compared the body masses of the largest extant frugivorous vertebrate—mammal, bird, or reptile—to the largest that has gone extinct since the late Pleistocene. On continents, the body masses of extant frugivores are an order of magnitude lower than those of extinct frugivores; in contrast, in some continental and oceanic islands, body masses of extant animals are two or even three orders of magnitude lower than those of their extinct predecessors (see the supporting online material).

For instance, the largest frugivores in South America were gomphotheres (7580 kg), whereas the largest living frugivores are the tapirs (300 kg). On the continental island of Madagascar, the role of largest frugivore has passed from the elephant bird (450 kg) to the radiated tortoise (10 kg). On Mauritius, giant tortoises weighing up to 100 kg were the largest native frugivores; today, the title goes to a fruitbat weighing only 0.54 kg. Thus, the loss of the island giants—tortoises, lizards, and flightless birds such as the dodo that were once found on many islands—has,

An expanded megafauna concept elucidates how extinctions of the largest vertebrates in any ecosystem have similar effects.

in relative terms, led to a greater megafaunal downsizing than the extinction of even the largest gomphotheres in South America (see the figure).

Moreover, in the relatively species-poor and simple island ecosystems, cascading effects of megafaunal loss may manifest themselves faster and with more devastating results than in more complex continental ecosystems. For example, lost megafaunal seed-dispersal interactions on islands will not be compensated for by surviving frugivores, because they are too small. In continental ecosystems, there is a higher functional redundancy, with medium- and even small-sized species capable of filling at least part of the megafaunal niche (12).

Anthropogenic impacts are set to cause further extinctions among large vertebrates, with dramatic consequences for ecosystem dynamics (11). If all currently threatened vertebrate frugivores were to go extinct, the relative ecological shrinkage in many continental ecosystems would equal that of islands. For instance, if all threatened frugivores in South America were to go extinct, the largest remaining frugivore would be the howler monkey, weighing 9 kg—a factor of 700 less than the giant ground sloth. Even some islands

stand to suffer further losses; in Mauritius, the largest nonthreatened native frugivore is the gray white-eye, a bird weighing a mere 0.009 kg (see the supporting online material).

An extended megafauna concept has the potential to promote synergy between otherwise disparate research and conservation foci, and to facilitate broader syntheses of ecosystem-level effects of extinctions of the largest vertebrates and the resulting ecological shrinkage. It is high time to more fully understand and ameliorate the recent and ongoing losses of all “the hugest, and fiercest, and strangest forms” (13).

References and Notes

1. R. Dirzo, A. Miranda, in *Plant-Animal Interactions: Evolutionary Ecology in Tropical and Temperate Regions*, P. W. Price, T. M. Lewinshon, G. W. Fernandes, W. W. Benson, Eds. (Wiley, New York, 1991), pp. 273–287.
2. P. L. Koch, A. D. Barnosky, *Ann. Rev. Ecol. Evol. Syst.* **37**, 215 (2006).
3. A. D. Barnosky *et al.*, *Science* **306**, 70 (2004).
4. D. H. Janzen, P. S. Martin, *Science* **215**, 19 (1982).
5. P. R. Guimarães Jr., *et al.*, *PLoS ONE* **3**, e1745 (2008).
6. P. S. Martin, R. G. Klein, *Quaternary Extinctions: A Prehistoric Revolution* (Univ. of Arizona Press, Tucson, 1995).
7. R. N. Owen-Smith, *Megaherbivores: The Influence of Very Large Body Size on Ecology* (Cambridge Univ. Press, New York, 1988).
8. H. J. Meehan *et al.*, *J. Biogeogr.* **29**, 695 (2002).
9. D. M. Hansen *et al.*, *PLoS ONE* **3**, e2111 (2008).
10. R. G. Colevatti *et al.*, *Mol. Ecol.* **12**, 105 (2003).
11. S. J. Wright *et al.*, *Biotropica* **39**, 289 (2007).
12. W. Hallwachs, in *Frugivores and Seed Dispersal*, A. Estrada, T. H. Fleming, Eds. (Kluwer, Boston, 1986), pp. 285–304.
13. A. R. Wallace, *The Geographical Distribution of Animals* (Harper, New York, 1876).
14. Supported by the Velux Foundation (D.M.H.), Fundação de Amparo à Pesquisa do Estado de São Paulo (M.G.), and Conselho Nacional de Desenvolvimento Científico e Tecnológico (M.G.).

Supporting Online Material

www.sciencemag.org/cgi/content/full/324/5923/42/DC1

Fig. S1

Table S1

References

10.1126/science.1172393

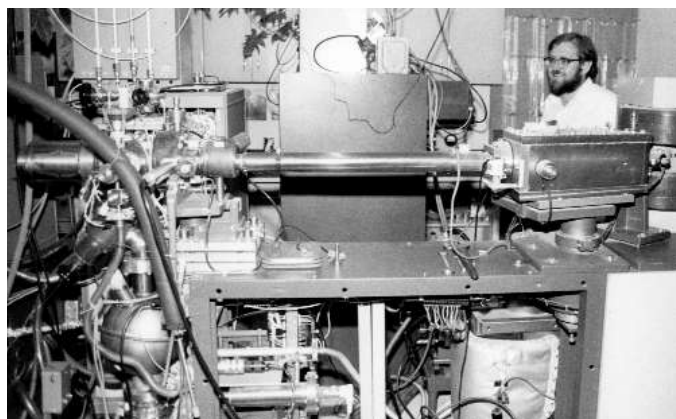
COMPUTER SCIENCE

Automating Science

David Waltz¹ and Bruce G. Buchanan²

The idea of automating aspects of scientific activity dates back to the roots of computer science, if not to Francis Bacon. Some of the earliest programs automated the processes of creating ballistic tables, cracking cyphers, collecting laboratory data, etc., by carrying out a set of instructions from start to finish. Starting with DENDRAL in the 1960s (1), artificial intelligence programs such as Prospector (2), Bacon (3), and Fahrenheit (4) automated some of the planning, analysis, and discovery portions of the scientific enterprise. However, most of these programs were still designed to run a calculation to completion, produce an answer, and then stop. They did not fully “close the loop” in the sense of examining the results of their actions, deciding what to try next, potentially cycling forever.

Two reports on pages 85 and 81 of this issue push the boundaries of automatic scientific experimentation and discovery. King *et al.* (5) describe a robotic system for running biological experiments, evaluating their results, and deciding what experiments to try next. Schmidt and Lipson (6) describe their work on discovering compact equations that characterize complex nonlinear dynamical



Semiautomated. Scientists at Stanford’s Instrumentation Research Laboratory (circa 1970) linked a gas chromatograph and high-resolution mass spectrometer to computers to automate studies of biological fluids, meteorites, and other materials. Stanford’s DENDRAL Project experimented with automated interpretation of the data and experiment planning to specify nuclear magnetic resonance or infrared data that would resolve ambiguities in the mass spectral data.

systems, derived from visual observation of such systems. As these reports show, it is possible for one computer program to step through the activities needed to conduct a continuously looping procedure that starts with a question, carries out experiments to answer the question, evaluates the results, and reformulates new questions.

The main goals of automation in science have been to increase productivity by increasing efficiency (e.g., with rapid throughput), to improve quality (e.g., by reducing error), and to cope with scale, allowing scientific treatment of topics that were previously impossible to address. Tycho Brahe spent a lifetime recording observations that allowed Johannes Kepler to formulate Kepler’s laws of planetary

Computers with intelligence can design and run experiments, but learning from the results to generate subsequent experiments requires even more intelligence.

motion; today, computer-controlled data collection is commonplace and necessary for both experimental and observational science. Automating many activities beyond data collection offers even more benefits.

In the near term, a useful metaphor is to consider computers as intelligent assistants. Some assistants gather data and attend to such tasks as noise filtering, data smoothing, outlier rejection, and data storage. Other assistants are specialists at statistical analysis, still others at bench work. This metaphor has driven many research projects over the past several decades and has led to many of the most successful applications of computers.

An early articulation of this metaphor is Joshua Lederberg’s effort at Stanford University School of Medicine to develop an automated biomedical laboratory to examine the soil of Mars for traces of life, as part of the 1975 Viking mission deployed by the U.S. National Aeronautics and Space Administration. The robot assistant Lederberg designed, with engineer Elliott Levinthal, consisted of a conveyor belt that scooped up samples of Martian soil and deposited them within a computer-controlled mass spectrometer. Each soil sample was bombarded with electrons, producing a fragmentation pattern that sorted the charged particles (ions) according to their mass. This pattern was transmitted to Earth, where scientists could analyze it for

¹Center for Computational Learning Systems, Columbia University, New York, NY 10115, USA. ²Computer Science Department, University of Pittsburgh, Pittsburgh, PA 15260, USA. E-mail: buchanan@cs.pitt.edu; waltz@ccls.columbia.edu