

expected to result from energetic events that depleted the Moon in all other volatile elements relative to the Earth. Furthermore, the Rb/Cs ratio in the Earth's mantle is higher than that of the Moon⁷. Caesium, however, is more volatile than Rb, and the terrestrial Rb/Cs ratio should be the same as or lower than the Moon's. Finally, the ⁴¹K/³⁹K ratio in lunar feldspars is lower than in the terrestrial feldspars⁸. If the Moon were derived substantially from the Earth's mantle, the ratio would be expected to be the same or higher, as the lighter isotope would be preferentially lost in any energetic process responsible for the depletion of volatile elements in the Moon relative to the Earth.

CONSERVATION BIOLOGY

Taxonomy as destiny

Robert M. May

THE tuatara is a large, iguana-like reptile whose main claim to fame is as the sole survivor of a once-flourishing group whose heyday was the Triassic Period, more than 200 million years ago. Daugherty *et al.*, on page 177 of this issue¹, suggest that the greatest threat faced by the tuatara, which is now confined to a few islets off the coast of New Zealand, is a persistent failure to recognize that populations of the animal are genetically far more diverse than legislators have cared to admit.

Completely unrelated to the superficially similar lizards, the tuatara has a well-developed third eye in the centre of its head (most other vertebrates retain this organ in vestigial form as the pineal gland, behind the third ventricle of the brain) and a row of yellow spines down its back (hence the name, from the Maori *tua*, 'on the back'; and *tara*, 'spine').

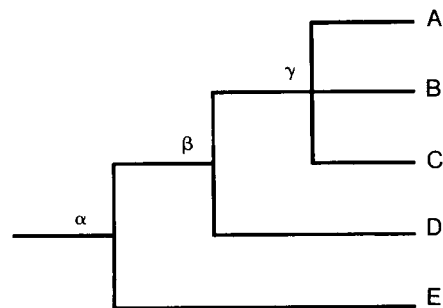
As Daugherty *et al.*¹ point out, three species of tuatara were recognized and named in the 19th century. One is now extinct. A second, *Sphenodon guntheri*, has suffered the curious fate of being ignored by the legislation designed to protect the tuatara, which has only ever acknowledged a single species, *S. punctatus*. This discrepancy dates back to the 1895 Animals Protection Act in New Zealand, even though *S. guntheri* had been described and recorded as a distinct species in 1877. Daugherty *et al.* argue that this legislatively-defined monotypy of the tuatara has affected its destiny, engendering a belief that 'the species' is relatively widespread and the documented extinction of 10 out of a total of 40 populations over the past century is not too serious.

Daugherty *et al.* report allozyme variation and morphological differences from 24 of the 30 islands on which tuatara populations are thought to survive — studies

Until positive proof is obtained that the abundances of V, Cr and Mn in the Earth and Moon would be the result of megabar metal/silicate partitioning processes acting deep inside the Earth, the idea that the Moon was derived substantially from the Earth remains a theory. Ringwood and co-workers have done the scientific community a service in reminding us that bandwagons are dangerous things⁹ and that the giant-impact theory for the origin of the Moon does not readily explain all chemical and isotope parameters with sufficient robustness for the matter to be closed. □

Michael J. Drake is in the Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA.

that unequivocally support the status of *S. guntheri* as a distinct species. At present fewer than 300 individuals of this species exist, confined to just one island, North Brother Island in Cook Strait; one other



A hierarchical classification or tree for 5 imaginary species, labelled A, B, C, D and E. The symbols α , β and γ label the nodes or branching points in the tree.

population became extinct earlier this century. There are clear implications for conservation management on North Brother Island. In practice, intervention and management on behalf of any endangered population of tuatara has been limited, and contrasts with successful conservation techniques applied to some threatened species of birds in New Zealand. On four islands where existing populations of *S. punctatus* are currently on the brink of extinction, endangered birds have been deliberately introduced and sometimes intensively managed, possibly to the detriment of the tuatara.

The new work¹ raises larger questions about the ways in which relative values are assigned to different creatures — about how we weigh, as it were, taxonomic distinctness. As more and more species face extinction in the wild over the next few decades, how do we go about making choices for the ineluctably limited number of places on the ark? For a given group of

organisms, or more generally, how do we go about designing a limited set of reserves that will, in some defined sense, optimize what is saved?

To be specific, how might we value the tuatara, be it one species or two, against any other species of reptile? At one democratic extreme, it could be argued that all species are to be valued equally, each a unique evolutionary product. But does a conservation biologist regard the tuatara — questions of relative abundance set aside for the moment — as equal to any other one or two species of skinks or grass-snakes? Could the World Wide Fund for Nature replace its panda logo with any one species of rodent?

At the opposite extreme, Vane-Wright *et al.*² propose that we might consider turning to the taxonomy of the group, expressed as a hierarchical 'tree', and give equal weight to each 'sister group'. Sister groups may be roughly defined as those ultimately having branched from a common node at some point in the hierarchical tree: for example, in the figure, species E and the set of four species A, B, C and D are sister groups (sharing the node labelled α); similarly, the groups D and A, B, C are sisters (from β); and so on. On this basis, the two living species of tuatara would be weighed equally with the sum of all 6,000 species of snakes, lizards and amphisbaenians (which are like the As, Bs and Cs to the tuatara's E in the complex real version of the tree for all reptiles).

Clearly, a sensible intermediate between these two extremes is required, to give some precision to Atkinson's commonsense observation³ that "Given two threatened taxa, one a species not closely related to other living species and the other [a] widespread and common species, it seems reasonable to give priority to the taxonomically distinct form". At recent meetings in Bergen and Canberra on biodiversity, R. I. Vane-Wright, C. J. Humphries and P. H. Williams (from the Natural History Museum, London) discussed these problems, proposed several possible solutions, and explored the implications of measures of 'taxonomic distinctness'. The work has been submitted for publication² under the title "What to protect? Systematics and the agony of choice".

Vane-Wright *et al.* base their ideas on the information content of the topology of a particular hierarchical classification. The broad outlines of their scheme, however, can be grasped without reference to the underlying details. For each species, or twig tip, we trace down to the root of the tree, counting nodes. Thus, in the figure, we count three nodes (α , β , γ) for species A, B and C, two for species D, and one for species E. The species are then each given an index of taxonomic distinctness that is inversely proportional to this node-count. Scaling the minimum such

index to 1, species A, B, C, D and E then have the relative weights 1, 1, 1, 1.5 and 3, respectively. This is clearly different from weighting all five species equally, although in this excessively simple example it is not too different from the extreme of weighting sister groups equally (giving relative weights 1, 1, 1, 3 and 6 to A, B, C, D and E respectively).

This particular scheme of Vane-Wright *et al.* has the slight disadvantage that, for the values accorded individual species, it rests solely on topology, taking no account of how many lines branch from each node. A minor refinement, retaining the spirit of their ideas, is to count not simply the number of nodes between twig-tip and root, but rather the sum of the branches at all such nodes. In this scheme, the nodes labelled α , β , γ in the figure have 2, 2 and 3 branches respectively, and consequently we count 7 for A, B and C; 4 for D, and 2 for E. Taking these numbers to give inverse measures of taxonomic distinctness, as before, we arrive at the relative values of 1, 1, 1, 1.75 and 3.5 for A, B, C, D and E respectively. The differences from Vane-Wright *et al.*'s scheme are small here, and disappear altogether in fully resolved trees, but can be significant in partially resolved hierarchies in which some branches are binary whereas others are multifoliate.

Returning to the tuatara, if all species are weighted equally, the two species represent only 0.03 per cent of all reptiles. At the opposite extreme — equal weight for all sister groups — they represent 50 per cent. Depending on how one approximates the complex topology of the hierarchical classification of all reptiles, I estimate that the scheme developed by Vane-Wright *et al.* implies that tuataras represent between 0.3 and 7 per cent of the taxonomic distinctness found among the 6,000 reptile species (and probably closer to the lower number).

Lifting our sights from species to faunal assemblies, suppose we wish to find, from some larger list, the minimal set of reserves that will include, say, every one of the 158 species of milkweed butterflies. In its simplest form, this is a version of the travelling-salesman problem⁷. Ackery and Vane-Wright⁴ have shown that, in practice, a good solution is obtained by examining a compendium of some 350 sample areas distributed around the globe, and noting the numbers of species (and patterns of endemism) in each area. They then work up a solution by first choosing the most species-rich region, which is the island of Sulawesi with 33 of the 158 (9 of which are endemic). Next comes the region with the highest remaining total, excluding the species already present in Sulawesi. And so on, always choosing the best region to compensate for species not yet incorporated.

In this way, Ackery and Vane-Wright

find that a total of 31 reserves provides a critical set that embraces all species of milkweed butterflies. Although, as Vane-Wright *et al.* point out², this simple method does not necessarily give the minimal set, it is a sensible and efficient method that is surely close to, if not exactly, optimal. A much more complex example of this kind is the recent assignment of priority-grades to different areas of Amazonia, according to measures of the richness of plant and animal species⁵.

The above-mentioned studies were essentially based on counting species. Were it not possible to acquire a range of reserves that included all the species in the designated group, the criterion would presumably be to maximize the attainable number. But if we weigh the species according to some measure of taxonomic distinctness, along the lines just developed, the answers can be significantly different. Vane-Wright *et al.* illustrate this by first using the topology of a current classification of the bumble-bees in the *Bombus sibiricus* group to assign indices of taxonomic distinctness to each of the 43 species in question, and then carrying out an analysis of priority areas among the 120 equal-area grid squares occupied by members of this group on a global map. By a simple species count, the top-ranking grid square centres on Ecuador, with 10 species (23 per cent of the total). But when taxonomic distinctness is taken into account, the top square lies in the Gansu area of China, containing 23 per cent of the total weighted scores for taxonomic distinctness, versus 15 per cent for the Ecuador-centred square.

All this work represents only the beginnings of what might be called the calculus of biodiversity. At very least, we need to combine quantitative measures of taxonomic distinctness with more familiar ecological considerations of abundance and geographical distribution^{6,7}. Some may find it surprising that taxonomy, embodied in the hierarchical trees of systematists, stands alongside ecology in the emerging calculus. There should be no surprise. Without taxonomy to give shape to the bricks, and systematics to tell us how to put them together, the house of biological science is a meaningless jumble. □

Robert M. May is in the Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK.

1. Daugherty, C.H., Cree, A., Hay, J.M. & Thompson, M.B. *Nature* **347**, 177–179 (1990).
2. Vane-Wright, R.I., Humphries, C.J. & Williams, P.H. *Biological Conservation* (submitted).
3. Atkinson, I. in *Conservation for the Twenty-First Century* (eds Western, D. & Pearl, M.) 54–69 (Oxford University Press, Oxford, 1989).
4. Ackery, P.R. & Vane-Wright, R.I. *Milkweed Butterflies* (British Museum (Natural History), London, 1984).
5. Kuliopulos, H. *Science* **248**, 1305 (1990).
6. Rabinowitz, D., Cairns, S. & Dillon, T. in *Conservation Biology* (ed. Soule, M.E.) 182–204 (Sinauer, Sunderland, Mass., 1986).
7. Pagel, M.D., May, R.M. & Collie, A.R. *Am. Nat.* (in the press).

Tame twisters

SOLAR energy, says Daedalus, is usually too dilute and diffuse to be harnessed easily. A tornado, however, gathers it from a very wide area. The Sun-heated land of the region warms the air just above it; this low-lying stratum of warm air, seeking to rise, forms a large convection cell with a small central rising column. All the heat energy of the indrawn air, and its angular momentum from the Earth's rotation, is concentrated in this narrow updraught, which spins and rises violently. Daedalus is now devising a 'tame tornado', capable of generating useful power.

A wild tornado, of course, wanders destructively about. Daedalus's tame one will be safely anchored to one spot. Its central rising column will be defined and located by a tall chimney. At first the engineering problems looked daunting. Some sort of vast cooling tower seemed called for, many hundreds of metres tall, supported clear of the ground to admit radially inrushing air, and strong enough to withstand its violent spin and upflow inside. But Daedalus then recalled the airport windsock, that simple fabric sleeve kept extended and inflated by the wind blowing through it. So his tame tornado is now simply an outside vertical windsock. Like its airport counterpart, its inlet will be kept circular by attachment to a rigid hoop, anchored by cables to a single axial point. The air rising within it will keep it inflated and vertically extended; the cable anchorage will stop it blowing away upwards, but will allow hoop and sock to spin freely about their vertical axis. Internal 'sails' on the windsock will act as turbine blades driven by the spinning air column within. Thus the whole windsock will spin with the twisting updraught inside it, delivering useful power to a generator attached to the anchorage.

The tame tornado will be activated whenever the weather seems promising. The process will be something like launching a big fire balloon. The windsock will be inflated by a powerful draught of warm air, blown by big ducted fans and heated by propane burners, until natural tornado convection takes over and the windsock is self-sustaining. Thereafter, the installation will run for days or weeks on end, capturing much of the solar energy over a wide radius of countryside. Even at night, the Sun-heated soil will keep the convection cell in being.

A tame tornado will handle much less energy than the wild variety, and should be a relatively mild and safe device. Nonetheless, a grid of them spread across tornado country would usefully steal the energy needed by wild tornadoes. Any tornado approaching the grid would find itself rapidly starved of power, and would soon collapse exhausted.

David Jones