Salvaging the Library of Life

Gregory Benford

The next century may well be dominated by the biological sciences. Both biotechnology and advancing medicine promise much.

But consider: We have only begun the elementary counting and description of the world biota. Each species contains genetic variations of potential use, and at least of scientific interest. Although about 1.4 million species have been given scientific names, estimates of the total number of species range up to roughly 30 million, with some people guessing 100 million. This means we may very well not know the species diversity of the world flora and fauna to the nearest order of magnitude.

Yet time is running out in which we can even catalog our living wealth. Very conservative estimates of the current extinction rate give roughly 5000 species lost annually, at least several species per day. Some suspect the true level may be 30,000 per year.

And so we accelerate toward a calamity unparalleled in planetary history.

The best known cause of present day species extinction is the cutting of tropical forests. They have lost about 55% of their original cover of, say, two centuries ago—and are shrinking at the rate of 1.8% per year.

We now co-opt about 40% of plant growth worldwide, favoring monocultural crops, which must greatly affect genetic diversity. Given the blunt economic and cultural forces at work, even slowing the rate of destruction seems doubtful in the immediate future.

Worse, the rate seems doomed to increase, since its ultimate cause is human activity, and human numbers and expectations grow apace. To improve the economic lot of a swelling human tropical population would require at least a five-fold increase in economic activity there, bringing a crushing load on the already strained biosphere.

Other biological zones such as coral reefs and oceanic islands also dwindle at alarming rates. Because warmer regions host the greatest species diversity, losses are most severe in precisely the tropical continents where our own numbers swell so alarmingly.

Everywhere there are calls for a halt to tropical deforestation. In October 1991, I gave a reasonably optimistic speech about our future at California Institute of Technology's Centennial Celebration. It was a festive occasion, studded with Nobel Prize winners, amusing stories, wry wisdom—a testament to the rise of science and technology in our era.

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But then, listening to the biologists' full-day review of our biological prospects, I got quite gloomy. Paul Ehrlich and Edward Wilson despairingly suggested that we could lose a quarter of all species in half a century, with incalculable effects on our biosphere.

I came away from the Caltech Celebration quite sobered. If the experts were pessimistic, what should a relative layman in this area like me feel?

One point loomed over all else—that this dire moment demands radical thinking. In the half year since, in the spirit of a thought experiment, I've begun discussing publicly a proposal which I'll admit startled me, too, when I first thought of it.

I feel the time is right for us to take seriously the possibility that all the good will by an alarmed minority will, finally, fail. In so doing, this idea links the so-called in situ preservation community—which emphasizes protecting wild areas, keeping species in their present situation—and the ex situ conservationists such as zoos, botanical gardens, etc., which keep species far from their natural homes.

For in situ measures there are economic, environmental and aesthetic arguments—that's what the public thinks of when you appeal for conservation. To preserve the genome of many species, though—that is, the genetic record—ex situ methods may suffice. And they could be easier politically and economically.

Considering this possibility serves to separate the kinds of arguments we make for conservation methods, including concepts of our moral debt to posterity. In the spirit of sharpening debate by considering plausible scenarios, we can test our ideas.

Our situation resembles a browser in the ancient library at Alexandria, who suddenly notes that the trove under inspection has caught fire. Already a wing has burned, and the mobs outside seem certain to block any fire-fighting crews. What to do?

There's no time to patrol the aisles, discerningly plucking forth a treatise of Aristotle, or deciding whether to leave behind Alexander the Great's laundry list. Instead, a better strategy is to run through the remaining library, tossing texts into a basket at random, sampling each section to give broad coverage. Perhaps we would be wise to take smaller texts—in order to carry more—and then flee into an unknown future.

Although efforts to contain and control our accelerating biodiversity disaster are admirable, and should be strengthened, the time may well have arrived for us to consider a desperate method of salvage. I have proposed that we systematically sample threatened natural habitats, then store them for the very long term by freezing.

This would more nearly resemble an emergency salvaging operation than an inventory, for we would give minimal attention to studying the sample. The total sample mass might be reduced by judiciously trimming oft-repeated species of the prolific ants and beetles, but even that might be not worth the trouble. The essential aim would be to save what we can for future generations, relying on their better biological technology to extract the maximum benefit.

Sampling of tropical trees by insecticidal fogs and active searching of the canopy is common. Teams fog an area, killing nearly everything, and then bag the species. Of course this gives you damaged specimens, but for many purposes the harm is minimal. (We may want only the DNA, after all.)

People trained to simply collect, without analyzing, require little help from pricey research biologists. Extensive work by taxonomists enters only when samples are studied and classified.

Here lies our current bottleneck, the reason why only 1.4 million species have been classified. There are far too few taxonomists to tally the world's species within our generation, let alone analyze them.

We sidestep this problem if our primary aim is to pass on to later generations just the essentials of our immense biodiversity. Current methods simply aren't doing this job. Captive breeding programs, parks, microhabitats, and zoos can preserve only a tiny fraction of the threatened species. Here I'll use the term "preservation" to mean keeping alive representatives of at least each genus—in situ, protection in reserves—and argue that this is essential to eventually studying and potentially resurrecting frozen species.

To save the biosphere's genome heritage demands going beyond existing piecemeal strategies of seed banks, of germplasm and tissue culture collection, and cryo-preservation of the genetic material alone—gametes, zygotes, and embryos. These programs concentrate mostly on saving traditional domesticated varieties.

Not that they are useless. The "frozen zoo" of San Diego has immersed 240 mammal cell cultures and 145 tissue pieces in liquid nitrogen—about 300 species, in all.

Still, as a culture, our goal should be a complete sample of all threatened species. We owe it to our grandchildren.

For this, freezing is essential. Banking cells by drying them with silica gels, for example, is useful for short times, but at room temperatures thermal damage to DNA will accumulate over the decades.

We know that seeds can germinate after lengthy freezing, and that microbes can sustain cryogenic (extreme cold) temperatures. Simple cells such as sperm and ova survive liquid nitrogen preservation and function after warming. Generally, organs with large surface/volume ratios preserve well, such as skin and intestines. Such capabilities are already familiar businesses. Already, the Ageria Group of Tucson, Arizona will freeze your while blood cells, for your later use when your own immune system might be compromised by age or disease—taking a loan from your past, so to speak.

Of course, more complex systems suffer great freezing damage, though research proceeds into minimizing this. Biochemical and biophysical freezing injury arises from shrinking cell volume as freezing proceeds. Several kinds of damage occur, and we know little about methods of reversing such injury.

Still, even low survival rates of one cell in a million are irrelevant if the survivor cells can produce descendants. Our minimum aim can be to simply retain DNA, the least we should expect from a sample.

For this, liquid nitrogen is suitable for long term storage, especially since it is by far the cheapest method. At 25 cents/liter, liquid nitrogen is the lowest-priced commercial fluid, excepting water and crude oil. It allows suspension in large, easily tended vaults, simply by topping off the lost nitrogen. Only a wholesale breakdown of industry can plausibly destroy the samples; no mere power failure will do. Multiple storage at different sites avoids even this.

Further, although neither liquid nitrogen nor freeze-drying damages DNA, freeze-drying does cause far more injury to tissues. For the broad program envisioned here—which should also include tiny samples of ocean water, with its teeming viruses and bacteria—plainly liquid nitrogen is essential.

There's a further benefit when we save whole creatures, since we also gain their passenger parasites, bacteria, and viruses. We already know that these are very well preserved cryogenically, and can often be revived from liquid nitrogen storage even today.

A crucial point is that we need not rely on present technology for the retrieval. Progress in biological recovery can open unsuspected pathways.

Recent advances underline this expectation. A technique called the polymerase chain reaction can amplify rare segments of DNA, copying them over a million-fold. Such methods have enabled resourceful biologists to recover specific segments from such seemingly unlikely sources as a 120-year-old museum specimen. That mere scrap yielded DNA of a quagga, an extinct beast that looked like a cross between a horse and a zebra.

A 5000-year-old Egyptian mummy has yielded up its genetic secrets, too. More dramatically, the 5000 year old man found frozen in an Alpine snowdrift in the summer of 1991 promises to yield great knowledge of his medical and genetic conditions—all saved for us by a late summer snowstorm which apparently caught him unprepared.

Genetic tricks can even amplify DNA in old bones, opening study of the bulk of surviving organic matter we have from prehistory. The most truly amazing achievement in bringing the past alive in the genetic sense is DNA extracted from a fossilized magnolia leaf between 17 and 20 million years old. Apparently the leaves settled into the oxygen-free mud of a lake, then were covered by more mud.

This feat of recovery defied earlier predictions that DNA could not survive intact beyond about 10,000 years. What's the limit on our seeing into the genetic past? Nobody knows.

We should recognize that future biological technology will probably greatly surpass ours, perhaps exceeding even what we can plausibly imagine. In keeping species samples, we should imitate archaeologists, who deliberately leave a fraction of a site untouched, assuming that future archaeologists will be able to learn more from it than they can.

We need a combined strategy to salvage biodiversity out of catastrophe. The best approach may be two-pronged:

a) preserving alive some fraction of each ecosystem type ("biome"), keeping at least one of a closely related group of species (a genus); and
b) freezing as many species related to the preserved system as possible.

What would this mean in practice? Freezing your collie, for example, while keeping a pack of canines alive in the wild. With some crafty bioengineering, someday your collie could re-emerge, mothered by a completely different breed.

At a minimum, this method would allow future biologists to extract DNA from frozen samples and study the exact genetic source of biodiversity. Genes of interest could be expressed in living examples of the same genus, by systematic replacement of elements of their genetic code with information from the frozen DNA. Obviously, the preserved genus is essential.

The biodiversity catastrophe bearing down upon us will, at a minimum, make life tough for a lot of creatures. When populations dwindle, they get into genetic trouble. With a small selection of mates, inbreeding increases.

Bioengineering techniques would open broad attacks on the problem of inbred species—if we had a Library of Life to work from. A ravaged environment can easily constrict the genetic diversity of individual species. Reintroducing diverse traits from frozen tissue samples could help such a species blossom anew, increasing its resistance to disease and the random shocks of life.

Beyond this minimum—the DNA itself—future biologists will probably find great use for recovered cells. They could use uterine walls, elements of the sexual reproductive apparatus, etc., to re-express a frozen genome.

Suppose that somehow the North American bison became extinct. Getting a future mother antelope, say, to give birth to a genetically repaired baby bison, say, will demand that we know a great deal. For example, we might not know the intricate chemistries of the lost bison womb.

Sure, the information is somewhere in the bison genes, but puzzling it out might be tedious and error-prone. We would be highly unlikely to make appropriate choices in the many steps from genome to newborn, merely from reading DNA.

As saviors of the Library of Life we are at best marginally literate, hoping that our children will be better readers, and wiser ones. They may read DNA in a way utterly different from our clumsy methods. Many biotechnological feats will probably emerge within a few decades—many ways, let us say, of reading and using the same genetic "texts." But no advanced "reader" and "editor" can work upon texts we have lost.

This holds out the hope of selectively reintroducing biodiversity in the future, to gradually recover lost ecosystems. Individual species can be resurrected from very small numbers of survivors, as the nearly extinct California condor and black-footed ferret have been.

Fidelity in reproducing a genome may not be perfect, of course. Many practical problems arise (placenta environment, chemistry, etc.) which complicate expression of a genotype.

Make no mistake about it—losing nearly all of a local ecosystem would require a huge regrowth program. Humanity has never attempted anything like it—though we've destroyed plenty of species, long ago decimating the entire middle eastern region and the Hawaiian islands.

To regenerate such vast damage, the Library of Life would prove essential. For a moment, though, suppose that we avoid the worst, and manage to save a large fraction of, say, our tropics. Would the Library of Life be pointless?

No—because then the species library will provide a genetic "snapshot" of biodiversity at a given time and place. Such a research tool has never been had before.

Evolutionary biologists could then compare the tropics of our time with the tropics a century or two later, as it has evolved further—through tens of thousands of insect generations. This would let us study how systems evolve own their own, and how they react to human activities.

The far larger prospect of eventually reading and using a Library of Life is difficult for us to imagine or anticipate, since we are at the very early stages of a revolution in biological technology. Our situation may resemble the Wright brothers, who could not possibly have envisioned a moon landing within three generations.

In any case, future generations may well wish to edit and shape genetically those species within an ecosystem as they repair it, for purposes we can't anticipate. That's the point—to pass on records and tools, not to determine their use.

So the eventual uses of the Library are conjectural, but plausibly important. To estimate the practical aspects of the distant future is surpassingly hard; science fiction's successes at this have been mostly accidental.

Ah, but there is one immediate, practical question we can debate—can we afford this immensely larger Library?

Such a sweeping proposal avoids the problem of deciding which species are of probable use to us, or are crucial to biodiversity. By sampling everything we can, we avoid some pitfalls of our present ignorance. Too often, for example, preservation efforts focus on what some call "charismatic vertebrates"—animals that appeal to our Disney-soaked sensibilities—neglecting the great bulk of diversity, which includes a lot of rather boring or ugly creatures.

But remember, the samples need not be studied as they are taken. This avoids the scarcity of taxonomists, speeding field work and lowering costs. Plausibly, much of the gathering can be done with semi-skilled labor.

This suggests immediately that the bulk of the funding come from "debt swap" between tropical and temperate nations, as has been used with some limited success to "buy" rain forests and set them aside from cutting. Further, this will create a local work force which profits from controlled, legal forest work, rather than from cutting it.

As a very rough estimate, consider a sampling program which collects all life forms from a single stand of 100 trees, for each 100 square kilometers of rain forest, i.e., a sampling fraction in the range of one out of a million. That would yield about 100 kilograms of species, all jumbled together.

Suppose this costs on average $1000 per tree to yield a frozen sample, and keep it in nitrogen for a century. (This is a reasonable number, given some savings from doing such large samplings.) Then a million square kilometers coverage will cost a billion dollars.

Alot of money, indeed. On the other hand, current outstanding debt by tropical nations well exceeds 100 billion dollars.

Of course, this does not touch upon side costs in training biologists, transport, etc. The task is monumental; so is the plausible benefit. Traditional economics cannot deal with transactions carried out between generations. As biologist Harold Morowitz (1991, pp. 752-754) has remarked, the answer to "How much is a species worth?" is "What kind of world do you want to live in?"

This drastic proposal does not address many legitimate reasons for preserving ecospheres intact, and it should not be seen as opposing them. Indeed, only by preserving a wide cross section of living creatures can we plausibly use much of the genetic frozen library.

An obvious possibility is that, for many ardent conservationists, preservation of habitat may seem to compete politically with a sampling and freezing program. There is no intrinsic reason why this need be so. They are not logically part of a zero-sum game, because they yield different benefits over different time scales.

Further, sampling is much less expensive than in situ preservation. Even competition for 'debt swap' funds will not necessarily be of the same kind. Conservationists seek to buy land and set up reserves, putting funds into the hands of landowners. A freezing program will more strongly spur local employment, affecting a different economic faction.

Of course, there are a lot of unattractive features to a freezing program. Freezing species does not affect the immediate benefits which preservation yields. (Samples would be taken only from areas not already highly damaged, so that we don't worsen a critical situation.) Then too, sampling and freezing has little aesthetic appeal. You can get many more dollars with pictures of big-eyed Bambis in sheltered enclaves, than with the chilly prospect of simply freezing a representative.

Then too, to some, such ideas will smack of fatalism; unfortunately, they may be merely realism.

More concretely, this proposal will not hasten benefits from new foods, medicines, or industrial goods. So there will be no quick profits. The library of Alexandria, salvaged and kept in a cave for centuries, likewise would do no one any good until people were both willing and able to read it.

More important, the Library of Life will not alter the essential services an ecosphere provides for maintenance of the biosphere. This task is explicitly designed to benefit humanity as a whole, once this age of rampant species extinction is over.

Let's look more closely at the objection that this idea may be a slippery slope: that to undertake salvaging operations weakens arguments for biodiversity preservation. To avoid this, the two parallel programs of preservation and freezing must be kept clear.

In this sense the analogy to the library at Alexandria is false—for us, there is no true conflict between fighting the fire and salvaging texts.

Further, in the real world, funds for conservation of DNA today do not come directly from in situ programs. If the Topeka Zoo budget is cut, the city does not transfer funds to Zaire to save gorillas.

Indeed, one can make the opposite argument—that the spectacle of the scientific community starting a sampling program will powerfully illuminate the calamity we face, alerting the world, stimulating other actions.

Beginning with local volunteer labor and contributions—say, with the Sierra club sampling the redwood habitat—grass-roots momentum could be generated to overcome the familiar government inertia. In larger campaigns, by requiring that samplers accompany all legal logging operations, we could help develop a local constituency for controlled harvesting.

Perhaps the most difficult argument to counter is basically an unspoken attitude. Scientists are trained to be careful, scrupulous of overstating their results, wary of speculation—yet these militate against the talents needed to contemplate and prepare for a future which can be qualitatively different from our concrete present.

Paradoxically, scientists labor to bring about this changed future. Most think their work will find some positive use. Now, I think, is the time to bank on the expectation that we will probably succeed.

The Caltech celebration made me think of the species-loss problem in a way I never had—to regard it as virtually inevitable. Once you truly believe that, I believe the kind of strategy I've outlined here seems reasonable. So I've begun to try to spread this notion, so far with some success among the leading figures in the field.

After all, these same figures in biodiversity argue that a large scale species dieback seems inevitable, leading to a blighted world which will eventually learn the price of such folly. But their calls seem to go largely unheeded, even though the damage is easy to see—far more concrete, for the layman, than abstract discussions of the lofty ozone layer or statistical wranglings over greenhouse heating.

The political impact of such a disaster will be immense. Politics comes and goes, but extinction is forever. We may be judged harshly by our grandchildren, our era labeled the Great Dying or the Age of Appetite.

A future generation could well reach out for means to recover their lost biological heritage. If scientific progress has followed the paths many envision today, they will have the means to perform seeming miracles. They will have developed ethical and social mechanisms we cannot guess, but we can prepare now the broad outlines of a recovery strategy, simply by banking biological information.

Such measures should be debated, not merely by biologists, but by the entire scientific community and beyond, for all our children will be affected. These are the crucial years for us to act, as the Library of Life burns furiously around us, throughout the world.

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