Darwin in the City

Humans are changing the course of evolution

By Menno Schilthuizen

IN BRIEF

Species as varied as snails, dandelions and fish are adapting to urban environments in surprisingly novel ways.

In many cases, the speed of evolution is faster than would have occurred in natural settings.

Because cities worldwide present similar evolutionary pressures, species there may become more alike.

Many species will never be able to adapt to what are often extreme conditions, so they still need protections.

"Whoosh!" exclaims my friend Frank, as he thrusts his cupped hands upward, nearly knocking over his drink on the table between us. We are sitting in my backyard in Leiden, the Netherlands. Frank is demonstrating how, once or twice each day, a peregrine falcon swoops upward past his hospital office window with a freshly killed pigeon in its talons, headed for its lair underneath the giant illuminated logo at the top of the building. A few seconds later plucked feathers come drifting down.

Peregrine falcons are one of many bird species that have recently taken up an urban lifestyle. They traditionally hunt medium-sized birds around rocky cliffs, but as humans worldwide have filled the environment with an artificial cliff-scape of churches, chimneys and office buildings, the birds have happily exchanged escarpments for skyscrapers and jays for pigeons. In some parts of Europe and North America the majority of peregrine falcons nest in cities.

Such accidental similarities between urban and natural environments are attracting more fauna and flora to the metropolis. Cave cockroaches are preadapted to live in our dark, dank homes. Beach plants readily sprout along the briny edges of roads that are salted in winter. Raccoons, with their nimble, handlike forepaws, are eminently suited to manipulate garbage and compost bins strewn across the man-made landscape. Homo sapiens have established extensive settlements on nearly every continent, and by 2030 more than 600 cities will each be home to greater than one million people. No single species has ever produced new conditions for other species to live in, on such a global scale.

Something even more surprising is going on as well. The city—with its countenance of brick, glass and steel, the racing pulse of its vehicle-filled veins, its luminescent artificial light and the chemicals emanating from its pores—is an extreme yet bountiful environment. Although the conditions can be harsh, they can also provide many benefits, notably all the food and resources that humans accumulate. As in naturally extreme environments, such as deserts, sulfur springs and deep caves, this combination of risk and opportunity is driving the evolution of animals and plants that venture there. As my colleagues worldwide and I are discovering, cities have become pressure cookers of evolution—places that force adaptation to happen quickly and pervasively.

STREET-SMART SNAILS

You can witness urban evolution on a field trip that begins right outside your door. My own small backyard is a good example. I must admit that, for a biologist, my garden is an embarrassment (as Frank keeps reminding me). All kinds of weeds are sprouting between old pavement tiles on the ground. There is a neglected rose bush in one corner and a potted hydrangea in another. That's about it, except for the sprawling hop plants that relentlessly scale the wall looming over my yard.

The hop leaves shroud one of my favorite examples of urban evolution. I carefully peel them away from the wall, showing Frank grove snails nibbling at the dead branches of previous years. The snails, Cepaea nemoralis, native to Europe and introduced across North America, can have a variety of shell colors and patterns. The variations are coded in their DNA. My snails are pale yellow, adorned with up to five black spiral bands.

Why yellow? The answer has to do with the heat island effect. Cities tend to be hotter than the countryside around them because the buildings and streets absorb the sun's heat. That absorption, plus added heat generated by the activities of millions of people and their machines, creates a bubble of hot air. In a modest municipality such as Leiden, the air in the city center is on average two to three degrees Celsius warmer than it is in the surrounding area. In big cities such as New York or Tokyo, the difference can be more than 10 degrees C. For snails, which are sometimes forced to spend weeks of summer drought clinging to a wall, the extra heat can become fatal—more so if they have a dark shell, which absorbs the energy. Natural selection is causing grove snail shells in my city and others to become lighter in color. Outside the city perimeter they are more likely to be red or brown.

As Frank and I pass through my garden gate into the alley, we stumble across a second example of urban evolution: dandelions! They are pushing up from cracks in the pavement. Some are in full yellow bloom; others sport a head of fluffy, umbrellalike seeds. Under natural conditions, the seeds, suspended from feathery parachutes, are supposed to drift in the wind and eventually land and germinate far away from their parents and siblings. This system prevents competition. But in the city, the strategy is not likely to work, because the stamp-sized bit of soil where the parent grows is often the only fertile spot around. Seeds that blow far in the wind will likely land on barren asphalt or concrete. It would be better to have a heavy seed that drops straight down to the soil at the parent's feet. That is exactly what Arathi Seshadri of Colorado State University discovered in 2012. The parachutes of urban dandelion seeds, she found, are more elongated and drop up to twice as fast as the parachutes holding dandelion seeds out in traditional meadows.

Ironically, this adaptation is similar to what a relative of the dandelion, cat's ear (Hypochaeris radicata), has undergone in a natural, extreme environment. On tiny islets off the Canadian western coast, cat's ear has evolved seeds that descend faster than those of plants on the mainland. Here the risk of being blown out to sea drove the modification.

BRIGHT LIGHTS, BIG CITY

Continuing our field trip to uncover urban evolution, Frank and I emerge from the alley and cross the main street to reach the river, Galgenwater(Gallows' Water). A cluster of houseboats hugs the embankment where Rembrandt's birthplace once stood. As we approach a suspension bridge, we notice spider webs everywhere: between bars on the bridge railings, against the windows of the houseboats. Large circular webs, ranging in size from dessert plates to bicycle wheels, glisten in the sun. The sucked-dry corpses of midges and moths hang from the threads, a reminder of the gallows that once stood here.

DOWNTOWN ADAPTERS: Dandelions in cities are reshaping their seeds so they drop straight down into precious small patches of soil. Bridge spiders, which usually avoid sunlight, are bravely spinning webs under streetlights.

The bridge spiders (Larinioides sclopetarius) themselves are nowhere to be seen. The species is nocturnal, hiding in crevices that block daylight, waiting for night to venture to the web hubs to snare prey. Yet these webs are constructed right below the bridge lights. This now urban spider has thrown tradition to the wind because the lights attract insects. In the 1990s Austrian arachnologist Astrid Heiling determined that urban bridge spiders are born with a love for artificial light, even though they still avoid sunlight.

Interestingly, an opposite evolution is happening in at least one species of the spiders' prey. For insects, the lure of a lightbulb is often fatal. They get fried by the heat, exhaust themselves circling the lamp when they should be feeding or mating, or end up in a bridge spider's jaws. Many entomologists believe the attraction to light is so hardwired in an insect's brain that it cannot switch off, even in the face of a severe death toll.

SURVIVAL SKILLS: Pigeons, unafraid of the author, must learn to hide from the rising number of urban peregrine falcons that hunt them. Snails that live on city walls are evolving lighter shells to absorb less heat.

But Swiss entomologist Florian Altermatt was not convinced. He targeted the small ermine moth (Yponomeuta cagnagella). He collected hundreds of the caterpillars in the illuminated center of Basel and a similar number in dark forests outside the city. He reared them all in the lab and gave each moth a little paint mark to denote its urban or rural origin. Then he released more than 1,000 of them in a large dark cage that had a single fluorescent tube at one end. True to form, the rural moths tended to hover near the lamp, but the urban ones were more likely to ignore the light and settle elsewhere in the cage. Apparently, Altermatt concluded, the urban moths had evolved a resistance to artificial light.

RAPID EVOLUTION

The handful of examples of urban Darwinism that Frank and I encountered on our brief stroll represent a ubiquitous process under way in city ecosystems around the globe. In addition to the heat island effect, impervious surfaces and light pollution, urban wildlife faces a panoply of other challenges: noise, chemical pollution and traffic, to name but a few. Urban evolutionary biologists have found many instances of wildlife adapting to such stressors. Some creatures can even overcome the seemingly insurmountable obstacle of heavy toxic pollution. Andrew Whitehead of the University of California, Davis, and his colleagues found that little estuarine fishes on the U.S. East Coast, called mummichogs, have developed tolerance to PCB concentrations up to 8,000 times higher than what is normally lethal for them.

Perhaps even more important than physical and chemical factors are the biological ones. The new city dwellers rub shoulders with a motley crew of foreign species, brought in accidentally or intentionally: ornamental plants, agricultural crops and pests, domesticated pets, and all the insects and weeds that people unwittingly carry in on their clothes and vehicles. Together these organisms form an ecosystem of species that cohabit willy-nilly, without ever having had the opportunity to adapt to one another. This unorthodox mix sets the stage for the mutual evolution of new attack and defense abilities: exotic parakeets might adapt to feed on native city seeds, whereas native city birds could evolve immunities against foreign parasites.

Never before has an extreme habitat had such a global presence. It may turn out that all the intrepid creatures adapting in parallel to cityscape conditions could become more alike, coming up with the same solutions for the many pressures.

All these challenges and opportunities create a powerful mix in which urban species evolve rapidly. Substantial adaptation often happens in a couple of decades, sometimes only a few years. Mummichogs evolved their PCB tolerance in just a few dozen fish generations; theoretical models show that is about as fast as evolution could take place for them.

Many people doubt evolution can really happen so quickly. After all, Darwin wrote: “We see nothing of these slow changes in progress, until the hand of time has marked the long lapse of ages.” Yet under strong natural selection pressure, evolution can proceed much more rapidly than Darwin thought possible. This is especially true for organisms that can reproduce multiple times in a year.

In a meta-analysis of more than 1,600 case studies, published last year in the Proceedings of the National Academy of Sciences USA, a group of researchers led by Marina Alberti of the University of Washington found a clear signal that urbanization does speed up evolution, in some cases as much as double the rate. One of the strongest drivers of greater speed was the introduction of exotic species into an environment.

Given that rapid urban evolution is happening all around us, does that mean everything is fine? Will all species simply adapt to the human-altered habitats that will increasingly dominate Earth in our current geologic epoch, the Anthropocene? Sadly, no. Only certain species will be able to colonize, survive and thrive in cities. For each success story, there may be a dozen cases of urban extinction: species that simply could not adapt and therefore disappear. Many, many species will continue to need the reserves, protected areas, laws and other safeguards that allow pristine habitats to survive in the citified future.

Nevertheless, urban ecosystems expanding around the world do represent an exciting new phase in the history of life on Earth. Never before has an extreme habitat had such a global presence. Cities everywhere share a suite of common features that flora and fauna will adapt to in similar ways. Perhaps spare-time naturalists can help the full-timers track the extent and pace of change. Many urban species, such as city pigeons, white clover and dandelions, are prevalent across the planet; a global community of citizen scientists could effectively monitor how they are changing. (Indeed, the evolution of yellow-shelled grove snails was revealed by volunteers using the smartphone app SnailSnap, which has yielded data on more than 12,000 snails in Dutch cities.)

It may turn out that all those intrepid creatures adapting in parallel to comparable cityscape conditions could become more alike, coming up with the same solutions for the many pressures. Global homogenization could be the characteristic that actually sets urban evolution apart from “natural” evolution and become the hallmark of human influence on other species. Because such a situation is unprecedented ecologically, we can only guess what the future will hold.

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Alone in the Milky Way

Why we are probably the only intelligent life in the galaxy

By John Gribbin

IN BRIEF

With so many exoplanets out there in the galaxy, it seems reasonable to hope that life may be prevalent. But a series of unusual coincidences occurred to give rise to our intelligent civilization, and it is quite unlikely such serendipity has taken place elsewhere.

The timing of our solar system's birth in the history of the galaxy was fortuitous, for example, as is our location in the Milky Way. Furthermore, several features of our planet are very rare, and the conditions that sparked the evolution of life here might be irreproducible.

Perhaps most unlikely of all was the development of our technological species from those first sparks of life—a feat that is probably unique.

Astronomers have now found thousands of planets orbiting other stars in the Milky Way, and 100 billion more stars in the galaxy presumably host planets of their own. Given the sheer number of worlds out there, scientists find it easy to hope that some of them must be harboring sentient beings. After all, could Earth really be unique among so many planets?

It could. Optimism about the possibilities of intelligent extraterrestrial life ignores what we know about how humans came to exist. We are here because of a long chain of implausible coincidences—many, many, many things had to go right to result in the situation in which we find ourselves. This chain is so implausible, in fact, that there is good reason to conclude that humans most likely are the only technological civilization in the galaxy. (Let us leave aside the other countless galaxies in the cosmos because, as the saying has it, "in an infinite universe, anything is possible.")

SPECIAL TIMING

The coincidences begin with the manufacture of heavy elements, which include everything heavier than hydrogen and helium. The first stars were born in clouds of these two lightest elements, the residue of the big bang, more than 13 billion years ago. They cannot have had planets, because there was nothing to make planets from—no carbon, oxygen, silicon, iron or any other metals (with cavalier disregard for chemical subtleties, astronomers call all elements heavier than hydrogen and helium metals).

Metals are created inside stars and spread through space when stars throw off material as they die, sometimes in spectacular supernova explosions. This material enriches interstellar clouds, so each successive generation of stars made from the clouds will have a greater metallicity than the one before it. When the sun came into being about 4.5 billion years ago, this enrichment had been going on for billions of years in our galactic neighborhood. Even so, the sun contains roughly 71 percent hydrogen, 27 percent helium and just 2 percent metals. Its composition mirrors that of the cloud that made the solar system, so the rocky planets, including Earth, formed from only that tiny amount of elemental construction material. Stars older than the sun have even fewer metals and, correspondingly, less chance of making rocky, Earth-like planets (giant gaseous planets, such as Jupiter, are easier to form but not as likely to host life). This means that even if we are not the only technological civilization in the galaxy, we must be one of the first.

SPECIAL LOCATION

Our place in the Milky Way is also propitious. The sun is located in a thin disk of stars about 100,000 light-years across; it is roughly 27,000 light-years from the galactic center, a little more than halfway to the rim. By and large, stars closer to the center contain more metals, and there are more old stars there. This situation is typical of disk galaxies, which seem to have grown outward from the center.

More metals sounds like a good thing from the point of view of making rocky planets, but it may not be so good for life. One reason for the extra metallicity is that stars are packed more densely toward the center, so there are many supernovae, which produce energetic radiation—x-rays and charged particles known as cosmic rays—that is harmful to planets of nearby stars. The galactic center also is home to a very large black hole, Sagittarius A*, which produces intense outbursts of radiation from time to time.

Then there is the problem of even more energetic events called gamma-ray bursts. Using recent gravitational-wave studies, astronomers learned that some of these explosions are caused by merging neutron stars. Observations of gamma-ray bursts in other galaxies show that they are more common in the crowded inner regions of galaxies. A single burst could sterilize the core of the Milky Way, and statistics based on studies of other galaxies suggest that one occurs in ours every one million to 100 million years.

Farther from the center, all these catastrophic events have less impact, but stars are sparser and metallicity is lower, so there are fewer rocky planets, if any. Taking everything into account, astronomers such as Charles H. Lineweaver of the Australian National University infer that there is a “galactic habitable zone” extending from about 23,000 to 30,000 light-years from the galactic center—only about 7 percent of the galactic radius, containing fewer than 5 percent of the stars because of the way they are concentrated toward the core. That region still encompasses a lot of stars but rules out life for the majority of them in our galaxy.

The sun is close to the middle of the habitable zone, but other astronomical idiosyncrasies distinguish our solar system. For example, there is some evidence that an orderly arrangement of planets in nearly circular orbits providing long-term stability is uncommon, and most planetary systems are chaotic places, lacking the calm Earth has provided for life to evolve.

SPECIAL PLANET

All the talk of Earth-like planets obscures another critical distinction. Astronomers have found around 50 of these worlds, but when they say “Earth-like,” all they mean is a rocky planet in the habitable zone that is about the same size as ours. By this criterion, the most Earth-like planet we know is Venus—but you could never live there. The fact that you can live on Earth is the result of fortuitous circumstances.

The two planets differ in several important ways. Venus has a thick crust, no sign of plate tectonics and essentially no magnetic field. Earth has a thin, mobile crust where tectonic activity, especially around plate boundaries, brings material to the surface through volcanism. Over Earth's long history, this activity has carried ores up to where humans can mine them to provide the raw materials for our technological civilization. Plate tectonics has also brought nutrients to the surface to replenish those that get depleted by the cells living there, and it is crucial for recycling carbon and stabilizing the temperature over long timescales. Earth also has a large metallic (in the everyday sense of the word) core that, coupled with its rapid rotation, produces a strong magnetic field to shield its surface from harmful cosmic radiation. Without this screen, our atmosphere would probably erode, and any living thing on the surface would get fried.

All these attributes of our planet are directly related to our moon—another feature that Venus and many other Earth-like planets lack. Scientists' best guess is that the moon formed early in the solar system's history, when a Mars-size object struck the nascent Earth a glancing blow that caused both protoplanets to melt. The metallic material from the two objects settled into Earth's center, and much of our planet's original lighter rocky material splashed out to become the moon, leaving Earth with a thinner crust than before. Without that impact, Earth would be a sterile lump of rock like Venus, lacking a magnetic field and plate tectonics. The presence of such a large moon has also acted as a stabilizer for our planet. Over the millennia Earth has wobbled on its axis as it goes around the sun, but thanks to the gravitational influence of the moon, it can never topple far from the vertical, as seems to have happened with Mars. It is impossible to say how often such impacts occur to form double systems such as Earth and its moon. But clearly they are rare, and without our satellite we would likely not be here.

SPECIAL LIFE

Once the Earth-moon system settled down, life emerged with almost indecent rapidity. Leaving aside controversial claims for evidence of even earlier creatures, scientists have found fossil remains of single-celled organisms in rocks 3.4 billion years old—just about a billion years younger than Earth itself. At first, this sounds like good news for anyone hoping to find extraterrestrials—surely if life got started on Earth so soon, it could arise with equal ease on other planets? The snag is that although it started, it did not do much for the next three billion years. Indeed, microbes that are essentially identical to those original bacterial cells still live on Earth today—arguably the most successful species in the history of life on our planet and a classic example of “if it ain't broke, don't fix it.”

These simple cells, known as prokaryotes, are little more than bags of jelly, containing the basic molecules of life (such as DNA) but without the central nucleus and specialized structures such as mitochondria, which use chemical reactions to generate the energy needed by the cells in your body. The more complex cells, the stuff of animals and plants, are known as eukaryotes, and they are all descended from a single merging of cells that occurred about 1.5 billion years ago.

The merger involved two types of primordial single-celled organisms: bacteria and archaea. The latter are so named because they were once thought to be older than bacteria. The evidence now suggests that both forms emerged at about the same time, when life first appeared on Earth—meaning that however life got started, it actually emerged twice. Once it was here, it went about its business largely unchanged for about two billion years. That business involved, among other things, “eating” other prokaryotes by engulfing them and using their raw materials.

Then came the dramatic turning point: An archaeon engulfed a bacterium but did not “digest” it. The bacterium became a resident of the new cell, the first eukaryote, and evolved to carry out specialized duties within it, leaving the rest of the host free to develop without worrying about where it got its energy. The cell then repeated the trick, becoming more complex.

The similarities between the cells of all advanced life-forms on Earth show that they are descended from a single single-celled ancestor—as biologists are fond of saying, at the level of a cell there is no difference between you and a mushroom.

Of course, the trick might have happened more than once, but if it did, the other protoeukaryotes left no descendants (probably because they got eaten). It is a measure of how unlikely such a single fusion of cells was that it took two billion years of evolution to occur.

Even then, not much happened for another billion years or so. Early eukaryotes got together to make multicellular organisms, but at first these were nothing more than flat, soft-bodied creatures resembling the structure of a quilt. The proliferation of multicellular life-forms that led to the variety of life on Earth today only kicked off nearly 550 million years ago, in an outburst known as the Cambrian explosion. This was such a spectacular event that it is still the most significant one in the fossil record. But nobody knows why it happened—or how likely it is to happen elsewhere. Eventually that eruption of life produced a species capable of developing technology and wondering where it came from.

SPECIAL SPECIES

The progression from primitive to advanced species was not easy. The history of humanity is written in our genes, in such detail that it is possible to determine from DNA analysis not only where different populations came from but how many of them were around. One of the surprising conclusions from this kind of analysis is that groups of chimpanzees living close to one another in central Africa are more different genetically than humans living on opposite sides of the world. This can only mean that we are all descended from a tiny population of humans, possibly the survivors of some catastrophe or catastrophes.

Even if we are not the only technological civilization in the galaxy, we must be one of the first. Is another such civilization likely to exist today? Almost certainly no.

DNA evidence pinpoints two evolutionary bottlenecks in particular. A little more than 150,000 years ago the human population was reduced to no more than a few thousand—perhaps only a few hundred—breeding pairs. And about 70,000 years ago the entire human population fell to about 1,000. Although this interpretation of the evidence has been questioned by some researchers, if it is correct, all the billions of people now on Earth are descended from this group, which was so small that a species diminished to such numbers today would likely be regarded as endangered.

That our species survived—and even flourished, eventually growing to number more than seven billion and advancing into a technological society—is amazing. This outcome seems far from assured.

As we put everything together, what can we say? Is life likely to exist elsewhere in the galaxy? Almost certainly yes, given the speed with which it appeared on Earth.

Is another technological civilization likely to exist today? Almost certainly no, given the chain of circumstances that led to our existence. These considerations suggest we are unique not just on our planet but in the whole Milky Way. And if our planet is so special, it becomes all the more important to preserve this unique world for ourselves, our descendants and the many creatures that call Earth home.

ABOUT THE AUTHOR

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