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Wild things

Life on Earth, Charles Darwin wrote in *On the Origin of Species*, is full of "endless forms most beautiful and most wonderful". Anyone who has visited a rainforest, a coral reef or even an English meadow knows what he was talking about. Life is dazzling, fecund, diverse and yet fragile. Earth is the only planet we know where it exists, and we are right to exult in it.

This issue of *New Scientist: The Collection* is dedicated to Earth's stunning, fascinating and most fragile wildlife. From the tropics to the poles, the depths of the oceans to the peaks of the Himalayas, life is everywhere. In these pages you'll encounter the most interesting organisms the planet has to offer complemented with stunning wildlife photography.

We begin, in Chapter 1, with our own kin: the mammals. From the plight of the rarest primates to the extraordinary social bonds of some of the largest animals on Earth, these are tales of survival, recovery and, in some cases, extinction. Pulling the stories together, it is possible to see a glimmer of hope for the 26 remaining Hainan gibbons in the remarkable comebacks of Europe's large predators and Canada's adorable sea otters. Or will they go the way of the world's largest ape and the mysterious wolf of the south Atlantic?

In Chapter 2, we take to the skies. Birds are no less fascinating than mammals, and in some cases equally imperilled. One particularly poignant story is the operation to save the Chatham Island black robin, a heroic and successful effort – although it did have a strange effect on the bird's eggs. You'll also meet pelicans, cormorants, wild turkeys and an owl that appears to be horribly lost.

Chapter 3 is all about the oceans and the fascinating beasts that live in it. Did you know that by eating vast quantities of fish and krill, whales make the oceans richer not poorer? That a sly red devil is taking over the eastern Pacific? Or that one of the most valuable materials on Earth is rotten marine excrement? One of our writers has gone hunting for it, so you don't have to.

Chapter 4 brings us back to earth with an exploration of some of the most peculiar plants the planet has to offer. Some are carnivorous and seem to draw in small bats and shrews. Others, incredibly, show signs of intelligence.

Chapter 5 is dedicated to the cold, slimy and yet oddly endearing. We learn that the "Lazarus frogs" offer hope for a group of animals that has been decimated by a ferocious fungus, and then head to the Balkans on a quest to find the world's largest and fiercest cave dweller (spoiler alert: it is neither very large nor very fierce, but incredibly rare). Along the way, we learn a thing or two about where snakes come from and how turtles find their way home.

The weirdest and most wonderful wild things are saved for last. Chapter 6 is all about the extremes, from the Arctic Ocean's very own sea unicorns to the tiniest geckos, fish and frogs, which fit on a human fingernail. What is the biggest organism on Earth? The oldest? The driest? All will be revealed.

Catherine Brahic, Editor

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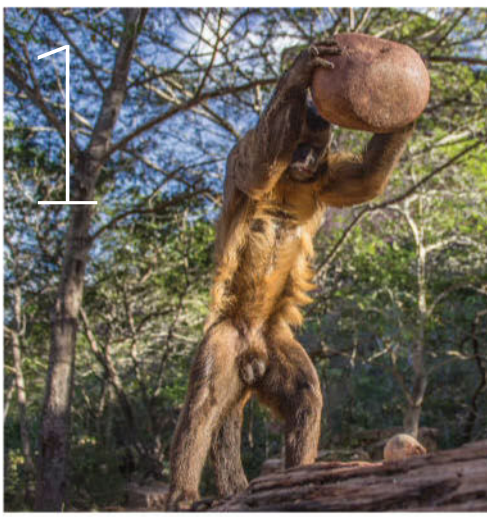

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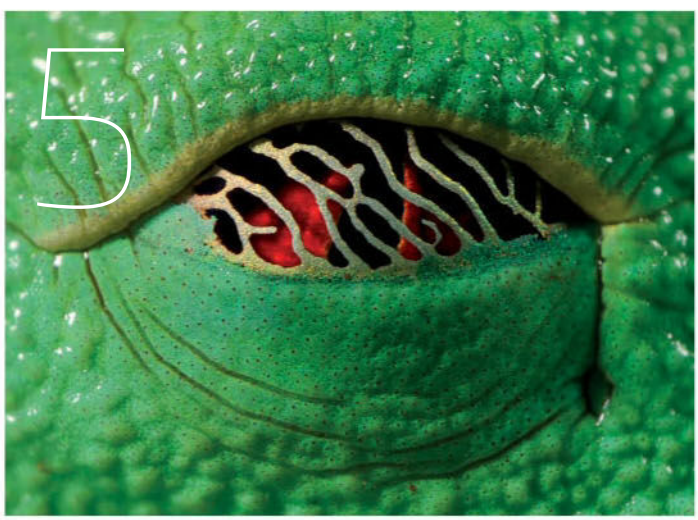

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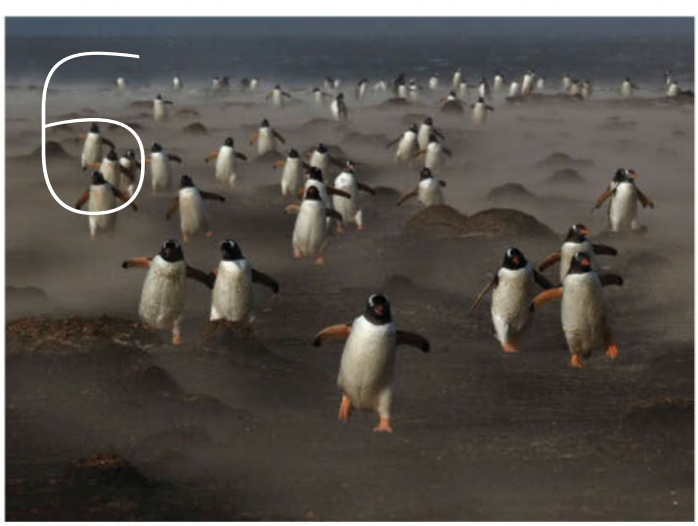


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CHAPTER ONE

MAMMALS

Tough nut to crack

CRACKING this nut will take strength, skill and a grasp of physics – and the capuchin is equal to the task.

The monkeys choose nuts that are easiest to split. An individual finds a groove in a log where one fits snugly, placing the flattest surface of the nut face down so that it's stable. Then it chooses a heavy stone, raises it above its head and hammers the nut with force.

The behaviour is considered one of the most complex forms of tool use by non-human species, putting the capuchin on a par with chimpanzees.

This alpha male, weighing 4.2 kilograms, is using a 3.5 kilogram stone to break into a piassava nut in Fazenda Boa Vista, Brazil.

He was photographed by Luca Antonio Marino, a biology student at Roma Tre University in Rome, Italy, who studied the foraging strategies of wild capuchins for his master's thesis. The image was a runner-up in the behaviour category in the Royal Society Publishing photography competition.
Sam Wong

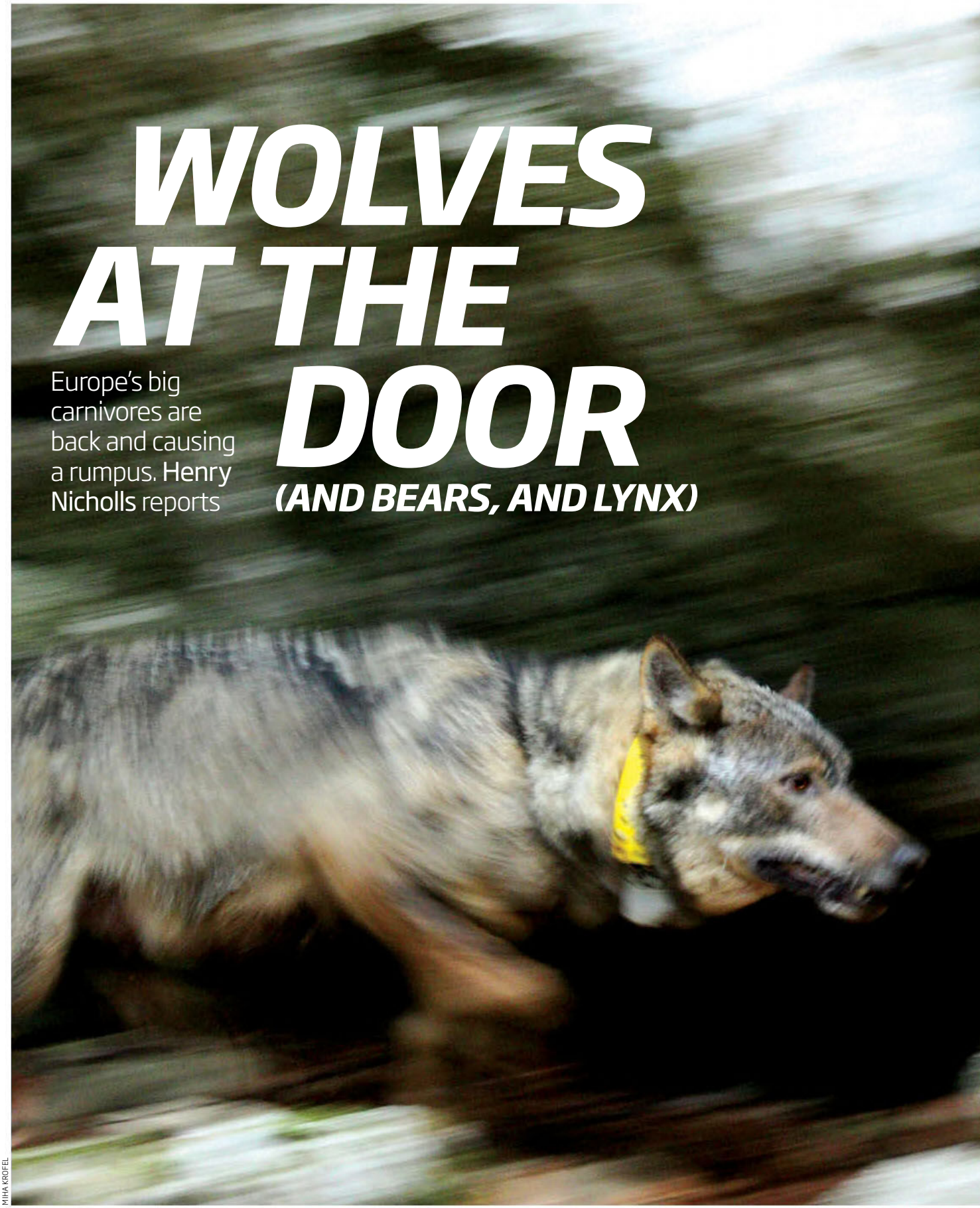
Photographer

Luca Antonio Marino
lucamarino.weebly.com

WOLVES AT THE DOOR

(AND BEARS, AND LYNX)

Europe's big carnivores are back and causing a rumpus. **Henry Nicholls** reports



MIHA KROFEL

NOBODY will ever know why Slavc abandoned his family. But in the winter of 2011, the young male wolf left his home territory and began an epic trek. He had spent the first years of his life meandering through the forests of southern Slovenia, occasionally straying into Croatia. Then, as Christmas approached, he struck out towards the north, alone.

Slavc was one of an estimated 4000 wolves living on the Balkan peninsula of south-eastern Europe, a continent not usually known for its big, fierce predators. Twenty years ago that was quite right, but no longer. Europe – the most urbanised, industrialised and farmed continent on Earth – is now home to some 12,000 wolves, 17,000 brown bears and 9000 Eurasian lynx. To put that in perspective, there are as few as 32,000 lions left in Africa and fewer than 2000 tigers in India.

The return of Europe's big three is an uncelebrated conservation success story. But as these charismatic mammals recolonise places they disappeared from long ago, age-old tensions between man and beast are starting to return. Can humans and wild predators really live alongside each other in harmony in Europe?

Several months before Slavc left home, ecologists had fitted him with a GPS collar programmed to send its position seven times a day. By the middle of December, it was clear he had left home for good.

"We knew something was different because he had crossed two large motorways far outside his home territory," recalls Hubert Potočnik, a biologist at the University of Ljubljana in Slovenia. At one point the collar pinged a signal from the centre of a town called Vipava. Potočnik was worried that the wolf had been shot. But just as he was about to call the police, another signal showed that Slavc was on the move again.

A week later, having travelled some 200 kilometres north, Slavc crossed into Austria. On New Year's Eve he reached the river Drava. That night Potočnik received two signals, one from the south bank and one from the north. Slavc had swum across the river.

Bears, wolves and lynx were once widespread across Europe – including the British Isles – but centuries of hunting, persecution and habitat destruction took their toll. Reliable numbers are hard to come by, but by the mid-20th century, the big three had effectively been exterminated everywhere except for small, precarious populations on the continent's wildest fringes.

In the 1970s, however, there was a U-turn in attitudes. The environmental movement raised awareness of the predators' plight and laws protecting them came into force.

By happy coincidence, changes in land use after the second world war – particularly reforestation – led to a boom in the prey species on which carnivores depend. "The carnivores didn't hang around," says John Linnell of the Norwegian Institute for Nature Research in Trondheim and a member of the International Union for Conservation of Nature's Large Carnivore Initiative for Europe. "They just said 'thank you'."

As well as natural expansion there were also some deliberate reintroductions – lynx to several areas of central Europe in the 1970s and 1980s, for example, and bears to the Pyrenees and Italian Alps in the 90s. With a few exceptions, populations are now stable or growing (see maps, page 10).

Wolves in particular continue to recolonise former territories. In 2012, birdwatchers in Thy National Park in northern Denmark reported seeing the first wolf in the country for some 200 years. A few weeks later it was found dead, apparently from natural causes. DNA analysis showed that it had come from a pack inhabiting the borderlands between Germany and Poland, almost 1000 kilometres away.

But it hadn't come alone. It is thought that there are now at least three wolves in the country. And if wolves can re-establish themselves in the fragmented habitat of Denmark, they can probably do it anywhere.

Hiding in the dark

One of the challenges of counting large carnivores is their secretive and mainly nocturnal nature. "These animals are masters at being there but not being seen," says Linnell. "Lynx, especially, are invisible." In a 20-year career he has only ever seen lynx while capturing them to fit radio collars.

As a result, there are arguments over how many animals are actually out there. Head counts are impossible so researchers have to make use of indirect methods, which usually means working with faeces. "You pick up a piece in the woods and you go home and work out which species, which sex, which individual it is," says Linnell.

Slovenia, for example, has a network of some 2500 foresters, hunters and ›

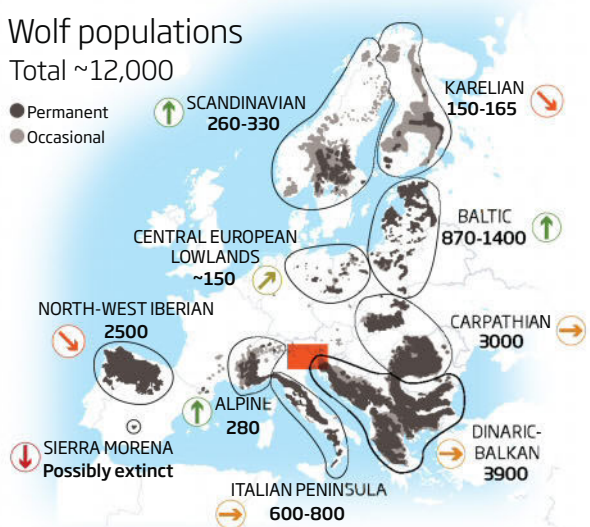
LASSI RAUTIAINEN/NATUREPL

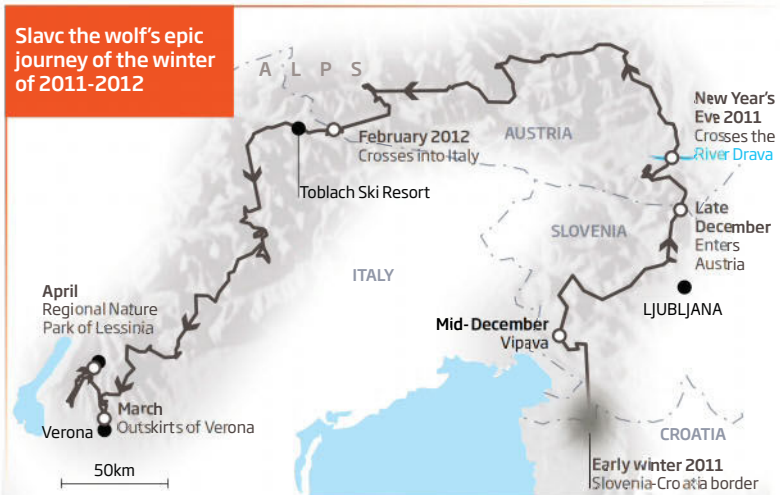
A wolf in Slovenia with a GPS collar (left); wolves approach a bear in Finland (below)

Numbers of the beasts

Europe is now home to approximately 40,000 large predatory mammals

Strongly increasing · Increasing · Stable · Decreasing · Strongly decreasing





volunteers who collect scats, urine and other samples such as hair and saliva swabbed off dead livestock and send them to Potočnik's colleague Tomaž Skrbinšek. By analysing the DNA in these samples, it's possible to estimate the size of the population. The latest data suggests that the country's wolf population has remained stable over the past three years, at around 40 to 50 individuals in nine or 10 packs.

GPS readings like those from Slavc's collar yield other insights. "Everyone thinks these animals live in the forest and they don't move," says Linnell. "Yet every time you put on a collar and track them you find these animals cover huge areas." A single lynx, bear or wolf can cover 1000 square kilometres or more.

In heavily populated Europe, that inevitably means coming into contact with people. As the Large Carnivore Initiative for Europe's manifesto puts it: "wild areas without human land-use or activity… are virtually non-existent in Europe".

That seems to suit the animals just fine. "I don't think there's anywhere they couldn't live if they were allowed to," says Linnell. Even cities aren't off limits: in Brasov, Romania, bears make frequent, bold visits to gorge themselves on garbage. In 2008, a 20-year-old man was killed by a bear in the city centre.

As Slavc headed across Austria, through farmland, villages and around the edges of towns, Potočnik became increasingly anxious that he would have a run-in with farmers.

The concern is a real one, especially for wolves, which have the biggest impact on livestock. Bears and lynx will also take livestock, but because they are solitary and only tend to pick off one animal at a time they don't generate the same hostility.

The impact can be costly. Exact numbers are impossible to obtain but unofficial estimates suggest that between 50,000 and 100,000 livestock, mostly sheep, are killed each year. Bears also cause costly damage to bee hives, orchards, vehicles and buildings. "The situation is getting worse," says Pekka Pesonen, secretary-general of Copa-Cogeca, the voice of farmers in the EU.

Fences and guard dogs

Governments pay out millions of euros a year in compensation for these losses, which may explain why initiatives are being rolled out across Europe to encourage farmers to reintroduce old methods of protection, notably fences, guard dogs and shepherds.

There are, however, limitations to these measures. Putting up fences in mountainous

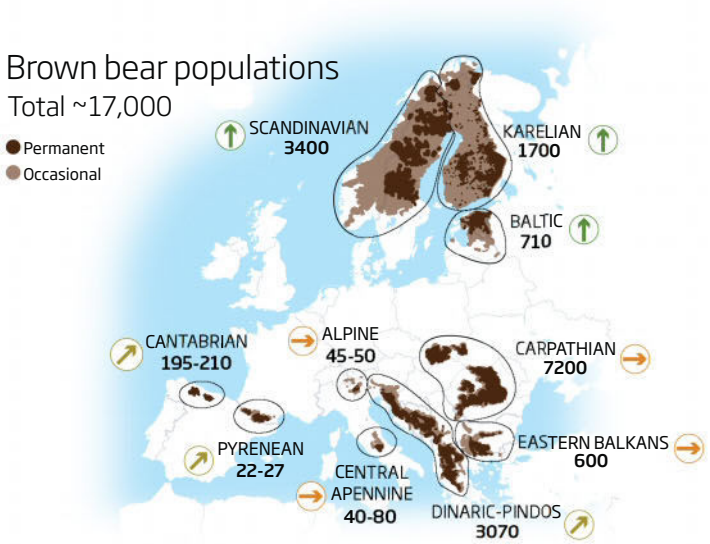
MIHA KROFEL

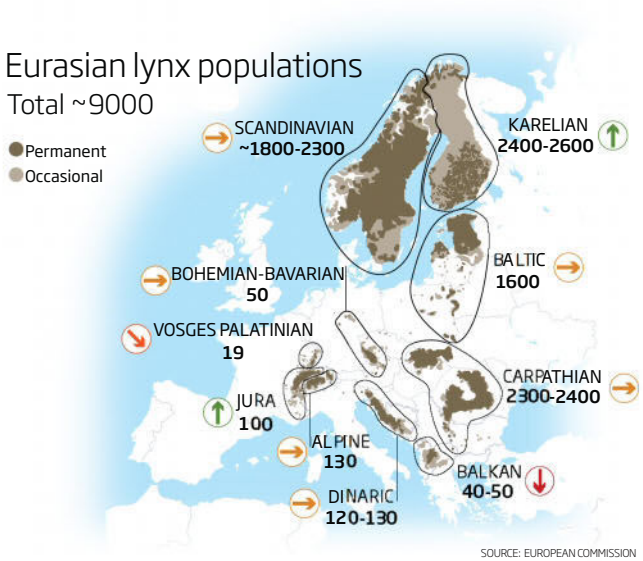
KNOW YOUR WILD BEASTS

EURASIAN LYNX (see left)
(Lynx lynx)
A medium-sized cat distributed patchily across Eurasia from the western Alps to Siberia. Adult males are about the size of a golden retriever. Not to be confused with the critically endangered Iberian lynx, which is confined to southern Spain.
Danger to humans? No.
Best place to see: A zoo. In the wild the best you can realistically hope for is to see tracks in the snow.

EURASIAN BROWN BEAR
(Ursus arctos arctos)
Europe's largest native carnivore, though it eats fruit, nuts, vegetables and honey as well as meat. An adult male can weigh up to 320 kilograms.
Danger to humans? Yes. Attacks are rare but do happen, mostly in Romania.
Best place to see: Eastern Finland, close to the Russian border, where close-up views are possible in special bear hides.

EURASIAN WOLF
(Canis lupus lupus)
Europe's most widespread and successful large mammalian carnivore, and also its most controversial.
Danger to humans? Yes. Though Western Europe hasn't seen an attack by a wild wolf for decades.
Best place to see: The plains and wetlands of central and north-west Spain, home to a population of about 2500 wolves.





SOURCE: EUROPEAN COMMISSION

or forested terrain is impractical, electric fences require monitoring and there are labour costs associated with shepherds and guard dogs. In Italy, there is strong resistance from farmers to implementing these kinds of measures. "Some of them refuse out of principle," says Valeria Salvatori of the Institute of Applied Ecology in Rome, who is also a member of the Large Carnivore Initiative for Europe.

Pesonen puts it more bluntly. "By no means should farmers accept the costs resulting from the presence of large carnivores," he says.

Another group with strong views is hunters. Some have a sense of empathy with their fellow predators; a few want to hunt them. As a general rule, however, most express concern about competition for game species like deer.

Sometimes tensions boil over. In 2013, a group of men in rural Finland organised an illegal wolf hunt in protest at what they saw as preferential treatment for the carnivores. They killed three wolves before they were stopped; the ringleader later shot himself. His suicide note blamed his death on the green movement and the EU.

Such illegal hunting is quite widespread, says Linnell. Again there are no numbers, but there is some evidence that poaching in the Alps may be causing lynx, bears and wolves to decline. The same may be happening to Finland's wolves, he says.

In recognition of these growing tensions, in June 2014 the EU launched the Platform on the Coexistence between People and Large Carnivores, a forum to promote dialogue and understanding.

In some cases that means taking difficult decisions. Carnivores are heavily protected by European law: with the exception of Estonia, where lynx hunting is permitted, it is illegal to kill a bear or a lynx anywhere in the EU. Wolves are a different story. They are protected, but strictly controlled culls are carried out in many countries to keep the population stable.

For many people this might seem like a backward step. But such intervention can benefit wolves, says Cy Griffin, director of conservation at FACE, the European Federation of Associations for Hunting and Conservation. It can also serve a political purpose, he says. "The controlled management of some of those populations is going to be a very useful tool for easing some of those tensions."

The Large Carnivore Initiative for Europe agrees. "As long as hunting is humane, regulated and sustainable then it may well be the price of acceptance," says Linnell.

For Garry Marvin, an anthropologist at the University of Roehampton, UK, who studies conflicts between animals and humans, co-existence is possible. "I think we can live with large populations of wolves in Europe," he says. "The trick is to bring together the environmentalists, the biologists, the hunters and the farmers and get them to talk."

"There is no creature in Europe as emotionally charged as the wolf"

"There is no creature in Europe that is so emotionally charged, both for it and against it, as the wolf," Marvin continues. "It's one of the big tests of how you can get a proper conservation programme going. If you can do it over the wolf, you can do it over anything."

Somehow, Slavc managed to navigate his way to the Alps without getting into trouble. In February 2014, he battled through snowdrifts that were 6-metres-deep in order to cross a mountain pass. Soon afterwards he entered Italy, crossed several ski runs and then headed south.

By now Slavc's travels were well known to Potočnik's colleagues in Austria and Italy. In March a forestry official sent him a video of a wolf in the Regional Natural Park of Lessinia north of Verona – the first sighting of a wolf there for almost 100 years. It wasn't Slavc, but a female. "We started joking that Slavc was on his way to find her," says Potočnik.

But Slavc bypassed Lessinia and continued into the vineyards on the fringes of Verona. What drew him was probably a female wolf in a private zoo on the outskirts of the city. Unable to break in, Slavc loped back north.

In April, Slavc finally entered the Lessinia park. Potočnik asked a park manager to check out a couple of GPS coordinates. She found the tracks of two wolves. Later in the year a camera trap photographed two wolf pups, the first time in recorded history that a wolf from the Balkans had bred with a wolf from the Apennines. With such a powerful love story set so close to Verona, it was inevitable that the Italian media would name the female Juliet.

Slavc's collar ceased transmission in August 2012 so Potočnik can no longer keep regular tabs. But his excitement is undiminished. As far as he can tell, Slavc and Juliet are still together. "They probably have another litter this year," he says. "Following Slavc across Europe offered a rare insight into the secret life of the wolf. It was one of the most amazing events in my life." ■

The rarest of them all

YANG GUANYU/XINHUA/ALAMY LIVE NEWS

When Sam Turvey stared into the face of a Hainan gibbon he knew he had to join the effort to save the world's rarest mammal

IN TINY villages, home to Li and Miao communities, the tattooed old folk still tell stories about gibbons. Stories about the pair of orphans driven out by an evil stepmother, who hid in the trees and turned into apes; or the bet between the gibbon and the earthworm over who could climb the best. But very few of the storytellers have ever seen a gibbon.

The tales are told on Hainan, China's southernmost province, an island the size of Belgium in the South China Sea. Once a sleepy backwater, it is now a top tourist destination, known for its white sand beaches and golf courses. It is also the last stand of the Hainan gibbon. Forget orangutans, tigers and giant pandas: with just 26 or so left, this is the world's rarest mammal.

The Hainan gibbon has had it tough for some time. Visiting naturalists in the 19th century described the apes as rare. They were hunted heavily. Boiling a whole animal for a few days until it was reduced to a hairy paste was said to produce a potent traditional medicine. Chopsticks made from their long arm bones could supposedly be used to test for poison. Later, local forests were chopped down for timber and to make way for agriculture, worsening the ape's plight.

By the 1980s, the species was in dire straits, with only a few survivors in remote, forested mountains. They may have been saved by sheer luck. In one story, shortly after a hunter shot one of the last gibbons, his entire family died of some horrible disease, and killing gibbons became bad luck. Whether or not the story is true, a handful of animals somehow clung on in a nature reserve at Bawangling. I was privileged to come face-to-face with some of these survivors early one morning in 2010. There were seven of them, feeding, playing and grooming in the treetops: more than a quarter of all the Hainan gibbons left on Earth.

The 300 square kilometres of Bawangling's forest are fragmented by roads, power lines and plantations of rubber and pine. The gibbons are restricted to a 15 square kilometre patch, where, until recently, they lived in three social groups. Local rangers have monitored them for many years. The group I saw in 2010 was Group B – uniquely used to humans, which allows researchers to get reasonably close.

Hearing the Hainan gibbon's dawn chorus is a rare privilege

Group A is much more wary and usually vanishes before you can get anywhere near. Group C, which only formed a few years ago, has set up its territory close to the edge of the forest patch. Villagers in a nearby Miao village can hear them duetting at dawn every morning.

All three groups are breeding successfully, yet the overall population has stayed below 30 since the reserve was established in the 1980s. As they mature, young gibbons leave their social group and disperse into the forest, but in Hainan they rarely form new groups.

Getting to the bottom of what happens to these solitary animals is key: normally, new social groups drive population growth. Maybe

"A male appeared in the treetops, then a female with a baby: a new social group"

the gibbons have simply run out of space. Their small patch of forest, on the slopes of Futouling mountain, may also not be the best habitat for a species that once lived in lowland rainforests. And gibbons can be picky about mating. The remaining individuals could be so closely related that they are simply choosing not to mate with each other. Or perhaps human disturbance is stopping groups forming.

Thankfully, there has been a breakthrough. Until recently, wardens and researchers located the gibbons by listening for their dawn songs from posts high up on the Bawangling mountains. But solitary animals don't tend to sing. Last year, we trialled a technique widely used in bird surveys. We played a recording of a gibbon call in an area where no gibbons were thought to be. Amazingly, a male appeared in the treetops, drawn by the sound. Then a female showed up with a baby. This was a fourth, previously unknown social group.

JESSICA BRYANT

We hope that call-playback might also be useful for locating the cryptic solitary gibbons, but we need to think carefully about doing this. Playing gibbon calls could affect the behaviour of animals or stress them.

Once a species drops to perilously low numbers, it can remain vulnerable to extinction even if the factors responsible for the initial population crash – in this case, deforestation and hunting – are removed. In Hainan, there are only six breeding females left. It's not hard to imagine how a disease outbreak, typhoon or just a chance death could spell the end of the species. And with a population this small, the effects of inbreeding cannot be ignored. Any of these factors could push the Hainan gibbon into what conservation biologists call the "extinction vortex".

Despite this, I strongly believe we can save the world's rarest ape. It's not too late: the population seemed to hit a low of 13 in 2003 and has since grown, and two of the four groups at Bawangling formed in the past few years. But it's not going to be easy. We need a close collaboration between reserve staff, who understand the local politics and logistics of working in Hainan, and international organisations that have experience with extremely threatened species. A top priority has to be reconnecting the forest fragments in Bawangling. Long term, this means planting trees. In the short term, artificial canopy bridges may encourage gibbons to move between patches. The hard work is already under way, with local forest restoration projects supported by Kadoorie Farm and Botanic Garden in Hong Kong.

It is possible to bring species back from the very edge of existence. The Mauritius kestrel recovered from just four wild birds in the 1970s, and the Chatham Island black robin came back from five individuals in 1980 (see "On the edge", page 40). My hope is that we will one day be able to list the Hainan gibbon alongside these success stories and those lucky enough to visit Hainan will continue to hear the haunting dawn song of the gibbon. The alternative – that it will be remembered only in stories told by old villagers – is a future we cannot allow. ■

Pachyderm politics

It takes wisdom, experience and two X chromosomes to successfully lead a herd of elephants, finds **Lesley Evans Ogden**

IMAGEBROKER/FLPA

Like humans, elephants live in a complex fission-fusion society

ELEANOR was nearly 50 when she collapsed and died. While African elephants can live up to 70 years, female life expectancy is just 22 in her group in Samburu, Kenya, and Eleanor was the oldest member of her family – the matriarch. This made her passing particularly significant. For almost a week after her death her carcass was visited not just by members of her immediate family, but by a succession of animals from four unrelated families. Elephants are mysteriously curious about death, a response perhaps heightened when a leader dies.

It has long been clear that elephant groups rely on their elder stateswomen, but just how important these females are is only gradually becoming apparent. Matriarchs are at the hub of a complex, multilayered social network, and we are now getting insights into the nature of the ties that bind these close-knit groups and the key role that wise old leaders play in enhancing the survival of their members. Matriarchs carry with them a treasure trove of crucial information. They have a unique influence over group decision-making. And, like our own leaders, the most successful may even possess certain personality traits.

Much of what we know about elephant social life comes from research done at Amboseli National Park in Kenya, where the population lives in conditions close to a natural, undisturbed state. But this is unusual. Demand for ivory has surged in recent years. On the black market, a pair of tusks can fetch the equivalent of 15 years of an unskilled worker's salary, so the incentive for poachers is high. Once poachers have killed the biggest males, mature matriarchs are their next targets. What happens to a group that loses its matriarch is not clear. But one thing is certain; if we want to help elephants we need to understand the structure and function of leadership within their society.

Amboseli's elephants number around 1500. They roam over approximately 8000 square kilometres, inside and outside the park, and across international boundaries. With Mount Kilimanjaro towering in the distance, this is a region constantly in flux, which has big effects on its residents. For elephants, which must drink every day, access to water is the biggest issue. Although there are predictable wet and dry seasons, sometimes the rains fail. And seismic wobbles alter the flow and salinity of underground rivers feeding the springs and swamps on which elephants depend.

These are the world's longest studied elephants. Every individual is known and visually catalogued by distinct ear notches. And nobody knows them better than Cynthia Moss, who has led the Amboseli Elephant Research Project (AERP) since she founded it in 1972. After four decades of near-continuous observation of elephants going about their daily lives, she has a vast knowledge. In particular, Moss and her colleagues have discovered much about elephant families and their social interactions. "Our studies show how absolutely crucial matriarchs are to the well-being and success of the family," she says.

At Amboseli, the elephant family unit, consisting of a mother and her immature young, sometimes along with sisters, aunts and grandmothers, is the core of elephant society. Within family groups, which range in size from two to more than 20, the oldest, most experienced female takes the lead. But group size is constantly changing, responding to the seasons, the availability of food and water, and the threat from predators. An adult female elephant might start the day feeding with 12 to 15 individuals, be part of a group of 25 by mid-morning, and 100 at midday, then go back to a family of 12 in the afternoon, and finally settle for the night with just her dependent offspring. Known as a fission-fusion society, it is a complex social dynamic relatively rare in the animal kingdom, but not uncommon in primates, including humans.

It has long been assumed that the structure of the wider social network grows out of natural patterns of mother-offspring associations, where daughters remain within their group for life, while sons strike out on their own as teenagers. A team led by Beth Archie of the University of Notre Dame in Indiana – who at the time was at Duke University in Durham, North Carolina – decided to test this idea. By genetically analysing faecal and tissue samples from 236 elephants at Amboseli, they determined how closely related they were to each other, and then superimposed the familial ties onto observed patterns of association. They found a remarkable fit, indicating that the fission-fusion dynamic mirrors relatedness – the more closely related individuals are, the more time they tend to spend with one another.

"Matriarchs carry a treasure trove of crucial information and have a unique influence over their group"

So, at Amboseli at least, a matriarch heads up a group of her immediate relatives and the social network extends beyond this core family unit. Multiple families that engage in regular friendly associations, including ceremonial greeting and touching, are known as bond groups. These multifamily groupings can number as high as 70 to 100, but have historically averaged about 30 at Amboseli. Networks of elephants can reach further still, to include friendships between unrelated individuals, and less frequent aggregations of families known as clans, which when together can reach numbers in the hundreds.

To investigate the dynamics of multi-tiered elephant social networks from the level of ›

family to the population level, Moss, together with Vicki Fishlock, a resident scientist with the AERP, and Phyllis Lee from the University of Stirling, UK, have used a computer model to generate spiderweb-like "sociograms" indicating the extent and strength of associations. Analysing sightings of 31 families seen more than 500 times over four decades, they found something remarkable. While average family size has grown considerably, from 7 in the 1970s to 22 by 2011, families have become less cohesive, and spend less time associating with other families.

Mama knows best

Amboseli is an undisturbed population, so habitat fragmentation, poaching or other mass mortality have not driven this shift. Although it may be partially attributed to a slow social readjustment to a safe environment after protection from hunting and poaching in the late 1970s, Fishlock suspects that matriarchs hold the key. As the Amboseli population has thrived, matriarchs have become older, and families larger under their leadership. A family's propensity to spend time with other families within the network has declined. From Fishlock's network analyses of the Amboseli elephants, it looks like matriarchs become less gregarious and more conservative in their old age.

When it comes to survival, however, having a wise old matriarch to lead you is just as important as having other elephants to learn from in a wide social network. And the two influences are intertwined because that matriarch determines who is in your network to learn from. "Good matriarch decisions balance the needs of the group, avoiding unnecessary travel while remembering when and where good resources are available," says Fishlock. Studies in Amboseli have revealed that families with older, larger matriarchs range over larger areas during droughts, apparently because these females better remember the location of rare food and water resources. "The matriarch has a very strong influence on what everybody does," she says, although exactly how they communicate their will to the group remains a mystery.

The idea that groups led by older matriarchs might have a survival advantage gains support from a study of elephants in Tarangire National Park in Tanzania. In 1993, infant elephant death rates rose from an annual average of just 2 per cent to around 20 per cent during a nine month period of drought. With their dry-season refuge parched, some family groups stayed in the park, while others made off for places unknown. Young mothers were far more likely to stay put and to lose calves than older ones, and families that migrated out of the park had lower mortality than those that remained.

As well as being killed for their tusks, some elephants, like this one, die in conflicts over land

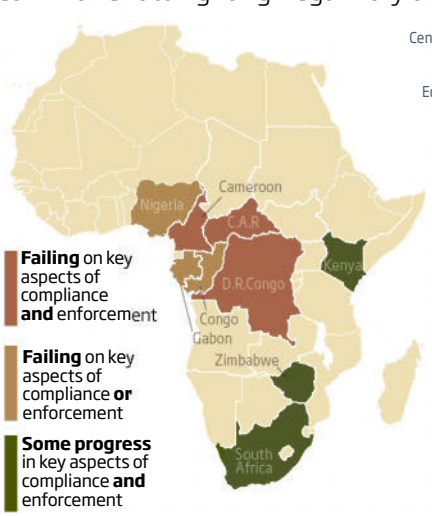
Since matriarchs lead long-distance group movements, it suggests that older females, with their specialised knowledge of where to go to find enough food and water, provide a survival advantage for their extended family, says Charles Foley of the Wildlife Conservation Society, who co-published the findings in 2008.

More recent and direct evidence of the benefits of wise old matriarchs has come from Karen McComb at the University of Sussex in the UK. Using recordings of lions roaring, she tested the responses of Amboseli matriarchs of different ages in the social context of their family group. Elephants encounter lions infrequently, but they are one of the few predators that pose a real threat, especially for young calves. That threat is enhanced if the lion is male, as males, unlike females, are capable of overpowering a young elephant even when hunting alone. McComb found that older elephants – aged 60 and over – seemed to listen longer to male than female roars, and their group huddled together more frequently and closely than did those of younger matriarchs. It suggests elephants defer to the knowledge of their elders, and that matriarchs call the shots when it comes to deciding what anti-predator strategy to adopt, she says.

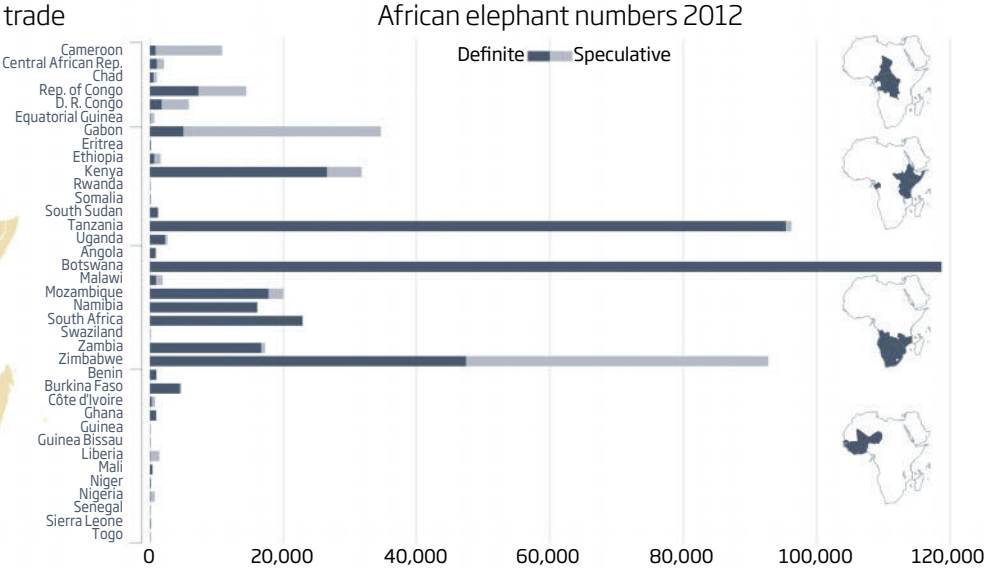
Taken for tusks: illegal ivory trade is on the rise

With growing demand from the Far East, poachers target mature female elephants as well as males

Commitment to fighting illegal ivory trade



African elephant numbers 2012



SOURCE: WWF.ORG / ELEPHANTDATABASE.ORG / CITES

MICHAEL NICHOLS/NATIONAL GEOGRAPHIC CREATIVE

Older matriarchs also seem to be better at judging "stranger danger" from other elephants. At Amboseli, each family group encounters some 25 other families in the course of the year, representing about 175 other adult females. Encounters with less familiar groups can be antagonistic and if a family anticipates possible harassment it assumes a defensive formation called bunching. McComb tested whether a matriarch's age influenced her ability to discriminate between contact calls. In a playback experiment, her team found that families led by older matriarchs were less reactive overall, but bunched more in response to the sound of less familiar individuals than did families led by younger females. They suspect this is because older matriarchs have a larger memory catalogue for elephant voices, allowing them to more precisely distinguish between familiar and unfamiliar ones, and respond appropriately.

There may be more to good leadership than just the wisdom that comes with age, though. Elephants appear to have personalities and Lee and Moss wonder whether certain character traits might be associated with effective leadership. They identified 26 traits possessed by elephants – things like confidence, fearfulness, opportunism and aggression – which group into four main personality dimensions: playfulness, gentleness, constancy and leadership. So far they have analysed just 11 adult females from one Amboseli family, and the matriarch does score highly in the leadership dimension. That may be expected. But by assessing more elephant families, the researchers hope to identify the traits shared by the most and least successful matriarchs, which in turn could help them pinpoint families best able to cope when the going gets tough.

> "It looks like matriarchs become less gregarious and more conservative in their old age"

If effective leadership is important in Amboseli, it is even more crucial in parts of Africa where threats are greater. During the 1980s, poaching halved Africa's elephant population. Things improved after activists and researchers including Iain Douglas-Hamilton, founder of Save the Elephants, alerted the world to the devastation and helped bring about an international trade ban on ivory in 1989. Relief came earlier in Kenya, where all trophy hunting, not just for elephants, was banned in 1978. However, in recent years poaching has been on the increase again as growing wealth in the Far East fuels demand for illegally procured ivory. The oldest animals with the largest tusks are prime targets.

An inkling of the potentially dire consequences of killing matriarchs for ivory comes from Mikumi National Park in Tanzania, where elephants were heavily poached before 1989. The effects are still measurable. In 2008, a team led by Kathleen Gobush, now at Save The Elephants, reported that elephant groups hardest hit by poaching had younger matriarchs, weaker social bonds and lower relatedness. Analysis of their faeces revealed high levels of glucocorticoids, indicating chronic stress. And compared with groups with intact social structures, only half as many females had infants under the age of 2. The stress of family disruption had clearly reduced their reproductive success.

Losing a leader

In northern Kenya's Samburu and Buffalo Springs National Reserves, where Eleanor lived, there are more signs that poaching is disrupting elephant family life. A team led by George Wittemyer at Colorado State University in Fort Collins superimposed the genetic relationships of elephants there onto the social relationships they had observed over five years. They found that in this disrupted elephant society, cohesive social groups had formed even between unrelated individuals. One of Wittemyer's graduate students is now focusing on elephants orphaned by poaching, looking at the physiological stress and behavioural changes that result from losing their families, and what these animals do to rebuild their lives and societies.

We do not yet know the full extent of the damage caused by the killing of wise old matriarchs. Given that they are instrumental in solving the everyday problems of keeping their groups fed, watered, safe and reproducing, their entire social network will feel the loss. But work by Wittemyer and Douglas-Hamilton on heavily poached elephant populations suggests that despite disruptions to social structure, over the long term, the elephants and their networks are resilient. They can and will recover if poaching pressure can be lifted, but that is a big "if".

Matriarchs may be adept at solving the problems faced by the elephants that look to them for leadership, but at the moment humans are their greatest problem, one that they cannot resolve for themselves. ■

ALL CANADA PHOTOS / ALAMY

The comeback cubs

The sea otter population is booming in Canada, with dramatic results. **Jude Isabella** reports

IT'S shortly after dawn on Canada's west coast. We're standing on a rocky islet, and below us are the animals we have come to watch: about 15 sea otters are grooming, snacking and snoozing in the ocean. Then four fishing skiffs zoom by and the otters scatter.

I'm here with marine ecologist Erin Rechsteiner, who has been watching sea otters at this particular spot since they first arrived in autumn 2013. The raft of males, numbering up to 130 animals in winter and spring, is a sea otter vanguard.

"We're right on the edge of their range, for the moment," Rechsteiner says. When the males turned up, they feasted on sea urchins. "We're watching them shift to different foods now that they've been here for a few months. It would be like if you arrive in town where no one else is around and you raid the candy store, and once the candy is hard to find you raid the vegetable garden next."

Once sea urchins become less common, though, the whole nature of the ecosystem changes. The sea otter's return to British Columbia's coast is a blitzkrieg, a lightning transformation of an ecosystem.

It is estimated that at least 300,000 sea otters roamed the coastline of the North Pacific, from Japan to California, when hunting began in earnest in the 1740s. Their luxurious fur was so sought after that only a few thousand remained by 1911, when commercial hunting was stopped.

Once protected, most of the surviving pockets of sea otters scattered around the Pacific bounced back remarkably rapidly, although their range remained small. In the 1960s, a few hundred sea otters were relocated to some of the places where they had been wiped out.

Today most populations are stable or growing, although there are a few exceptions. The recovery of the famous California population has been very slow and now seems to have stalled just short of 3000 animals. And in south-west Alaska, a thriving population was suddenly decimated in the 1990s, with as many as 65,000 being lost. It's not clear why: one idea is that declining seal numbers caused orcas to start feeding on the otters instead.

Here in British Columbia, 89 sea otters were reintroduced to Vancouver Island's west coast in the 1960s. The population now numbers about 5000, and the animals are advancing north up the coast. Rechsteiner and her colleagues at the Hakai Institute on Calvert Island are studying their advance.

Groups of otters are known as rafts because of their habit of floating together on the sea surface between dives, often holding hands to keep from drifting apart. Male rafts, like the one Rechsteiner watches, are the first to arrive in an otter-free zone and indulge in the stellar buffet on the ocean floor.

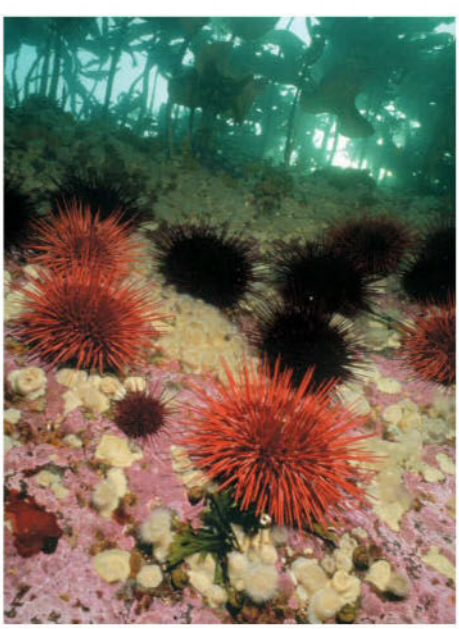
Obsessive groomers

The animals have a voracious appetite: while we eat food equivalent to around 2 per cent of our body weight each day, an otter consumes about 30 per cent. They have to eat so much to stay warm in these cold waters, especially as, unusually for a sea mammal, they have no blubber. Instead they have the fur that was so nearly their downfall, and to keep it warm and dry they have to groom it obsessively. As we see over the course of the day, eating and grooming take up much of their time.

Their favourite food is sea urchins – some of which may be a century old – and the result of their feasting is striking. Around the rocky islet, the ocean surface has been transformed, with bulbous kelp bobbing in the water where there was none a few months ago. With the remaining kelp-grazing sea urchins hiding in rock crevices to avoid otters, the ecosystem reaches a tipping point and the kelp forests return. "The urchins become lazy, scaredy-pants drift feeders and eat dead kelp as it passes them by," Rechsteiner says. "They no longer graze on kelp in the open or get out to mow down the kelp forest because if they're out in the open, an otter eats them."

Once they have devoured all the urchins, the males turn to clams, crabs, abalone and other shellfish. Rechsteiner suspects that within months, the raft will have moved on in search of another habitat rich in sea urchins. The pioneering males will be replaced by females, pups and territorial males waiting to mate. These resident otters will keep the urchins in hiding and the kelp thriving.

Where sea otters start feasting on urchins, kelp forests bloom on long-barren sea beds



VISUALS UNLIMITED/NATUREPL.COM

That's good news. "I always tell people they should appreciate kelp because it does a lot of amazing things," says Jane Watson of Vancouver Island University, who has been studying the otter-kelp ecosystem for over 20 years. "Perhaps the most important thing it does is increase the productivity of near-shore ecosystems."

Kelp forests harbour a much wider range of species than a sea floor grazed bare by urchins, and increase overall fish numbers. The forests also form natural breakwaters, protecting coasts from erosion. And it's not just local people who benefit – the kelp forests even help remove significant quantities of carbon dioxide from the atmosphere.

But not everyone is thrilled about the otters' return. Coastal residents who harvest shellfish, including many members of First Nation tribes, compete directly with sea otters. In some waters, people already harass and sometimes illegally shoot the animals. So conservationists have met local leaders to try to head off a looming conflict.

Guujaaw, a member of the Haida Nation, says it is necessary to recognise that indigenous people are a natural part of the ecology. "Otters are also natural in the ecosystem, even a benefit to marine plants, and ultimately to ourselves," Guujaaw says. "At the same time, populations out of control could upset the balance and deprive people of food sources."

In practice, this may mean allowing limited hunting in some areas. After all, the evidence suggests that prior to the arrival of Europeans a balance existed, with coastal communities hunting sea otters for thousands of years without wiping them out. But finding a new balance as the otters reclaim their lost territory won't be easy, says Watson. "It's going to take a tremendous amount of cooperation, collaboration and interaction between different groups of people." ■

Romeos or rapists?

Few animals look as cute and cuddly as a sea otter. But their adorable appearance belies a side to them that in the human world would be considered deviant – some males will mate with anything vaguely otter-like, including dogs and baby seals. On one occasion a sea otter was recorded copulating with a cormorant.

The victims often drown in the process or suffer serious injuries. The behaviour may be a result of the otters' social structure. "Not many of the males get to have their own territory," says Erin Rechsteiner of the Hakai Institute in British Columbia, Canada. "There can be many years of a male otter being sexually active but having no access to females."

Even adult female otters can be seriously injured during mating, but this is not particularly unusual in the animal world.

The white lemuroid ringtail possum was last spotted in 2010. **Jo Chandler** joined the search to discover its fate

Anybody home?

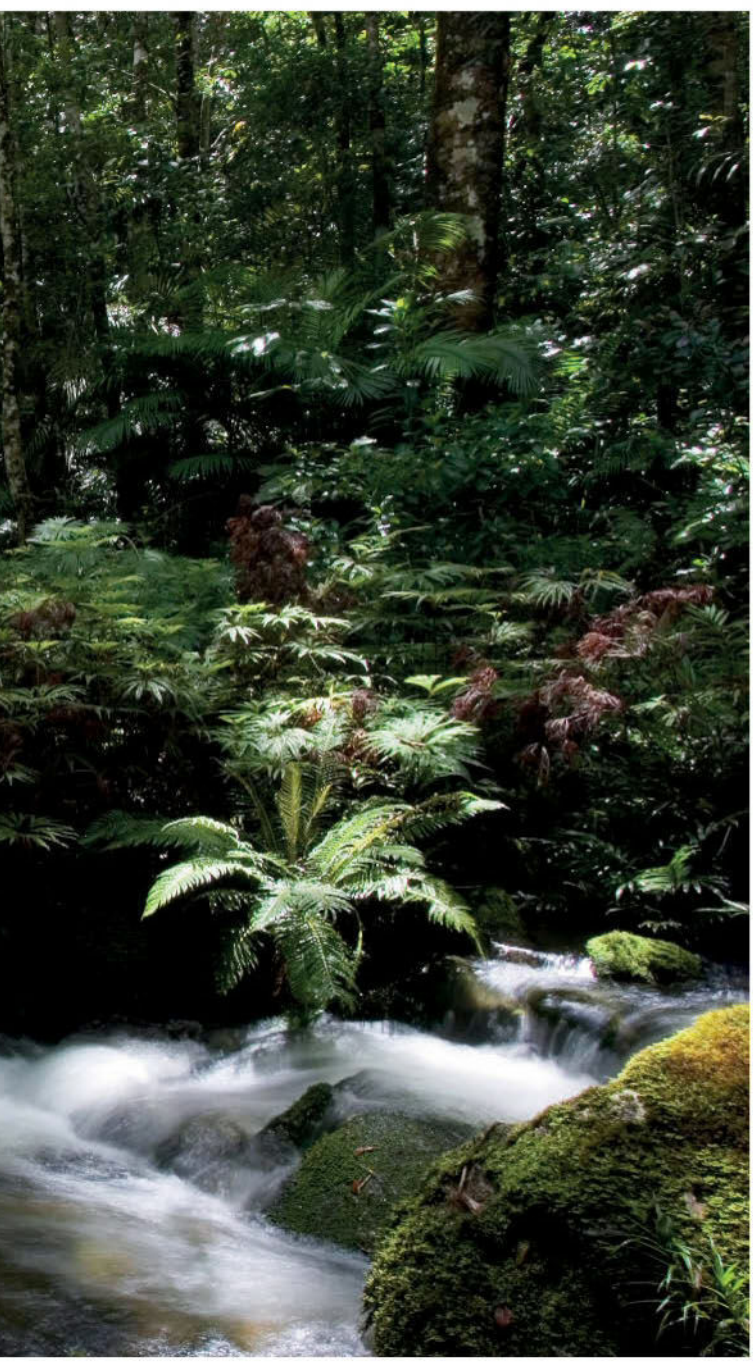
PHOTO: TIM GRAHAM/GETTY IMAGES

IT TAKES less than three hours to travel from the busy tarmac of Cairns Airport, back 100 million years to Queensland's primeval Wet Tropics rainforest. By the time the sprawling malls and suburban estates have given way to blue sky and sugar cane, we have already rewound several decades. Veering inland, we swim against the tourist tide streaming towards the Great Barrier Reef. As jungle encloses us, the notion that we have crossed into a more primitive dimension is encouraged by road signs cautioning drivers to watch out for southern cassowaries – stroppy, flightless birds sometimes likened to prehistoric turkeys.

A boom gate restricts access to the sanctum of Mount Lewis National Park, to stop it being loved to death by naturalists and birdwatchers. The barrier rises and the rugged track lurches through some of the most ancient landscape on the planet, a dense tangle of living fossils. There are conifer species here that evolved more than 200 million years ago, but the dominant flowering plants are a mere 60 to 120 million years old.

At 1200 metres above sea level, the track gives up. This is the cloud forest, where mountain peaks float like cool islands in mist from the Coral Sea. Marooned up here are creatures of a lost world, with such fine-tuned adaptations that they can never leave.

Fifty million years ago, rainforests covered two-thirds of Australia, but as the continent drifted into warmer latitudes they gradually dried and shrank. They are now confined to a 450-kilometre ribbon along the far north-east coast. Although these rainforests cover just 0.1 per cent of the Australian landscape, they contain the country's richest diversity of plants and animals, including two-thirds of the butterfly species, half of the birds and a third of the mammals. There are 100 vertebrate species in this rainforest that are found nowhere else. We are here in search of one of the most elusive, the white lemuroid ringtail possum.



Australia's Wet Tropics is a World Heritage Site. Out of more than 173,000 places protected globally, a 2013 analysis in the journal *Science* named it as the sixth most valuable overall and the sixth most irreplaceable landscape. It is also one of the most threatened ecosystems, facing profound upheaval as climate change bites. The predicted problems include higher temperatures, longer dry seasons, erratic rainfall and increased evaporation.

I am here with Stephen Williams and his team from James Cook University in Queensland. They have been closely monitoring conditions and species in the Wet Tropics for more than a decade, indeed up to 20 years in some locations. According to their findings, the future is already here.

In 2003, when most climate concern was focused on icy high latitudes, Williams and his colleagues predicted an impending catastrophe in the Wet Tropics. Here temperatures vary little between summer and winter, or even day and night. Temperature is tied to elevation: for every 1000 metres you ascend, it drops by an average of 6 °C. Species occupy different altitudes according to their long-adapted preferences. Some are confined to warmer lowlands; some thrive in the mid-elevations; others specialise in misty peaks.

Williams and his team have been monitoring 200 species, including birds, frogs, reptiles and mammals. The story they are starting to tell is of creatures chasing cooler conditions up the gradients, and ›

WET TROPICS IMAGES/MIKE TRENERRY

The white possum has been dubbed the polar bear of the rainforest

A PLACE OF REFUGE

Our survey trip to Australia's Wet Tropics had another objective, aside from seeking the white lemuroid ringtail possum (see main story).

Stephen Williams and his team from James Cook University in Queensland had dotted the rainforest with a network of data-loggers – discs about the size of a coin, hung around the forest inside tea strainers. These recorded temperature and humidity over the recent southern summer. Our aim was to download this information to get a snapshot of conditions in particular locations: in a shadowed nook, by a stream, on a north-facing and south-facing slope, up a tree or under a log.

Complex landscapes interact with meteorological processes to create refugia, microhabitats where creatures can shelter when conditions become hostile or extreme. Williams likens refugia to air-conditioned alcoves, buffered from extreme heat by dense canopy, and shaded from surrounding peaks, exposure to coastal breezes and cloud.

The discovery that the core habitat of 45 per cent of the Wet Tropics species is contained in just the coolest 25 per cent of the rainforest spawned a project to identify these locations, so that they can be targeted for preservation, expansion or reforestation. That's where the data-loggers come in, together with special software to analyse the information they collect.

The refugia mapping pioneered here was adopted in other countries too. For instance, Williams and his colleagues Nadiah Roslan and Brett Scheffers took it to Ecuador and Colombia, where the approach helped conservation managers locate and rank sites to safeguard the most species.

In a warmer world, Williams believes climate refugia will provide critical sanctuaries, at least in the medium term. However, on present trajectories, by 2100, no amount of air conditioning will offset the effects of predicted warming.

becoming scarce when they reach their physiological limits or hit geographical ones – like running out of mountain. "Everything we predicted 10 years ago is starting to come true," says Williams.

The lemuroid ringtail possum, *Hemibelideus lemuroides*, is among several creatures – including about 28 species of birds and at least three possums – that have shown noticeable declines or population shifts. A member of Australia's rich endemic possum population, it is named for its lemur-like eyes. These creatures are found in only two locations – above 1100 metres elevation in the Mount Lewis and nearby Mount Carbine range, and in the Atherton Tablelands about 100 kilometres south, where they have been found as low as 450 metres (see map, right).

Although both sets of lemuroids are thought to belong to the same species, white animals are extremely rare in the south, so anyone wanting to glimpse one has always come north, where they have historically made up about 40 per cent of the population. Nonetheless, given fears that the species is on the brink of extinction here, I know my chances of spotting a lemuroid of any colour in the next couple of days are slim.

Twenty years ago, when Williams was a PhD student, he would often drive up here with his university pals to look for wildlife. They might spot six lemuroids in an evening, which was already well shy of the 10 an hour students in the mid-1980s found. By the late 1990s and early 2000s, surveys were turning up fewer than one an hour on average.

Then there were none. From 2005 to 2008, Williams's team clocked up around 150 hours surveying over 50 kilometres of Mount Lewis, flushing out not a single lemuroid. Meanwhile, surveys on the Atherton Tablelands had noted a shift in the southern population: more lemuroids were showing up at 1000 metres elevation, while they had disappeared from sites at 600 metres.

In 2008, Williams wondered aloud to a local journalist whether the northern lemuroid population might have already been wiped out. Happily this was not the case. After widening the survey areas, his team spotted a couple of individuals. However, as we set out on our hunt, there had been no confirmed sightings here since 2010.

"My gut feeling is that they got badly whacked in 2005," says Williams. That year, summer temperatures were over 28 °C for 25 days running. "What happened since? I don't honestly know." Which is why we have come here, as an advance team for an intensive schedule of surveys.

The trick for spotlight surveys is to paint the forest with light. Keeping the beam fixed to your forehead or close to your eyes, you steadily sweep low to high, trying to ensure each 1-kilometre transect is walked at about the same pace. The wildlife spotted in each sliver of forest can vary greatly but the process gains integrity by repetition. The transects are walked again at dawn, listening for birdsong, and at midday, on the hunt for reptiles.

Surveying in the dark can be diabolical,

FROM RIGHT: HANS + JUDY BEST/ARDEA; WET TROPICS IMAGES/QUEENSLAND GOVERNMENT

navigating tree roots and rocks while craning to see the upper canopy. Shoulders ache from looking up. It is always damp, often foggy and sometimes pouring with rain. Leeches are an occupational hazard and will find their way into your boots, under your shirt, or behind your eyes. Despite it all, a rainforest by night is magical. There's the flapping of the nocturnal birds and the chorus of frogs, some with a trilling ululation, others with a clunking plop, like a marble down a stair. And there are the eyes – sparkly emerald-green ones for the spiders, single bright spots of amber betraying geckos. Pairs of orange coals at ground level belong to frogs. Those staring down from the canopy will be a possum. With luck, it will obligingly freeze in the spotlight while the team

"Leeches will find their way into your boots, under your shirt and behind your eyes"

confers about the species and notes GPS coordinates, conditions and behaviour.

One of our surveys on Mount Lewis is along the access road, so it's a piece of cake. But three others are strewn along an overgrown logging route, dating from before 1988, the year when logging was stopped in the Wet Tropics. We spend an afternoon cutting through the undergrowth and the clinging wait-a-while vine with machetes. Mercifully we are too high up for the stinging tree, perhaps the most painful plant in the world.

We warm stew on a camp stove at sundown, then walk out in the dark. It is a punishing, 8-hour round trip with few sightings: six Daintree ringtail possums, three long-nosed bandicoots, two large rodents from the genus *Pogonomys*, a couple of frogs and a gecko.

Most imperilled: the beautiful nursery frog and golden bowerbird

On the second night we spot a gaggle of Daintree ringtails. In the past they would have been found in abundance lower down, but now they are occupying what used to be prime lemuroid country. There's not a single lemuroid to be seen.

Lemuroids and other endemic Wet Tropics ringtail possums face a particular problem as the rainforest hots up. They live almost entirely in the high canopy and get their water from eating leaves. But those leaves also contain toxins, the forest's defence against overgrazing, so hot possums have to weigh their need for fluid against the risk of poisoning.

Research by Andrew Krockenberger, also at James Cook University, indicates that the endemic ringtails can't cope with temperatures much higher than 30 °C. He says that unless they find a cool hiding place, four or five hours of this heat, especially repeated over several days, pushes them beyond their limits. The problem is amplified at Mount Lewis because poor soil makes it harder for the trees to grow leaves, so they value their foliage, lacing it with more toxins to protect from hungry possums. The cost-benefit ratio of grazing for hydration may be more acutely balanced here than on the Atherton Tablelands, where the soils are better and leaves less poisonous.

The lemuroid's plight highlights the need to consider specifics when assessing the impact that climate change will have on a particular creature. In their 2003 paper, Williams and his team identified the beautiful nursery frog (*Cophixalus concinnus*) as the most imperilled animal in the Wet Tropics. A subsequent analysis used more sophisticated models and generated a substantially different list. It gave the status of most vulnerable to the golden bowerbird (*Prionodura newtonia*) and put the lemuroid possum in the top 10. "Assessments that include the biology of each species, rather than just pure climate predictions, really improve predictions about how vulnerable each species will be," says Williams.

The updated results predict that the current carbon emissions trajectory will cause more than half of the region's endemic species to become critically endangered or extinct by 2085. That is 24 per cent of all species in the vicinity. However, the models also indicate that this could be cut to just 2 per cent of all species if global warming were to decrease in line with the Intergovernmental Panel on Climate Change's RCP 4.5 scenario, under which greenhouse gas emissions stabilise by mid-century and drop thereafter. "[It's] a reasonable, doable mitigation scenario," says Williams. "And it would have a huge positive impact on biodiversity loss in this region."

Living in the clouds

Lemuroid ringtail possums are endemic to Australia's Wet Tropics and are found in just two areas: around the Atherton Tablelands and Mount Lewis

A month after our trip, Williams's team returned to Mount Lewis for an intensive week looking for the lemuroid. They surveyed 20 transects and spotted 13 lemuroid ringtail possums, including three white ones. None were on the original survey sites; they were all in areas that had never been logged. "It seems that the possums hung on in the unlogged sites, although at such low numbers that we could not find them for years," Williams tells me. "This could be very interesting, as it suggests that despite the forest structures not appearing any different now, the undisturbed forest had a greater resilience. Perhaps there were older trees with large hollows for the possums to find protection."

These numbers suggest the abundance of the Mount Lewis lemuroids is back close to where it was before the 2005 heatwave. But such episodes are becoming more frequent and intense. For now, the white lemuroid lives on, although in nothing like the numbers once recorded. It seems that this possum, while an emblem of how vulnerable highly specialised rainforest creatures are, might yet provide some insights into nature's resilience. ■

PAUL D STEWART/NATUREPL.COM

Beast of the southern wild

The "wolf fox", as depicted in a 1773 engraving

Among the penguins and albatrosses of the Falkland Islands a large, fearless predator once lived. How did it come to be there, asks Christopher Kemp

IT IS not often that we can pinpoint the exact spot where a species went extinct, but Shallow Bay on the remote north coast of West Falkland is such a place. There, in 1876, a very peculiar animal – the last of its kind – was mercilessly slain. Chances are it was quick. The creatures were known to be unafraid and easy to kill. And so, as Charles Darwin himself had predicted, the Falkland Islands wolf went the way of the dodo.

It hadn't taken long. Half a century earlier, the islands were largely uninhabited and the wolf was abundant. Then people began to arrive – shepherds from Scotland and gauchos from Argentina. They did not take kindly to having a voracious predator in their midst. When fur trappers arrived from America, it was only a matter of time.

In 1914, taxonomist Oldfield Thomas of the Natural History Museum in London dealt the wolf a final, posthumous insult by naming it *Dusicyon australis*: foolish dog of the south.

And that might have been that, except for the fact that the wolf presented a biological mystery par excellence. The Falklands are 500 kilometres off the coast of Patagonia and the wolf was their only native land mammal. How did it get there? Even Darwin was baffled. Finally, more than 300 years after the wolf was first described, that mystery appears to be solved.

From above, the Falklands resemble a bright green inkblot. There are two main islands surrounded by almost 800 smaller ones, little commas and elbows of land scattered across the turbulent South Atlantic. The archipelago is as far south of the equator as the British Isles are north, but has a much colder climate.

Although just dots on the map, the Falklands have been engulfed by political and military turmoil for centuries. Historically ruled by both France and Spain, the islands are now administered by the UK but claimed by Argentina. In 1982, the two countries fought a brief war over them. The British won, but the Argentines still assert ownership over what they call the *Islas Malvinas*.

How fitting, then, that the islands' eponymous predator has itself been the subject of a long-running dispute.

The first recorded sighting was made in 1690 by the crew of a British ship, the Welfare, which landed on the islands after being blown off course en route to South America (the captain named the sound between the main islands Falkland Channel in honour of a funder of his expedition). The animal was stocky, russet-coloured and about the size of a Labrador. Its skull was broad, its snout slender and elegant. It had a thick woolly coat and a white-tipped, brush-like tail. In most respects it resembled a large, muscular fox, albeit one that ate penguins, geese and seals.

In 1764, Louis Antoine de Bougainville claimed the islands for France. He was unsure exactly what kind of dog it was, so he hedged his bets by calling it *loup-renard*, or wolf-fox.

Fearless creatures

Almost 40 years before the last one was killed, Darwin visited the islands aboard the HMS Beagle and observed the wolf for himself. He knew it as *Canis antarcticus*, the Antarctic wolf, a name given it in 1792 by Linnaeus's translator Robert Kerr. Islanders simply called it the warrah, a bastardisation of *aguara*, which means "fox" in the South American language Guarani. The 20th-century name change was made to better reflect its taxonomic relationship to other canid species.

With no natural enemies, the wolves were unafraid of humans. The crew of the Welfare easily captured one and kept it aboard for months until it jumped overboard in the South Seas, reportedly startled by the firing of a cannon. In 1765, Royal Navy officer John Byron landed on the islands and, unaware that the French were already there, claimed them for King George III of Great Britain. He mistakenly described the wolves as "creatures of great fierceness" that would run towards his men whenever they encountered them.

Because of their fearlessness and aggression the wolves were regarded as vermin. In *The Voyage of the Beagle*, Darwin wrote: "They have been observed to enter a tent, and actually pull some meat from beneath the head of a sleeping seaman. The Gauchos also have frequently in the evening killed them, ›

by holding out a piece of meat in one hand, and in the other a knife ready to stick them."

Darwin seemed to be the only person who understood the implications of this bloody relationship. "Within a very few years after these islands shall have become regularly settled, in all probability this fox will be classed with the dodo," he wrote. He himself contributed to the wolf's decline by bringing four specimens back to England.

During this era of exploration, the discovery of a new canid species was not in itself remarkable. They had turned up almost everywhere else, from the Arctic to the Sahara. But the Falklands were different. Isolated and remote, they belonged to ocean-going species such as penguins, albatrosses and seals. Until colonists arrived there were no land mammals whatsoever – except for the wolf.

The anomaly was not lost on Darwin. "As far as I am aware," he wrote, "there is no other instance in any part of the world, of so small a mass of broken land, distant from a continent, possessing so large a quadruped peculiar to itself."

"It was a pretty big evolutionary mystery," says Alan Cooper, director of the Australian Centre for Ancient DNA at the University of Adelaide. If other mammals had lived on the islands, such as rodents – of which South America has many different species – then we might have presumed that there was once a link to the mainland: "either some sort of land bridge now submerged, or floating rafts of vegetation," he says. "The fact that there was just this one species of terrestrial mammal, and it was a large carnivore, was a real challenge."

Mainland connection

The first person to hazard a guess at the wolf's origin appears to have been a crewman on the Welfare named Richard Simson, who wrote an account of the voyage. Noting that they could not fly, and were unlikely to have swum across, Simson proposed – presciently, as it turned out – that the islands were once connected to the mainland.

Scholars were having none of it. In his *History of Quadrupeds*, published in 1781, naturalist Thomas Pennant suggested the wolves had been carried to the Falklands on ice floes. By Darwin's time, they were widely believed to be descended from dogs left on the island by early colonists – probably the Spanish, who acquired the colony in 1767 as part of a pact with France. Later authors suggested they were domesticated *culpeos*, a South American fox which the Yaghan people of Tierra del Fuego used for hunting.

"The suggestion had been that to be so friendly, the species must have been domesticated or semi-domesticated," says Cooper. Perhaps some time in the distant past Patagonians crossed the churning waters in flimsy boats with their hunting foxes, and later abandoned them: dogs with no masters, stranded on a distant archipelago.

There is some unconfirmed archaeological evidence of an early Patagonian presence on the islands in the form of 4000-year-old charcoal deposits that could conceivably have come from camp fires.

But in the age of genomics we have another historical record to consult: DNA. Cooper decided to go in search of the wolf's. His first port of call was the Natural History Museum in London, which he knew had at least one specimen. "It was one of the ones that Darwin himself had collected, with handwriting on the label and the whole bit," he says.

The museum said yes, but under one condition: the wolf could not be damaged. That ruled out Cooper's usual *modus operandi* of removing a tooth, taking a sample of the root and popping it back into the socket. OK, he said to himself, and headed to London.

Cradling the skull in his hands under the curator's watchful eye, Cooper inspected the surface and found a small hole in the cheekbone. Bingo. "There was a bit of blood vessel in there, still attached," he says, even though the specimen had been nicely cleaned, probably by Darwin himself.

Cooper was allowed to remove the blood vessel. It was enough for him and his team to compare Falkland Islands wolf DNA with that from other South American canids. They concluded that the Falkland Islands wolf had no close living relatives. "It was a completely unique lineage," Cooper says. "The closest living canid that we could relate it to was the maned wolf, a great big long-legged fox that jumps around in pampas grass hunting rodents. But the genetic difference between the two was enormous." In fact, the two species had diverged about 7 million years ago.

That was interesting enough, but not much help in answering the big question. So Cooper

OTAGO MUSEUM

This beast from New Zealand's Otago Museum helped crack the case

FRANS LANTING/NGS STOCK

Hungry wolves would grab a goose or pick up a penguin

"The fact that there was just this one species of terrestrial mammal – and it was a large carnivore – was a real evolutionary challenge"

went in search of more wolves, eventually gathering samples from four other specimens in museums across the world. By comparing mitochondrial DNA from the five animals, he estimated that their most recent common ancestor lived at least 70,000 years ago – well before humans reached the Americas.

But five wolves is an awfully small sample. And even if the DNA evidence appeared to rule out human involvement, it ruled nothing *in* either. And so Cooper started again.

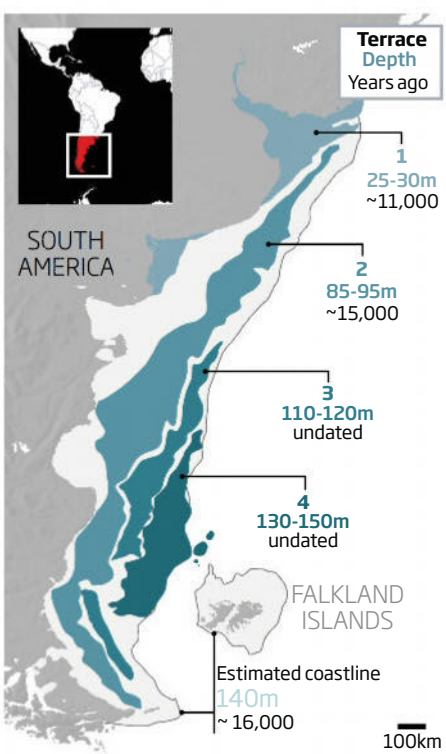
Until a few thousand years ago, South America was home to a much more diverse group of canids than it is today. Among the now-extinct species was a fox-like animal called *Dusicyon avus*, which died out just 1600 years ago. Perhaps, Cooper thought, this was the missing link between the Falklands wolf and its closest living relative. He went in search of specimens, eventually tracking down six in museums in Argentina and Chile.

"We got DNA and found that it was incredibly closely related to the Falkland Islands wolf," he says. That explains the wolf's origins, Cooper suggests: it split away from *Dusicyon avus* about 16,000 years ago.

It was no coincidence, says Cooper, that the wolf diverged from its mainland cousin then. This was when the last ice age was at its peak and sea levels were very low; the South American coastline extended much farther out than it does today.

The way of the wolf

At the peak of the last ice age the sea was 140 metres lower and South America and the Falklands were just 20km apart. When the strait between them froze, wolves could trot across. The history of sea level change is preserved in four seabed terraces



SOURCE: NATURE COMMUNICATIONS, DOI: 10.1038/NCOMMS2570

"There's a series of terraces off the coast of Argentina that mark where the shoreline sat for some time," Cooper says. The one indicating the coastline at the glacial maximum is 150 metres underwater and stretches almost to the Falklands (see map).

When at its narrowest, the strait between the mainland and the islands was roughly 20 kilometres wide and 10 to 30 metres deep, says Cooper – so shallow that it almost certainly froze over from time to time. It seems the wolves' ancestors could simply have walked across the ice.

This could also explain why no other land mammals made it. The ice bridge was a kind of ecological filter that large terrestrial carnivores were able to cross, but excluded omnivores and herbivores. "Twenty kilometres of ice is not a great place to be for a rodent," says Cooper.

That argument doesn't convince everybody. Graham Slater, an evolutionary biologist at the Smithsonian Institution in Washington DC, makes the comparison with Isle Royale, a small island in Lake Superior about 25 kilometres from the shoreline. During the last ice age, he says, wolves made their way across the ice from the mainland. So did other mammal species, including moose, coyotes and beavers. "They got there," he says. "Why did nothing else get to the Falklands?" Large hoofed animals could have traversed the ice, he suggests.

That is not the only objection to Cooper's idea. Cooper's estimate of when the Falkland Islands wolf appeared – 16,000 years ago – is quite uncertain, with a give-or-take of 7000 years either side. That means the wolf could have arrived on the Falklands as recently as 9000 years ago, long after humans arrived in South America. Could the wolves have been the descendants of domesticated foxes after all?

"We're pretty sure we can rule out humans," says Cooper. "It would seem pretty odd that humans might have domesticated a dog, carried it across to the islands within the first thousand years or two that they were in South America, and then never do it again." In the absence of unequivocal evidence of pre-European settlement, we must assume the wolf arrived under its own steam.

And so the case is, virtually, closed: the Falkland Islands wolf was a truly wild species which walked across the ice and ruled for thousands of years. Then humans arrived, and the wolves, bold and unafraid, bounded toward the settlers, who stood with a lump of meat in one hand and a knife in the other. ■

RUI RICARDO/FOLIO ART

Millions of years ago, the jungles of South-East Asia were home to a veritable King Kong. **Colin Barras** joins the search and finds a whole lot of teeth

HUNTING FOR THE GREATEST OF APES

Hong Kong, 1935: a young palaeontologist picks his way through the back streets, ducking in and out of apothecary shops. He's looking for dragon teeth, the name the Chinese give to old animal teeth used in traditional medicines. In a dusty drawer of trinkets, his eyes fall on a large molar unlike that of any living animal, and he instantly knows his search is over. The tooth belongs not to a dragon but an ape, and if its teeth are anything to go by, it was huge.

So begins the story of the discovery of a truly fantastic beast, the greatest of all great apes. According to some estimates, it stood 3.5 metres tall, weighed over 500 kilograms, and stalked the nightmares of the earliest humans to reach China. Its name? *Gigantopithecus*.

Eighty years after Ralph von Koenigswald stood dumbstruck in a Hong Kong drugstore, fossils of the giant ape remain sparse. A jawbone fragment described earlier this year is just the fourth ever found. The four pieces and several thousand teeth are our only evidence it even existed. But from these scraps, we are slowly piecing together an image of this real-life King Kong*, how it lived and why it eventually vanished from the face of the planet.

Von Koenigswald was born in Berlin, Germany. From an early age, he yearned to hunt for evidence of humanity's ancestors. That meant one thing: a journey to South-East Asia, home to the oldest and most primitive human fossils at the time. After a stint looking for *Homo erectus* in Indonesia, von Koenigswald's attentions turned to orangutans and their poorly studied ancestors. His particular stroke of luck was born of the realisation that he could take his search to Asian apothecaries, where ground-up teeth are an important part of many traditional medicines.

"I began to hunt for fossils in the Chinese drugstores in Java," he later wrote. "I discovered that I had made a grave mistake in simply inquiring about 'teeth'. I should have asked for 'dragon teeth', since that was the name of the 'drug' I sought. When I finally learned the correct name and obtained a prescription, I succeeded in finding these teeth in every Chinese drugstore in every Chinese community."

Subjected to von Koenigswald's expertise in extinct fauna, the so-called dragon teeth proved almost systematically to be fossils of ancient mammals, from horses to large giraffes.

A DRAGON'S TOOTH

In 1935, on a tip-off, he headed for Hong Kong – a decision that would lead him to one enormous molar and change his career. "He took one look at that tooth," says Russell Ciochon, a palaeoanthropologist at the University of Iowa, "and knew it was ape. And it was huge." At roughly an inch across, its grinding surface was easily twice as big as a typical human molar.

For the next few years von Koenigswald scoured drugstores for more evidence of the extinct behemoth, with little success. "The rarity of this giant form is obvious," he wrote. By 1939, he had examined thousands of fossil teeth but discovered only three more belonging to *Gigantopithecus*.

Still, each new find added weight to the idea that he was dealing with a new species. He was categorical that the four molars had belonged to four different individuals. He also noticed a trend that gave him clues about when the apes had lived. The molars were always found in shopkeepers' trays, mixed in with other teeth in a similar state of preservation. Von Koenigswald knew the owners of these other teeth well: giant pandas, tapirs, bears and the extinct, elephant-like stegodon. The giant ape was systematically surrounded by middle Pleistocene animals. It was about a million years old.

Then came the war. Japan's imperial army rolled into Java in 1942 and von Koenigswald was interned in a prisoner-of-war camp. The teeth he had gone to such lengths to collect saw out the Japanese occupation in a milk bottle buried in a neighbour's garden on the island. For von Koenigswald's colleagues in the US, the wait was interminable. Franz Weidenreich at the American Museum of Natural History in New York was particularly exasperated. He had big ideas about *Gigantopithecus* and was itching to share them with the scientific world.

In 1945, with von Koenigswald still a prisoner, Weidenreich pushed ahead with the publication of his theory. He had noticed that smaller breeds of dog often have relatively large brains and small faces compared with larger ones. Humans also have much larger brains and relatively smaller faces than ›

* …or King Louie – as portrayed in the 2016 remake of *The Jungle Book*

Ancient porcupines, this guy's ancestors, are accused of eating the evidence for *Gigantopithecus*

chimps, gorillas and orangutans, something that had puzzled researchers for years. Weidenreich believed it all made sense if our family tree included some unusually large ancestors. As the millennia passed, our bodies shrank but our brains remained large. In other words, we were descended from Asian giants, and *Gigantopithecus* was one of them.

"No one gives the idea much credibility now," says Ciochon. "If von Koenigswald had not been in prison, that episode probably would never have happened." But it's not the craziest theory ever concocted and for a brief time, Weidenreich's idea that humans evolved from an enormous Asian ape was in the scientific mainstream. Then the war ended, von Koenigswald was released, and he gently but firmly plucked *Gigantopithecus* out of the human evolutionary tree and plonked it back with the other apes.

The downgrading didn't diminish scientific interest. Far from it: Chinese authorities, determined to find fossils of the giant ape in their proper geological context, launched a series of field expeditions in the 1950s. The quest took them to southern China's fantastical karst landscapes, where limestone sugarloaf mountains loom over rice paddies. They met with farmers who had long collected *Gigantopithecus* teeth to sell on the lucrative medicinal market, and were directed to caves carved into the sheer cliff faces.

In Liucheng cave, no fewer than 1000 *Gigantopithecus* teeth were recovered, together with fragments of three giant jawbones. From the size of the jaw fragments, the Chinese researchers deduced that *Gigantopithecus* might have stood 3.5 metres tall. In truth, there's little to go on. Ciochon believes the ape was more like 2.5 metres tall.

So what was *Gigantopithecus* and how did it live? Von Koenigswald named the Chinese species *Gigantopithecus blacki*. Its oldest reliably dated remains are 2 million years old. Another, older and slightly smaller species has also been found in northern India: *G. giganteus*, known from an 8.6-million-year-old jawbone and teeth.

The idea that the enormous apes might have been part of our family history stuck around until quite recently. In the 1980s, Bruce Gelvin of California State University argued that if it wasn't a direct ancestor, it might have been a very early cousin species, much like African *Australopithecus* species. Around the same time, a team including Ciochon found more than a dozen *Gigantopithecus* teeth with a couple of stone tools in Longgupo cave in China. And two years ago, a Chinese team raised the possibility that *Gigantopithecus* was the toolmaker.

Ciochon rejects the idea. If they did make tools, he says, these would probably have been made of organic material like sticks, bamboo or leaves, and in any case tools are not necessarily evidence of an intelligent ancestor. There are at least three living species of non-human primate that use stone tools: chimpanzees, bearded capuchins and long-tailed macaques. Ciochon says the stone tools at Longgupo were probably left much later by early humans.

PRICKLY POST-MORTEM

There's another reason to doubt the image of *Gigantopithecus* as a cave-dwelling toolmaker. The caves its teeth were found in were not caves when the ape was alive. At the time, the deep valleys had not yet been carved into the karst landscape to produce the iconic limestone mountains. Ground level was much higher up, and what we now see as lofty caves dug out of cliff faces were small sinkholes and

ZUMA PRESS, INC/ALAMY STOCK PHOTO ABOVE: JOEL SARTORE/NATIONAL GEOGRAPHIC/GETTY

We'll be piecing his story together for a long time yet

underground fissures. They were home to porcupines, not giant apes.

Those porcupines offer an answer to one of the enduring questions about *Gigantopithecus*: how come it left so many teeth and so few bones? Porcupines need calcium to make their quills, explains Ciochon. They are known to gather bones, drag them back into their underground lairs, and gnaw on them until there's nothing left. You could say that Pleistocene porcupines ate most of the evidence for the world's biggest ape.

It's lucky, then, that we can reconstruct a fair amount about an animal from its teeth and jaws alone. "Even from tiny pieces of dental tissue, we learn about the diet, ecology and life history," says Kornelius Kupczik at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. What emerges is a picture of *Gigantopithecus* as a forest-dwelling herbivore. Analysis of carbon and other elements in the fossil teeth reveals no signs of a meat diet: the ape was vegetarian.

Gigantopithecus also suffered from unusually poor dental health. Something like 10 per cent of the teeth that have been found have caries, and the recently discovered fourth jawbone shows that some individuals lost a tooth or two during their lives. Both features suggest the ape ate lots of sugary fruit. Earlier this year, Hervé Bocherens of the University of Tübingen, Germany, published a study of *Gigantopithecus* teeth that argued we should think of the ape as an overgrown orangutan confined to the forest floor by its great size.

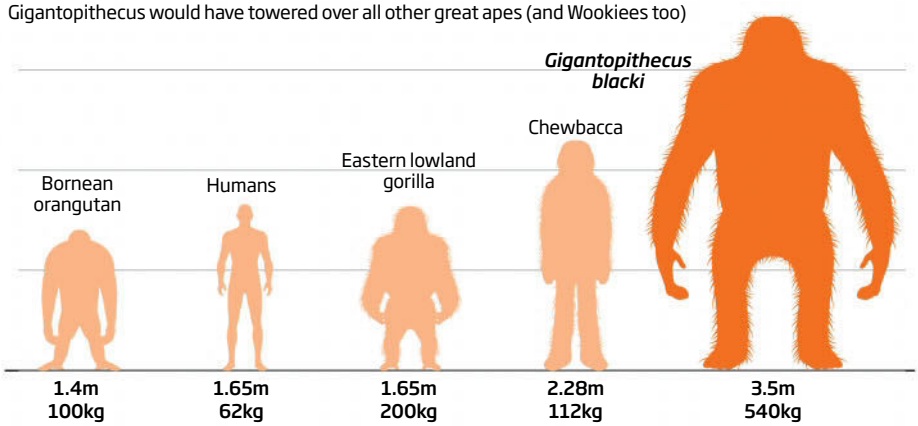
The shape of its dental roots suggests another possibility, say Kupczik and Christopher Dean at University College London. It had a bite powerful enough to chew through tough foods like bamboo. Other lines of evidence, including food residues on some teeth, also suggest bamboo was on its menu. In other words, perhaps *Gigantopithecus* was more like a giant panda than an oversized orangutan.

Either diet leaves a central puzzle unsolved. Both species that *Gigantopithecus* has been compared with – giant pandas and orangutans – lived alongside it in Asian forests. Why did they survive and the ape die out? "The extinction of *Gigantopithecus blacki* is still mysterious," says Yingqi Zhang at the Chinese Academy of Sciences in Beijing. On present evidence, it seems it may have vanished around 320,000 years ago. This is the age of the youngest teeth yet found, which Zhang and his colleagues described in 2013.

We now know that those last apes might well have been the grandest of the bunch.

A truly great ape

Gigantopithecus would have towered over all other great apes (and Wookiees too)



SOURCE: DOI: 10.1186/1471-2458-12-439/WWF/WOOKIEEPEDIA

Last year, Zhang, Ciochon and their colleagues collaborated on a systematic study of teeth from a number of sites. They were able to confirm that the last *Gigantopithecus* had exceptionally large teeth, even by its own standards. The biting surfaces were 1.5 times larger than those of earlier members of the species. "This does not necessarily mean their body size increased accordingly, although I prefer to believe so," says Zhang. If he's right, that would suggest *Gigantopithecus* was larger than it had ever been just before vanishing.

Zhang and his colleagues recently noticed something else about those last teeth. The biting surfaces were not just larger, they were also distinctly more complex. The team hasn't yet worked out exactly what that means, but it

"Maybe *Gigantopithecus* was more like a giant panda than an oversized orangutan"

might hint that the giant ape was facing a drastic change in its menu before its extinction, perhaps because the region's plants were changing.

Bocherens agrees with this assessment. His team's work suggests that while *Gigantopithecus* ate any leaves, shoots and fruits it could lay its hands on, it drew the line at grasses and other vegetation from the savannah. That doomed the species, says Bocherens, because climate change during the Pleistocene meant grasslands got bigger at the expense of forests, where the apes lived.

That might not be the full picture, though. *Homo erectus* arrived in Southeast Asia about 1.7 million years ago and could have rubbed shoulders with *Gigantopithecus* for a million years. If *Homo erectus* hunted the apes, or competed with them for resources, this might have added to their problems. *Gigantopithecus* may even have been one of the first species that humans pushed towards extinction. Then again, maybe not – for here too, the *Gigantopithecus* story is plagued by open questions.

In the mid-1990s, Ciochon and others found *Gigantopithecus* and *H. erectus* teeth together in Chinese and Vietnamese caves, and declared that the two apes had had a "long coexistence". But Ciochon now thinks the "*H. erectus*" teeth belonged to another ape, and there were no hominins in the cave. "I think today most people agree humans and *Gigantopithecus* were not living side by side," he says. "They were certainly both present in China 1 million years ago, but I don't think they were inhabiting the same areas."

Gigantopithecus, he says, was confined to dense forests, whereas early humans were far more likely to live and hunt in open grasslands. That's not to say they never, ever met. "Let's not forget that humans may kill for other purposes than feeding," says Bocherens. "We cannot rule out that humans hunted *Gigantopithecus* even if they did not feed on the same resources." Proof would come with the discovery of *Gigantopithecus* bones with butchery marks. "This is probably a bit too much to ask," he concedes.

We've learned more about *Gigantopithecus* in recent years than von Koenigswald could have hoped as he stood in that Hong Kong drugstore 80 years ago. Yet still the story of our largest fellow ape eludes us. "We need to find its face," says Zhang. Such a momentous discovery would at last tell us what *Gigantopithecus* really looked like. ■

CHAPTER TWO

BIRDS

Symbol of divinity

STARE into the eyes of a Christian icon. This formidable creature is the largest living animal able to fly. The average weight of a Dalmatian pelican (*Pelecanus crispus*) is 11.5 kilograms, and its wingspan reaches an albatross-beating 3.5 metres. In medieval times the bird was thought to stab itself in the chest to provide a blood meal for its young. This apparent act of devotion led to the pelican being selected as a religious symbol by, among others, Thomas Aquinas and Queen Elizabeth I of England. The bird doesn't stab itself, though it does bash its chest with its bill to help bring up fish.
Rowan Hooper

Photographer
David Pattyn/naturepl.com

A turkey is not just for Thanksgiving or Christmas – it's a bird with a noble history and a bright future, finds **Lesley Evans Ogden**

Return of the native

TIM LAMAN/NATIONAL GEOGRAPHIC CREATIVE

WE HUMANS have a fondness for calling someone or something we consider inept a "turkey". Could turkeys talk, they might be inclined to throw the insult back the other way.

Ecologist Michael Chamberlain of the University of Georgia has witnessed the bird's ability to outsmart people at first hand. He was in the field tracking a mother turkey and her poults. Thanks to the micro-GPS units he co-developed, he knew their exact whereabouts, and sent a fieldworker into the forest to find them. His colleague walked around for almost an hour trying to track them down, and never once spotted them. Chamberlain did, though. "I was sitting in the truck," he says. Through the windshield, he saw the turkey sneak across the road with her brood, right in front of him. It turns out the fieldworker had been behind her the whole time, but she was clever enough to keep out of sight.

"Smart" isn't a word most of us associate with the bird that graces many a Thanksgiving and Christmas dinner plate. Yet it is the domesticated cousin of the wily wild turkey, *Meleagris gallopavo*, which without its guile might well have gone the way of the passenger pigeon. However, in a heart-warming success story for conservation, this native American has made it back from the brink of extinction. Better yet, while many other species are feeling the heat of climate change, the wild turkey is going from strength to strength.

Turkeys are native to North and Central America, with six regional subspecies. Although domesticated by the indigenous peoples of Mesoamerica some 2000 years ago, the wild variety was an important resource for many Native American peoples, not just for its meat and eggs, but also for feathers, bones

TALKING TURKEY

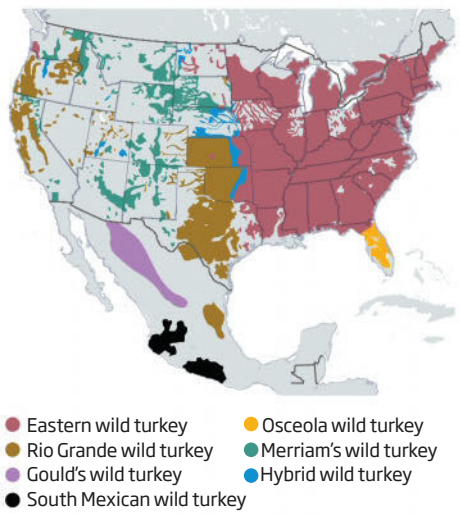
- Wild turkeys will eat anything from flowers to salamanders, but acorns are a firm favourite.
- Turkeys are sophisticated talkers with separate alarm calls for "ground predator" and "aerial predator"
- The average clutch size is 11 but hens lay eggs in each others' nests, so one female can incubate up to 26.
- Male turkeys are known as toms or gobblers. Females don't gobble.
- The pendulous flesh hanging down over a male's beak is called a snood.

MICHAEL FORSBERG/NATIONAL GEOGRAPHIC CREATIVE

Wild turkeys need trees to roost in, which a century ago was almost their undoing

Where gobblers roam free

A century ago, wild turkeys were almost extinct. Today there are over 6 million, divided into six subspecies, plus a hybrid



and spurs, which were used to make clothing, spoons, musical instruments, arrow tips and more. Estimates put the wild turkey population before Columbus arrived at some 10 million, though no one was counting. Around 1600, when Europeans first began settling in North America, the wild birds were so abundant they could be seen in flocks of hundreds.

Ironically, early settlers brought domesticated turkeys with them – these were the descendants of Mesoamerican poultry that had been introduced to Europe by earlier explorers. But turkey farming was small-scale and settlers soon learned that wild turkeys were good tucker and easy prey, owing to their habit of roosting in large groups in trees. Turkeys became so established in the pioneer psyche that in 1784, commenting on the choice of the bald eagle as the national bird, Benjamin Franklin quipped: "The turkey is in comparison a much more respectable bird, and withal a true original native of America… He is besides, though a little vain and silly, a bird of courage, and would not hesitate to attack a grenadier of the British Guards."

Despite such affection, the hunting of wild turkeys continued unregulated. And the birds faced another threat, too. Turkeys aren't particular about where they live, but they do have one requirement: trees. As settlers crossed the country, logging for timber and clearing forest to create farmland, suitable turkey habitat diminished. All this unfettered felling and trapping meant that by the end of the 19th century – around the time that passenger pigeon populations began to plummet – the wild turkey was in trouble. By 1920, it had been eradicated in 18 of the 39 states it had once occupied, and had also disappeared from Ontario, Canada.

Estimates of the population size at its nadir range from 30,000 to 200,000. Yet, as the passenger pigeon was sucked into the vortex of extinction, concern arose about the disappearance of wild turkeys. This was especially fervent among those who liked to hunt them, and efforts were launched to bring the birds back from the brink. In 1937, these came to fruition when a new excise tax on guns and ammunition generated revenue earmarked for wildlife management and restoration. The wild turkey was to get a share.

Armed with conservation dollars, wildlife agencies in several US states began collecting turkey eggs from nests in the wild, bringing them into captivity to rear for later release. Two decades of time and money later, nothing had changed. Almost all of the efforts were "dismal failures", says Tom Hughes, a biologist with the National Wild Turkey Federation – most of the young turkeys didn't survive once released. "They hadn't grown up under the direction of a wild hen," says Hughes, so they had no idea how to behave in the wild. "They didn't know what to avoid. They didn't know what to look for."

By 1960, most wild turkey breeding had been ditched. Instead, wildlife agencies used spring-loaded rocket nets to capture whole flocks and relocate them to a suitable turkey-free habitat. Bingo! Turkeys began spreading like wildfire. Able to adapt to and thrive in new settings before potential predators had learned to hunt them, they enjoyed a short honeymoon period in many places that enabled populations to establish and thrive, says Hughes.

> "In a warmer world we can expect to see more of these canny birds"

Fast-forward to today, and wild turkeys are abundant across the continent, with numbers estimated at over 6 million. One factor that limits their northward expansion is snow. "When the snow is really deep, turkeys can't move through it, and can't find their food," says Britney Niedzielski. While at Trent University in Peterborough, Canada, she found that many wild turkeys don't survive the winter at the northern limits of their range. However, those hanging out near farms can often get enough spilled grain and corn to see them through.

And with a helping hand from climate change, wild turkeys are likely to spread further north, says Niedzielski. So, in a warmer world we can expect to see more of these canny birds… and fewer frozen ones. ■

Tracking devices have revealed the wild turkey to be a wily and adaptable bird

RAYMOND GEHMAN/CORBIS

ANGELS OF DEATH

Fish thieves, riverbank wreckers, alien invaders. Cormorants are despised and persecuted – but for no good reason, says conservation biologist **Linda Wires**

IN JULY 1998 I visited Naubinway, Michigan, for the first time. The town is one of the state's few remaining commercial ports and fishing is the mainstay of its economy. But I wasn't there for the fish. I was headed for a small island about a kilometre offshore, uninhabited by people but teeming with bird life in the summertime.

Herring gulls and double-crested cormorants begin nesting in this part of the Great Lakes in May, and by mid-June there are thousands of chicks. I went there with my University of Minnesota colleagues Francie Cuthbert and Dave Smith as part of a study of cormorant population dynamics. I didn't know it then, but it was the beginning of a journey that would shape much of my life.

That year, low water levels had made the public jetty inaccessible, so we drove to the one used by commercial boats. Two fishermen watched us as we pulled up. Dave asked them if it was OK to use the jetty.

"What do you want to do out there?" the older man asked. Francie explained that we were conducting research on cormorants. The man nodded. "Yeah, those birds are causing lots of trouble. Something needs to be done if we're gonna fish here."

"Fishing bad?" Dave asked. The younger man snorted. "Real bad. Won't be no fish left soon. Gotta do something about those birds."

"Is your research gonna help?" the first man asked. Francie answered that it might help us understand the population better. The men looked sceptical, but gave their permission. As we put in, Francie told them we wouldn't be on the island long. The younger man smiled. "Take your time. Get as many cormorants as you can. We won't tell."

It took only minutes to reach the island but it was as if the journey transported us to another world. As we approached, the cormorants took wing in a thunderous rush while the gulls swooped and shrieked overhead. The desolation of the island and the wildness of its inhabitants had an extraordinary effect on me. Though I had encountered cormorants many times before, seeing them in such numbers made me feel like I was experiencing them and their world for the first time. Since then I have visited many cormorant colonies, and come to realise that this bird is one of the most remarkable creatures I have ever encountered.

JOEL SARTORE/NGS

The same year I took that trip, two events occurred that would affect cormorants across North America for years. In March, the US Fish and Wildlife Service published a "depredation order" allowing fish farmers to shoot an unlimited number of cormorants without a permit. The order covered 13 states, 12 of them in the south-east, where catfish ponds are abundant and hundreds of thousands of cormorants overwinter. By the end of 2010, an estimated 300,000 cormorants had been killed under the order.

The second event was a vigilante-style slaying of double-crested cormorants at Little Galloo Island in Lake Ontario, which at the time supported some 8500 pairs, the largest known colony in the world. In July, biologists made a routine visit to the island and encountered a grisly scene: more than 800 dead, decaying cormorants and piles of shotgun shells.

Months later, nine men, many of whom were fishing guides, pleaded guilty to killing the birds. They were fined and sentenced to house arrest, but the incident was likened to the Boston Tea Party and the men attained local hero status.

This incident brought the cormorant "problem" into sharp focus for the Fish and Wildlife Service, culminating in 2003 in a second depredation order covering 24 states in the eastern US and allowing the killing of ›

Around 50,000 double-crested cormorants are killed each year

SHAUN/GETTY

"Their fishing talent is a double-edged sword, as it brings them into conflict with humans"

any cormorants deemed to be a threat to public resources, including fish, wildlife and land. By the end of 2011, this had resulted in the death of around 146,000 birds and the destruction of countless numbers of nests and eggs, mostly in the Great Lakes region. Thus began the modern American war on cormorants.

To begin to sense the injustice of this war, one must first understand just how extraordinary cormorants are. Consider their occurrence at Disko Bay in Greenland, where glaciers and icebergs abound. Most of the region's animals are insulated from the cold by dense coats of fat, fur or waterproof feathers. All, that is, but for the great cormorant – the most widely distributed of the 40 or so species worldwide – which survives year-round in this frozen landscape despite lacking a substantial fat layer.

Not only does the cormorant survive, it thrives. Its fishing performance is the highest ever recorded for a marine predator. How do cormorants – which originated in the tropics – manage to live so successfully in the high Arctic? The answer lies partially in their exceptional plumage.

Cormorant feathers are unique amongst birds that hunt underwater, with an outer, wettable section and an inner, waterproof one. This confers two advantages: the outer section soaks up water, reducing the cormorant's buoyancy, while the inner section retains an insulating layer of air against the skin. The result is a bird that can dive and pursue fish in a range of water depths and temperatures.

The eyes have it

This balance between buoyancy and insulation is just one of many unique adaptations. Another is their eyes. Not only are these often described as among the most beautiful of all birds' eyes, they are also functionally remarkable. The unusually flexible lens changes shape extremely rapidly, while the muscles that regulate pupil size also act on the lens. These features presumably help cormorants find and catch fish underwater.

Yet how much the cormorant relies on vision isn't clear. They hunt successfully in turbid waters and throughout the dark Arctic winter. So their hunting prowess must also depend on artful strategy, or some other adaptation as yet unknown.

Humans noticed this remarkable fishing skill a long time ago. For more than 2000 years, people in China have been taming cormorants and training them to bring back fish. This style of fishing is still practised in some parts of Asia.

Alas, the bird's fishing talent is a double-edged sword, for it is this that brings it into direct conflict with humans. As a result, many cormorant species have been, and continue to be, persecuted in many parts of the world. In Europe, the great cormorant was almost hunted to extinction in the 19th century and is still widely culled. In Australia and New Zealand, many species have been intensely persecuted.

In North America, the persecution falls almost exclusively on the double-crested cormorant, the most common and widely distributed of six native species. In recent years, millions of US and Canadian dollars have been spent on reducing its numbers, based on a perception that it is the most significant bird predator on fish in North America.

The double-crested cormorant is certainly an efficient and adaptable predator, capable of exploiting a range of habitats from coastal bays to inland waterways. More than 60 families of fish have been documented in its diet. When birds are shot and their stomach contents examined, large numbers of intact fish are often observed, which only reinforces their reputation as voracious eaters.

Cormorants are also powerful agents of environmental change. Through their nesting and roosting habits – they are equally at home on the ground or in trees – they can denude a landscape of vegetation and cover it in guano. They can also defoliate and ultimately kill the trees they nest in. This destroys habitat for some groups of birds, though creates it for others.

Breeding colonies can build up to tens of thousands of birds filling every available space; occasionally, cormorants are observed nesting on top of dead cormorants. Guttural grunts, raucous calls, gargles, hisses and

CRISTOBAL SERRANO/WWW.CRISTOBALSERRANO.COM

ARTO HAKOLA/GETTY

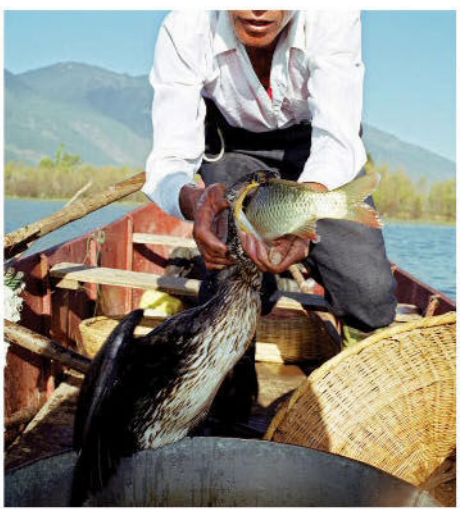
ARISTOTLE'S RAVEN

The persecution of cormorants can be traced to antiquity. Around 350 BC, Aristotle wrote his *History of Animals*. In it he identified the cormorant by a name that would haunt it for centuries: *hydrokorax*, or water raven.

To Ancient Greek sensibilities this would have been highly significant. Birds were an important source of omens; certain birds were considered more ominous than others, and the raven was regarded as one of the most ominous of all.

Taxonomists recognised the difference between ravens and cormorants long ago. But the essential qualities that linked these birds in Ancient Greece continue to link them today. The cormorant resembles the raven in looks and sound. Its sombre black coat, combined with its sinister demeanour, infuses it with a certain ominous aspect, and it persists as an evocative figure of power and ill repute.

The legendary hunting skills of cormorants have long been exploited by us



TESSA BUNNEY/IN PICTURES/CORBIS

whines provide constant background noise and further amplify the impression of numerical greatness. Approaching such a colony from downwind, the reek of guano and rotting fish is detectable from quite a distance.

These attributes inspire fear, disgust, anger and hatred. Cormorants are often described as "invaders" in regions in which they are actually native, and are often considered "overabundant", even when they occur in relatively moderate numbers. For centuries, humans have gone to great lengths to destroy cormorants. Adults and chicks are usually shot and eggs are coated in oil, which asphyxiates the embryo but tricks the parents – which normally re-lay if their eggs are destroyed – into incubating eggs that will never hatch.

The depredation orders opened Pandora's box, and those authorised to kill cormorants took extraordinary liberties. To grasp the magnitude of the persecution, consider that the number of cormorants legally destroyed in the US between 1998 and 2011 is in the same ball park as the total number of birds killed in the worst environmental disasters. The Exxon Valdez oil spill, for example, killed somewhere between 250,000 and 580,000 sea birds. The number of double-crested cormorants killed since 1998 is well over 500,000.

However, the extent to which cormorants actually harm human interests is unclear. Some prey species are commercially valuable, but the bulk of the cormorant's diet consists of species not valued by humans. And despite its reputation for devouring fish, its daily food consumption relative to body mass is no greater than that for other fish-eating birds. Cormorants do not appear to pose a threat to the survival of healthy fish populations in natural systems.

To the agencies managing cormorants in the US, this is inconsequential. Scientific proof of impacts isn't a required component of the regulations for management. Nor has there been any consideration of ethical dimensions.

The western front

To the extent that the agencies employ data, it is to argue that the number of birds destroyed is inconsequential relative to the total population. This is arguably true. An annual cull of 40,000 to 50,000 double-crested cormorants represents less than 5 per cent of the North American population. Clearly, the species isn't in any imminent danger of being culled to extinction.

But is this the only criterion by which the efforts to suppress cormorant numbers should be judged? Half a million of anything is a large number. In addition, millions of dollars have been spent to sustain the effort, with little evidence that it does any good.

Nonetheless, the war on cormorants continues. Record numbers were killed in Michigan in 2012, and Minnesota expanded operations in 2013. The Great Lakes Restoration Initiative – a huge project to reverse decades of environmental degradation – has identified their destruction as an essential measure, on a par with cleaning up toxic substances and combating invasive species. In August 2014, both depredation orders were extended for another five years.

The war is also expanding westwards. In 2012, the Pacific Flyway Council, which coordinates the management of migratory birds in western North America, proposed managing cormorants to address conflicts over fish resources, largely for the benefit of hunters. And in 2014, the US Army Corps of Engineers proposed killing thousands of cormorants on the Columbia river estuary on the Oregon-Washington border, to protect commercially valuable juvenile salmon and trout. If carried out, this would be the largest cull to date.

> "The reek of guano and rotting fish is detectable from quite a distance"

Yet there are also glimmers of hope. Scientists are increasingly questioning cormorant control in the scientific literature, in their comments on cormorant management plans, and in popular books. Encouraged by these moves, the US Center for Biological Diversity and other wildlife organisations petitioned the Obama administration to reconsider the routine use of lethal force to manage "nuisance" wildlife including cormorants. More recently, Public Employees for Environmental Responsibility, a non-profit group that aims to improve management of public resources, has mounted a legal challenge to the renewal of the depredation orders.

In Canada, cormorants are culled to a much lesser extent and there is a greater willingness to use non-lethal methods. The largest colony in eastern North America, just outside downtown Toronto, is managed by deterring cormorants from nesting in trees or in sensitive areas. Efforts are also made to increase appreciation of the cormorant colony as a spectacular natural phenomenon in the heart of an urban wilderness.

I hold out hope for cormorants. As more information becomes available to dispel the myths and misconceptions about these birds, understanding, tolerance and even appreciation for them will increase.

Ultimately, the cormorant's story reflects a culture still deeply prejudiced against creatures that exist outside the boundaries of human understanding and acceptance. To determine wildlife policy for these and other such creatures in the absence of scientific evidence is deeply flawed. I hope that by telling the cormorants' side of the story, I can help to encourage a more nuanced and humane approach to this unique and fascinating family of birds. ■

On the edge

If we want to give endangered species a helping hand, we should heed this cautionary tale, says **Stephanie Pain**

MELANIE MASSARO

"OLD BLUE was a saint," says Melanie Massaro. In her lifetime, Old Blue was the heroine of one of the most gripping tales in the annals of wildlife conservation. The cheeky little bird with the blue leg-band captured the hearts of millions and was feted around the world. Thirty years after her death, Old Blue's name lives on. There is even a memorial plaque to remind people that she was the saviour of her species.

For decades, the rescue of the Chatham Island black robin has offered conservationists hope: no matter how bad things look, it is possible to bring a species back from the very brink of extinction. But Massaro and her colleagues at the University of Canterbury in New Zealand have discovered that the legendary team of conservationists who helped Old Blue and her offspring unwittingly nudged the black robin onto an evolutionary path that almost led to disaster. So the great success story is also a cautionary tale, with important lessons for anyone thinking of stepping in to save a species.

The Chatham Island black robin, *Petroica traversi*, is in fact not a robin. It is an all-black flycatcher with a passing resemblance to the European robin. It is native to the Chatham Island archipelago, remote dots in the Pacific some 800 kilometres east of New Zealand (see map, right). The islands, which lie in the path of the Roaring Forties, are cold, battered by gales and pounded by huge seas. They were once home to many unique bird species, but following human settlement, these began to go extinct, most of them killed by the rats, cats and other alien predators brought in by settlers.

Once widespread on the islands, by the 1880s the black robin appeared to have vanished. Then in 1938 between 20 and 35 were discovered on the predator-free island of Little Mangere. Known to local fishermen as "the fort", Little Mangere is a rock stack that rises 200 metres out of the sea, its sheer cliffs topped with a patch of woody scrub covering just 9 hectares. Despite the improbably small population, the black robin hung on there for more than 70 years. Then, in the 1970s, with the island's woodland habitat fast deteriorating, the number dropped still further. By 1976, when the New Zealand Wildlife Service sent Don Merton to see if anything could be done, there were seven left, only two of them female.

Merton and his team became headline news when they achieved the seemingly impossible. They scaled the terrifying cliffs of Little Mangere to capture the remaining robins, returning the way they had come before leaping into a small boat rising and falling on the enormous swell at the base of the stack. Eventually, all the birds were transported to neighbouring Mangere, a larger predator-free island where they stood a better chance of recovery.

At first, the team simply kept an eye on the birds, hoping the number would rise. It didn't. In 1979, it dropped to just five, making the black robin the world's rarest bird. It was clear that without more help, the species would "go down the gurgler", as Merton put it.

Old Blue to the rescue

Then, Old Blue stepped up to the plate. At 8 years old she was positively ancient, and a poor breeder. Astonishingly, she dumped her mate, took up with a young male called Old Yellow and they became the only pair to breed successfully. Black robins usually lay two eggs per clutch but if they lose these they generally

Increasing numbers of black robins were seen laying eggs on the rim of their nest

RODMORRIS

Island hopping

In 1976, the last seven Chatham Island black robins were moved from Little Mangere to Mangere. Then, when numbers started increasing, a second population was established on Rangatira

lay again. So Merton and his team decided to speed the production of young by removing eggs after they had been incubated for a few days and placing them under female tomtits, which would finish the job while the robins laid again. "A single female could lay up to four clutches in a breeding season so cross-fostering really speeded up population growth," says Massaro.

During the first fraught years, Merton and his team followed every move the birds made – who mated with whom, where the nests were and when and how many eggs each bird laid. In 1990, with 100 robins – one group on Mangere and a second installed on Rangatira, a larger island with more wood and scrub to nest in – the team adopted a more hands-off approach, leaving them to breed without intervention. By 1998 there were 200 birds, the black robin was pronounced "saved" and the project ended.

The story is no longer headline news but it remains iconic, featuring in TV documentaries, books and countless articles. Yet nearly two decades after the robin was saved, the population has hardly grown. In 2013, a census counted 287. Suitable habitat is one limiting factor, but inbreeding is also likely to be hampering recovery, and this is where Massaro's interests lie. She wants to know what happens to species that come back from near extinction with a very restricted gene pool. "The black robin is the ideal species to investigate because it went through the most severe bottleneck possible – with all today's birds descended from a single pair," she says. How has that affected them? To find out, in 2007 Massaro set off for Rangatira.

Unlike Merton's team, Massaro did not have to dice with death to reach the robins. "Little Mangere is terrible. I don't know how they got up there," she says. But getting to Rangatira is no picnic either. The deafening 2-hour flight from New Zealand in an old propeller plane ends on a tiny airstrip on Rekohu, the main Chatham Island. Quarantine procedures take three days. "To protect the wildlife everything has to be washed, disinfected and picked clean of seeds, soil, little ants and so on." Then the kit is piled into plastic buckets and loaded aboard a small crayfishing boat for the ride to Rangatira. "The final stretch as you approach the island is really rough and there's no landing place. When you get there the skipper runs ›

"The observation that baffled Massaro most was seeing nests with an egg resting precariously on the rim"

the boat up on a rock platform and you have to leap from the bow." The buckets follow.

Getting around the island is awkward too. The ground is riddled with the nesting burrows of endangered petrels, so to avoid putting a boot through the roof and crushing eggs or chicks, visitors wear plywood "petrel boards", the Rangatira version of snowshoes. "You walk like a duck, but the boards spread your weight so you don't damage the burrows," says Massaro. The discomforts are worth it. "You only have to go a couple of metres into the bush and the robins come out to see you." As with so many of New Zealand's endemic birds that evolved in the absence of predators, they have no fear of people. Finding the nests is easy too. "You just give a male a meal worm and if he has a mate sitting on a nest he takes it off to her. All you do is follow him."

There are signs that inbreeding has taken its toll. In the six years she has been visiting Rangatira, Massaro, now based at Australia's Charles Sturt University, has found birds with deformed beaks, some near-naked ones and several clutches of chicks with poor bone development in their legs. But from the first visit, the observation that baffled her most was seeing nests with an egg resting precariously on the rim. "I thought it was really weird. Why would a bird lay an egg where it wouldn't be incubated?"

She asked Merton what he knew about it. He had seen the odd behaviour many times and it had puzzled him too, he told her. But in the early years of the rescue programme every egg was vital, so he and his team nudged them into the nest to ensure they were incubated. The eggs produced healthy chicks. Once intervention stopped, the team continued monitoring every nest, meticulously recording who laid how many eggs and every instance of an egg left on the rim. Merton had 10 years of records if Massaro would like to see them.

Even a cursory look was revealing. "There were no rim eggs until 1984," says Massaro. "At that time there were five female robins and only one laid a rim egg. But after that the habit really took off." Within six years, more than half the females were laying rim eggs, on average one per clutch. "That suggested this odd behaviour had a genetic basis." Egg nudging would have prevented natural selection weeding out what was clearly a harmful, or maladaptive, behaviour, leaving it free to spread rapidly through the population. "Intervention would have allowed the survival of the not-so-fit," says Massaro.

RODMORRIS

To rescue black robins from extinction, a team had to scale the terrifying cliffs of Little Mangere

And when intervention ended, natural selection would be reinstated, explaining why rim-laying was far less common by the time she arrived on Rangatira.

A near-fatal error

Back at the University of Canterbury, Massaro teamed up with geneticist Marie Hale and mathematician Raazesh Sainudiin to look for evidence to support her suspicions. "When I looked at the pedigree I immediately thought the trait was inherited," says Hale. But where had it originated? Did it result from a mutation in a single gene and, if so, was the mutant version of the gene dominant, meaning an individual needed just one copy to exhibit the behaviour? Or was it recessive, requiring two copies before a bird acquired the bad egg-laying habit?

Using Merton's detailed records and a family tree showing how every bird was related to every other, Sainudiin modelled all the possibilities to find out which one best fit the data. His results were unequivocal: the problem had started with Old Yellow, who carried one deviant but dominant copy of a gene involved in egg-laying.

Only 9 per cent of females now lay rim-eggs. This rapid decline is what you would expect for such a deadly trait once the conservationists' egg-nudging ended, says Hale. Still, an intervention intended to help could easily have led to disaster. With more than half of the females laying rim-eggs in 1990, the trait was a short step from becoming universal. Once every female carried a single copy of the rim-laying version of the gene, it would have been impossible to get rid of and the survival of the species would have depended on human help – forever. "By sheer coincidence intervention ended just at the right time and the black robin escaped that fate," says Massaro. "But it was a narrow escape."

The rise and fall of the badly laid egg offers a salutary lesson in the potential pitfalls of offering critically endangered species a helping hand. "If you have an extremely small population, you have to get the numbers up as fast as possible," says Massaro. But with a tiny gene pool, a single maladaptive mutation can have a disproportionately large impact. "You do need to be aware that these things can creep up on you." ■

LOUIS MARIE PREAU/NATUREPL.COM

When owls go south

What happens when a blizzard of Arctic owls takes a holiday, asks **Stephanie Pain**

AS AUTUMN 2013 drew to a close, naturalist Scott Weidensaul hung up his outdoor gear and settled down for a quiet winter at home in Pennsylvania. He was writing a book about owls and planned on finishing it before nature perked up again in spring. But he hadn't reckoned on the biggest invasion of snowy owls for a century. As reports of sightings flooded in from eastern Canada and the north-eastern US, Weidensaul and other owl enthusiasts swung into action. "We all knew we'd never get such an opportunity again," he says.

Most people will never see a snowy owl in the wild, but its distinctive white plumage and golden eyes are familiar to millions thanks to Hedwig, Harry Potter's message-carrying pet. "They are one of the world's sexiest birds. Everyone recognises them, but there's so much we don't know about them," says Weidensaul. The reason is ›

"One snowy owl in Florida attracted so many sightseers it was given its own wildlife ranger"

simple: snowy owls inhabit the high Arctic, where summer is brief and winter long, dark and lethally cold. For eight months of the year fieldwork is impossible in the region, so the owl's winter habits have long been a mystery.

Snowy owls spend summer at the very highest latitudes, from North America to Siberia, via Greenland and Scandinavia. A top predator of the tundra, their success is intimately linked to the regular boom-and-bust population cycles of their summertime prey: lemmings. When lemmings are plentiful, owls raise many chicks. When scarce, they may not breed at all.

Such an unpredictable food supply has made nomads of snowy owls. While most other birds return to the same place to nest each year, snowy owls roam the tundra searching for somewhere with an abundance of lemmings, and can travel thousands of kilometres before settling on a site.

In autumn, as the lemmings begin to disappear beneath deep snow, some owls fly south where the hunting is easier. Sometimes they migrate en masse, a phenomenon known as an "irruption". These are unpredictable and can be triggered by many things, but they are especially common in years when owls breed successfully, increasing pressure on the Arctic's limited resources. Every four years or so there's an irruption and every few decades there's a big one.

In the summer of 2013 the Salluit region of northern Quebec saw a massive explosion of lemming populations, which attracted owls from across the Canadian Arctic. "Each pair produced seven or eight fat chicks instead of the usual one or two," says Jean-François Therrien of the Hawk Mountain Sanctuary in Pennsylvania, who spends his summers studying owls in the Canadian Arctic. By early December, thousands were pouring south across the Canadian border into the north-eastern US and the Great Lakes region. During normal irruptions, birds rarely get further than Cape Cod and New York. This time, some travelled as far south as Georgia, Florida and even Bermuda. "You have to go back to 1926/27 or perhaps even to the 1890s to see the same size irruption," says Weidensaul.

ALAN RICHARD

Solar-powered transmitters are revealing what snowy owls get up to in winter

As the number of sightings snowballed, Weidensaul, David Brinker and Steve Huy, who coordinate a network of owl researchers called Project Owlnet, leapt into action. "With no advance warning, there had been no time to plan research or apply for funding," says Weidensaul. Yet within a week, Project SNOWstorm was up and running. "We were riding a wave of publicity. Everyone knew about the owls. The one in Florida was attracting so many sightseers it was given its own wildlife ranger." Dozens of wildlife experts, owl researchers, bird banders, vets and pathologists volunteered their services. Bird groups and ornithological organisations donated cash to get the project started and crowdfunding raised enough money to buy tracking devices. Donations flooded in from as far afield as Spain, Norway and the UK.

The aim was to squeeze as much information from the irruption as possible. Thousands of people sent in photos to help identify the sex and ages of the owls. Experts were on call to perform autopsies and tissue analyses on casualties found by the public, checking their condition and measuring levels of toxins and pollutants.

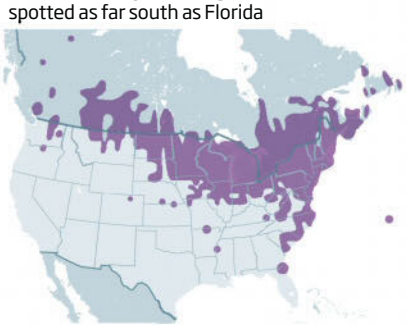
The key to that essential mystery of what owls do in winter, however, lies in tracking the activities of individual birds. Before winter ended, the team had captured 22 owls in seven states, from Minnesota to Massachusetts, and fitted them with state-of-the-art transmitters that would follow their every move (see "Hedwig phone home", above right).

From the start, it was obvious that snowy owls weren't going to conform to expectations. "What we thought we knew about this part of the owl's life cycle we didn't," says Therrien.

The most oft-repeated assumption to bite the dust is that snowy owls are diurnal – active during the daytime. The tracking data showed clearly that

Southerly swoop

During winter 2013/14 snowy owls left their normal territory in the high Arctic and were spotted as far south as Florida



they rest by day and hunt and migrate under cover of darkness. "Yes, they hunt in daylight in the Arctic summer," says Weidensaul. "But only because it never gets dark." Given a choice, they are as nocturnal as most other owls.

Nor, as supposed, are irruptions triggered by starvation. "We could see these owls were fat – comically fat," says Weidensaul. Instead, Therrien suggests, when there are so many owls, the experienced adults probably monopolise territories closest to the breeding grounds, forcing younger birds to move elsewhere. The photos sent in by the public indicated that almost all the owls flying south that winter had been born that summer.

As seasoned snowy-watchers, the team wasn't entirely surprised by these findings. What did astonish them was where the owls went in search of food. "We thought we'd see them feeding mostly on open farmland where there are lots of rodents and rabbits," says Therrien. The owls had other ideas.

Owls in the Great Lakes region seemed fixated on ice, moving onto the frozen lake surface for weeks on end. "At first we couldn't imagine what they were finding to eat," says Weidensaul. But by comparing their movements with satellite images of the lake's surface, the team realised the owls were focusing on cracks in the ice created by shifting winds – slivers of open water that harbour large numbers of waterbirds, especially diving ducks.

Although unexpected, this fitted with something Therrien had reported in 2011. He and colleagues at Laval University in Quebec found that some of the owls they tagged during their summer studies in the Arctic had headed north for the winter and spent weeks on the Arctic ice pack, where they could only be feeding on sea ducks.

Owls that spent winter 2013/14 along North America's Atlantic coast also had a taste for waterbirds. "Some hunted exclusively over water, sometimes using channel markers and buoys as hunting perches," says Weidensaul. Tracking data can't reveal what they were catching, but there were clues in the pellets they regurgitated after feeding. Those from some owls around the Great Lakes contained nothing but the indigestible remains of waterbirds. Those found by the coast included the feathers of ducks, coots and gulls.

Inland, some owls were hunting rodents and rabbits, as expected. But a few were more ambitious. In the Amish country of south-central Pennsylvania, the open farmland attracts great flocks of snow geese in winter. Although bigger than snowy owls, some still became prey. "We shouldn't be so surprised," says Therrien. "Look at the size of the owls' feet – they are far too big just to catch lemmings and mice."

So, snowy owls are unexpectedly flexible about where they breed and what they eat. "This is an enormously adaptable bird," says Weidensaul. That could prove important to a species facing an uncertain future in a rapidly warming Arctic. Already there are signs that changing climate is disrupting the lemmings' regular boom and bust cycles with knock-on effects for snowy owls. To make matters worse, the global population of owls may have been seriously overestimated. Long thought to number some 300,000 birds, the latest estimates suggest there are more like 30,000. "Their future is very much in question," says Weidensaul.

Project SNOWstorm might help to answer some of the key questions. To everyone's surprise, the owl invasion of 2013 was not a one-winter wonder: 2014 saw an "echo-irruption", with a new batch of young joining many of the birds that had flown south the previous year. So, instead of spending last winter analysing data from the mega-irruption, the team turned out to capture and tag another dozen owls and get re-acquainted with old friends.

"Through Project SNOWstorm we hope to understand a big chunk of the owl's life history that until recently had largely been a blank slate," says Weidensaul. "That's a good first step towards knowing how we can preserve these birds in the years ahead." ■

In years when lemmings are abundant, snowy owls can raise seven or eight chicks

AUDREY ROBILLARD

HEDWIG PHONE HOME

Over the past two winters, Project SNOWstorm has provided unrivalled insights into the behaviour of snowy owls. At its heart is a state-of-the-art tracking device designed by biologist Mike Lanzone, head of Cellular Tracking Technologies (CTT) in Pennsylvania. Weighing just 40 grams, the solar-powered transmitter fits into a backpack-style harness made of soft Teflon ribbon that won't chafe.

Unlike traditional transmitters, it uses the GPS satellite system to log a bird's latitude, longitude and altitude – and then sends the data to CTT's server via the cellphone network. The transmitters are designed to phone home every few days, but if an owl flies out of range of a cellphone mast, they can store up to 100,000 locations and transmit the data when the bird next flies into an area with coverage – even if that is many years later.

The link to the phone system also means the team can communicate with the devices. "We can send them messages, changing the frequency of data collection for instance," says Scott Weidensaul, an architect of Project SNOWstorm. In most cases, the devices were set to collect data every half hour, giving 48 locations a day in three dimensions. A few were programmed to track owls minute by minute, and some every 30 seconds, in the hope of learning about their hunting techniques. "But they move so fast when they hunt it can be all over in 30 seconds," says Weidensaul.

"One thing we discovered was that snowy owls are like sunflowers," says Weidensaul. "They always turn to face the sun, which means their backs are always in the shade, so we had to be careful not to set the transmitter to collect data too often or it would drain the battery."

CHAPTER THREE

OCEANS

A face in the dark

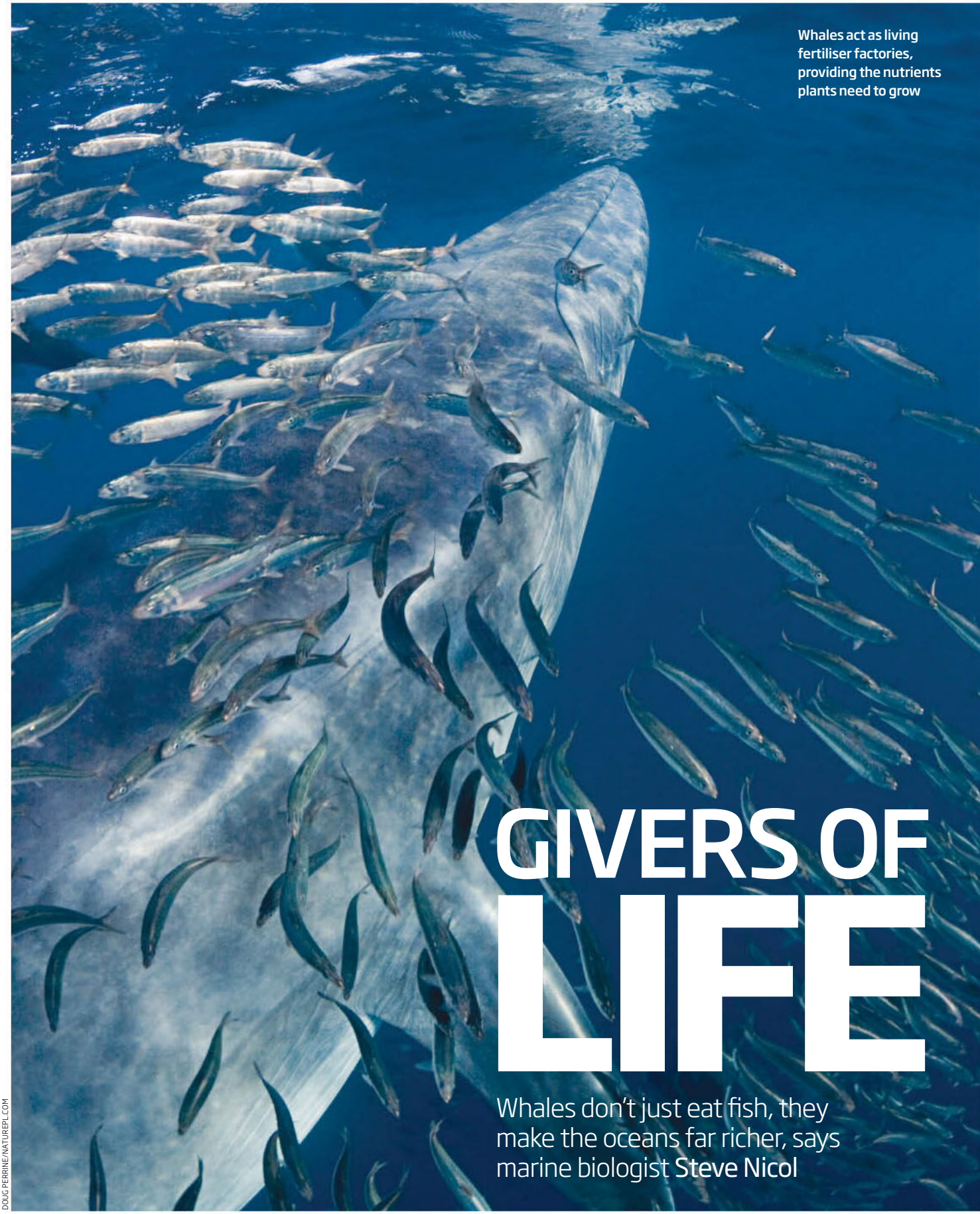
IT'S looking at you, with its mouth slightly open. For Jean-Marie Ghislain, meeting this thresher shark was a moving experience, because it is a timid and distant animal. Not, perhaps, the impression that most of us would form if we came face to face with a 3-metre shark. Especially one that uses an incredible elongated tail as a whip to stun its prey before eating it.

But Ghislain is on a mission to rehabilitate the image of sharks. He set up Shark Revolution, a non-profit organisation aimed at educating people on the plight of sharks around the world. This shot was taken in Malapascua in the Philippines, a site renowned for encounters with threshers. He shoots in black and white when the conditions would otherwise make the image saturated with blues. "This meeting touched me deeply," Ghislain writes in his new book, *Shark: Fear and beauty*. "Its gaze is reminiscent of a frightened animal and its wide eyes reinforce the impression that you are looking at a cartoon character."

The pelagic thresher, *Alopias pelagicus*, feeds on small fish, so isn't a danger to humans. But that doesn't mean it is safe from us. Sports fishermen target it, and it is also sometimes killed as by-catch in drift nets and longline fishing. And according to the IUCN Red List, which rates it as vulnerable to extinction, the pelagic thresher has a slow life cycle, hampering its ability to recover from such exploitation. Rowan Hooper

Photographer

Jean-Marie Ghislain ghislainjm.com
Shark: Fear and beauty, Thames & Hudson
Publication date: 3 November 2014



Whales act as living fertiliser factories, providing the nutrients plants need to grow

GIVERS OF LIFE

Whales don't just eat fish, they make the oceans far richer, says marine biologist **Steve Nicol**

DOUG PERRINE/NATUREPL.COM

Historical records show the oceans used to support far more life

PICTURE an ocean teeming with life: the sky darkened by massive flocks of birds, giant whales clouding the air with the vapour from their blows, and as far as the eye can see, schools of fish breaking the surface to escape myriad predators. Such sights were common before we arrived on the scene.

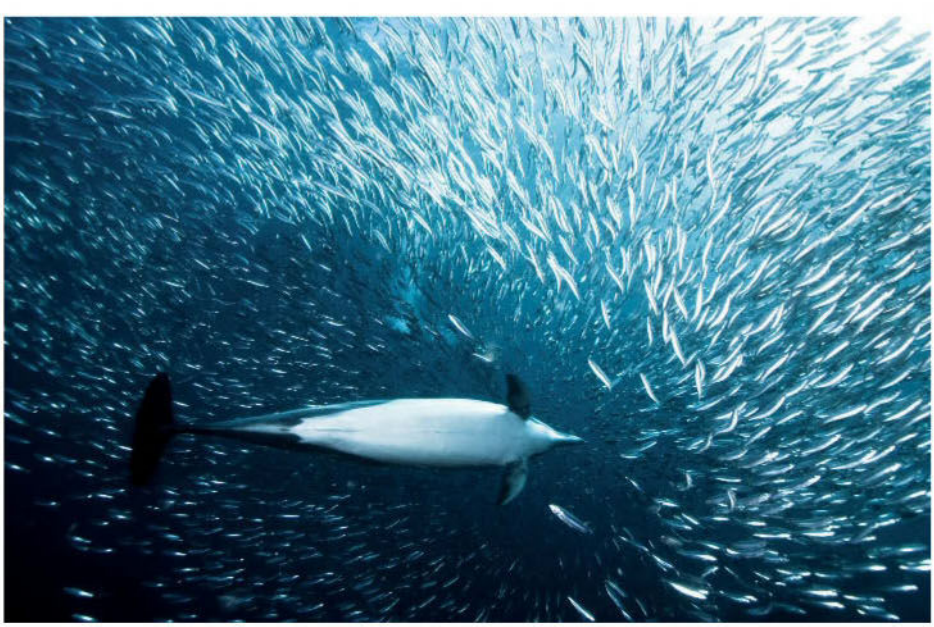
From historical accounts, it is clear that today's oceans are a pale shadow of their former glory. We know what happened to the whales – we killed almost all of them – but why aren't the seas swarming with other animals instead? With fewer whales eating them, for instance, you would expect there to be far more krill in the Southern Ocean, but strangely there seems to be a lot less than before. It appears that the oceans have somehow lost their ability to support such an abundance of life.

In recent years, my colleagues and I have begun to suspect the reason for this is that large animals do far more than just gobble up food: they also play a critical role in maintaining and enhancing the productivity of the seas. By removing them, we may have made the oceans a far poorer place.

If these ideas are confirmed, there are profound implications. We would have to completely rethink the way we manage ocean resources. For instance, fishermen have often killed large predators such as seals and whales in the belief that this will increase fish numbers. Our work suggests the opposite is true.

The amount of life the oceans can support ultimately depends on how much food plants make. Photosynthesis can only occur in the sunlit upper layer, and for the microscopic plant cells, or phytoplankton, that do almost all the photosynthesising in the open ocean, there is a huge problem – gravity. A few species float or swim, but most plant cells tend to sink a few metres per day. Not only does this take them away from the sunshine, it also leads to a constant loss of nutrients from the surface layer.

In winter, strong winds churn up the waters, returning some nutrients to the surface. However, in summer, just when there is most light for photosynthesis, surface waters warm, become less dense and stop mixing with the colder water below. The boundary is known as the thermocline, and once particles sink below it, the nutrients they contain are usually lost to the surface ecosystem. As the planet warms, this stratification effect is expected to become stronger, reducing the oceans' productivity.



ALEXANDER SAFONOV ABOVE: AVALON/ALAMY

The rate at which nutrients are lost is accelerated by the small animals that feed on plant cells. The faeces of animals such as copepods and krill can sink between 100 to 800 metres per day, and fish faeces can sink more than a kilometre per day.

So the growth of phytoplankton and the animals that feed on them effectively converts dissolved carbon and other elements into particles that sink to the sea floor and end up locked away in sediments – a process known as the biological pump. The loss of carbon is not a problem, as carbon dioxide is absorbed from the atmosphere as fast as it is removed from waters, but other elements are in short supply. In large parts of the ocean, for instance, the growth of plants is limited by a lack of iron in the water. Adding soluble iron to the surface waters in these areas creates a bloom of phytoplankton.

What all this means is that the productivity of the oceans depends on the rate at which essential nutrients are delivered to the sunlit layer or are recycled within it.

Until recently, our understanding of this process was driven largely by studies of physics and chemistry. Winds blowing iron-rich dust from the land, rivers pouring into the sea and the upwelling of deep water were seen as the key processes supplying nutrients to surface waters.

Animals were rarely viewed as players in this process. However, it is now becoming apparent that animals, particularly large ones, play a very important role in delivering and recycling nutrients.

They do so in at least three ways. The first is simply by mixing up ocean waters, which can return some nutrients to the waters above the thermocline. Whenever animals move through the water rather than merely drift with it, some of the water moves along with their bodies – a phenomenon known as "induced drift". Swimming animals also generate turbulence as they cut through the water, redistributing nutrients as they go. This wake turbulence effect may be negligible for small animals, but there is no doubt that dense aggregations of larger animals moving through the thermocline would have a significant local effect.

Every day, vast numbers of marine animals, from microscopic zooplankton to large fish, do move through the thermocline. Most remain in deep water during the day and visit the surface at night. These vertical migrations can involve movements of thousands of metres, and are probably the largest concerted movement of animals on the planet. In ›

"It might well be that allowing whales to recover to something like their previous levels would boost fish numbers rather than reduce them"

addition, air-breathing animals such as whales and seals often dive below the thermocline.

Astonishingly, some say the movements of animals may be one of the main forces mixing the oceans and redistributing nutrients. According to recent calculations, this force is similar in magnitude to winds and tides. What's more, these calculations are based on estimates of the current density and abundance of swimming animals. Since animals, particularly larger animals, were far more abundant in the past, their effect would have been much greater.

The second way in which animals can boost ocean productivity is by nutrient scavenging – feeding at depth and bringing nutrients back to the sunlit zone. Sperm whales, for instance, feed on squid and fish at great depths, and defecate at the surface. Models suggest that this recycling of deep material may well be significant for essential elements such as iron.

On a local scale, humpback whales in the Gulf of Maine have also been shown to scavenge nutrients. In fact, they release more nitrogen at the surface than flows in from all the rivers.

Many other species are known to feed in deep waters on occasion and return to the surface, including seals, penguins, turtles, seabirds and sunfish, so it is possible these animals also return significant amounts of nutrients to surface layers.

Surprisingly, even krill may play a part. While they were thought to live in the upper 200 metres of water, krill have been observed at much greater depths. There is footage of krill 3500 metres down on the sea floor, apparently feeding on material that has sunk to the bottom. If krill regularly feed on the sea floor and return to the surface, this may be an important route for bringing nutrients from the sediments back to the surface.

Of course, the opposite process also occurs. Animals that feed near the surface at night and return to deeper waters take nutrients back down with them. We don't yet know on what scale nutrients are removed from and returned to the surface in this way or what the overall net effect is, so the importance of nutrient scavenging to the productivity of the oceans remains to be established.

Recycling nutrients

What is clear is that without species such as sperm whales and humpbacks, surface nutrient levels would be significantly lower in some areas. What's more, by greatly reducing the numbers of air-breathing animals that feed at depth, it is possible that we have unwittingly altered the balance between nutrient return and removal.

The third way in which animals may boost ocean productivity is by recycling nutrients within the sunlit zone. Take the Southern Ocean. It lacks iron because little dust blows off Antarctica, so any mechanism that keeps this element in the surface layer and allows it to be recycled helps to maintain productivity.

The huge populations of krill in these waters are effectively a buoyant reservoir of iron. They incorporate iron into their tissues and, because they are strong swimmers and live for up to seven years, they can keep iron in the upper layer for a long time. A quarter of all the iron in the top 200 metres of water may be found within the bodies of krill.

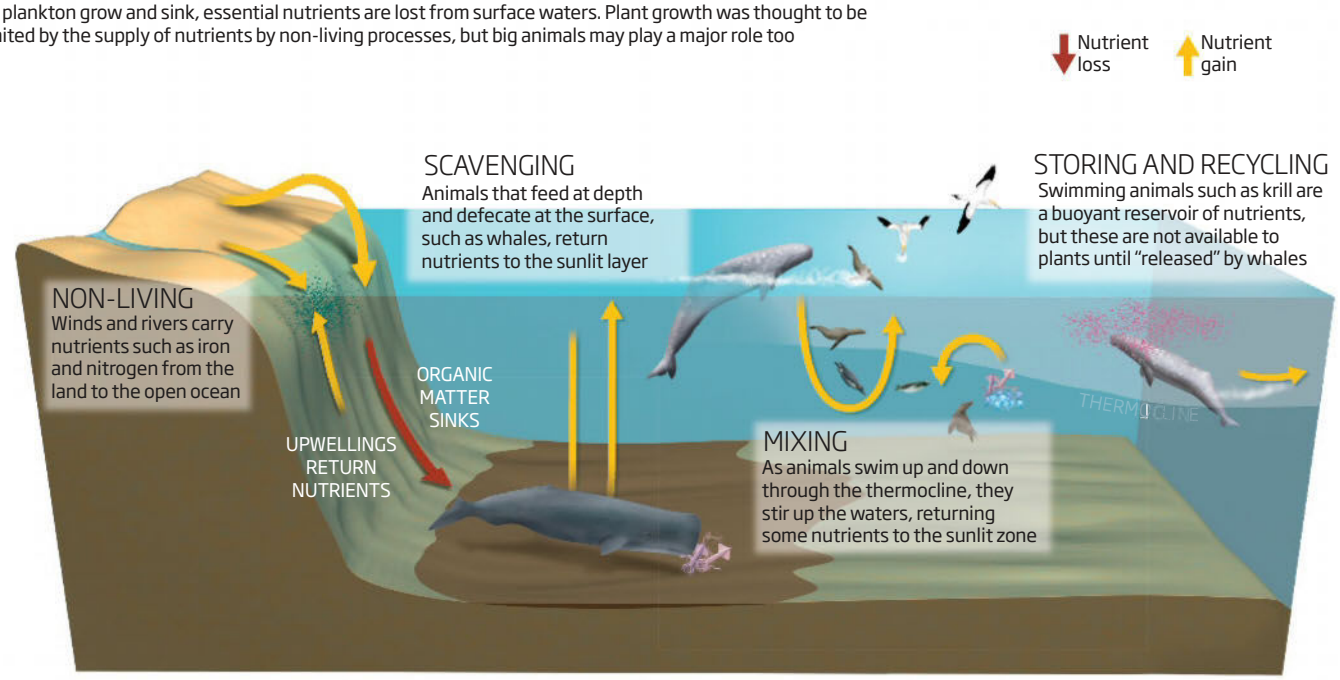
However, phytoplankton cannot use this iron if it remains locked away in the bodies of krill and sinks to the ocean floor when they die. This where the whales come in.

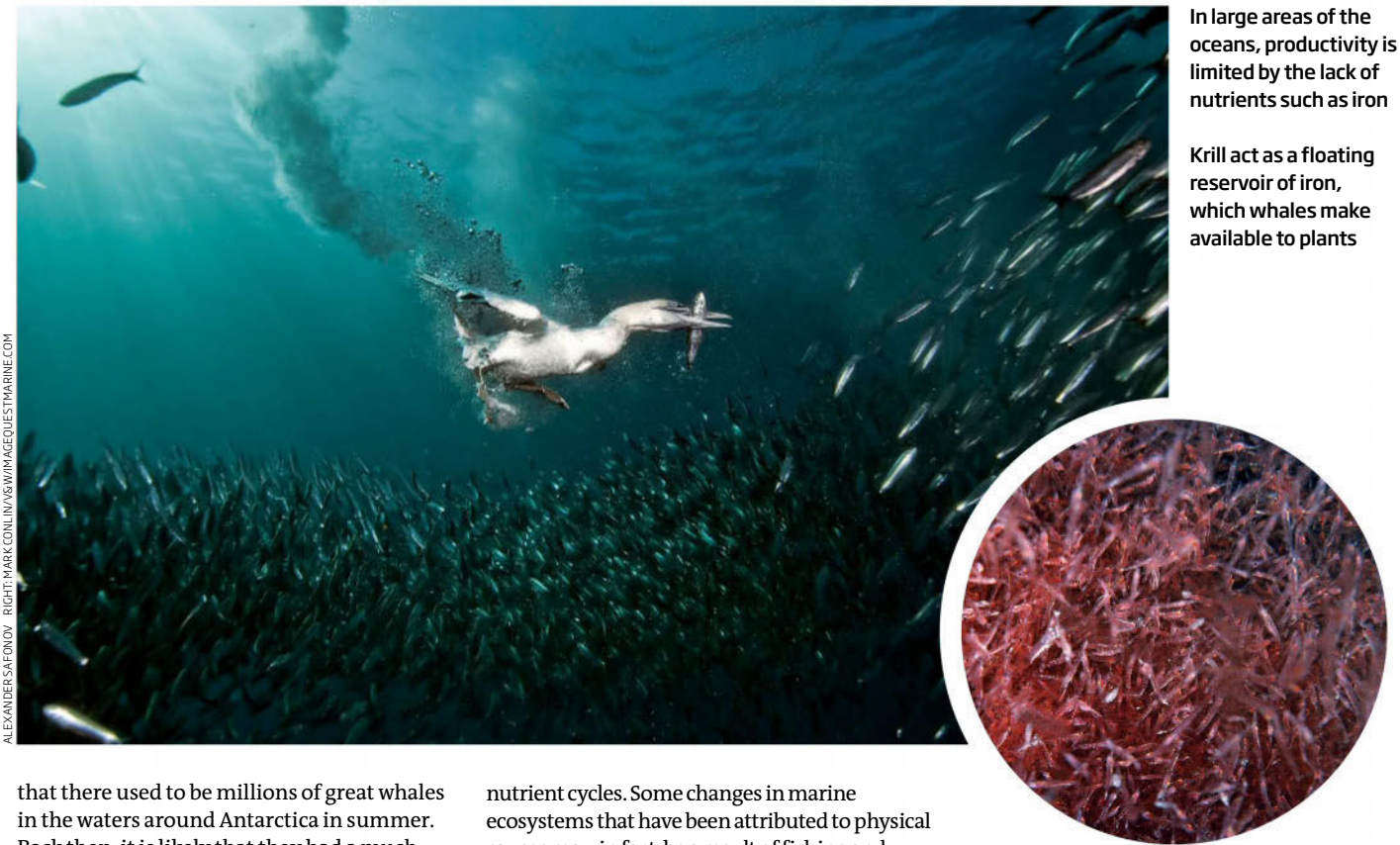
The idea is that large whales act as fertiliser factories, converting krill into plant food. Whales produce buoyant plumes of faecal material that functions as liquid manure. Measurements of the iron content of the faeces of baleen whales by my team show that concentrations in whale faeces are at least 10 million times the background level in seawater.

Whales probably play only a small role in fertilising the oceans today, but we know from the records of catches by whaling ships

How large animals bring the ocean to life

As plankton grow and sink, essential nutrients are lost from surface waters. Plant growth was thought to be limited by the supply of nutrients by non-living processes, but big animals may play a major role too





ALEXANDER SAFONOV RIGHT: MARK CONLIN/V&W/IMAGEQUESTMARINE.COM

In large areas of the oceans, productivity is limited by the lack of nutrients such as iron

Krill act as a floating reservoir of iron, which whales make available to plants

that there used to be millions of great whales in the waters around Antarctica in summer. Back then, it is likely that they had a much greater effect. Significantly, there is evidence that when there were more whales, there was also more krill. This may have been the result of a positive feedback cycle. The more whales there were, the more "fertiliser" they would have produced. That would have allowed more phytoplankton to grow, providing more food for krill and thus for whales. As the krill population grew, the total amount of iron stored in these buoyant reservoirs would have increased. And as the whale population grew, the ecosystem would have become ever more productive.

If this picture is correct, the past abundance of life depended on a juggling act that kept lots of iron circulating in the sunlit zone. When we killed the whales, the "balls" fell. As a result, the ocean is no longer able to support the same amount of life.

In other ecosystems, there may be similar mechanisms involving different groups of predators and prey. It is unlikely that the role of animals as buoyant nutrient reservoirs is solely restricted to the Southern Ocean, or exclusively to the iron cycle.

The fertilising role of whales has another implication. Air-breathing predators were thought to be a major "leak" in the biological carbon pump, returning up to a quarter of the carbon captured by phytoplankton to the atmosphere. In fact, whales may actually help remove carbon dioxide from the atmosphere.

Put it all together and the evidence suggests large animals play a big role in the ocean's nutrient cycles. Some changes in marine ecosystems that have been attributed to physical causes may, in fact, be a result of fishing and hunting. According to one study, for instance, phytoplankton abundance has declined in eight of the 10 oceanic regions over the past century – especially in areas where many whales and seals have been culled over the past century.

The idea that large animals affect ecosystem productivity would not surprise terrestrial ecologists. It has long been accepted that large land animals "engineer" the ecosystems on which they depend. When you have seen elephants pushing over trees, it is easy to understand how they can change the landscape. In the vast oceans, it is perhaps harder to see how animals can have an effect – especially in an era when whales, seals and large fish are rare as a result of centuries of over-harvesting.

But this does not mean that such effects do not exist; they may just be more subtle and difficult to measure. In fact, ecosystem engineering may actually turn out to be more important in the open ocean than on land because of the cumulative effect of a vast array of organisms acting on all manner of scales simultaneously.

More whales, more fish

Progress is being made in quantifying the effects animals have through mixing waters, nutrient scavenging and storing and recycling nutrients. Researchers have been building models of some of the key components and we are beginning to better understand which of the many processes involved are the most critical.

Monitoring the fertilising effect of a pod of whales, although potentially unpleasant to do, could answer questions about the effects of defecation at the surface, such as whether the recycled nutrients are readily available to phytoplankton. If such studies confirm that the overall effect of large animals is to increase marine productivity – or that they did so in the past – it could challenge some long-cherished concepts in marine ecology. For instance, simple models suggest that removing top predators such as seals and whales would increase harvests of intermediate level species such as fish, squid and krill. This has never been taken seriously by fisheries managers, but Japan has used this argument to try to boost support for a resumption of commercial whaling.

None of the models, however, takes account of the recent discoveries about the positive effects of large animals. The intricate feedback loops of marine ecosystems mean the effects of targeting particular species can be counter-intuitive. More realistic models may produce quite different results and support different harvest strategies. It might well be that allowing whales and other large animals to recover to something like their previous levels would boost fish numbers rather than reduce them. That would be great news for the oceans, for conservationists and for fishing communities. ■

RIGHT: FLIP NICKLIN/MINDEN PICTURES/NGS. BELOW: CHRISTOPHER KEMP

Heaven scent

A sperm whale's gut is the unlikely source of a perfume ingredient that's worth its weight in gold. **Christopher Kemp** goes in search of ambergris

IT'S a rainy afternoon on Long Beach. I am standing beneath a mackerel sky, holding a strange little object in the palm of my hand. It's pale green-grey and looks like a potato. It could be a stalk of decomposing seaweed, a waterlogged piece of driftwood or a shrivelled piece of sponge. It could actually be a potato.

I bring it to my nose and smell it. Nothing. It has no discernible odour, except perhaps a faint briny trace. And so I discard it and move on, slowly making my way along the beach, bending occasionally to pick up an object before smelling it and then pitching it over my shoulder.

I have come to this remote strip of sand north of Dunedin, New Zealand, to find ambergris, a substance I have never seen or smelled before. Even if a piece of it is lying there, half hidden by a tangle of kelp, I will probably walk past it. Despite this, I reassure myself every few paces that if I just spend long enough searching, I will find some.

My interest in ambergris had been sparked a few months earlier by news reports of a strange object that washed up on Breaker Bay near Wellington in September 2008. It was roughly cylindrical, about the size and shape of an oil drum, and weighed an estimated 500 kilograms. It was soft, greasy and the colour of dirty week-old snow.

Rumours spread quickly. Some said it was a large piece of cheese, probably Brie. Others suggested it was soap. Then another rumour began to circulate: it was ambergris. Soon, people were carving off large chunks and taking them home. Three days after it washed up there was nothing left. All around the bay, people were celebrating their sudden and unanticipated wealth.

When I first heard about the object, I went online thinking I would learn everything I needed to know about ambergris in minutes. As a former scientist, I'm used to being able to access whatever information I want. But I found almost no useful information at all, mostly esoteric scientific papers and medical texts published in the 18th century.

One of the few recent accounts was from *The New Zealand Herald*. In May 2006, 10-year-old Robbie Anderson was walking his dog on Long Beach when he found something on the sand. It was mottled white and grey, irregular in shape and about the size of a loaf of bread. It had a strong odour, which was unusual and difficult to categorise. So he took it home.

The following two days, Robbie and his father returned to the beach. They had researched the object and realised it could be ambergris. On the second day, they found more. In total, their haul was worth about NZ$10,000.

Since reading about the Andersons' find, I started to visit Long Beach, walking along the tide line searching for ambergris. I also began visiting libraries, leafing through encyclopaedias, reading old ledgers and journals and calling museum curators and ambergris traders. It was as if I had fallen down a rabbit hole. More than anything else, my motivation was the lack of reliable information about ambergris. Even descriptions of its odour seemed inadequate. I decided to do everything possible to experience it for myself.

From my initial online search, I had learned a few important things. First, ambergris is an intestinal secretion of sperm whales that washes ashore with the tide and has a complex and hard-to-describe smell. It has been used for centuries as an ingredient in perfume, and also as a medicine, aphrodisiac, incense and flavouring. Its name means "grey amber", although it is not amber; it is also known as ambergreen, ambergrease or simply "floating gold". Most importantly, it is rare and extremely valuable. It is traded for up to US$26 per gram, depending on its quality. At times it has been worth more than gold.

Given its origins, the value attached to ambergris is somewhat strange. Its journey begins in darkness, in the cavernous hindgut of a sperm whale, as a mass of undigested squid and faeces.

An adult male sperm whale measures up to 20 metres long and weighs as much as 50 tonnes. To maintain its prodigious size it must consume about a tonne of food a day, diving repeatedly to great depths to guzzle squid. In 1993, cetologists surveyed the stomach contents of 17 sperm whales killed in the Azores and found the remains of almost 29,000 squid from 40 different species.

In the digestive system, most of a squid is broken down quickly, leaving only the beak-like mouthparts, eye lenses and a tough internal organ called the pen undigested. It is these remnants that give rise to ambergris.

Like cows and other ruminants, sperm whales have four stomachs. Food passes from one to the next, being digested along the way. Steadily the stomachs begin to fill with indigestible remains, which coalesce into a dense, glittering mass. Every couple of days, a sperm whale will vomit this into the ocean. This is quite normal – and despite persistent reports that this is where ambergris comes from, it is not. ›

"The faecal smell softens to a rich, complex odour that has been compared to old churches and fine tobacco"

TARANAKI DAILY NEWS

As oceanographer Robert Clarke explained in his 2006 paper *The Origin of Ambergris*, the production of actual ambergris requires abnormal processes. Occasionally, the mass of beaks finds its way into a whale's intestines. As the jagged mass passes from the stomach, it chafes and irritates the intestinal lining. Pushed further along the intestines it becomes a tangled solid, saturated with faeces, which obstructs the rectum. Faeces build up behind it. The gastrointestinal system responds by increasing water absorption from the lower intestines and gradually the mass becomes a concretion – a smooth and striated boulder. Faeces can now make their way past again, between the shrunken boulder and the wall of the intestines. Slowly, the process repeats, adding additional strata to the boulder, which grows larger with each new layer. This process occurs in just 1 per cent of sperm whales, which explains why ambergris is so rare.

A block of raw ambergris can grow to enormous size. The largest piece on record was extracted from a sperm whale killed in 1953. Clarke's account of it, *A Great Haul of Ambergris*, includes a photo of a boulder-like object suspended above the deck of the whaler (see right). It weighed nearly half a tonne.

In some instances, a whale may be able to expel the obstruction. In others, it is terminal, blocking the gut completely until the whale suffers a fatal intestinal rupture, expelling the boulder into the ocean.

The black and viscous mass – slightly less dense than seawater – is now at the mercy of the currents. It can ride the swell for decades, bobbing and rolling through cyclones and equatorial heat, sometimes getting trapped in large rotating currents called gyres.

Like wine, ocean-going ambergris slowly matures. It is oxidised by salt water, degraded by sunlight and eroded by wave action until, finally, it beaches somewhere along the coastline. Where, nobody can predict.

By the time a well-travelled piece of ambergris washes up on the shore, it has changed. Depending on how long it has been at sea, it will have evolved from a tarry mass to a pale, waxy ball. Over the years, it loses most of its water to become smaller and denser. Its exterior hardens so it resembles a grey stone, a little like pumice or chalk, its interior flecked black with embedded squid beaks.

Most importantly, the faecal smell softens and is replaced by a rich, complex odour that has been compared to fine tobacco, the wood in old churches, the smell of the tide, sandalwood, fresh earth and seaweed in the sun. Clarke once wrote that it reminded him of Brazil nuts.

Whatever it smells of, mature ambergris is highly prized by perfumers, who value it for two properties. First, it is a powerful fixative, slowing the breakdown of a fragrance on the skin and making the scent last longer. Equally important is its singular, animal, odour.

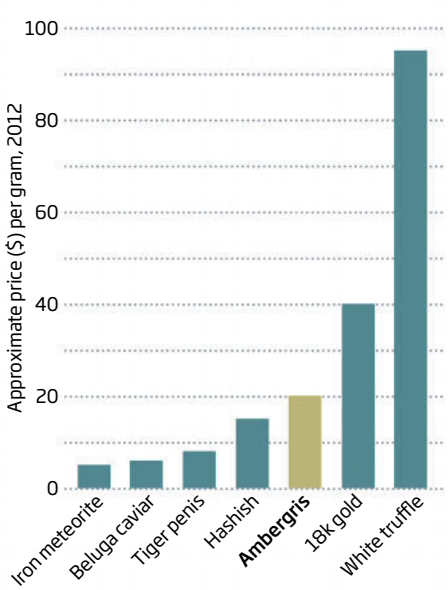
This much I knew, but to experience the smell for myself I needed to speak with people in the business. For more than six months, that was what I attempted to do. Without exception, I failed. I learned that the merest mention of ambergris can change a conversation. Talkative people become taciturn. Wary of revealing too much, anyone familiar with its value and scarcity will say nothing, or respond in generalities.

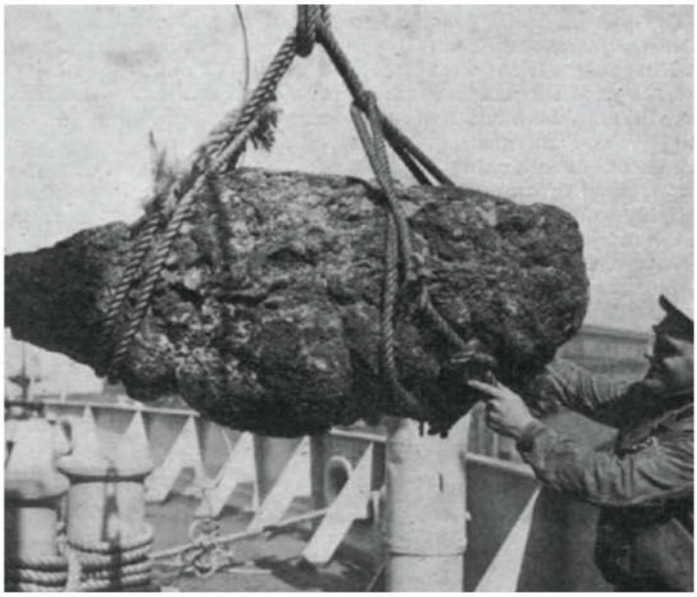
There is a reason for this: the legality, or otherwise, of trading in ambergris. The regulations are a tangled web of restrictions and treaties that differ from country to country. It is almost impossible to find out what the regulations are, who decides them and who enforces them. In Australia, for example, a strict classification of sperm whales under the Convention on International Trade in Endangered Species prohibits the importation and exportation of ambergris. In the US, meanwhile, commercial trade in ambergris is allowed under CITES, but prohibited by the Marine Mammals Protection Act. As a result, the ambergris industry is shadowy and difficult to penetrate.

So I went back to square one. I began collecting reports of beach walkers stumbling over strange objects, taking them home and then discovering they are ambergris. Every account I found filled me with hope. I would drive to another beach and walk for miles, picking up any object that I might be ambergris. I have scrutinised pieces of kelp, plastic, coal, driftwood, bone, glass and broken

Expensive taste

Ambergris - used in perfume - is one of the most valuable natural substances in the world





NORBERT DENTRESSANGLE/SALVESEN ARCHIVE/EDINBURGH UNIVERSITY LIBRARY

MARK MITCHELL/NEW ZEALAND HERALD

The real thing (far left) and the worthless mass that washed up in New Zealand in 2008 (left)

CHRISTOPHER KEMP

Small samples of ambergris (above) and the largest piece ever recovered (left)

shells. One day I almost smelled a dead seagull. But mostly I have sniffed rocks, which don't smell of anything much.

I found I was not alone. Anton van Helden, the marine mammals collection manager for the Museum of New Zealand, is frequently contacted by beachcombers who believe they have found ambergris. Their finds always turn out to be worthless: dog faeces, coal, rotting vegetables, soap, whale blubber, seaweed, rubber, tallow, even a decomposed sheep.

The people of Breaker Bay were similarly fooled. The mass that washed up in 2008 wasn't ambergris. It was a block of tallow that had probably fallen off a ship. It was worthless.

Molecular mystery

The quest to characterise the odour of ambergris has a long and venerable history. In 1820, chemists Pierre-Joseph Pelletier and Joseph Bienaimé Caventou of The School of Pharmacy in Paris, France, made the first scientific attempt to do so, applying revolutionary techniques they had developed to extract compounds from medicinal plants.

They had already isolated chlorophyll, strychnine and, earlier that year, the anti-malarial quinine. Now they were turning their attention to a small lump of ambergris.

They weighed and measured it, calculated its density and measured its boiling point. After dissolving it in alcohol, filtering the solution and leaving it to stand, they noticed white crystals forming in irregular clumps. This, they surmised, was the active compound. They named it ambrein.

Ironically, ambrein is odourless. But chemists have since broken it down further, dismantling it atom by atom to find the source of the elusive odour. As ambergris slowly matures, the ambrein degrades into a rich mixture of fragrant compounds. One is dihydro-gamma-ionone, which smells strongly of tobacco. Another is a derivative of butanal which smells like seawater. A third is alpha-ambrinol, which is mouldy, animal and faecal. Finally there is naphthofuran, also known as ambergris oxide. This is the compound that is most characteristic of ambergris and the one that is impossible, or nearly impossible, to describe.

Chemists have gone to great lengths to try to produce synthetic compounds that smell like ambergris. They have succeeded to some extent. The results – molecules with trade names like Ambrox and Synambrane – are used by many perfumers as a substitute for ambergris. But mimicking the real thing is all but impossible. As Luca Turin and Tania Sanchez wrote in their 2008 book *Perfumes: The Guide*, they "smell nothing like the natural material".

Mandy Aftel, founder of Aftelier Perfumes in California, has used ambergris in her company's scents. "It has, I'd say, two functions in a perfume. It has a very beautiful, sweet, ambery, rich aroma," she says, "but it also has this kind of transformative quality. It creates almost, if you can stretch your mind to imagine this, a kind of shimmery, sparkly effect on the other essences. It changes the way that they smell."

Finally, after months of searching, I am about to experience that smell for myself. I am in the office of Mike Hilton, a geographer at the University of Otago in New Zealand. He is standing by his desk, holding a small container. Inside are three small pieces of ambergris.

Hilton transfers them onto the cover of a book, which he lays on the table in front of me. Marbled and pocked, their uneven surfaces are mottled with yellow, green and white patches like mouldy pieces of cheese. They look like countless pebbles I have walked past and ignored on the beach.

Even from several feet away, a powerful and revelatory odour fills my nostrils. I smell old cow dung, lumps of wet and rotting wood, tobacco, drying seaweed and the grassy open spaces of Long Beach. Beneath it all there something else… something indescribable.

When I leave, the smell stays with me for hours. Only when I wake up the following morning do I realise I'm unable to smell it anymore. And I miss it immediately. ■

Invasion of the bowhead snatchers

Climate change is having unexpected consequences for the marine mammals of Hudson Bay, finds **Sharon Oosthoek**

WHEN a pod of orcas swam past the Canadian town of Churchill on the edge of Hudson Bay in August 2011, word of the sighting spread immediately. Walkie-talkies crackled to life as Parks Canada staff radioed nearby tour operators piloting boats full of tourists: "Killer whales in Button Bay. They're coming around the point."

Remi Foubert-Allen, the driver of a boat for Sea North Tours, could barely contain himself as the animals swam just a stone's throw away. "Look at the male's dorsal fin – it must be seven feet! I can't believe I'm looking at orcas. I've wanted to see orcas my entire life," he shouted above the noise of the outboard motor.

The lifelong Churchill resident had good reason to be excited. Killer whales are extremely rare visitors to Hudson Bay. Extensive writings from European explorers, dating from the early 1600s, contain no mention of orcas before 1900, and only a handful of sightings over the next 60 years. Since the 1960s, however, there has been a small but steady increase, leading to a peak of 40 sightings in the last five years, and prompting plenty of questions from scientists and Inuit hunters.

"We're wondering what's going on," says Noah Nakoolak, an Inuit hunter from Coral Harbour, Nunavut, across the bay from Churchill. "It's exciting to see them, but why are they here and what are they eating?" Biologist Steve Ferguson at Fisheries and Oceans Canada is among those looking for answers. His findings suggest there is much at stake. It would appear that the orcas, a population at risk of extinction in this part of the world, are preying on other endangered marine mammals. What's more, they may threaten the Inuit hunters' livelihood.

Ferguson is convinced that climate change explains the whales' presence in the bay. The entire Canadian Arctic is covered in ice for most of the year. Orcas, with their tall dorsal fins, generally avoid ice, which can trap or injure them as they swim beneath it. But recent declines in the extent of summer sea ice in Hudson strait are opening up the route to Hudson Bay, says Ferguson, and that could explain how killer whales from the north-west Atlantic end up in these waters. In a paper published in 2009, he and independent

Inuits are permitted to hunt beluga whales, bowheads and narwhals (right). Orcas in Hudson Bay are now preying on these species too

B&G ALEXANDER/ARCTICPHOTO; FAR LEFT: FLIP NICKLIN/MINDEN PICTURES/FLPA

consultant Jeff Higdon concluded: "Hudson strait appears to have been a significant sea ice choke point that opened up approximately 50 years ago allowing for an initial punctuated appearance of killer whales followed by a gradual advancing distribution within the entire Hudson Bay region."

The big thaw

The latest figures from Stats Canada bear this out. They show that in the past four decades, summer sea ice in Hudson strait has declined by 5000 square kilometres, or 16 per cent, per decade. In Hudson Bay, ice cover is down by 16,500 square kilometres per decade – an 11 per cent fall every 10 years – and the ice now starts breaking up three weeks earlier than it did in the 1970s. "As the open ice period continued to expand, killer whales learned to use the area to capture prey and were able to stay longer," says Ferguson.

To track orca numbers over the same period, Ferguson and Higdon turned to Inuit hunters and other people living around Hudson Bay for information. They tallied 12 reported sightings of a single animal or a pod in the bay during the 1960s. The 1970s saw a drop to just three sightings. But every decade thereafter there has been an increase in numbers: eight in the 1980s and 12 in the 1990s. Then came a big jump with 23 in the five years from 2000 to 2005. That's when scientists at Fisheries and Oceans Canada started to pay close attention, encouraging those living around the bay to systematically report any orcas they spotted. This resulted in 40 sightings between 2006 and 2011, although Ferguson acknowledges that the increased surveillance probably had an impact on the number of sightings.

The trend surprised Ferguson and others who study such ice-covered ecosystems. "We weren't thinking about killer whale predation when we were thinking about warming and loss of sea ice," he says.

Nevertheless, orca predation could have a big impact on the local ecosystem. Narwhals, bowheads and beluga whales are already on the menu, according to research by government researcher Cory Matthews at Fisheries and Oceans Canada, who looked at stable nitrogen isotopes from the teeth of two orcas that died in the bay.

A predator is not what these already threatened whales need. Belugas in the eastern bay are classified as endangered by the Committee on the Status of Endangered Wildlife in Canada, while the larger western population is listed under special concern, ›

meaning that it is not in imminent danger but could be if circumstances change. The local bowhead population has the same rating, despite having recovered well from commercial whaling. But Ferguson is most worried about the narwhals. Although in Canada as a whole narwhals are listed as being of special concern, the population in Hudson Bay is hovering at a barely sustainable 5000 individuals.

All three species are unused to dealing with killer whales. Their normal tactic is to use ice to hide from predators, but with less of it around in summer that is becoming increasingly difficult. Instead they have had to adopt a different approach, taking advantage of the Hudson Bay orcas' dislike of shallow water. "When the killer whales are around we see creatures huddling in the inlet and close to shore," says Gabriel Nirlungayuk, former director of the department of wildlife and environment for Nunavut Tunngavik, an organisation which represents the native treaty rights of the Inuits of Nunavut, many of whom live around Hudson Bay. "If these creatures could walk on land to escape, they would. They're that scared of killer whales."

There is no doubt that they are up against a formidable foe. Orcas are opportunistic predators, switching prey depending on availability. They can roam far in search of food, and they adapt as they travel and are exposed to different ecosystems. "Killer whales can learn very complicated behaviours that allow them to hunt and catch large, dangerous and difficult prey," said John Durban at the US National Oceanic and Atmospheric Administration. Perhaps the most extreme example is seen in Antarctica, where pods of orcas use their bodies to make waves that wash seals off small ice floes. "It approaches what primates do in terms of using tools," says Ferguson. Inuit hunters have seen the same behaviour in Hudson Bay.

This is not the only hunting technique that the Hudson Bay orcas use that is also seen elsewhere. For example, they have been observed suffocating bowheads by covering their blowholes, and holding down mothers long enough to kill calves. When they are hunting in groups, some will bite onto a tail or fin while others go in for the killer blow. However, their preferred technique is still the tried and tested method of ramming their prey from below.

Ferguson admits that it is hard to know what impact orca predation will have on Hudson Bay's mammals. Mads Peter Heide-Jørgensen of the Greenland Institute of Natural Resources in Nuuk believes it might not be as bad as some fear. He points out that an increase in orca sightings does not necessarily mean an increase in numbers. "You don't need a lot of killer whales in Hudson Bay to make it look like a lot," he says. "These are animals you notice." He detects an orca phobia, which he believes is unjustified. "Ten years ago, the scientific community argued that killer whales were responsible for the failure of the bowheads to recover in eastern Canada, but the bowheads have recovered," he says.

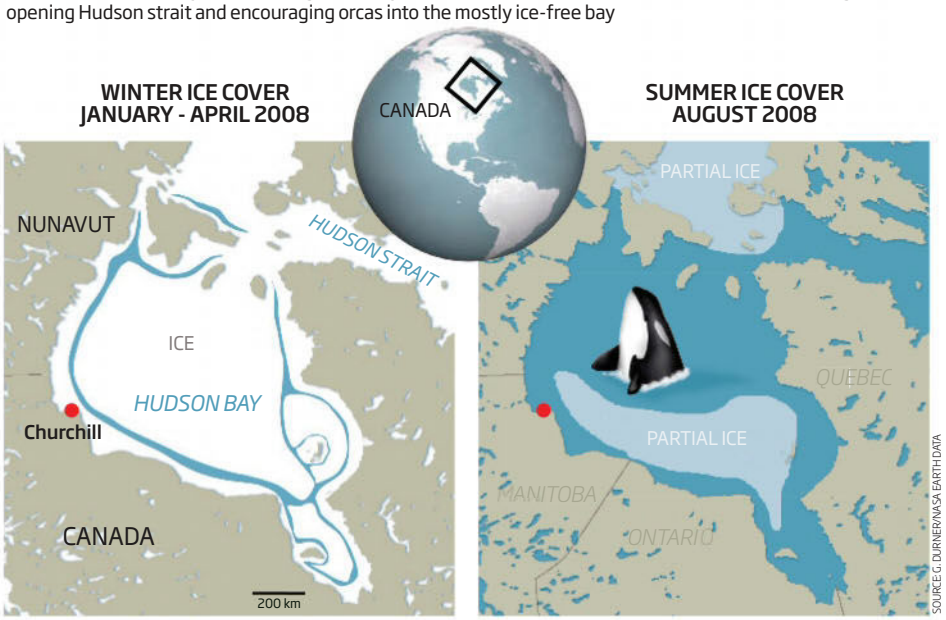
John Ford from Fisheries and Oceans Canada is similarly unconvinced that orcas will harm other whale populations in Hudson Bay – at least in the short-term. "But it's going to be important to keep track of how things change over the coming years," he cautions.

Biologists won't be the only ones keeping a close eye on the orcas. "They are hunting the same species we're hunting," says Nirlungayuk. The Inuit are the only people in Canada permitted to hunt belugas, narwhals and bowheads under a system meant to keep the whale populations healthy. "Are there going to be some implications? I couldn't tell you yet," says Nirlungayuk.

Nevertheless, in Hudson Bay the orcas are eating the Inuit's lunch. That has prompted Ferguson to warn that the local marine ecosystem is shifting from one with Inuit hunters at the top, to one where orcas reign supreme. "It could be a problem in the future for traditional subsistence culture," he says. ■

Ice floes out, orcas flow in

Ice cover in Hudson Bay varies throughout the year. Since the 1960s summer ice cover has been falling, opening Hudson strait and encouraging orcas into the mostly ice-free bay



SOME LIKE IT HOT

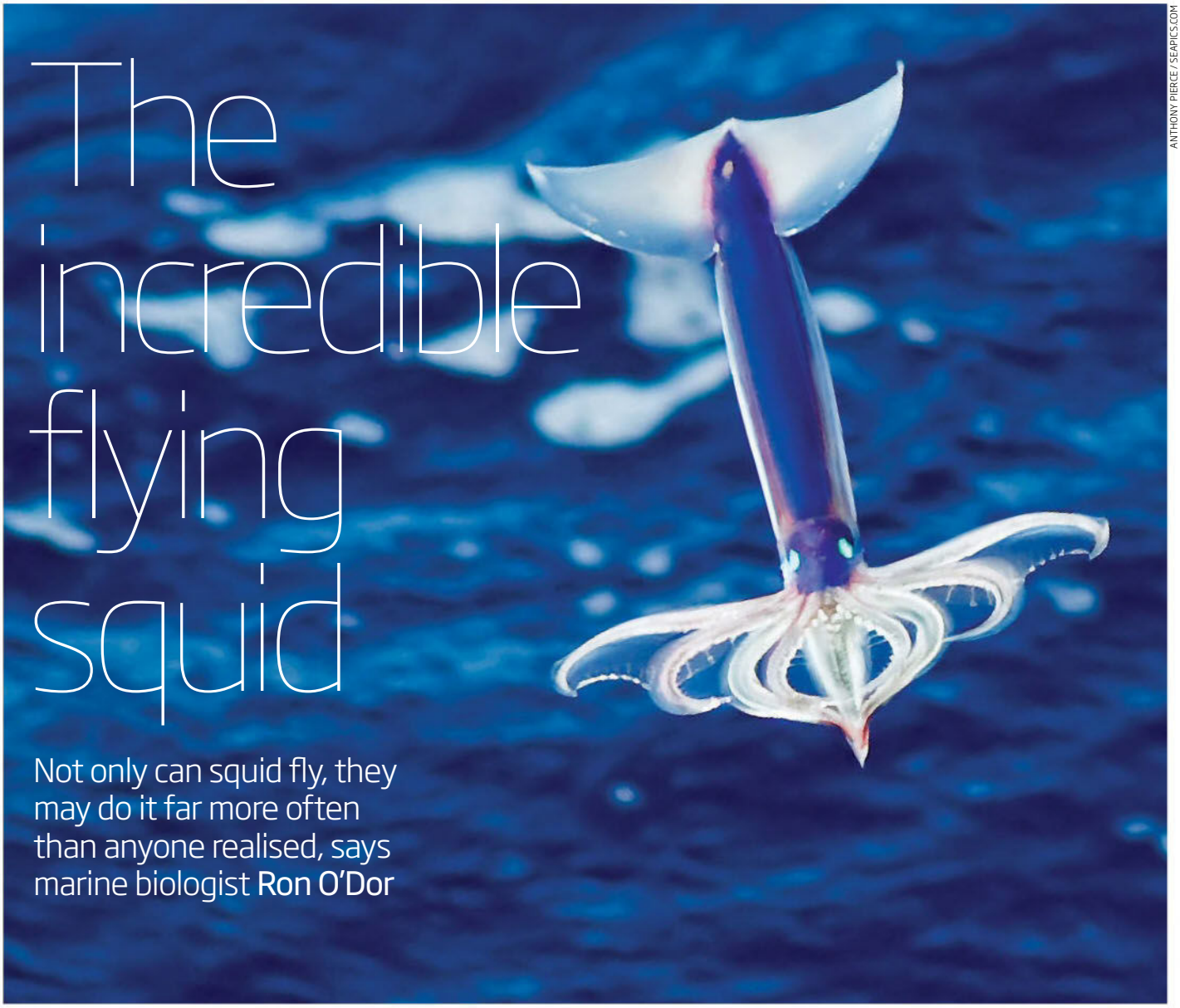
Orcas are not the only marine mammals cashing in on global warming. Along the west coast of Greenland, harbour porpoises (*Phocoena phocoena*) are thriving. They visit seasonally to feed on Atlantic cod, and Mads Peter Heide-Jørgensen of the Greenland Institute of Natural Resources in Nuuk has found that they now hang around longer than they used to, feeding on the fish whose numbers are rising along with water temperatures. He believes this helps explain the porpoise's fat, healthy condition.

Bowhead whales also appear to be benefiting from global warming. In August 2010, Heide-Jørgensen's team used satellite tracking to record two individuals – one from the Atlantic Ocean, the other from the Pacific Ocean – meeting in the North-West Passage where sea ice once blocked their route. He suspects the two populations have been breeding since the ice began to disappear, which may explain why the Greenland population is bouncing back so quickly from the ravages of commercial whaling.

Thawing of the North-West Passage might even allow grey whales to recolonise former habitats. Grey whales have been extinct in the Atlantic Ocean for more than 200 years, but in May 2010, one was spotted swimming off the coast of Israel in the Mediterranean. It probably made its way there from the north Pacific by traversing the passage.

The incredible flying squid

Not only can squid fly, they may do it far more often than anyone realised, says marine biologist **Ron O'Dor**



ANTHONY PIERCE / SEAPICS.COM

A neon flying squid glides above the water in the Sea of Japan

REPORTS of flying squid go back to 1892, but I may be the first person ever to see them fly indoors. I stumbled into the world of flying cephalopods in the late 1970s, when a series of auspicious events led me to spy on squid in the dark. It sounds like a creepy, psychedelic dream, but I assure you it did actually happen.

It all began with a question from Canada's Department of Fisheries and Oceans: "You used to study octopus. If we gave you a grant, could you learn something about this crazy squid fishery?" Off-shore fleets had begun targeting short-fin squid, and catches had soared to nearly 200,000 tonnes a year along the North American Atlantic coast, 50 times that of earlier catches. It was an offer a new assistant professor could not refuse, so I became a squid biologist.

To help understand the squid, I decided to bring a whole school into Dalhousie University's Aquatron seawater research facility in Nova Scotia, where I was carrying out my research in marine biology. No one had ever held oceanic squid in captivity before.

With tanks full of icy seawater and veins full of caffeine, my graduate students and I made a moonlit trek to a nearby fishing village at 3 am. We loaded healthy, live squid out of a big net box trap and into tanks. A fisherman ferried our catch up Halifax's Northwest Arm and met us at a dock close to the Aquatron. From there, we trucked the squid to Dalhousie and gently lowered them into the Aquatron pool. Our relief was immediate – we had made it. Excitement ballooned as we watched the cephalopods swim out of the tanks to form a school. ›

"I stumbled into the world of flying cephalopods in the 1970s, when a series of events led me to spy on squid in the dark"

The next day, we were shocked to find two squid lying dead on the pool deck. The only logical explanation was that they had jetted right out of the water. We immediately lowered the water level by a metre to stop other squid from winding up high and dry. Then we turned down the lights to see if darkness triggered this behaviour. Sure enough, as soon as the lights went down we heard splashing and saw squid rocket into the air. Most plopped back into the water, but occasionally one would bounce off a wall.

At the time, squid rocket science was the last thing on our minds. Anxious to prevent the animals harming themselves, we kept the tanks dimly lit the next night and found they stopped launching into the air. With that, our observations of squid flight came to a halt.

Because of the confined space of the pool, none of us realised back then that squid can not only propel themselves into the air, but also glide for long distances. Over the following years, as we learned more about previous observations and new reports came in, we realised we had witnessed a phenomenon very few people have seen.

As it is so seldom seen in the wild, studying squid flight is extremely difficult. Recently, though, some of my fellow squid biologists and I had a rare chance to study it in more detail, thanks to a series of photos of squid flying. Our findings suggest that flying is actually an energy-efficient way for small squid to travel. If so, squid may fly far more often than anyone suspected – they may just do it at night, when no one can see them.

While published reports of squid flying go back as far as 1892, until recently there were only a dozen or so recorded observations of this behaviour. What is clear, though, is that some species of squid really can fly. Not only do their fins function as wings at the "front", the animals also arrange their tentacles in a fan-shape to form a second wing at the "back". Photographs taken in the Sea of Japan in 2010 show how beautifully they can do this (see photo, page 59).

DOC WHITE/NATUREPL.COM

Juvenile Humboldt squid take to the air to avoid hungry adults

Dual wings

These two wings provide enough lift for squid to glide well over 10 metres. When Norwegian explorer Thor Heyerdahl crossed the Pacific on a raft in 1947, he reported seeing squid gliding for at least 50 metres. That's comparable to most flying fish, which is very impressive given that the "wings" of squid are so much smaller.

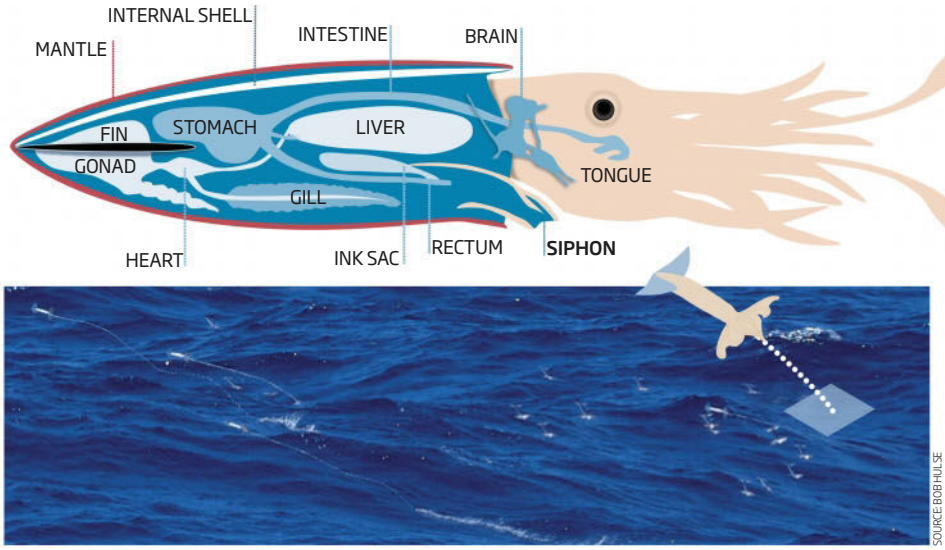
Flying squid also seem to have an impressive degree of control when they are in the air. This may be because squid "glide" underwater in a similar way, so flying is an extension of an existing behaviour rather than something entirely new. Caribbean reef squid have even been seen flaring their tentacles downwards to act as an air brake, bringing their flight to an abrupt end.

What's more, unlike flying fish, squid flight is powered, at least initially. Squid breathe by pumping water in and out of their mantles through a short siphon (see photo, left, and diagram, above right), and this doubles as a propulsion system, allowing them to swim by squirting out a jet of water.

This method of propulsion works just as well out of the water. An extraordinary film shot in 1964 shows a 1.2-metre-long, 40-kilogram adult Humboldt squid launching

Rocket propelled

Some squid, like the orange-backs shown in the photo, launch themselves into the air by squirting water out of their siphon. They can accelerate 5 times faster in air than in water, and may be able to glide for tens of metres



SOURCE: BOB HULSE

itself out of the water. A 1970 analysis of the grainy black-and-white footage proved that the squid was not merely jumping but actually accelerating through the air as it jetted.

Of course, being so large and heavy, this animal travelled just 2 metres or so. But smaller squid, including juvenile Humboldt, can use their rocket power to gain speed and height before they begin gliding. Squid may even be able to propel themselves to the dizzy height of 6 metres above the water.

But why fly at all? There is a report of a school of long-fin squid flying while chasing fish in Long Island Sound near New York. In most cases, though, squid appear either to have been startled by boats or to be fleeing predators. Juvenile Humboldt are commonly seen flying to avoid being eaten by adults, for instance. So when Silvia Maciá of Barry University in Miami and her colleagues reviewed all the published reports of flying squid in 2004, and described their own sighting, they concluded that flying is primarily a means of escape.

Ocean's gliders

I suspect there might be more to it than that. An amateur photographer called Bob Hulse took a sequence of photos of orange-back squid flying off the coast of Brazil, using a rapid camera system with known intervals between images. With these photos my colleagues and I, including Julie Stewart Lowndes at the University of California, Santa Barbara, could measure the speed, acceleration and energy consumed when squid launch.

We found that squid can accelerate 5 times as fast in the air as in the water when they are jetting. And once aloft, they can then glide a lot further without expending any more energy. In other words, flying may be the most energy-efficient way for squid to travel. Put together with our earlier observations that short-fin squid only launched in the dark, we realised that flying at night might be a great way to save energy and avoid visual predators such as birds and big fish.

Saving energy is vital for migrating squid, because they have only tiny fat reserves. When I was studying short-fin squid, my team discovered that these half-kilogram animals migrate all the way from Newfoundland to the Gulf Stream off Florida. There, they lay eggs in large masses of jelly that float back to Newfoundland. With so little fat, it was hard to understand where they got the energy for such a long migration. Then we noticed the smaller male squid disappearing from the pools. After sex, the females, like black widow spiders, cannibalise their mates. Males are expendable because squid only breed once, so we figure the males are fuel for the migration.

> "During his voyage across the Pacific, Norwegian explorer Thor Heyerdahl reported seeing squid flying over 50 metres"

Flying would also help save energy. Stewart Lowndes has been studying Humboldt squid on the Pacific coast of North America, which have recently expanded their range all the way to Alaska (see "March of the Red Devil", page 62). Like the short-fin squid, they migrate to warmer waters to breed. The most northerly known breeding site for Humboldts is the Sea of Cortez in Mexico.

In 2007, I estimated that the optimal swimming speed for 10-kilogram squid would be around 1.2 kilometres per hour. Stewart Lowndes's recent tracking studies show that squid of this size travel a bit faster, at 1.5 kilometres per hour on average, and that some travel much faster, with the fastest moving at up to 2.3 kilometres per hour. How do the fastest squid maintain such high speeds, we wondered. Do they spend part of the time flying?

When Stewart Lowndes mentioned this possibility in a poster she presented about our analysis of squid flight at an ocean sciences meeting earlier this year, the story went viral. Apparently, scientists had known for 100 years that squid can fly, but no one told the public.

As part of our study comparing the energy costs of swimming, launching and gliding for a range of squid species, we also retranslated some rather confusing squid stories from Thor Heyerdahl's description of his voyage, and concluded that at least some of the squid that landed on the deck of his raft were Humboldts in their original home, the Humboldt current off Peru.

Of course, the idea that any species of squid flies during migrations remains speculative for now. But we hope to prove it with tags containing accelerometers like those in smartphones. Since squid accelerate so much faster in air, the tags should tell us when they take flight. The plan is to confirm this in the Aquatron pool before tagging squid in the wild. We haven't figured out how to stop the squid banging into the wall yet, though. Perhaps wet pillows will do the trick.

Out in the ocean, the Ocean Tracking Network will help us learn more about the overall rates of squid migration, as well as when and how often they fly. This global project uses lines of hydrophones to follow species carrying ultrasonic tags, each of which emits a unique signal, like a sonic barcode. This system is particularly well developed in the region where short-fins migrate, but as the network expands it will be possible to study many other flying squid species too.

With the help of new technology, and thanks to the efforts of people like Stewart Lowndes, we are gradually uncovering the secret lives of squid. I look forward to learning more about these crazy cephalopods and one day solving the mystery of squid rocket science. ■

BRIAN SKERRY/NGS

March of the Red Devil

A fierce predator from the deep is taking over the eastern Pacific with extraordinary feats of transformation, finds **Michael Tennesen**

IN 1940, author John Steinbeck and biologist Ed Ricketts took a trip from the Californian city of Monterey, across the Mexican border and into the Gulf of California to survey the intertidal zones around its shores. In 2004, William Gilly of Stanford University and a team of graduate students retraced the voyage to draw attention to a changing world.

Where Steinbeck and Ricketts had found large sea snails, Gilly's crew found only smaller or dead specimens. Where Steinbeck and Ricketts had seen schools of tuna, marlin, sailfish and swordfish, Gilly's expedition sighted few. The Gulf of California, formerly known as the great Cortez fish trap, has seen a massive decline in fish and shellfish in recent decades. Most fishermen will attest to it.

The thing that fascinates Gilly is what is replacing these dwindling species. Near San Pedro Martir Island he found a little pocket full of life – plankton, fish, squid and sperm whales. As the boat drifted over 1000-metre deep waters, the group was greeted by an incessant stream of Humboldt squid darting toward the boat and flashing their underbellies red and white. "This was a profound and qualitative change," says Gilly, referring to the new and vast squid population.

Adult Humboldt squid (*Dosidicus gigas*) are roughly the size and weight of an adult human, have eight arms, two long tentacles covered with toothed suckers and are notoriously aggressive (see "Humboldt squid facts", page 64). They will fearlessly latch on to divers with their powerful arms.

They aren't the largest squid in the sea, but deserve your attention for another reason. While many ocean dwellers are suffering as climate change makes waters warmer, less alkaline and less oxygenated, these beasts thrive and push into new territories. Recent observations suggest that this is all down to

"When pulled from the sea they flash an angry red and flail muscular tentacles"

extraordinary feats of transformation.

You may have heard of Humboldt squid under a different name. Some people call them jumbo flying squid, contrasting with the larger colossal squid and giant squid. Mexican fishermen call them *diablos rojos* – red devils. When pulled from the sea they flash a deep, angry shade of red and flail muscular tentacles. Underwater, they use their two tentacles with barbed suckers to capture passing prey in a flash and pull them to their arms and parrot-like beak.

Until a few decades ago, Humboldt squid were mostly found off the coast of South America in the Humboldt current, which flows from the southern tip of Chile to northern Peru (see map, page 65). There are scant references to them in the Gulf of California before the 1960s. A thriving fishery for the squid developed in the Gulf during the 1990s, growing from almost nothing in 1993 to upwards of 110,000 tonnes between 1995 and 2009. They first appeared in California's Monterey Bay in 1998, coinciding with a strong El Niño event that swept warm waters across the Pacific. By 2004, they had roamed as far as Canada, before reaching Alaska in 2005. ›

HUMBOLDT SQUID FACTS

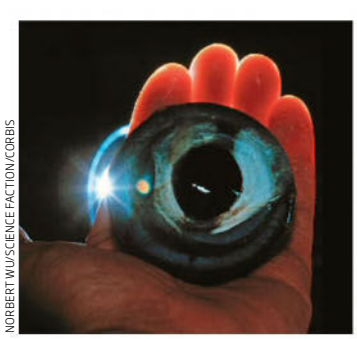
THEY ARE CANNIBALS
"As soon as a squid gets hooked and others see it is caught or behaving differently, they attack," says Roger Hanlon of the Marine Biological Laboratory in Woods Hole, Massachusetts. Unai Markaida, at the Colegio de la Frontera Sur in Campeche, Mexico, looked at 533 squid and found that 26 per cent had eaten other Humboldt squid. The bigger the squid, the more frequently it ate its own kind. Females resort to cannibalism more often than males, perhaps even eating their mates.

THEY ARE MASTER MIGRATORS
Scientists have tracked adult squid migrating from Monterey Bay in California to spawning grounds off Baja California in Mexico – a distance of 600 kilometres, which they cover in just 17 days. In addition to horizontal migrations, Humboldt squid migrate vertically every night, from at least 200 metres down to the surface.

THEY HUNT IN PACKS
William Gilly of Stanford University and Kelly Benoit-Bird at Oregon State University have seen groups of up to 40 squid swim in complex ascending spirals during night-time hunts.

THEY FLASH DIFFERENT COLOURS FROM WHITE TO A DEEP RED
One reason may be camouflage. Hannah Rosen at Stanford University says they can make muted waves of red and white scroll across their body like the undulating pattern of sunlight through the water.

They can also pulse like a strobe. According to Rosen's supervisor Gilly: "There's jitter, variation and change in the frequency and timing between two squid. It is highly unlikely this isn't some kind of communication. It's a very elaborate behaviour to accomplish nothing."



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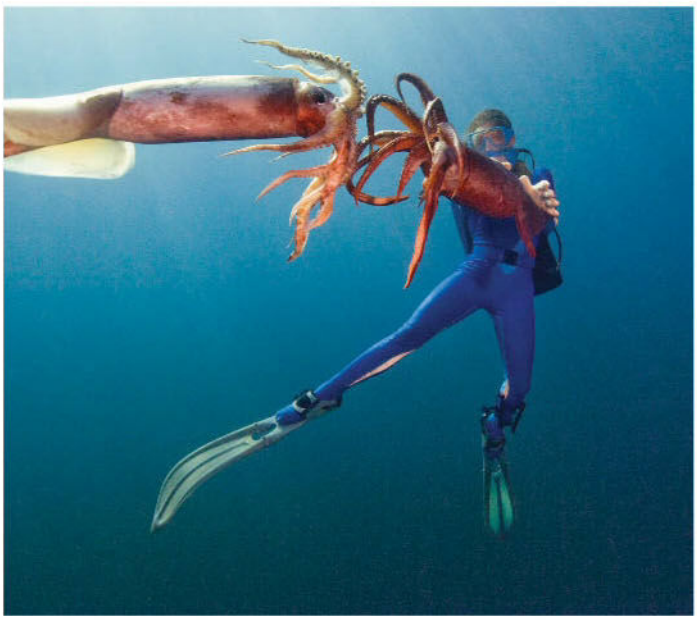


CARRIE VONDERHAAR/OCEAN FUTURES SOCIETY/GETTY

Red Devils are sometimes aggressive towards divers

One explanation for their frenetic Pacific takeover is that they are seeking prey farther and farther north as their usual hunting grounds become depleted. But marine biologists also have another theory.

Humboldt squid are masters at surviving in the oxygen minimum zone – vast volumes of deep water, devoid of sunlight but rich in floating microbes. The microbes break down any organic matter that drops from the surface and use up all the oxygen in the process. Unlike other large animals, Humboldt squid can spend hours at a time in these oxygen-starved regions. Recent studies have shown that they survive the low oxygen levels by drastically lowering their metabolism and slowing their pace. They are powerful swimmers capable of outmanoeuvring most fish, says Gilly, but in the oxygen-poor deep, they become far more sluggish – probably to conserve energy.

The red devils' ability to live in oxygen minimum zones could be an important factor in their recent expansion. Climate models predict that oxygen minimum zones will expand as temperatures rise, and Lothar Stramma at the Helmholtz Centre for Ocean Research in Kiel, Germany, has found evidence that this is already happening in places. Meanwhile, Julia Stewart Lowndes at the University of California in Santa Barbara has examined Humboldt squid expansion and found that it parallels the expansion of the oxygen minimum zones.

Life in the deep

A turning point for Humboldt squid came in 2009, when another El Niño hit the Gulf of California, causing the squid fishery to collapse. In the aftermath, the same weather patterns that brought California its current drought also reduced upwellings of nutrient-rich deep waters in much of the Gulf, punishing the entire food chain. In response, the squid moved deeper into the Gulf, to the Salsipuedes basin – a narrow strip of water that remained relatively rich thanks to localised, tidal upwellings. There, they performed a seemingly impossible transformation.

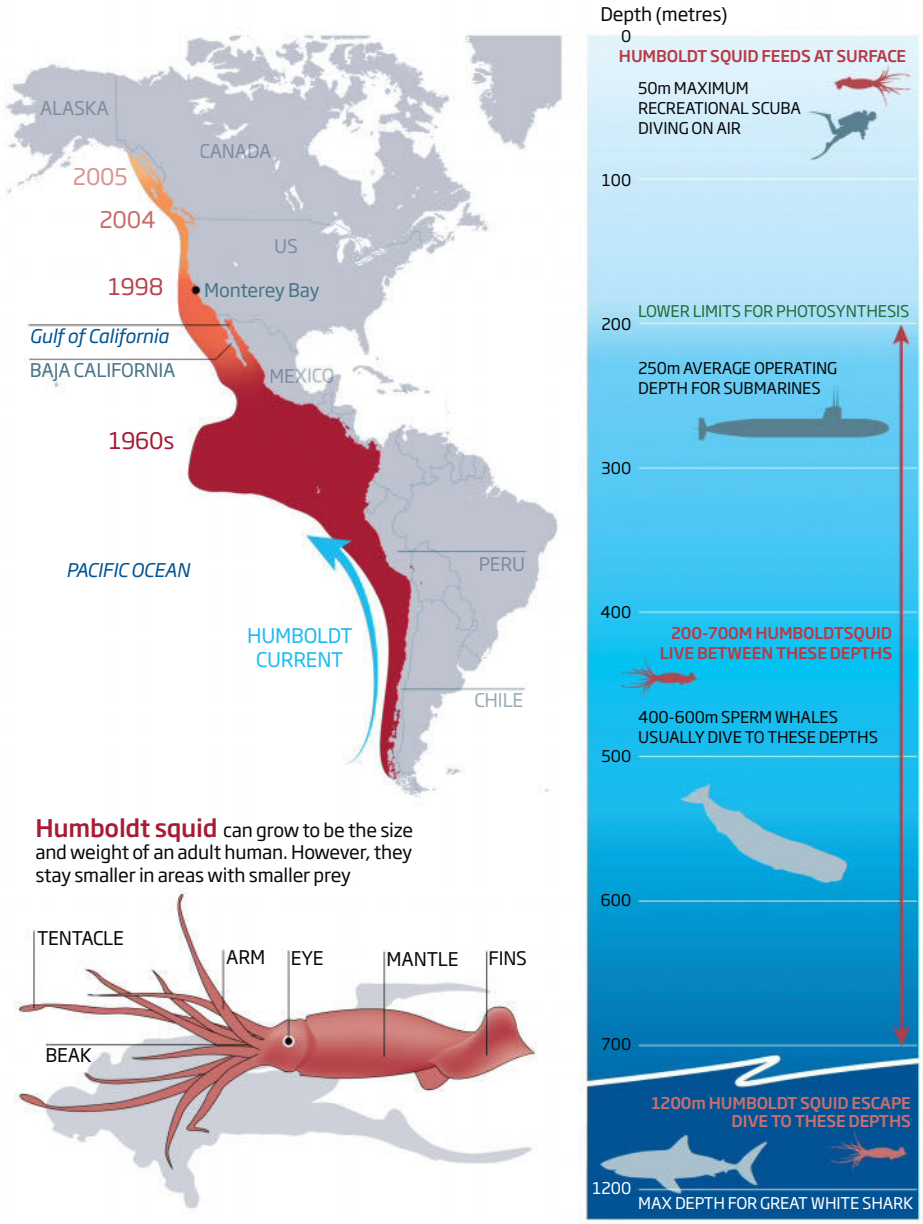
First, they shrank. Instead of catching squid with mantles more than 55 centimetres long, fishermen were now pulling in animals less than 30 centimetres long. That in itself could be explained. Humboldt squid grow with the size of their prey – smaller prey makes for smaller squid and vice versa. For instance, long-term survey cameras positioned underwater in Monterey Bay in the 1990s caught Humboldt squid switching from snacking on small lantern fish to feasts of rockfish, sole, barracuda and salmon. As they did so, their average body size got bigger.

So it's possible that the Gulf of California population simply adapted to smaller prey when the El Niño culled their usual meals. But that's not the end of it. Henk-Jan Hoving, also at the Helmholtz Center for Ocean Research, was one of the first to study the transformation. He found that not only were the squid growing to smaller adult sizes, they were also reaching sexual maturity earlier – much earlier. Instead of maturing in a year and a half, spawning and dying, in the Salsipuedes basin they were reaching sexual maturity at 6 months or less. He says the finding amazed him and his colleagues. Gilly finds it equally surprising. "It's like a tiger turning into a weasel," he says.

One of Hoving's theories is that the eggs and juveniles that were around during the 2009 El Niño were exposed to warmer temperatures,

Jumbo expansion

Until a few decades ago, Humboldt squid were mostly found in the Humboldt current off the coast of South America. Now they have reached much further north



Humboldt squid can grow to be the size and weight of an adult human. However, they stay smaller in areas with smaller prey

which altered biochemical pathways in their genes. "The environment may have an effect on gene expression during egg development, which leads to changes in growth and sexual maturity that are only visible later in the life of the animals," he says. Whether such changes are inheritable isn't known.

All this should have changed after the El Niño passed, as happened following the 1997 to 1998 event. Instead, the squid have maintained their dwarfed life-cycle.

Studies suggest that weather patterns are once more at play. Winter winds that blow into the Gulf from the US have greatly diminished during the California drought, prolonging the effects of the El Niño. Upwellings are still weak, food is still scarce and the squid are still small.

For the Humboldt squid, being small and reaching maturity earlier may be the better strategy for now. Certainly, there are advantages to gigantism – larger animals have fewer predators, for instance. Larger squid also produce more eggs, but they only do this once in their lifetime, so reaching sexual maturity earlier reduces the chances of being eaten before spawning the next generation. "That may be a suitable strategy when you're colonising new realms," says Hoving.

More change ahead?

The squid do indeed appear to be colonising. Measurements suggest that their biomass nearly doubled in the Gulf of California from 2010 to 2011. And Gilly believes we may see them return to jumbo sizes. "It may be that they need two seasonally distinct migration sites in order to grow larger body sizes," he says. Before 2009, the Gulf squid grew as large as their Peruvian cousins by migrating between a winter feeding ground on the continental side to a summer one on the peninsula. "We're watching to see if [a new winter site] develops," says Gilly.

If one thing seems certain, it's that this devil is full of surprises. To those who study the Humboldt squid, their incredible ability to survive when times are harsh by adapting at all costs is what sets them aside. It means that when an opportunity presents itself, they can bounce back and fill newly vacant ecological niches. Gilly thinks that if an extinction were to wipe out other animals higher up the food chain – like sharks, tuna or sperm whales – the Humboldt squid could be a contender to fill their shoes. "If someone wanted to design an ocean predator for the future," he says, "this would sure be it." ■

CLIMATE ANI-MORPHS

Humboldt squid aren't the only ones changing in the face of climate change (see main text).

Soay sheep live on the island of Hirta off western Scotland. Over the past 20 years, they have been shrinking. Natural selection has so far favoured bigger sheep able to cope with tough winters, but as global warming has shortened the winters, smaller sheep are now the norm.

When the temperature climbs in the Australian outback, male bearded dragon lizards turn into females. Researchers worry climate change could push them toward unisex extinction. That may not come to pass, however: sex-reversed females are laying more eggs than "normal" females. "One could argue that dad lizards make better mums," says Clare Holleley of the University of Canberra in Australia.

In Alaska's Auke Creek, pink salmon have responded to earlier springs by migrating two weeks earlier than 40 years ago. This turns out to be genetically inherited, demonstrating that pink salmon may be able to evolve to stay ahead of climate change.

Polar and grizzly bears have traditionally been kept apart by ice, snow and different hibernation patterns. No more. As temperatures rise, hybrid "grolar" bears have been confirmed by DNA analysis.

Under attack

NORBERT WU, NORBERTWU.COM

Should we care that the number of sharks is plummeting? Henry Nicholls looks at the consequences of killing the killers

ON 15 August 2011, Gemma Redmond was sitting on a beach in the Seychelles while her husband, Ian, snorkelled offshore. They were on their honeymoon. Suddenly she heard Ian call for help. Then there was a "most awful scream".

A shark had bitten off his arm and taken a huge chunk out of one leg. A boat brought him back to shore but he died of blood loss shortly afterwards. It was a horrific event but an extremely rare one: Ian was one of just 12 people killed by sharks that year. Even that figure is unusually high – on average, fewer than five people are killed each year in unprovoked attacks. By contrast, people kill around 100 million sharks annually.

As a result of this slaughter, the number of sharks is plummeting. Instead of fearing sharks, we should fear for them. But does it matter if we kill these killers, or will there be big knock-on effects throughout the ocean?

Sharks used to be regarded as a nuisance by most of the fishing industry. Many were caught, though seldom deliberately. During longline fishing for species like tuna, for instance, sharks were a common by-catch. Until 1999, no global records were even kept of how many sharks were caught.

In recent decades, though, sharks have become valuable, largely because of the growing hunger for shark fin soup. Once regarded as the food of emperors because of the cost and elaborate preparation required, this Chinese dish is growing more popular as the country becomes wealthier.

So what's been the impact of this growing demand? The abundance of fish is usually calculated from catch data, but official records only go back a decade. What's more, they are far from accurate, says Daniel Pauly of the University of British Columbia in Vancouver, Canada. "We are not just talking piddling, precision-type errors," he says. "The underestimation can be 30 to 50 per cent in developed countries, and 100 to 400 per cent in developing countries."

So there are only a few regions where researchers have been able to work out how shark catches have changed over time. By combing through the logbooks of the US longline fishing fleet, for example, Julia Baum of the University of Victoria in Canada and her colleagues found that in 14 years – from 1986 to 2000 – shark catches in the north-west Atlantic Ocean declined by more than half. They concluded that populations of scalloped hammerhead, white and thresher sharks had each declined by more than 75 per cent.

Precipitous decline

In a follow-up study based on a similar analysis of historical catch data, the same team estimated that in the Gulf of Mexico, the abundance of the oceanic whitetip shark declined by more than 99 per cent and the silky shark by more than 90 per cent.

It is likely that similar precipitous declines are occurring in most oceans. A rare global study, published in 2013, estimated that roughly 100 million sharks were caught each year. Part of the problem is that sharks are slow breeders. They can take years to reach sexual maturity and produce only a few eggs or a handful of pups at a time. A few live-bearing species, such as the basking shark, are thought to have gestation periods as long as three years – longer than an elephant. This makes them much more vulnerable to exploitation than many other fish species.

Some species could be lost altogether. The metre-long Pondicherry shark of south Asia has not been seen since 1979. Several species of bottom-dwelling angel sharks are now regarded as critically endangered.

Should we care if shark numbers are plummeting? It is clear from studies of other ecosystems that the effects of removing top predators can cascade down the food chain, altering the entire ecosystem. However, it is extremely difficult to study the effects of removing sharks, not least because there are hundreds of different species, some operating at great depths, others sticking closely to coral reefs, others to continental shelves and yet others covering thousands of kilometres in the open ocean. What's more, new species are still being discovered. ›

STOPPING THE SLAUGHTER

The five sharks cruise towards me in the warm, shallow water. One lunges towards the beach, almost stranding itself on the sand. It's not me it's after, but a shimmering shoal of tiny silver fish, which escape the shark's jaws by leaping into the air, making the surface of the water boil.

At a metre long, these baby blacktip reef sharks are no threat to people. In fact, they are positively cute. Which is just as well, given that dozens of them are patrolling the lagoon around the tiny resort island of Soneva Fushi in the Maldives.

Lagoons normally act as a nursery for juveniles, but for years there were no pups at all in this lagoon. However, since the Maldives banned shark fishing in its waters in 2010, at the urging of its tourist industry, they have reappeared. It is not possible to be sure if the sharks are back because of the ban, says the resort's resident marine biologist Kate Wilson, but it is certainly an encouraging sign.

A few other countries, including the Bahamas, have also banned shark fishing, while others have taken measures to outlaw or limit "finning", the practice of cutting sharks' fins off and discarding the body. However, local bans cannot save ocean-going species. What's more, with dried shark fins fetching up to $700 per kilo, enforcing bans will not be easy.

Ultimately, the only way to protect sharks is to reduce the demand for their fins, says Daniel Pauly of the University of British Columbia. "This product is so outrageous. You have the issue of waste because you use only part of the shark, you have the issue of cruelty because you cut off the fin, you have the issue of snobbery, with people only eating it to impress their neighbours," he says.

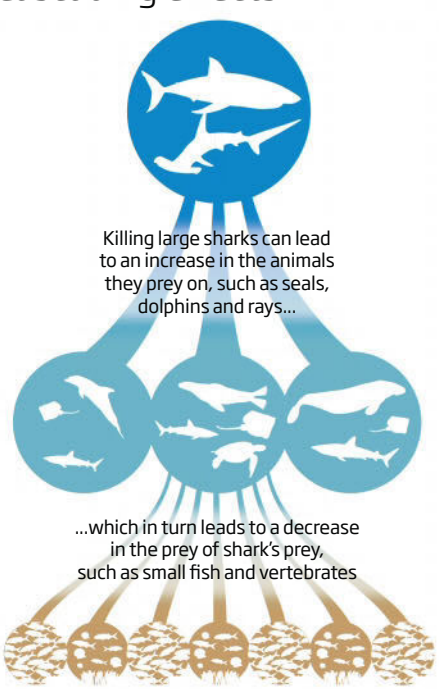
He thinks getting shark fin soup off the global menu is a battle that can be won. He could be right. In 2014, environmental group Wild Aid published a report showing that sales of shark fins in China had declined sharply.

"We're just guessing at the moment," says Callum Roberts at the University of York in the UK, who studies our impact on the oceans. "It's a bit like trying to reassemble a very complicated mechanism from its parts without having a good blueprint of what the mechanism once looked like."

Until a decade ago, the only evidence of the effects of killing sharks was largely anecdotal. In South Africa, for instance, the erection of large-meshed nets off swimming beaches to catch big sharks led to an explosion in the abundance of smaller shark species near the shore, and a decline in small fish. Similarly, a shark fishery operating off Tasmania was blamed for the collapse of a neighbouring crayfish farm. The removal of sharks is thought to have boosted the numbers of crayfish-chomping octopuses in the coastal waters. Both cases were open to question but appear to be examples of changes to the top of a food chain cascading downwards.

The strongest evidence comes from a study of the east coast of North America. Based on a combination of coastal surveys and fishery data, it found that there have been drastic declines in all 11 species of large sharks, with scalloped hammerhead populations crashing by 98 per cent and bull sharks by 99 per cent since the 1970s. At the same time, the populations of rays, skates and smaller sharks have all boomed. This sudden abundance of smaller predators resulted in the collapse of a century-old scallop fishery. This last link was confirmed by using barriers to keep cownose rays out of some areas; scallops survived only in these areas.

Cascading effects



SOURCE: FERRETTI 2010

Really scared

This suggests a textbook ecological pyramid with a few top predators having a big effect on more abundant prey species that feed on even more numerous invertebrates (see diagram, left). But recent findings suggest sharks don't just affect the numbers of their prey – they affect their bodies and behaviour, too.

In 2005, marine biologists from the Scripps Institution of Oceanography at the University of California, San Diego, set out to the Line Islands in the middle of the Pacific Ocean to compare the marine communities living on different reefs. They found the reef systems least disturbed by people, Kingman and Palmyra, had the healthiest corals and supported the greatest biomass of fish ever recorded on a reef. What astonished them, though, was the abundance of sharks. The vast majority of the fish biomass consisted of sharks, and the biomass of prey fish was actually lower than that on more disturbed reefs nearby.

"This turns the textbook trophic pyramid on its head," says Sheila Walsh Reddy, an expedition member now at the Nature Conservancy in Virginia. "It doesn't even seem energetically possible." The only explanation is that small fish are being eaten as fast as they breed, so their biomass at any one time is much lower than that of their longer-lived predators.

The fish with lots of predators behaved differently too. "They are just really scared," says Walsh. So scared that she and her fellow divers found it hard to catch fish for further study. "Man, are they good at escaping."

When the researchers dissected the prey fish, they found they had slender livers and were storing very little fat. By contrast, specimens of the same species from sites with fewer sharks were consistently fatter, Walsh says. "You open them up and their intestines are just lined with fat."

Walsh suspects prey fish may grow more slowly when there are fewer sharks, making reefs less productive. "These results are a warning to not take the simple assumption of a basic ecological model that says get rid of predators you'll have more prey," she says. "Maybe, in fact, having sharks around makes for faster, more productive

MASA USHIODA / SEAPICS.COM

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EMMANUEL VALENTIN/HOA-QUI/GAMMA/CAMERA PRESS

As a result of accidental catches and fishing for fins, shark numbers are plummeting

IS IT SAFE TO GO BACK INTO THE WATER?

With fewer sharks in the sea, is it at least safer to venture into the waters? Not at first sight. The number of unprovoked shark attacks worldwide has been rising steady, from less than 100 between 1900 and 1910 to over 600 between 2000 and 2010, according to the International Shark Attack File. However, the main reason for this is that there are a lot more people swimming, surfing and diving in the sea, and also better reporting of attacks. The number might be much higher were it not for the decline in shark numbers. But as the number of shark attacks is influenced by everything from the economy and the weather to people learning how to behave around sharks, there is no way to be sure of this.

fisheries. A lot of our findings are pointing in that direction."

So there is still much we don't understand. The uncertainties tend to be glossed over by those campaigning to save sharks. "Mostly what you find is fairly glib statements that loss of sharks will have profound consequences for the ecosystem," says Roberts. "There are these kind of arm-waving arguments about the importance of top predators."

"It may be that having sharks around actually makes for faster, more productive fisheries"

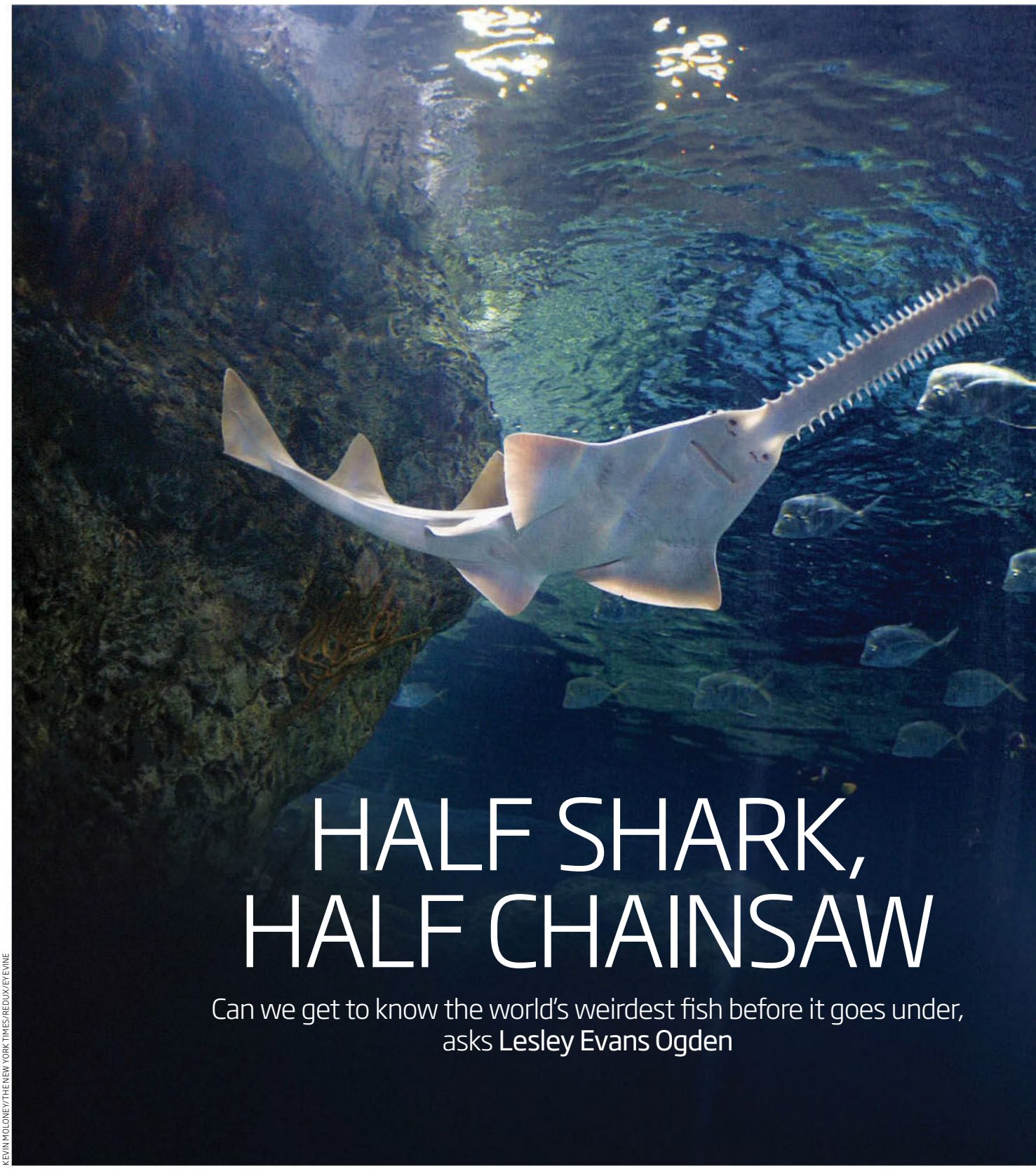
These claims may well be correct, he says, but proving them is another matter. "We've seen these top-down effects in a whole range of smaller-scale experiments using intertidal shore fauna, for example, but it is just much harder to grasp at the large scales and in the non-experimental settings that you have with big populations of sharks."

And it may now be too late to ever fully understand our impact. Even if sharks survive and their numbers eventually recover, things may not go back to the way they were. "Often we find that ecosystems have shifted in ways that mean the productivity of old – or the biomass of old – cannot be recreated," says Roberts. "There are various pieces that have been taken out of the food web. Those connections will probably take a very long time to reinstate."

The role sharks play in the ecosystem is not the only reason for being concerned about them. For starters, no one is going to make any money from catching sharks if there are none left to catch. In some regions, there are efforts to ensure that shark catches are sustainable.

And in many places, sharks may be worth more alive than dead. Diving is one of the fastest growing sectors of the tourism industry, and sharks are a considerable draw. Many divers visit the Galapagos in hope of seeing vast schools of hammerheads and other sharks, for instance. Dive tourism is worth at least $15 million a year to the islands, estimates Alex Hearn of the University of San Francisco de Quito in Ecuador – several times more than is generated by fishing in the protected Galapagos waters. "If well managed, dive tourism can bring income to local communities," Hearn says. "It can also serve as a deterrent, because if there's a bunch of divers, it's unlikely a big industrial longliner is going to come in and pull out all the sharks."

Clearly, there is value in sharks other than their fins. But will we recognise it in time? "The losses of megafauna are happening incredibly rapidly while the world sleeps," says Roberts. "I worry that we're going to be too late for many species." ■



KEVIN MOLONEY/THE NEW YORK TIMES/REDUX/EYEVINE

HALF SHARK, HALF CHAINSAW

Can we get to know the world's weirdest fish before it goes under, asks **Lesley Evans Ogden**

Sawfish populations have plummeted in the past 50 years

IT WAS an afternoon in January 2015, during a break in the weather, when a Florida State University research vessel headed out towards the Queen of Nassau shipwreck off the Keys. There had been sightings of smalltooth sawfishes in the area and ecologist Dean Grubbs was keen to investigate. Resembling a chainsaw with a shark-like body, sawfishes are extremely rare. With luck, Grubbs might catch one or two for tagging and study. It never occurred to him that he would soon have six snagged on a single line. That was when things started to get tricky.

Adult sawfishes can be more than 4 metres long and weigh over 300 kilograms, which meant reeling them in wasn't an option. The animals needed rescuing, and fast. So Grubbs jumped in. Holding his breath 6 metres underwater, he began to lasso their toothy snouts while trying to avoid being slashed to bits. "[It] was a little nerve-racking," he says.

Grubbs's heroic response was not misplaced. Sawfishes are the world's most imperilled marine fishes; over the past half century, smalltooth numbers have declined by at least 95 per cent, and the four other species are faring little better. They are also among the strangest of animals, their weirdness extending far beyond their looks. Until recently, we knew little about their unusual habits. But with numbers plummeting, there's a growing urgency to discover more so that we can try to work out if, and how, these extraordinary creatures can be saved.

Sawfishes are distant relatives of sharks, more closely related to rays. Once common across tropical and subtropical waters, all five species are now on the International Union for Conservation of Nature's Red List of Threatened Species. Narrow and dwarf sawfish are classed as endangered; green, largetooth and smalltooth as critically endangered. As well as being dangerous to handle, they spend most of their lives in muddy coastal waters, making them very difficult to study. As a consequence, much about these animals is as murky as the waters they inhabit.

Take the hallmark snout, or rostrum. It has between 18 and 37 pairs of teeth, depending on the species, but until a few years ago, its function was uncertain. Now we know that sawfishes use it for both sensing prey and rendering their prey insensible. They slash their snouts around on the muddy bottom of shallow waters, using specialised organs in them to detect tiny electrical signals generated by small schooling fish, shrimps, crabs and any other animals present. "The saw essentially gives them a very big antenna," says Colin Simpfendorfer at James Cook University in Townsville, Australia. Electric sensing serves them well in low visibility, he adds, and once they have located their quarry, the rostrum becomes a club to stun and lacerate prey before they "hoover it up".

Grubbs is trying to fill another gap in our knowledge of sawfishes. Within living memory, the smalltooth could be found along a wide swathe of the eastern coastline of North and South America as well as off Africa's west coast. Now, it is largely restricted to south-west Florida and the Bahamas. It was listed as endangered under the US Endangered Species Act in 2003 on the assumption that the US population is distinct. "But we don't really know if that is true," says Grubbs. He and his colleagues have tracked sawfishes in Florida and the Bahamas to discover whether the two populations intermingle.

That means tagging adults – perilous work, even when you don't have to dive in to rescue them. "I tell everybody that sawfishes require more respect and are potentially more dangerous than any of the sharks we deal with," says Grubbs, who handles some 3000 sharks a year. The main threat comes from their rostra, which they swing around like swords when captured. "The angular momentum on the end of the rostrum is unbelievable," says Grubbs. "And the teeth, especially on the large ones, are very, very sharp."

"Sawfishes use their hallmark snout, or rostrum, for both sensing prey and rendering their prey insensible"

To minimise the handling risks, the researchers typically secure the fish by tying one rope around its rostrum, another around its tail and perhaps a third on its mid-section. They then take its measurements and attach a pop-up satellite tag to its dorsal fin. The tag collects information on depth, light levels and temperature, and is programmed to come away after 45 to 180 days, when it floats to the surface and sends its data to a satellite.

The project began in 2001 and Grubbs' team is allowed to tag just 20 animals a year. So far the indications are that Floridian sawfishes are not long-haul travellers, preferring to stick ›

A FISH TO FETISHISE

Matthew McDavitt is not your typical cultural anthropologist. For a start, he has a day job as a lawyer. But when he's not navigating legalese in Charlottesville, Virginia, he is often found fossicking for evidence of human interactions with sawfish. It's "just a hobby", he insists, although he has been dabbling in it almost daily for 20 years.

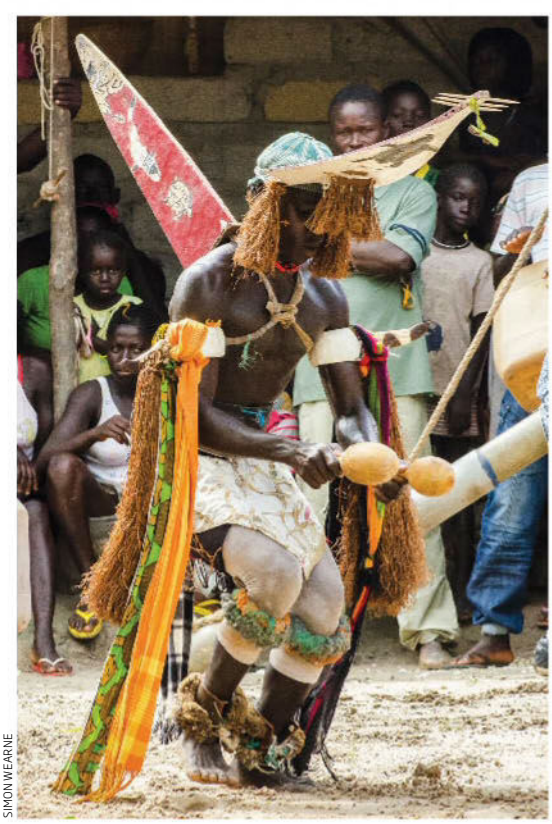
McDavitt's interest began in childhood, when he was drawn to the sawfishes' toothy snouts or rostra, but an undergraduate comparative religion course at the University of Virginia really ignited the spark. Exploring the last surviving divinatory almanacs of the Aztecs, "I kept seeing what I thought were sawfish snouts," he says – symbols that researchers of Aztec iconography had oddly missed. Digging deeper, he discovered that archaeologists had found dozens of sawfish rostra interred beneath the main Aztec temple in Mexico City.

McDavitt had uncovered a lacuna in our cultural knowledge of sawfishes and decided to fill it. He has since travelled the world looking for sawfish art and cultural symbolism, documenting artefacts from West Africa, South America, Indonesia and elsewhere. On Groote Eylandt in northern Australia, he found an aboriginal group for whom the sawfish is an emblem. "You see it on both their civic crests and traditional art all the time," says McDavitt. "It's as prominent to them as the bald eagle is to America."

Other stories have come from trawling the archives. In one account dating back two centuries, a traveller to Lake Maracaibo, Venezuela, describes baby sawfishes so plentiful it was difficult to walk in the shallows without stepping on them. Sawfishes have now been absent there for 150 years. More documents revealed a thriving sawfish fishery in Lake Nicaragua in the 1970s, as well as flesh and fins sold locally and in Chicago restaurants and supermarkets.

Art and folklore are now often the only reminders of how widespread and plentiful sawfishes once were. Depictions of these mysterious, revered creatures are found on ancient jewellery, tapestries, paintings and even on 5000-year-old clay seals found in Iran. In Gambia and Senegal, they were numerous in the 1970s, but are now rarely seen. Local ecological and cultural knowledge has declined too, reported Ruth Leeney of Benguela Research and Training in Namibia. These days, people in West Africa are more likely to know sawfishes from images on bank notes than as living creatures.

LUIS MARDEN/NGS/ALAMY



SIMON WEARNE

Ceremonies in west Africa still feature sawfish, which are no longer found there

"Rostra are sold as curios on eBay and teeth fashioned into spurs for cockfighting sell for as much as $220 a pair"

close to home. The researchers are also taking small tissue samples for genetic analysis to confirm whether the US population is truly distinct from the Bahamians. "It could only take one or two sawfish [interbreeding] every generation to keep the two populations mixed," says Grubbs.

As with all small, isolated populations, Floridian sawfishes are in danger of becoming inbred, but other research suggests the smalltooth has retained much of its genetic diversity despite the crash in numbers. Other sawfish species may not have fared so well. Working mostly off the coast of northern Australia, Simpfendorfer and his team are trying to discover whether the narrow sawfish has experienced a genetic bottleneck. Studying sawfishes here is particularly tough because researchers must be constantly vigilant not just for swinging sawfish rostra, but also for saltwater crocodiles. However, these waters are a magnet for research because they are the strongholds of four of the five sawfish species (see "On the slide", right).

One thing everyone is keen to find out more about is the sawfish's highly unusual way of reproducing. Unlike most fish, it goes for internal fertilisation. Maturing males develop pelvic fin extensions called claspers that they insert into the female during copulation. The embryos develop inside the mother's body without a placenta, feeding only on the yolk of their egg. After a gestation period of 4 to 6 months, the mother gives birth to several offspring – around a dozen is common, but the smalltooth can have up to 20. It sounds like a tall order. "Obviously, if you've got a rostrum with these little pointy teeth on it when they're being born, that would be a problem for mum," says Simpfendorfer. But

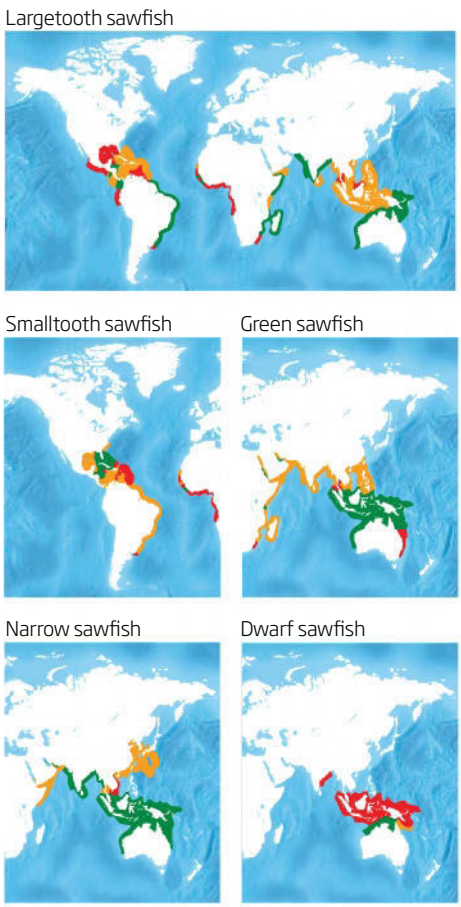
DEAN GRUBBS

Lake Nicaragua (far left) was once a thriving fishery for these strange creatures

Trying to tag sawfishes in Florida without getting slashed (left)

On the slide

Populations of all five species of sawfish have slumped in the past 100 years. They are now **extinct** in some of their former ranges, and in others their status is **unknown**. **Remaining strongholds** are limited



SOURCE: Aquatic Conservation/ DOI: 10.1002/AQC.2525

evolution has provided an elegant solution: a protective gelatinous sheath for the saw that dissolves away a few days after birth.

Producing young in this way poses another problem, however. The newborns are 60 to 90 centimetres long, depending on the species, making them vulnerable to being caught in fishing nets. Here again, we don't yet know enough about sawfishes to assess the scale of the problem. What we need to find out, in particular, is when females become sexually mature and how often they conceive, so as to judge their ability to rebound from population crashes.

Unknown quantities

To get a window on these matters, researchers take a blood sample from each female they catch, measuring levels of the hormones estradiol and progesterone to discover whether she is reproductively mature, has developing eggs or is pregnant. The findings so far indicate that female narrow sawfishes develop fastest, reaching sexual maturity at 3 years old. Female green, smalltooth and largetooth sawfishes all mature at around age 9, give or take a few years. For dwarf sawfish we still don't know. How often they conceive is even more of a mystery, although the hormone tests may reveal the answer in the future.

Even the lifespan of these fish is uncertain. What we know suggests the narrow sawfish lives for just 9 years, dwarfs and smalltooths may reach their 30s, largetooths their mid-40s and green sawfishes can live beyond half a century. More precise knowledge of fecundity and lifespan will help conservationists work out how quickly a sawfish population could grow if protected. As relatively long-lived and slow-reproducing fishes, they may take a long time to recover.

"Sawfish are an example of species that slipped through the cracks," says John Carlson at the US Southeast Fisheries Science Center in Panama City, Florida. "[Populations] have been fragmented all over the globe." Historically, sawfishes were caught for eating, with their rostra sold as curios, and although they now enjoy some legal protection across most of their range, they still face big threats. Their snaggle-prone snouts make them vulnerable to being accidentally caught in trawl and gill nets. The habitats they rely on, such as mangroves and seagrasses, are being degraded as coastal zones become ever more developed. And some are poached.

The fins are highly prized for shark fin soup, and a recent investigation found them on sale in China, Indonesia, Australia, Bangladesh and Madagascar. Rostra are still sold as curios and powdered for folk medicines, including a tea taken for asthma. They are even available on eBay, with buyers and sellers in the US, UK, Australia, Germany and Belgium. In Ecuador and Peru, sawfish teeth fashioned into spurs for cockfighting sell for as much as $220 a pair.

In the US, the biggest killer is shrimp trawling. With the pop-up tags, Grubbs and his colleagues are getting a better understanding of the locations of critical habitats at various stages in the sawfishes' life cycle. Their findings could some day make it possible to pinpoint the best times and places to temporarily close fisheries so as to promote sawfish recovery with minimum commercial disruption. For now, the aim is to teach fishers to safely release any sawfishes caught accidentally, since they can survive if quickly freed. To that end, the US and Australian governments have developed safe-release guidelines for commercial and recreational fishers.

Saving sawfishes is going to require a concerted effort, despite their cultural significance (see "A fish to fetishise", left). In the US, the public is encouraged to report sightings to the international sawfish encounter database, hosted by the Florida Museum of Natural History in Gainesville. But mustering support for conservation remains a challenge, especially in developing countries. Even when caught unintentionally, sawfishes are often retained because their fins and rostra fetch such a good price. Financial incentives to exploit these fishes won't go away no matter how well fisheries are managed, says Simpfendorfer. "We need to find ways to incentivise conservation… so that we can break that cycle." Just like handling these magnificent beasts, saving them will be no easy task. ■

CHAPTER FOUR

PLANTS

Ancient megatrees

THE devil upended the baobab and planted it upside down. So says Arab legend. In Burkino Faso and Tanzania, folklore has it that the tree wouldn't stop walking, so God planted it with root-feet in the air and branches underground. A Zimbabwean version has it that God inverted the tree in anger when he couldn't get a drink out of it.

It's no surprise that the mighty baobab attracts such legends. Various *Adansonia* species grow in arid regions of Africa, Madagascar and Australia and have provided resources for humans for thousands of years. Each can store up to 100,000 litres of water in its bloated trunk, so that Zimbabwean god was unlucky not to get a drink. The baobab's fruit is known as "monkey bread" and is apparently rich in vitamin C.

These shots were taken in Madagascar by Canadian photographer Elaine Ling. For an idea of scale, look at the man in the photo in the lower-right photo – the trees can grow up to 30 metres tall. Ling says her photographs are reflections on the ancient dialogue between these enduring megatrees and the people who live among them.

One baobab, the Platland tree in South Africa, was carbon-dated and found to be at least 1275 years old. It is extraordinary that an individual tree can have an influence on the lives of so many generations of people. Children playing under the local baobab can imagine time-travelling to ancient times when the very same tree grew in the same place – unless it had wandered around. Rowan Hooper

Photographer

Elaine Ling
elaineling.com

Roots of consciousness

The discovery that plants have their own kind of intelligence is both fascinating and challenging, finds **Anil Anathaswamy**

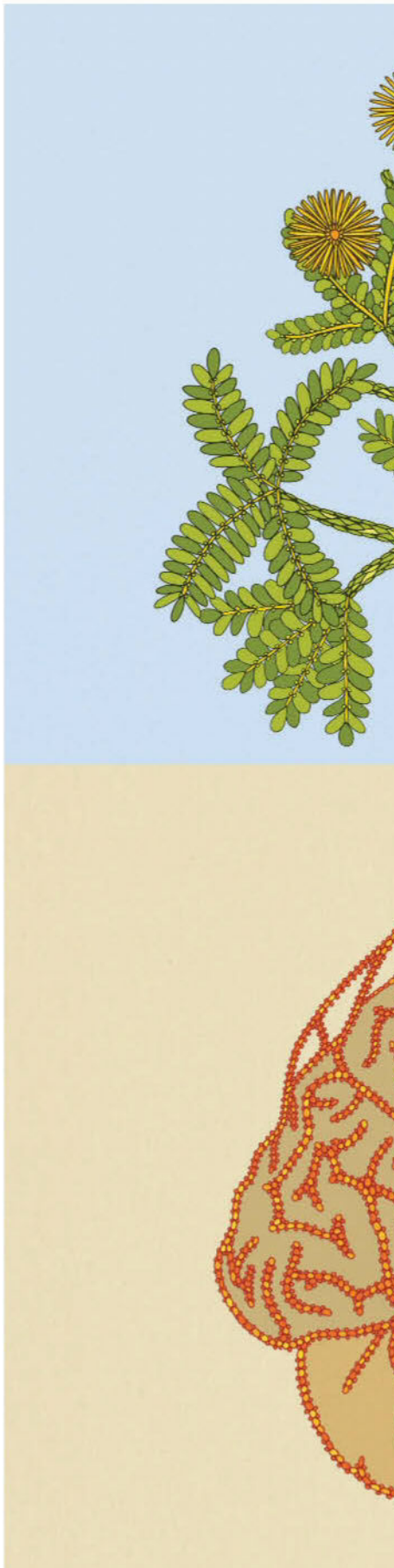
STEVE SILLETT has been hanging out with giants all his working life. He climbs and studies the canopies of giant redwoods along the coast of northern California. Sometimes, when traversing from the top of one tree to another, he is awestruck by the life that surrounds him. "There's this awareness of where you are, 90 metres up, in this breathing, living forest of ancient beings," says Sillett, who is at Humboldt State University, California. "You get into this space where you are interacting with another organism that functions completely differently."

Had Aristotle hung out among redwoods, he might not have consigned plants to the bottom rungs of his "ladder of life". But he didn't, and botanists have been tormented by his legacy. For centuries, few dared challenge his judgement. Now that's finally changing. In the past decade, researchers have been making the case for taking plants more seriously. They are finding that plants have a sophisticated awareness of their environment and of each other, and can communicate what they sense. There is also evidence that plants have memory, can integrate massive amounts of information and maybe pay attention. Some botanists ague that they are intelligent beings, with a "neurobiology" all of their own. There's even tentative talk of plant consciousness.

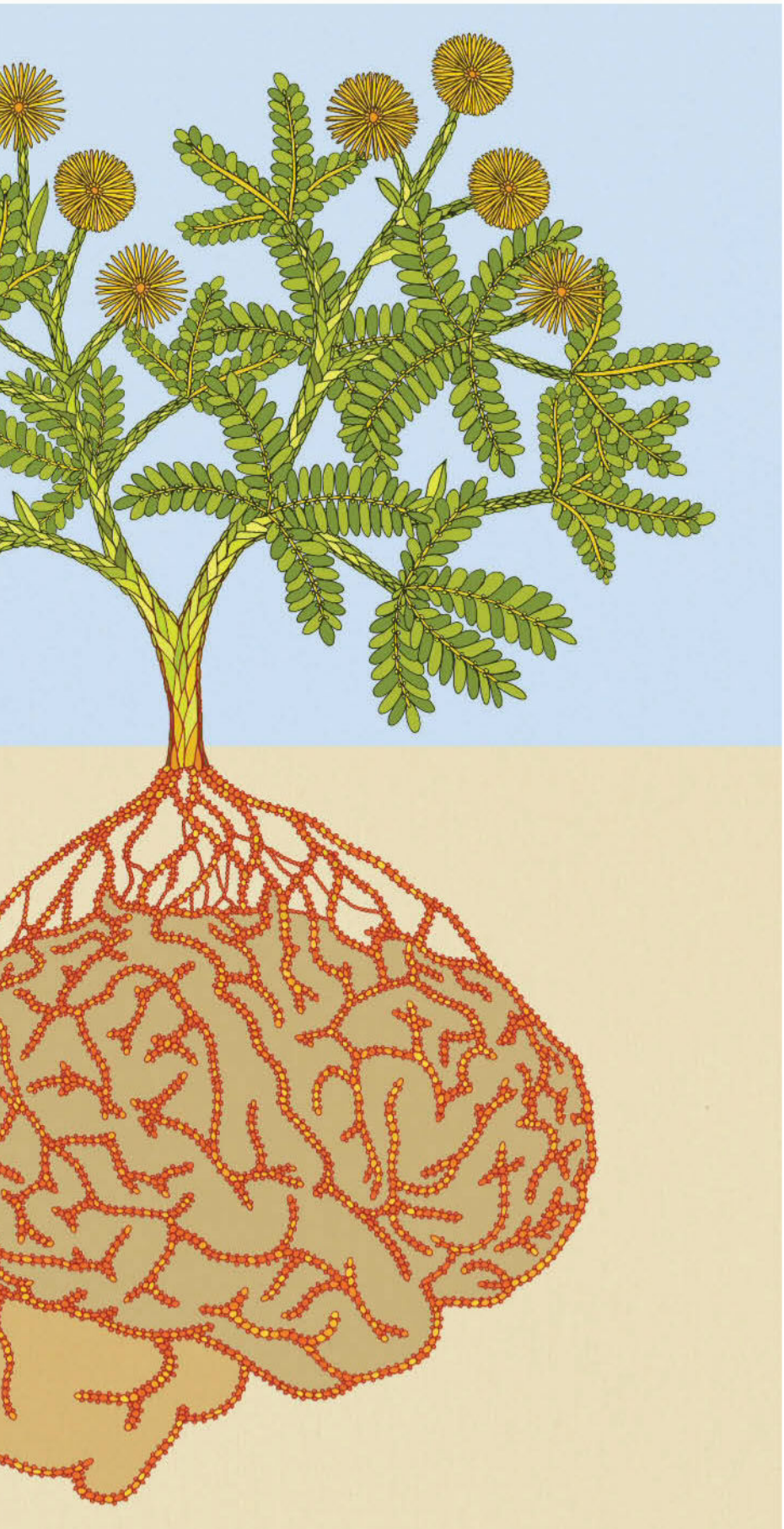
Charles Darwin would have approved. He was the first to seriously question Aristotelian ideas that plants don't have the stuff of life that animates us and other animals, simply because they don't move. One of his books, published in 1880, was provocatively titled *The Power of Movement in Plants*. But despite this patronage, plants didn't catch the fancy of biologists pondering intelligent life for more than a century.

Then, in 1900, Indian biophysicist Jagdish Chandra Bose began a series of experiments that laid the groundwork for what some today call "plant neurobiology". He argued that plants actively explore their environments, and are capable of learning and modifying their behaviour to suit their purposes. Key to all this, he said, was a plant nervous system. Located primarily in the phloem, the vascular tissue used to transport nutrients, Bose believed this allowed information to travel around the organism via electrical signals.

Bose was also well ahead of his time. It wasn't until 1992 that his idea of widespread electrical signalling in plants received strong support when researchers discovered that wounding a tomato plant results in a plant-wide production of certain proteins – and the speed of the response could only be due to electrical signals and not chemical signals travelling via the phloem as had been



CLAIRE SCULLY



assumed. The door to the study of plant behaviour was opened.

Even then, it would be another decade before Anthony Trewavas at the University of Edinburgh, UK, became the first person to seriously broach the topic of plant intelligence. Trewavas defines intelligence as the ability to sense one's environment, to process and integrate such sensory perceptions, and decide on how to behave. "The great problem of plant behaviour has always been that you can't see it going on," he says. There are a few exceptions, such as the snap of the Venus flytrap. "But the most visible plant behaviour is simply growth, and growth is a very slow business," he says. This problem has been reduced with the advent of time-lapse video and photography.

Take the parasitic vine *Cuscuta*, also known as dodder. In time-lapse, a dodder seedling seems to sniff the air looking for a host, and when it finds one, it lunges and wraps itself around its victim. It even shows a preference, choosing tomato over wheat, for example. "It is remarkably snakelike in the way it behaves," says Trewavas. "You'll stop doubting that plants aren't intelligent organisms, because they are behaving in ways that you expect animals to behave."

"Intriguingly, the function of the transition zone ties in with Darwin's 'root brain' theory"

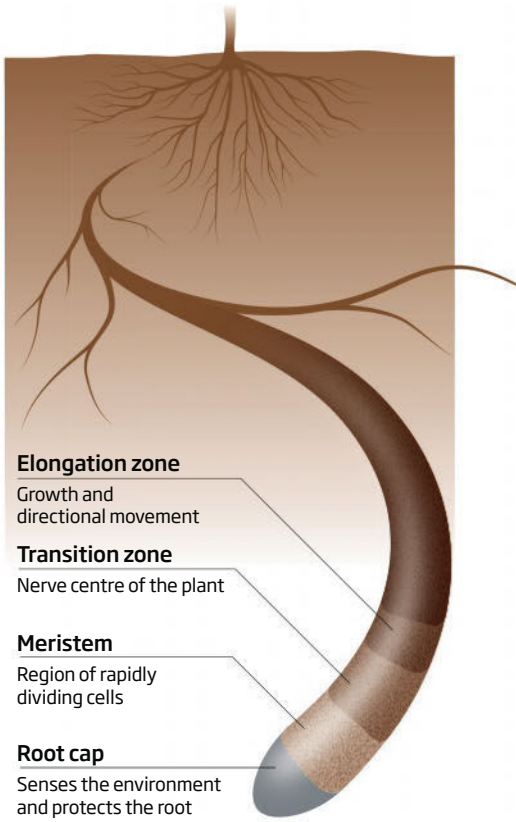
Once Trewavas mooted the idea of plant intelligence, others soon backed him up. So much so that in 2005, the Society for Plant Neurobiology was formed to foster debate and change the way we think about plants. "There is a kind of brain chauvinism," says Stefano Mancuso, one of the founders based at the University of Florence, Italy. "We think that a brain is something that is absolutely needed to have intelligence." Not so. Despite a lack of neurons and an animal-like nervous system, plants are perfectly capable of processing and integrating information to generate behaviour that can be called intelligent. Mancuso and society co-founder Frantisek Baluska at the University of Bonn, Germany, believe that roots are the key.

A root is a complex assemblage. There's the root cap, which protects the root as it navigates through soil, but also senses a wide range of physical properties, such as gravity, humidity, light, oxygen and nutrients. ›

The touch-me-not learns to stop reacting to a sham threat in just four lessons

Lateral thinking

Once considered to have no purpose, the transition zone near the tip of each root may be a kind of brain



Behind this is the meristem, a region of rapidly dividing cells. Further back is the elongation zone, where cells grow in length, allowing the root to lengthen and bend. And between the meristem and the elongation zone is a curious region called the transition zone (see diagram, right). Traditionally, it was thought to have no purpose, but Baluska and Mancuso think it is actually the nerve centre of the plant.

Underground intelligence

They have found that the transition zone is electrically active. What's more, within it a hormone called auxin, which regulates plant growth, is ferried around in protein containers called vesicles that are reused once they have released their load. This is similar to the transport of neurotransmitters in animal brains, where vesicle recycling is thought to be important for the efficient and precise information exchange across synapses. The transition zone is also a major consumer of oxygen, in another curious analogy to the human brain. All of which led Baluska and Mancuso to suggest that this is where sensory information gathered by the root cap is translated into commands for the elongation zone – and so control of root behaviour.

Intriguingly, this ties in with Darwin's "root brain" hypothesis. In the last paragraph of *The Power of Movement in Plants*, he dared readers to think of the root as the intelligent end of a plant. Referring to a plant's primary root, or radicle, he wrote: "It is hardly an exaggeration to say that the tip of the radicle… acts like the brain of one of the lower animals."

"He was right once more," says Mancuso. "If we need to find an integrative processing part of the plant, we need to look at the roots."

Parallels with animal intelligence don't end there. Besides the tantalising brain-like behaviour of the root's transition zone, many plant cells are capable of neuron-like activity. "In plants, almost every cell is able to produce and propagate electric signals. In roots, every single living cell is able to," says Mancuso. Likewise, the phloem is extremely electrically active, and capable of fast electrical signalling. "It is some kind of huge axon, running from the shoot tip to the root tip," says Baluska.

There's also the curious fact that plants produce chemicals that in animal brains act as hormones and neurotransmitters, such as serotonin, GABA and melatonin. Nobody quite knows the significance of these chemicals in plants – it could simply be that evolution has come up with similar molecules for very different purposes in plants and animals. Nevertheless, Susan Murch of the University of British Columbia in Kelowna, Canada, has shown that drugs like Prozac, Ritalin and methamphetamines, which disrupt neurotransmitters in our brains, can do the same in plants. "If you really mess with a plant's ability to either transport or make melatonin or serotonin, root development is very strange – they are malformed and disjointed," she says.

"Plants may even feel pain, a sign they could have a kind of consciousness"

Despite all this, the term "plant neurobiology" is controversial even among some of the most vocal advocates of plants. Daniel Chamovitz at Tel Aviv University in Israel says it's an oxymoron. "Plants just don't have neurons. It's like saying 'human floral biology'," he says. Indeed, the Society for Plant Neurobiology met with so much resistance that its founders were forced to change its name to the less controversial Society of Plant Signaling and Behavior.

Nevertheless, Chamovitz and others don't dispute that plants are extremely aware of their environment, and are able to process and integrate information in sophisticated ways. In fact, a plant's awareness of its environment is often keener than an animal's, precisely because plants cannot flee from danger and so must sense and adapt to it. For instance, while animals have a handful of photoreceptors to sense light, plants have about 15. "Plants are acutely aware of their environment," says Chamovitz. "They are aware of the direction of the light and quality of the light. They communicate with each other with chemicals, whether we want to call this taste, or smell, or pheromones. Plants 'know' when they are being touched, or when they are being shook by the wind. They integrate all of this information precisely. And they do all of this integration in the absence of a neural system."

Plants also manage to remember things without the benefit of neurons. Memory can

FRANK GREENAWAY/DORLING KINDERSLEY/GETTY

be defined, according to Chamovitz, as "recording an event, storing that event and recalling it at a later time in order to do something". And plants certainly do this. For example, just one touch isn't enough to spring the jaws of a Venus flytrap. Instead, it remembers the first touch and if it senses another within 30 seconds it snaps shut. That's because the first touch causes molecules to build up in the trap's sensory hairs and the second touch pushes the concentration of these across a threshold, resulting in an electrical impulse that activates the trap.

Smarty plants

There is even evidence that plants have long-term memories. *Mimosa pudica*, the touch-me-not plant, can close its leaflets when touched, but this defensive behaviour requires energy, therefore the plant doesn't indulge in it unnecessarily. When Mancuso and colleagues dropped potted mimosas on to foam from a height of 15 centimetres, the plants closed their leaves in response to the fall. But after just four to six drops they stopped doing this – as if they realised that the fall posed no danger. However, they continued to close their leaves in response to a physical touch, which would normally presage being damaged or eaten. "Even after one month, they were able to discriminate and be able to understand whether the stimulus was dangerous or not," says Mancuso.

This is all very clever, but it's not intelligence, says Chamovitz: "I don't like the term plant intelligence. We don't even know what intelligence is for humans. If you get five psychologists together you will get 20 different definitions."

Murch agrees. She acknowledges that plants seem to possess the various elements that make intelligence possible – sensing, awareness, integration of information, long-term memory and adaptive learning – but she is not convinced this adds up to intelligence. And despite years spent among towering redwoods, Sillett is also doubtful. "I wouldn't call it intelligence, but awareness. These trees are keenly aware of their environment, and they respond to it in many ways that we can measure as performance."

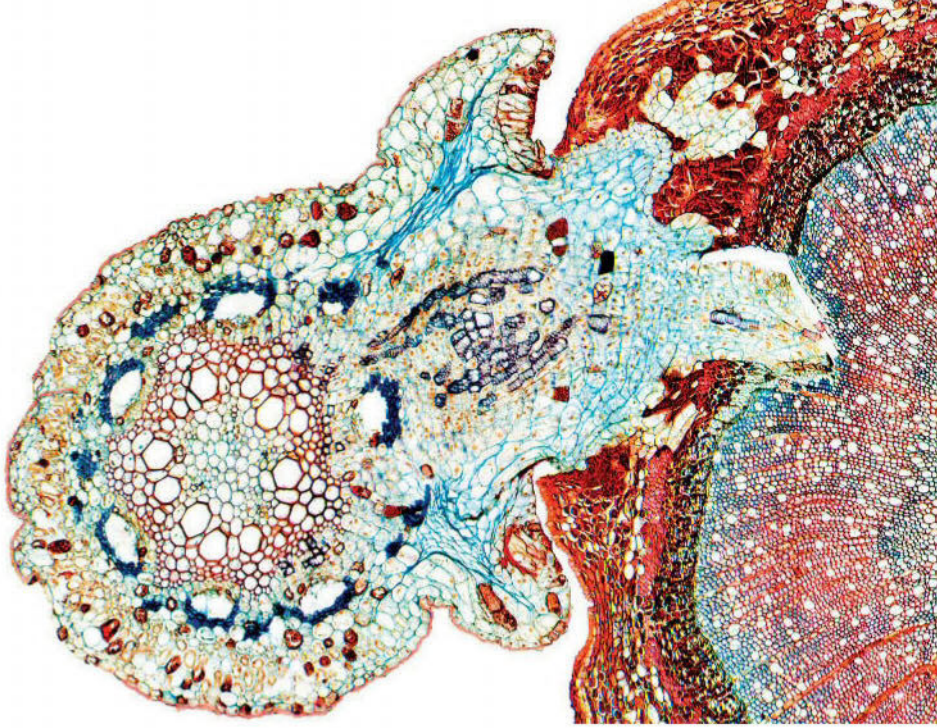
But while many researchers are cautious, others are keen to push the way that we think about plants into even more disputed territory. Baluska suggests that plants may even feel pain, and argues that this is a sign that they have a kind of consciousness. An animal can be knocked out with anaesthetics, including the gas ethylene. Plants produce ethylene to regulate everything from seed germination to fruit ripening. They also release it when stressed – when under attack by predators or being cut by humans, for example – and nearby plants can sense it. "Ethylene is the plant equivalent of a scream," says Murch. But Baluska goes a step further, pointing out that the gas is produced in large quantities by fruit when it's ready to be eaten. "If you consider ethylene as an anaesthetic, and if some organism is producing an anaesthetic under stress then you could get ideas that plants maybe feel some pain," he says.

Such notions are extremely controversial and, even Baluska agrees, speculative. To avoid simply pitting one side against another in the debate, we need a different framework to start thinking about notions of intelligence and consciousness, says Michael Marder of the University of the Basque Country in Vitoria-Gasteiz, Spain. The lone plant philosopher for now, he argues for a phenomenological approach to understanding plants, which involves asking: what does the world look like from the standpoint of plant life?

"Our task is to think about these concepts of attention, consciousness and intelligence in a way that becomes somehow decoupled from the figure of the human," he says. "I want [us] to rethink the concept of intelligence in such a way that human intelligence, plant intelligence and animal intelligence are different sub-species of that broader concept, which can somehow encompass these different life forms."

Murch has begun engaging with such questions in one of her classes, which brings together biochemistry and creative writing students to ponder plant intelligence. "Inevitably, there is a vegan in the audience who goes, 'Then what will I eat?'" she says.

That might seem like a flippant response, but contemplating whether plants are intelligent could lead us to change the way we live. As Marder points out, the sessile nature of plants means they don't exist in opposition to the place they grow. Rather, they become a focal point for myriad organisms. "Maybe we can use that model for ourselves, to temper a little bit the excessive separation from our environment that has led in large part to the profound environmental crisis we find ourselves in," he says. ■



Time-lapse video reveals a parasitic vine to be remarkably snakelike in pursuit of its prey

The Venus flytrap remembers a touch and only snaps shut if touched again within 30 seconds

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Pooper scoopers

Instead of catching insects, a few carnivorous plants have resorted to hunting a rather more unusual prey. **Stephanie Pain** reveals all

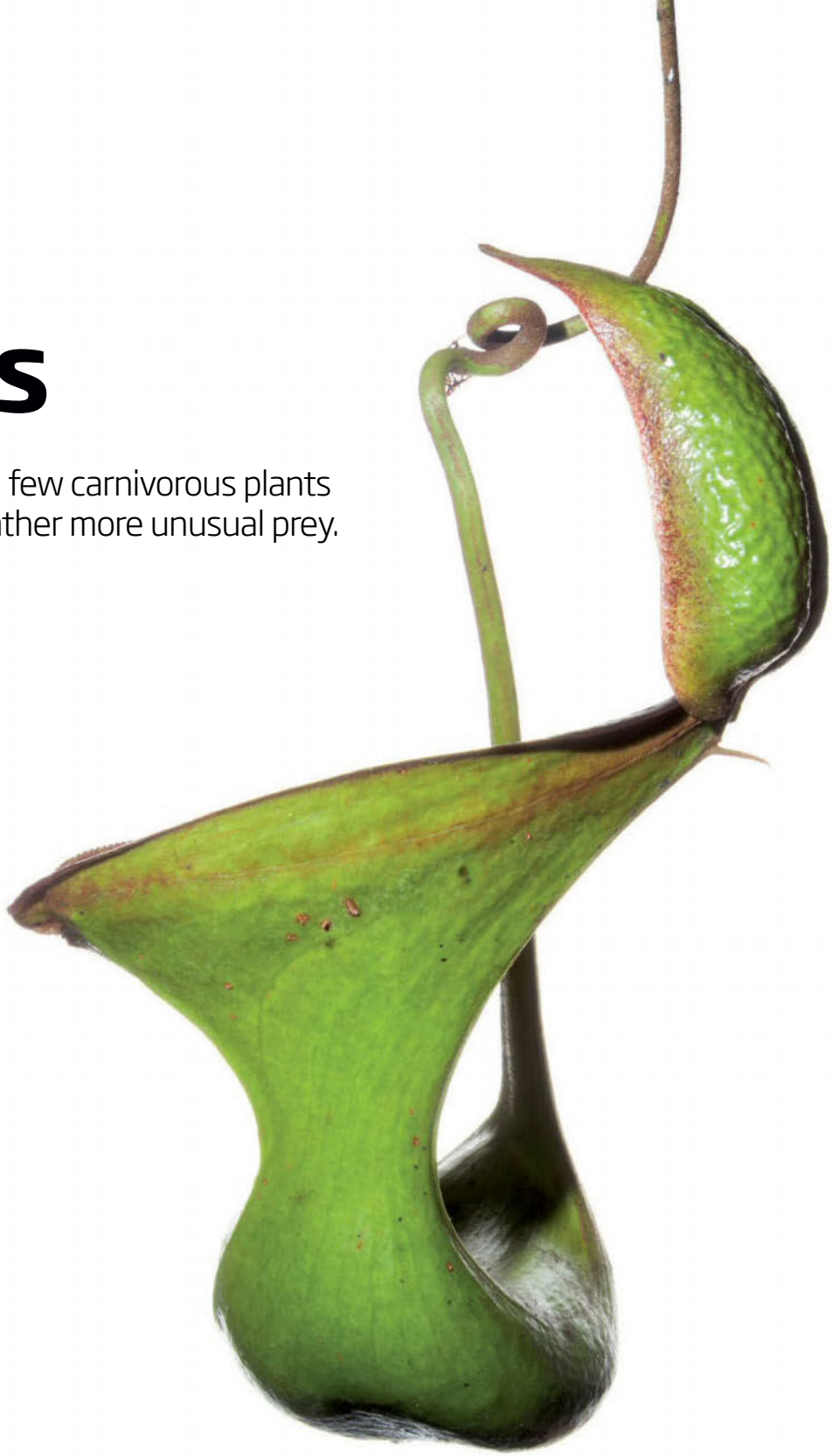
HIGH in the misty mountains of Borneo, death awaits the unsuspecting wanderer. This is the lair of the most awesome of the pitcher plants, with fearsome traps and a reputation to match.

The pitcher plants of South-East Asia are famed for their carnivorous habits. These merciless killers lure insects to the top of their traps with sweet nectar, where many lose their grip on the ultra-slippery rim and fall into the fluid-filled trap. As the victims desperately try to climb out, they discover too late that this is no ordinary fluid – it is filled with invisible stretchy fibres, and the more an insect struggles, the more entangled it becomes.

Sooner or later the trapped animals drown, and digestive enzymes in the fluid accelerate the breakdown of their rotting corpses. Only then does the plant gets its reward: nitrogen, a key nutrient that is in short supply in the places where these killers lurk.

Small insects, particularly ants, are the usual prey of the 120 or so species of *Nepenthes* plants. But the island of Borneo is home to several spectacular species with unusually shaped giant pitchers. The largest, *Nepenthes rajah*, has jug-like pitchers so big they can hold several litres of fluid, and its appetite is legendary. In the century-and-a-half since its discovery, there have been sporadic reports of it catching rats. So has the "king" of carnivorous plants really evolved to catch small mammals?

After staking out the giant pitchers and mounting 24-hour surveillance, ecologists have discovered that the truth is even stranger than this. It turns out that *N. rajah* and at least three other pitcher plants in Borneo have indeed evolved to lure small mammals into their traps – but not to kill them… ›

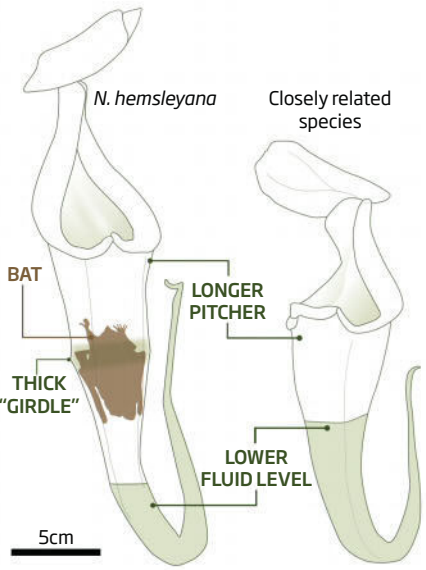


Nepenthes lowii **has a strange but fruitful elationship with a mammal**

MYN/JORIS VAN ALPHEN/NATUREPL

Safe haven

The pitcher plant *Nepenthes hemsleyana* has evolved to provide a safe roosting place for woolly bats



One of the first to suspect that some pitcher plants do things differently was Charles Clarke of Monash University Malaysia. During an expedition to Mount Pagon in north-west Borneo in the 1990s, he took a close look at one of the weird giant pitcher plants, called *N. lowii* (pictured on page 81). He noticed that its pitchers lack the slippery rim and smooth inner walls that help trap insects.

N. lowii is odd in other ways too: the rim is unusually narrow and the mouth unusually broad, while the leafy lid that normally keeps out rain is angled up and away from the opening. And while other pitchers secrete nectar from glands around the rim, this plant oozed much larger quantities of thicker, buttery nectar from the underside of its lid. Finally, the whole structure – both the pitcher and the tendril it dangles from – is reinforced with woody lignin.

All this suggests that this plant has evolved to attract something larger and heavier than insects to its pitchers. "Growing pitchers is costly for a plant, so if the pitcher is much bigger than required you have to ask why," says Jonathan Moran of Royal Roads University in Canada.

Could its prey be a nectar-sipping bird? Or a sweet-toothed mammal? In 2008, Clarke, Moran and colleagues found the answer in the cloud forest of Gunung Mulu in another part of Borneo. Keeping watch on *N. lowii* pitchers they found only one vertebrate visited them: the mountain tree shrew, *Tupaia montana*.

Intrigued, Ulrike Bauer, a member of the team from the University of Cambridge, set up cameras. Her footage revealed how tree shrews leap onto the pitcher's narrow rim and grip it with their hind feet before stretching up, across the yawning chasm to reach the nectar oozing from the lid. With a few wipes of a muscular tongue, the lids are clean and the tree shrews scamper off unharmed. It is all over in seconds.

So *N. lowii* does not prey on shrews. But it does not go unrewarded: the footage revealed that the tree shrews sometimes defecated in the pitcher. Clarke had noted on his earlier expedition that the pitchers contained few insects but a lot of droppings. The video evidence suggested that this is no accident: *N. lowii* not only looks like a toilet – it *is* a toilet for tree shrews.

An unusual relationship

"The orientation of the lid forces the tree shrew to position its rear end over the pitcher's mouth while feeding," says Moran. "That increases the chances of faeces being captured if the animal defecates while it's on the pitcher." It also means that any droppings left sticking to the walls of the pitcher are flushed to the bottom when it rains.

With tree shrews weighing around 150 grams, this also explains why the pitchers are more robust than those of insect catchers. "If they weren't reinforced they'd probably snap off," says Moran.

To the ecologists it seemed they had discovered an unusual and mutually beneficial relationship between a plant and a vertebrate. The pitcher plants provide tree shrews with a meal rich in carbohydrates in exchange for the occasional nitrogen-rich dropping. The clinching evidence came from an analysis of the source of the nitrogen in the plants. It showed that between 60 and 100 per cent of it came from shrew droppings.

Poo might seem the perfect fertiliser for a plant, but in fact mammal faeces are not as rich in nitrogen as ants are. So why would a pitcher evolve to capture faeces rather than insects? For a mountain plant there is good reason to seek alternative supplies of nitrogen: the density of ants and other insects diminishes with increasing altitude. Tree shrew droppings are also richer in nitrogen than those of most mammals, because they have short guts that do not extract all the nutrients from their food. Plus the speedy throughput means tree shrews make frequent deposits.

The strategy definitely works. The team's analysis of leaf tissue showed that *N. lowii* has a higher nitrogen content than insect-eating pitcher plants growing in the same habitat.

With the shortage of insects at altitude, it seemed likely other *Nepenthes* growing on mountains might have adopted a similar strategy. Sure enough, two more large species have been found to exploit the tree shrew's productive bowels. *N. macrophylla*, a close relative of *N. lowii* that grows on Mount Trusmadi, and *N. rajah* – the notorious "rat-catcher" of Mount Kinabalu – catch both insects and droppings.

Although these two plants hedge their bets with a dual-fuel policy, all three "toilet pitchers" share a unique set of features to ensure visiting tree shrews pay up after they've finished eating. All have large mouths and a large concave lid poised at about 90° from the pitcher's rim. The arrangement means tree shrews must approach the lid face

CH'IEN LEE/MINDEN PICTURES

THE VEGGIE OPTION

Faeces-eating pitcher plants aren't alone in adopting a radically different diet (see main story). One species is turning vegetarian.

Nepenthes ampullaria grows in lowland forests rather than the open habitats more typical of pitcher plants. It forms dense carpets of pitchers on the ground (left). These pitchers are unusually broad-mouthed, lack the normal insect-trapping features and have vestigial lids that grow away from the mouth instead of sheltering it. The clusters of pitchers present a sea of gaping mouths – and with good reason.

Under the forest canopy, a constant supply of nitrogen rains down in the form of falling leaves and other plant debris. These pitchers have evolved to intercept this nitrogen bonanza before it reaches the ground and becomes available to other plants. Leaf litter isn't the richest source of nitrogen but it is reliable and this species gets a third of its nitrogen this way.

on. Most crucially, the distance between the front of the pitcher and the farthest point on the curve of the lid precisely matches the head-and-body length of an adult tree shrew, Clarke and colleagues reported in 2010. Reaching to get the last drops of nectar, tree shrews cannot help but position themselves with their rear ends over the bowl.

So far, so neat, but *N. rajah* (pictured right) had another surprise in store. When Clarke returned to Mount Kinabalu in 2010 to learn more about tree shrew toilet habits, the team discovered more than one sort of dropping in the pot. The tree shrews' were dark and malodorous. The others were paler and less smelly. No matter how long the ecologists watched during the day, the only visitors they saw were tree shrews. Perhaps the mystery mammal only appeared after dark? To find

"Growing pitchers is costly, so if they are bigger than required to catch insects you have to ask why"

out, the team left cameras running through the night and finally unmasked the second visitor: it was the summit rat, *Rattus baluensis*. The rat, much the same size as a tree shrew, is also a prolific pooper.

This could explain the reports of *N. rajah* eating rats. "The stories stem from clumsy rats or tree shrews that lost their footing when feeding and slipped in," says Moran.

And the discoveries keep on coming. Down in the lowland peat forests of Brunei, another pitcher plant has adapted its traps to collect faeces, but has gone about it in a very different way. Instead of luring animals with nectar, *N. hemsleyana* provides them with accommodation. Once ensconced, the lodgers, tiny bats, have a habit of defecating on their bedroom floor.

When Ulmar Grafe at the University of Brunei Darussalam first found a Hardwicke's woolly bat inside the pitcher of an *N. hemsleyana* he thought it was a one-off. But then Grafe read that these pitchers trap far fewer insects than those of other species.

Grafe and his students began to patrol more than 400 of these pitchers each day and, over seven weeks of monitoring, they found that one in five pitchers played host to at least one bat. Some contained two bats, a mother and young. Analysis of leaf tissue showed that around 34 per cent of the plants' nitrogen content came from woolly-bat droppings. Here was another unusual partnership.

The team discovered that some woolly bats also roost in another species of pitcher, but because there is not enough space for them above the fluid, they roost only in dead or dying pitchers whose fluid has drained out.

Yes, the tree shrew is doing what you think it is on *Nepenthes rajah*

CHIEN LEE/MINDEN PICTURES

These plants therefore get no benefit.

A few other animals, from mosquito larvae and tadpoles to spiders and ants, have taken to living inside pitchers, but most appear to be uninvited guests. The pitchers of *N. hemsleyana*, by contrast, have evolved to accommodate bats in comfort and safety in exchange for regular dollops of dung (see diagram, page 82). The pitchers are longer and have a much lower fluid level than those of closely related species, providing ample room for two bats stacked one above the other. The walls also have a "girdle" of thick tissue that allows bats to wedge themselves in the pitcher a safe distance above the fluid. "Bats only use pitchers of the right dimensions," Grafe notes.

Rather than being shaped to trap and kill, then, these pitchers protect their lodgers. And the living pitchers of *N. hemsleyana* provide healthier homes than empty pitchers. The temperature is more stable, and cooler during the hottest part of the day. The fluid also keeps the air humid, helping to prevent dehydration in its minuscule lodgers. Not only do the bats prefer *N. hemsleyana*, Grafe's team reported last year, but those that roost only in its pitchers are bigger and in better shape than those roosting in other pitchers.

Why, though, would a plant that grows where insects are plentiful go to such lengths to acquire nitrogen from another source? Although there is less pressure pushing lowland species to exploit alternative nitrogen sources, it clearly happens occasionally (see "The veggie option", left). Nitrogen may be more easily assimilated from faeces, suggests Grafe, plus the plants don't need to produce as much nectar to attract insects.

Whatever the reasons, in the past few years it has become clear that a few pitcher plants have branched out from preying on insects, tweaking their traps to exploit other sources of essential nutrients. A lot of new species are being discovered and some have unusual shapes, says Moran. "Are there other weird nutrient strategies out there awaiting discovery? I suspect that *Nepenthes* may still have a few surprises in store for us." ■

Abominable snowplant

While all around it cower from the cold and wind, one plant thrives high in the Himalayas. Henry Nicholls reveals its extraordinary secret

THE foothills of the Himalayas are lush and verdant. But the higher you go, the shorter the plants get. Above the treeline, at around 4000 metres above sea level, conditions are extreme. It's cold and windy, the steep slopes consist mostly of shattered rocks rather than soil, and from above comes an invisible barrage of ultraviolet light. The plants here are tiny and cling closely to the mountainsides, barely peeking above the scree-clad slopes. Every now and then, though, a towering pale form looms, ghostlike, out of the mist.

When the botanist Joseph Hooker caught his first glimpse of this peculiar plant in the 1840s, he was "quite at a loss to conceive what it could be". From a base of normal green leaves rises a hollow column made of overlapping pale-yellow leaves. The columns can grow nearly 2 metres high, dwarfing the other vegetation around them.

So how does this plant manage to grow so much larger than others at this altitude? The translucence of the column suggests an amazing answer: it grows its own greenhouse.

When Hooker examined the plant closely, he identified it as a member of the rhubarb family. He named it *Rheum nobile*, the noble rhubarb. Like the species widely grown for food, the stems of the green leaves are edible. Hooker noted that they taste pleasant and are much eaten – perhaps too pleasant, for the plant is now endangered in the wild.

A few botanical gardens and plant enthusiasts grow *Rheum nobile*, but it rarely flowers away from its natural habitat, and the flowers are the extraordinary part. The hollow columns are actually flower spikes. The pale yellow leaves – or bracts, as botanists call these modified leaves – grow from each spike, surrounding and hiding the flowers inside. "On a scale of 1 to 10 for botanical novelty, it's probably getting towards 8," says David Simpson, honorary research associate at Kew Gardens in London, where the specimen collected by Hooker is still stored.

The bracts keep the flowers enclosed throughout their development and pollination, and while fruit and seeds form. Only after that do they turn brown and fall off, exposing the now-dead seed-bearing stem within. "In the winter these naked black stems, projecting from the beetling cliffs or towering above the snow, are in dismal keeping with the surrounding desolation of that season," Hooker wrote.

But why enclose the flowers in the first place? *Rheum nobile* is often referred to as a "glasshouse plant", but it is unclear who first suspected it might act as one. The earliest such reference *New Scientist* could find was by the Japanese botanist Sasuke Nakao in 1964. "The flowers open in the self-made warm room," he wrote. This boosts pollination, Nakao proposed, by providing favourable conditions for insects.

Flowers hidden inside the column are revealed in this illustration from 1855

JOHN FERGUSSON CATHCART/HIMALAYA MOUNTAINS; PLANTS; MISSOURI BOTANICAL GARDEN, PETER H. RAVEN LIBRARY

Another Japanese botanist, Hideaki Ohba, later suggested the warmth boosts the growth of the plant itself as well. "The inflorescence is sheltered by papery and translucent leafy bracts that can be compared to the glass of a hothouse," he wrote in a 1988 book.

In the 1990s, a study confirmed that the hollow columns do have a "greenhouse effect". The bracts allow visible and infrared light to pass through and they trap the resulting heat, just like the glass or plastic of a greenhouse.

A few other plants also appear to exploit this effect. Most are inconspicuous affairs, but *Rheum alexandrae,* another rhubarb*,* looks like a smaller version of *R. nobile*. It seems to be a case of parallel evolution, though. The genetic evidence suggests that their hollow columns evolved independently, says Jianquan Liu, a molecular ecologist at Lanzhou University in China.

But what exactly did they evolve for? Although the pale bracts lack chlorophyll, they are packed with substances that absorb ultraviolet light. It could be, for example, that they evolved to be, and are needed as, UV filters, and that the greenhouse effect is entirely incidental.

So Hang Sun, a botanist at the Kunming Institute of Botany in China, sent two students to investigate what, if any, benefits the bracts provide. Using the remote Tibetan village of Wengshui as a base, they drove a hired car up into the mountains each morning to monitor *Rheum nobile* plants growing in the wild. They removed the bracts from some plants before they flowered, from others after they flowered, and left a third group intact.

Their work confirmed Nakao's suggestion about insects. The main pollinator of *Rheum nobile*, a fungus gnat, showed a strong preference for visiting plants that still had all

HARRY JANS: WWW.JANSALPINES.COM

their bracts – presumably attracted to the warm shelter within. Intact plants are also easier to find, Sun thinks. "These bracts act as a flag to help pollinators to locate their host."

The team also confirmed the importance of the UV filtering. When pollen-bearing flowers were exposed to high UV levels in the lab without the protection of the bracts, far fewer pollen grains germinated. However, the normal, chlorophyll-containing leaves at the base of the plant provide more UV protection than the bracts, so the translucence of the bracts must have evolved for another reason.

The bracts also protect the flowers from rain and hail, Sun's team found. *Rheum nobile* flowers during the rainy season and, in plants whose bracts were removed, most of the pollen grains were washed away. Again, though, this does not explain the bracts' translucence.

It is, however, necessary for the greenhouse effect. On a sunny day, the air was around 10 °C warmer inside the columns than outside (see right), a finding in keeping with observations by other researchers. But Sun and his team went further, collecting pollen from several flowers and showing that grains kept at higher temperatures were much more likely to germinate. So the extra warmth really does matter for pollination.

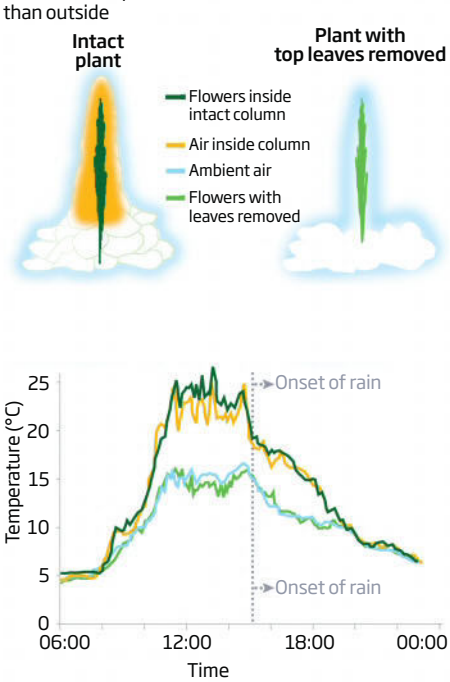
The warmth and shelter boosts seed development, too. Plants with intact bracts produced larger seeds that were more likely to germinate than those whose bracts were removed after flowering, the team found. "The bracts act as a greenhouse to increase the temperature, and thus promote pollen germination and seed development," Sun concludes. They are an ingenious solution to the hostile environment, he says.

There is one downside. The gnats that pollinate the plants lay their eggs in the flowers, and the larvae feed on the seeds. More seeds were eaten in plants with intact bracts. But the losses are outweighed by the bracts' other benefits. What's more, the gnats are needed to pollinate the next generation.

So it seems *Rheum nobile* evolved its extraordinary structure for much the same reasons that gardeners and farmers use greenhouses – to provide shelter and boost growth – and that it has the same problems, allowing pests to thrive as well. We can add the greenhouse to the long list of things that evolution invented first. ■

Keeping cosy

The temperature inside the flower columns of *Rheum nobile* plants can be more than 10°C warmer than outside



SOURCE: OECOLOGIA 2012

CHAPTER FIVE

REPTILES AND AMPHIBIANS

Smaug the magnificent?

BENEATH the translucent gold vein-like structure lies what looks like the eye of Smaug. But this is no dragon's eye. It belongs to something much smaller: a teacup-sized frog having a nap in the trees of a tropical rainforest.

The red-eyed tree frog (*Agalychnis callidryas*) lives all over Central America and the Caribbean. In the day, when the frog is asleep, a gold membrane creeps over its eyes. It lets in a small amount of light, enough so that if a predator approaches, the non-poisonous frog can wake up, show its bulging red eyes and present its yellow feet in a bid to make the would-be attacker think twice.

Nictitating, or blinking, membranes are found in a variety of animals, from cats and sharks to camels and polar bears. In all the animals that possess them, this extra eyelid moisturises the eye while still letting light through. "A nictitating membrane is found in many mammals, although we humans have lost it," says zoologist Sue Evans at University College London. "Its main function is to clean and wipe the surface of the eye. In frogs it is basically a modified part of the lower eyelid, and thus modified skin."

This close-up was snapped by German photographers Heidi and Hans-Jürgen Koch. The couple travel the world taking photographs of wildlife. They call their work Lifeform Photography. Abigail Beall

Photographers

Heidi and **Hans-Jürgen Koch** eyevine
lifeformphotography.com

Lazarus frogs

Amphibians are under attack. Climate change, habitat loss and the effects of the deadly skin disease caused by the chytrid fungus have wiped out many frog and toad populations worldwide. Some entire species are missing, presumed dead. But in a few spots in the forests of Central America, a fightback has begun. Meet the Lazarus toads

Photographs by Clay Bolt and Twan Leenders. Words by Catherine Brahic

In March 2013, Twan Leenders and a student were hiking in the Cocobolo reserve in central Panama when they spotted a precious jewel: a delicate string of white pearls floating at the bottom of a rocky puddle at a stream's edge. "That was absolutely tremendous," says Leenders. "Everything fit for *Atelopus*, there was nothing else it could be."

Leenders, a herpetologist at the Roger Tory Peterson Institute of Natural History in Jamestown, New York, has spent his career studying tropical frogs and toads. That had mostly meant documenting their astonishing decline. Climate change and human encroachment on the amphibians' favoured habitats were a major part of the problem – as was the advance of the deadly chytrid fungus.

Since the chytrid strain *Batrachochytrium dendrobatidis* was identified in 1999, it has been seen in amphibian populations across Europe, Africa, Australia and Central and South America. The fungus accumulates in the outer skin layers of amphibians, overstimulating production of the protein keratin and hardening the skin. That prevents ›

Atelopus limosus
Panama

Discovery of spawn from this toad species – known as "harlequin frogs" – (pictured in the main photo, left) in the streams of the Cocobolo reserve indicated the revival of a species thought almost gone. The toad's colourful skin harbours bacteria that produce a neurotoxin also found in blue-ringed octopuses and the notorious "fugu" pufferfish. Until the advent of chytrid, this was sufficient protection against most enemies.

Atelopus varius
Costa Rica

Before the arrival of the chytrid fungus, more than 100 populations of this harlequin species were once known in the mountains of Costa Rica and adjoining Panama. One population is now known to have survived and thrived in a single stream valley on an isolated mountain in Costa Rica's Pacific coastal plain. What conferred it with resistance to chytrid is a mystery.

the uptake of water and essential minerals – and is normally lethal.

The tiny, colourful toads of the *Atelopus* genus – known colloquially as harlequin frogs – suffered badly. "Harlequin frogs were particularly hard hit by the fungus, and dozens of species disappeared rapidly in the 1980s and 90s," says Robin Moore of Global Wildlife Conservation and the Amphibian Survival Alliance, both based in Austin, Texas.

Hence the reaction of Leenders and his crew to that pearl-string of spawn. It came from a species, *Atelopus limosus*, thought to have been wiped out in Panama. Here was a population that hadn't just survived, but was reproducing in the wild. A few days later, the team spotted juveniles further upstream. In the following years, more and more sightings were made around Cocobolo.

A. limosus is one of a small number of "Lazarus" amphibian species. In Costa Rica, Moore and Leenders are watching the recovery of *Atelopus varius*, a species thought extinct until one was found sitting on a rock a few years ago.

We still can't fully explain the comebacks. One theory is that long-term exposure to non-lethal levels of the fungus may confer individuals with resistance to the fungus. The Cocobolo reserve may also have been unsuitable for chytrid when it first took hold in Central America 10 to 20 years ago. At the time, it was pasture – too hot and dry for the fungus, which thrives on the cool surfaces of riverside rocks, just like the toads. *A. varius*, meanwhile, lives in a valley surrounded by a belt of agricultural land and plantations, which perhaps formed a protective barrier against the fungus.

The fact that the threatened amphibians have prospered in habitats that are far from pristine may point to new ways to protect them – for example, by managing farmed landscapes to create new habitats. "I would like to work with local farmers to help them restore some of the stream corridors," says Leenders.

"This species hadn't just survived – it was reproducing"

The amphibians aren't out of danger yet. "A few frogs have reappeared after massive declines and seem to be hanging on in relictual populations," says Ariadne Angulo, who co-chairs the International Union for Conservation of Nature's Amphibian Specialist Group. "They are not the norm, but there are some remarkable cases." As if to underline the point, Leenders's team is now getting reports of amphibian declines in areas just outside the Cocobolo reserve.

But Lazarus species give room for hope. "The fact that some of these species are reappearing years or even decades after they were last seen is enormously encouraging," says Moore – and an opportunity to understand what sets these populations apart. "After decades of witnessing rampant declines, these glimmers of hope are much-needed morale boosters." ■

An estimated

42%

of amphibian species have decreasing populations

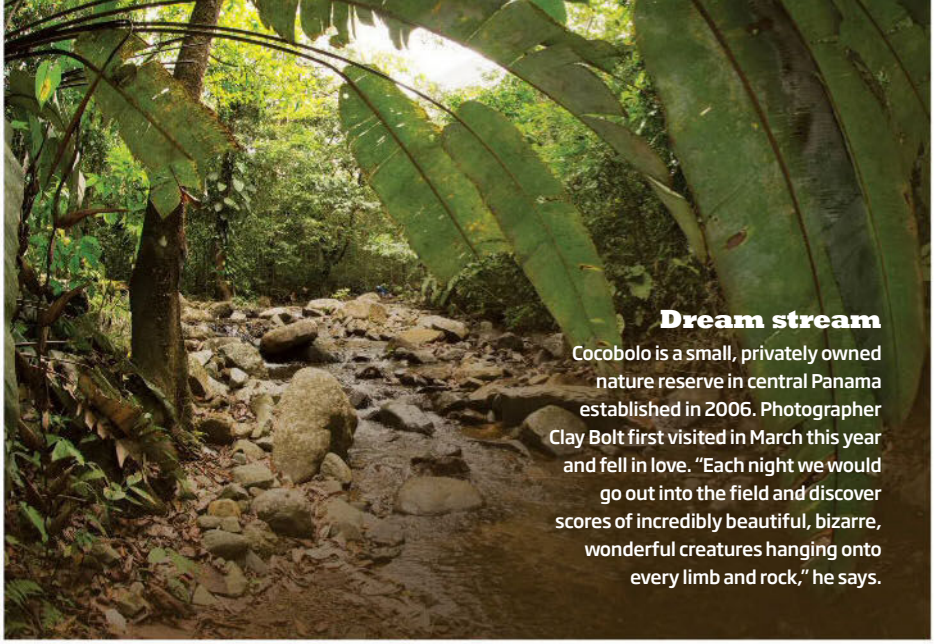
6424

amphibian species have had their extinction risk assessed

1961

species are currently listed as "threatened"

SOURCE: ARIADNE ANGULO/IUCN



Dream stream

Cocobolo is a small, privately owned nature reserve in central Panama established in 2006. Photographer Clay Bolt first visited in March this year and fell in love. "Each night we would go out into the field and discover scores of incredibly beautiful, bizarre, wonderful creatures hanging onto every limb and rock," he says.

Fungal menace

Many tropical amphibians had hardly been studied before the chytrid fungus kicked in, and population declines were initially put down to natural cycles. The Lazarus toads give a much-needed chance to see what factors influence survival in the wild. "This is where Cocobolo becomes a pivotal point in the research and conservation of these most at-risk species," says Leenders.

Desirable residence

Leenders and his students monitor temperature, humidity, water chemistry, sun exposure and other environmental parameters in two 1-kilometre-long sections of stream in Cocobolo, one that houses *Atelopus limosus* and one that doesn't. By superimposing that data on a biological and physical habitat map they hope to pinpoint the qualities of an ideal toad home.

Tiny survivor

Harlequin species such as this *Atelopus varius*, pictured in Costa Rica, have unique dorsal patterns that allow individuals to be "fingerprinted" and tracked throughout their lives. Skin swabs are used to test for chytrid fungus, allowing the researchers to assess how factors such as age and habitat use affect susceptibility to the fungus – and so how best to protect these species.

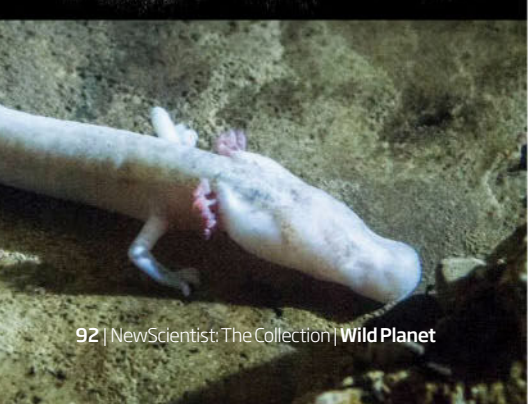
Toads in a hole

Faced with a worldwide collapse in frog and toad numbers, researchers around the world have begun to collect vulnerable species and try to get them to reproduce in captivity. Given the upbeat title of "reassurance colonies", these safe houses provide an environment to study the species' biology and perhaps understand why they are susceptible to chytrid fungus.

But they are a counsel of desperation as long as the captive populations have nowhere to go. "The longer we wait, the more generations have passed of frogs that have lived entirely in captivity," says herpetologist Twan Leenders. "To some extent [the projects] are a desperate measure to try and keep the last survivors of several species around."

Conservationist Robin Moore agrees, but points out that collecting species ahead of a wave of chytrid in Panama probably prevented their extinction there, and in general conservation activities help to educate the public about the amphibians' fate. And he sees room for optimism in stories of amphibian species rendered vulnerable to extinction through habitat loss that have bounced back.

The Mallorcan midwife toad, a "living fossil" thought to have been extinct for 2000 years before it was rediscovered in 1977, was revised from critically endangered to vulnerable by the International Union for Conservation of Nature in 2004, thanks to a programme that integrated breeding, reintroduction and habitat management. And Tanzania's Kihansi spray toad, driven to extinction in the wild around 2004 following the construction of a dam, has bred well in colonies. Preliminary reintroductions are promising.



STUART BUTLER

Our man descends into Slovenia's spectacular caves for a brief encounter with an olm

Graham Lawton goes in search of a strange subterranean predator long mistaken for a mythical beast

Crouching caver, hidden dragon

HERE'S what you need when you go in search of the world's largest and fiercest cave animal: a hard hat, wellies, a torch, a bottle of schnapps and a lot of patience.

One thing you don't need is anything to defend yourself with. The world's largest and fiercest cave animal is neither very large nor very fierce. Growing to about 25 centimetres long, it is pale, slender and clammy with short, feeble legs, much like a real-life Gollum. It is also virtually blind. So you are more likely die of boredom or cold than come under attack. But what it lacks in ferocity, it makes up for in strangeness.

I have come to Postojna in Slovenia in search of the olm, *Proteus anguinus* – a rare white salamander that ekes out a slow, silent and very long life in the caves of the western Balkans. Known locally as *človeška ribica*, or "human fish", because of their pinkish skin and aquatic lifestyle, olms were once only known from specimens washed out of caves by flooding; legend had it they were baby dragons. Now they are Slovenia's national animal. When the country became independent after centuries of French, Austro-Hungarian, Italian, German and Yugoslavian rule, it gave olms pride of place on its coins.

Postojna looks like the sort of nondescript town you would pass through on the way to somewhere more interesting. But beneath the surface it is breathtakingly beautiful. It sits on the edge of the Dinaric karst, a landscape of limestone and dolomite covering much of the former Yugoslavia. Karsts are made of porous, soluble rock and are famous for their spectacular cave systems, carved over millions of years by underground rivers and embellished by the steady drip, drip, drip of water percolating through the rocks above.

Slovenia has something like 10,000 karst caves, but the one at Postojna is the largest. It has been a tourist magnet for 200 years, with around 5 kilometres open to the public. But behind the scenes there's a lot more – around 24 kilometres in total, much of it still unexplored. A 3.5-kilometre section was discovered earlier this year. These quiet, largely unlit sections are the lair of the olm.

Foot-long megafauna

Our guide takes us through a little-used back entrance at the bottom of a deep sinkhole in the forest. Thus begins a 5-hour trek through some of the most spectacular subterranean scenery in the world, a glorious parade of cathedral-sized caverns and narrow passages festooned with stalactites, stalagmites and flowstones. There are also networks of tunnels blasted by the Italian army between the wars, when the cave passed under the border between fascist Italy and the Kingdom of Yugoslavia. Mussolini visited the cave system in the 1930s and was presumably impressed by its extremely punctual underground railway.

Geology and history aside, we are on the lookout for olms, though chances are slim. Accustomed to darkness and silence, they are spooked by light and noise, and vanish when people approach.

For hours, the only living things we see are bacterial colonies on the walls and the odd cave cricket. Then we try our luck in a low-ceilinged side tunnel that is too young to have accumulated any large stalactites. The mud is knee-deep, the air dank and cold. We pause and drink schnapps, for luck and warmth, and then slowly and quietly approach a shallow pool known to be an olm hangout.

You don't tend to think of small, pallid salamanders as charismatic megafauna,

but in cave terms that is exactly what they are. In this ecosystem they are the apex predator, devouring the equally pale and blind crustaceans that share the darkness with them. There's only one thing that eats olms – other olms (and occasional river fish that get lost in the cave after floods). The males are ferociously territorial.

Nonetheless, life down here is far from action-packed. With no sunlight to fuel photosynthesis the cave ecosystem is extremely low-energy; the only input is organic matter leaching in from the outside world, plus the meagre contribution of bacteria that get their energy by breaking down inorganic molecules. Olms have evolved to go long periods without food – in captivity they are fed just three tiny cave shrimps a day, and can survive quite happily for 12 years without eating anything at all.

The near-starvation diet, cold environment and low metabolic rate may go some way to explaining the olm's extraordinary longevity: they are estimated to live about 80 years on average and may get past 100, a remarkable innings for such a small animal. Olms have long been of interest to gerontologists keen to discover the secrets of eternal youth.

They are biological curios for other reasons, too. Their eyes are vestigial and they lack pigmentation, both classic adaptations to cave life. They are neotenous, meaning they don't metamorphose into an adult form, retaining juvenile characteristics including external gills and the ability to regenerate their limbs and tails (early experiments trying to force them to grow up failed). Unlike most other salamanders, they are entirely aquatic.

Their ecosystem is also remarkable, the Amazon of the energy-starved underworld. "We have the richest underground biodiversity in the world," says Tadej Slabe, head of the Karst Research Institute in Postojna. That includes crickets, spiders, pseudoscorpions, snails, millipedes and beetles. Among those are the slender necked beetle, the discovery of which in 1831 kick-started the study of cave-dwelling creatures, known as speleobiology, and *Anophthalmus hitleri*, discovered in 1933 and named after Hitler (fascist connections are never far away in this part of the world). All are true troglobites, which means they are unable to survive outside the caves.

Olms have been studied for the best part of a century, but there is much that remains unknown. They are presumed endangered thanks to their rarity and the presence of threats such as pollution and groundwater extraction, and they are protected. But assessing their numbers is challenging. The standard tool for estimating population size, capture-mark-recapture, is not much use: if you mark an olm by making a nick in its tail or cutting off a toe, the method typically used for amphibians, it just grows back.

So biologists at the Tular Cave Laboratory – another Slovenian karst cave, and a speleobiology lab since 1960 – are pioneering a new technique. Like many aquatic animals, olms leave traces of DNA in the water which can be collected and amplified, revealing their presence and allowing scientists to estimate their numbers even if the ghostly creatures are nowhere to be seen.

Environmental DNA will also help determine whether olms are a single species, or many. The members of one population, discovered in a cave in south-eastern Slovenia in 1986, have black skin and functioning eyes. They are classed as a subspecies but may deserve separate status, which could also be true of other isolated populations. Early results suggest that there could be at least three species of olm, each perhaps numbering no more than a few thousand individuals.

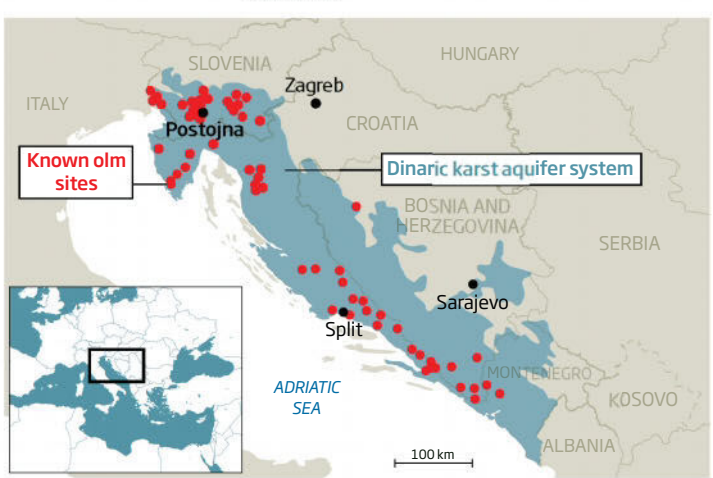
Postojna cave may be home to as few as 200 olms, which makes our mission seem even more quixotic. But at the end of our squelchy slog we are rewarded with a rare glimpse of three of them. They glide sinuously through the water in front of us before swimming away to escape the glare of our torches. Out comes the schnapps, this time in celebration, and we turn back towards warmth and light, leaving the darkness to the creatures that own it. ■

BLICKWINKEL/ALAMY STOCK PHOTO

Lounging in their frigid lairs, olms can go years without eating so much as a cave shrimp

Olm on the range

Deep in the underground caverns of the western Balkans lives Europe's only cave-adapted vertebrate – a bizarre salamander called the olm



JOEL SARTORE/NGC/GETTY IMAGES

Under the hood

Snakes have evolved in amazing ways, says **Bob Holmes**, and losing their legs was the least of them

SNAKE! Just the thought is enough to trigger a spasm of fear in many of us. Snakes make some biologists' hearts beat faster, too, but for a different reason: in evolutionary terms, they may be the most surprising group of vertebrates on Earth.

Their long, legless bodies, it turns out, are the least remarkable thing about them. It's on the inside that snakes have made extraordinary changes. They have pared down their internal organs, mostly eliminating one lung and all but one lobe of the liver. They have evolved a novel heat-detecting sense organ and the most sophisticated venom system of any animal, and they can turn their metabolism up and down more dramatically than any other vertebrate. This re-engineering even extends to the molecular level – proteins that have remained unchanged across other vertebrates have been rebuilt in snakes.

"It looks like evolutionarily, snakes are a kind of redesigned organism," says Stephen Mackessy, who studies snakes at the University of Northern Colorado in Greeley. And with the help of the first two snake genomes to be sequenced, we are beginning to piece together their remarkable evolutionary journey.

The story of how snakes evolved begins just over 100 million years ago, with a lizard or lizard-like reptile. Biologists are still debating exactly which group the ancestor of snakes belonged to. A few think snakes are descended from the marine reptiles known as mosasaurs, but they are in the minority. "I think the great bulk of the evidence points to a terrestrial origin for snakes, and even a burrowing or secretive origin," says Harry Greene, an evolutionary biologist at Cornell University in

The success of snakes is due to some remarkable internal re-engineering

Ithaca, New York. In 2015, a team announced they had discovered a strange fossil which they said was a burrowing four-legged snake, but not everyone agrees.

The mainstream view is that proto-snakes belonged to a group whose living representatives include the monitor lizards and Gila monsters. So why did some members of this group lose their legs and elongate their bodies? Most likely it was to chase insects through subterranean burrows or tangles of grass. Indeed, the most primitive snakes found today – a group called the blind snakes because of their vestigial eyes – still live underground feeding on ants and termites, supporting the notion that the earliest snakes might have been burrowers.

"The difference in metabolism between a live snake and a dead snake is minimal"

Acquiring a snake-like body involved surprisingly few mutations. The "grow limbs here" genes are still active in snake embryos, says Michael Richardson, a developmental biologist at Leiden University in the Netherlands, but the cells in these areas just ignore the signal, so no legs form. Snakes get their long bodies by budding off vertebrae at an unusually fast rate as embryos, so that they end up with many more than other animals – over 500 in some species.

In fact, it appears to be really easy for lizards to evolve a snake-like body, as it has happened on numerous occasions. "There are dozens of lizard lineages that have lost their limbs, " says Michael Lee, an evolutionary biologist at the South Australian Museum in Adelaide. Most, however, are small burrowers, seldom seen and little studied.

Extraordinary abilities

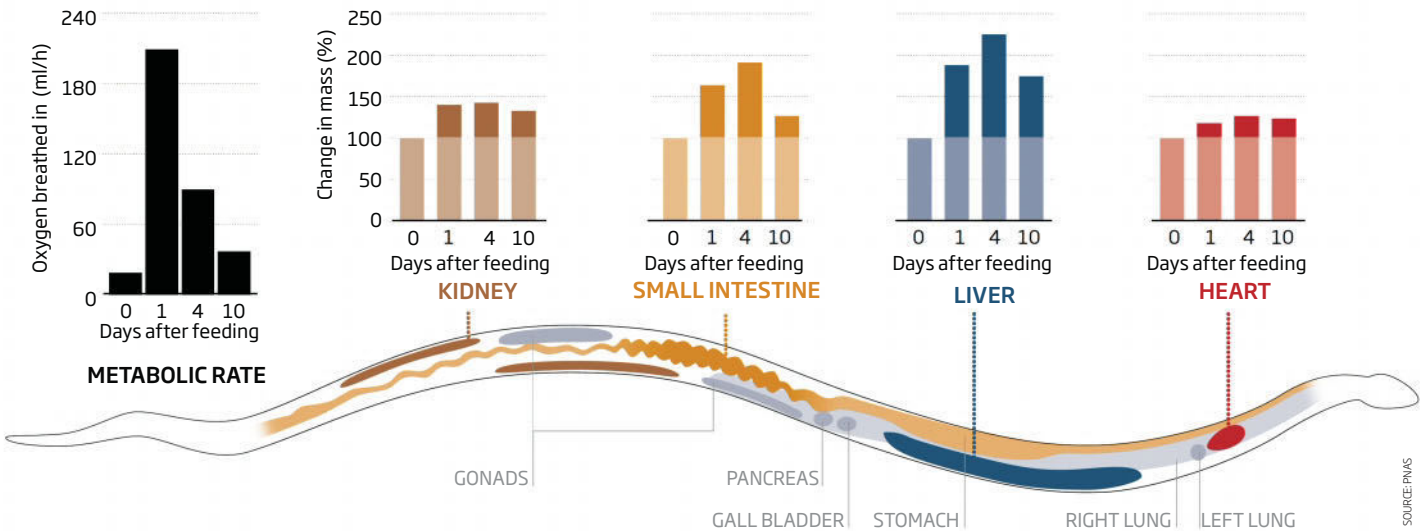
The ancestors of snakes, by contrast, slithered back above ground and started to hunt larger prey, eventually giving rise to fearsome predators such as rattlesnakes and cobras. There are around 3400 species of snake today, found everywhere except in the coldest polar regions. Some have colonised tropical seas, and never touch dry land. Others, like boas and pythons, have grown very large – although even the biggest snakes living today are small compared with Titanoboa, an extinct snake that grew to more than 10 metres in length and weighed over a tonne. No other group of legless lizards is as diverse and widespread. "None of them are as successful as snakes," Lee says.

What makes snakes special, then, are the less obvious changes that occurred after their ancestors lost their legs. In particular, snakes have some extraordinary metabolic abilities. These started to evolve very early on; blind snakes – which branched off early in snake evolution – show extensive changes to their mitochondrial genes that may have allowed proto-snakes to burn less energy by turning down their metabolism.

This paved the way for the very effective strategy early snakes adopted as they moved back above ground: eating occasional big meals rather than lots of little ones. As a ›

After the blowout

A huge meal leads to massive changes in snakes: their metabolic rate soars, and some internal organs increase greatly in size



result, snakes don't have to spend all their time hunting – when they are vulnerable to being preyed upon themselves – and can cope with times when food is scarce.

For an animal that swallows its prey whole, though, eating large meals is a challenge. Their remarkable ability to swallow prey much larger than their heads required extensive changes. The skin around their mouth is unusually folded, for instance, allowing it to expand much further than that of most animals, says David Cundall of Lehigh University in Pennsylvania. And his studies show that some muscles in the jaws can stretch so much that the interlocking actin and myosin proteins are ripped apart from one another, then gradually return to their normal positions after feeding.

The metabolic adaptations of snakes are even more dramatic. Between meals, for instance, the Burmese python goes into almost complete shutdown, reducing its resting metabolic rate to the lowest level known in any vertebrate. "When snakes are idling, the idle is extremely slow," says Todd Castoe of the University of Texas at Arlington. "The difference in metabolism between a live snake and a dead snake is minimal." This means large snakes can go many months without a meal.

Metabolic marvels

When, say, a python swallows an antelope, though, everything changes. Now the race is on to digest the huge meal. Within days of feeding, a python's small intestine and liver double in mass and its kidneys and heart also increase greatly in size, while its metabolic rate increases up to 45-fold (see diagram, above). That's about the same metabolic ramp-up as seen in a racehorse sprinting in the Kentucky Derby, says Castoe. "But that's running flat out across the field. When snakes are at their peak, they are motionless."

This frantic activity continues for several days. Within two weeks, its meal fully digested, the snake shuts everything down again.

What made these metabolic feats possible? Castoe is a member of the team that completed the first two snake genome sequences in 2013, belonging to the Burmese python and the king cobra. By comparing these genomes with those of other vertebrates, they were able to work out which genes had changed and when, and look for the fingerprints of natural selection.

What they found was astonishing. Of 7442 genes common to all land vertebrates, 772 had changed as a result of natural selection. And the vast majority of those changes – 516 of them – were present in both species, meaning they occurred more than 80 million years ago, before pythons branched off from the lineage leading to cobras.

Changes to a few hundred genes might not seem much, but it is an extraordinary number given that most genes are involved in basic processes that vary little from species to species. "It's somewhere around an order of magnitude more than we're used to," says Castoe. He thinks that these extensive changes are what allow snakes to ramp their metabolism and their organs up and down as required. Many of the genes concerned are indeed involved in metabolism and organ development.

A few years ago, Castoe found that snakes had even tinkered with one of the

SEEING THROUGH CLOSED EYES

Even as the first snakes were gaining some extraordinary abilities, they lost others. During the millions of years that the small, burrowing proto-snakes lived underground, their eyelids fused shut and their eyes degenerated. When early snakes moved back above ground, they had to cobble together working eyes from what was left. They had lost a special structure for nourishing the retina, so they evolved blood vessels to replace it - but these pass in front of the retina, obscuring vision.

Proto-snakes also lost the ability to focus images by changing the shape of the lens. Their descendants instead evolved a way of focusing by moving the lens back and forth within the eyeball, much as Sherlock Holmes moves his magnifying lens to focus on a clue.

The fused eyelids - called spectacles - have remained firmly shut to this day. Instead, they have become almost completely transparent. With no proper eyelids the spectacles are easily scratched, but they are renewed when the skin is shed.

Another problem is that there are blood vessels running through the spectacles. in 2013 it was shown that these blood vessels constrict for longer than normal when snakes see something threatening, presumably to give the animals clear vision when it is most needed.

While snakes' eyesight is probably not as good as it might otherwise have been, their other senses are highly developed. Some can even "see" in the infrared thanks to special heat-sensing pits on their faces.

"untouchables" of evolution: a protein called cytochrome oxidase I, which enables cells to "burn" food to produce energy. "It's the reason you breathe oxygen," says Castoe. Parts of this protein have remain unchanged in most organisms for a billion years, yet snakes have altered these key parts. Castoe has not yet shown whether these changes contribute to snakes' metabolic superpowers, but he thinks it is very likely.

Of course, being able to speed up your metabolism to cope with huge meals is one thing; catching those meals in the first place is quite another. One branch of the snake family evolved a very effective way to deal with large prey: venom.

It's not clear exactly when venom first evolved. Based on similarities between venom proteins, Bryan Fry of the University of Queensland in Brisbane, Australia, has suggested that the ability to make venom evolved around 200 million years ago in a lizard ancestor of snakes and modern venomous lizards. If so, early snakes may have had venomous saliva, which could enter their victims' blood through the puncture holes made by ordinary teeth. Other biologists, however, think the protein similarities Fry found may be the result of convergent evolution rather than a common origin, and that venom has evolved separately on several occasions.

What's clear is that the sophisticated fangs found in most venomous snakes today evolved some time after 80 million years ago, which is when the non-venomous boas and pythons branched off from the ancestor of vipers, cobras and other venomous snakes. This ancestor evolved rear fangs with grooves along which venom could flow. In some snakes these fangs moved forward in the mouth and the grooves deepened, eventually giving rise

"Snake venom can be a fantastically complex mix of more than 100 toxins"

to hollow teeth resembling hypodermic needles, along with a muscular system for pumping venom through them.

Freek Vonk, an evolutionary biologist at the Naturalis Biodiversity Centre in Leiden, the Netherlands, and his colleagues have been studying snakes' venom as well as their fangs. They identified venom genes in the cobra, then looked to see which genes were most closely related in the Burmese python and the anole lizard. To their surprise, they found that the cobra seems to have assembled its venom bomb from ordinary household materials: most of the 20 families of genes that code for toxins are related to genes that perform day-to-day housekeeping functions within cells.

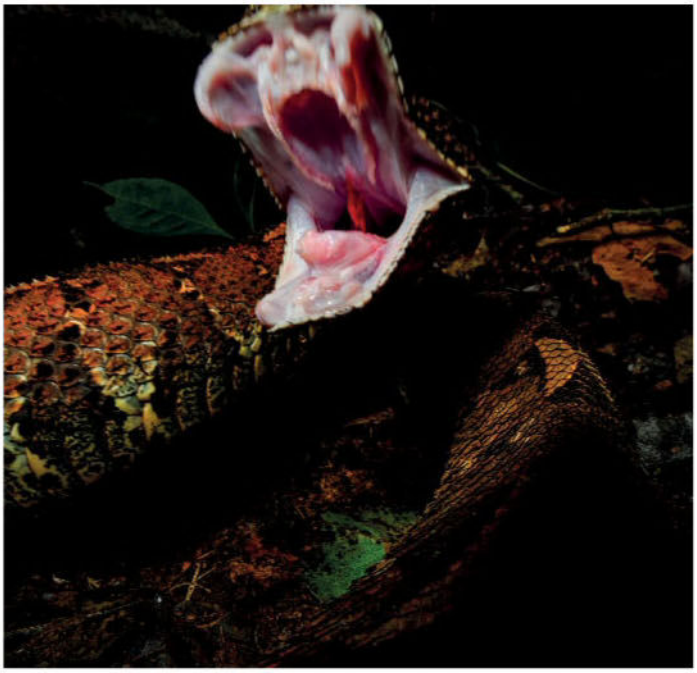
These day-to-day genes also tend to be active at low levels in all tissues. "That means when you make a new gland, the odds are good that the gene will be expressed there," says Castoe, who was also part of the team. Sometimes snakes simply hijacked the gene, converting it to a new, venomous function. More often, though, the original gene was duplicated, often many times, giving snakes lots of spare proteins to experiment with and turn into deadly toxins.

The result is that the venom of most advanced snakes is a fantastically complex mix of toxins – more than 100, by some counts – that varies depending on species, locality and sometimes even between individuals of the same species. All this diversity helps snakes keep ahead in the evolutionary arms race: if snakes had just a single toxin, it would be easier for their prey (and predators) to evolve resistance.

Not every component of venom is there primarily to kill prey or defend against predators, though. Many snakes, especially rattlesnakes, have venoms rich in toxins that break down the tissues of bitten animals. This helps rattlesnakes, which eat unusually large prey, win the race between digestion and rot, says Mackessy. In addition, Mackessy recently discovered that one component of rattlesnake venom, a toxin called crotatroxin that inhibits blood clotting, also serves as a scent trail that helps the snake locate bitten animals after they die.

All this is only the beginning. Castoe, Vonk and their colleagues are already working to sequence more snake genomes. At the top of their list are a blind snake – of interest because of its resemblance to early snakes – and the Malayan pit viper, with its infrared sense (see "Seeing through closed eyes", left). These two genomes should cast further light on the origin and evolution of the many adaptations that make snakes such unusual and fascinating organisms. "The potential for unlocking the secrets of snake biology is just huge," says Green. ■

MATTIAS KLUM/NATIONAL GEOGRAPHIC CREATIVE



Deadly venom is very useful when hunting prey

ONE ANTIVENOM TO CURE THEM ALL

If you get bitten by a venomous snake, a dose of antivenom containing antibodies that neutralise the toxins could save your life. But which antivenom will work? Many snakebite victims don't know which snake bit them, so drug companies produce cocktails of antivenoms that work against several species. This is expensive, however, and increases the chance of an allergic reaction.

Nicholas Casewell and his colleagues at the Liverpool School of Tropical Medicine in the UK think there is a better way. They are using genetics to identify regions of venom proteins that are the same in different snake species. They then design antibodies to bind to these regions, meaning each antibody should be effective against the bite of several snake species. The ultimate result should be cheaper and safer antivenoms.

The life and work of Alan Turing

Alan Turing is arguably one of the greatest scientists of the modern age. Join us as we explore his life, work and greatest achievements and learn more about this fascinating figure in 20th century science

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STUDENT DAYS
Cambridge

Visit King's College where Turing studied mathematics and went on to lay the theoretical foundations for modern computers. Marvel at the chapel's famous Gothic architecture and medieval stained glass. Our guided tour of the city includes the American Cambridge cemetery and the Eagle pub, where Francis Crick first announced that he and James Watson had discovered DNA. After dinner, enjoy a talk by intelligence expert Mark Baldwin and a demonstration of a rare four-wheel Enigma machine.

CODE BREAKERS
Bletchley Park

Soak up the atmosphere of the huts where Enigma messages sent by the Germany military were decrypted. Visit Turing's office to see how it would have looked during the second world war. Discover the ingenious mathematical techniques and devices that Turing and his colleagues designed to crack the Enigma code. At the nearby National Museum of Computing, see a rebuild of Colossus the world's first electronic computer. Reminisce over the museum's collection of home computers from the 1970s and 1980s.

TORTURED GENIUS
Manchester

After the war, Turing became deputy director of the computing laboratory at the University of Manchester. Here he worked on software for one of the earliest computers, the Manchester Ferranti Mark 1 and conducted pioneering work into artificial intelligence. He also turned his attention to pattern formation in biology, though his life was cut short in 1954. Our guided tour of Manchester takes in key locations associated with Turing, from the university and Museum of Science and Industry to the old cinema where a liaison led to tragic consequences.

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TRAVEL EDITIONS

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Not all turtles abandon their young to their fates. **Adrian Barnett** investigates reports of a motherly nature

I'm coming, mom

EMPEROR penguins endure months of subzero temperatures without eating, all to incubate their eggs. Wolf spiders carry their offspring – hundreds of them – around after they hatch. Poison dart frogs carry each of their tadpoles to its own little pond and return to feed it every few days.

Octopuses go even further, making the ultimate sacrifice for their offspring. After females lay their eggs, they spend the next month or two looking after them, cleaning them and fending off predators. By the time the eggs hatch, the mothers are so exhausted that they usually die or succumb to predators.

Not all parents in the animal world are so devoted. Among reptiles, especially, "lay and go away" is the norm. But have we been misjudging these animals? Out of South America have come the first hints that some turtles look after their young.

Canoe quietly along an Amazonian river at low water, and on rocks and logs you might see the smooth dark-grey shells of basking arrau river turtles (*Podocnemis expansa*), also known as giant Amazon river turtles. In favoured spots, where space is tight, they stack themselves like plates on a drying rack, forming a slanted series of shelly sun-worshippers. As one of their names suggests, they are the largest turtles in the Amazon. The shells of females can be nearly a metre long, and individuals can weigh up to 45 kilograms.

Female arrau turtles lay eggs during the dry season, when the low water exposes banks of sand for a few months. The turtles were once so numerous that Victorian naturalist Henry Walter Bates estimated that 400,000 clutches – each consisting of 100 or so eggs – were pulped annually for their oil. Even more were dug up to be eaten. It's no surprise that arrau turtle populations collapsed.

CLAUS MEYER/MINDEN PICTURES/NGS

Out in the river, this hatchling's mother may be calling for him or her

It was while digging up eggs to protect them from people and predators that turtle biologist Camila Ferrara, of the National Institute for Amazonian Research (INPA) in Manaus, Brazil, got thinking. Adult turtles make sounds, so could hatchlings do so too? If they do, it could explain some puzzling observations. For instance, it has been shown that eggs from a clutch all hatch at the same time, even if some are incubated at different temperatures, but ›

HOW THE TURTLE GOT ITS SHELL – AND LEARNED TO HIDE IN IT

The protective shell of turtles, terrapins and tortoises is unique. No other vertebrates have anything like it. But how did it evolve?

For more than a century, the earliest known ancestor of this group of animals was the 210-million-year-old *Proganochelys*, and it answered few questions because it looked remarkably like a modern turtle. It had already evolved a complete shell, although it still had some primitive features such as a few small teeth rather than the horny beak found in modern turtles and tortoises.

Then, in 2008, a spectacular "missing link" was uncovered in China. The 220-million-year-old *Odontochelys* was a lizard-shaped creature that had evolved the bottom half of the shell – the plastron – but not the top half. However, it did show signs of the development of a carapace, in the form of broad flattened ribs and some bony plates in the skin. It also had a full set of teeth. *Odontochelys* is thought to have lived in shallow seas, so the plastron probably evolved to protect against attacks from below.

For the half-shell of *Odontochelys* to evolve into the complete shell of *Proganochelys* just 10 million years later, a pretty spectacular piece of internal rearranging had to take place. The shoulder blades moved from being outside the ribcage to inside it, allowing turtles to move with a leverage that would be hard to obtain if this muscle-anchoring plate was fused to the bony carapace. Studies of turtle embryos have revealed how this probably happened, with a fold in the body wall early in development preventing the uppermost ribs from forming at the same time as the others, and pulling the shoulder blades through the resulting gap into the ribcage.

Proganochelys had a formidable shell, but the best it could do when feeling threatened was simply fold its neck sideways. This offered some protection under the shell's lip, true, but still left it vulnerable to a persistent predator. Some of its descendants, the pleurodirans, still fold their necks sideways. This group includes arrau turtles (see main story) and their extinct relatives *Carbonemys* and *Stupendemys*. These South American turtles lived around 80 million years ago, and at 2 metres long were the largest-ever freshwater turtles.

Around 190 to 150 million years ago, however, a different lineage evolved some rather kinky neck vertebrae that allowed them to bend their neck in an S-shape and thus retract their head completely inside their shell. These S-benders, or cryptodirans, were more successful than the side-necks and gave rise to most living members of the group today, from Galapagos tortoises to leatherback turtles.

ANDREW ALVAREZ/GETTY

no one knew how the baby turtles coordinate their emergence. Might they talk to each before they hatch, Ferrara wondered?

This opened up another possibility, too. Radio-tracking studies by Richard C. Vogt, a veteran biologist, also at INPA, who wrote the book on Amazon turtles, show that females often hang around in the water near their nesting beaches around the time the eggs hatch. What if the turtlets also talked to mum?

This, after all, is what caimans and other members of the crocodile family do. The females guard their eggs, waiting for a specific call from their offspring. When they hear it, they carry the hatchlings to water in their jaws and continue looking after them there, responding to distress calls and sometimes moving the young to a new nursery. Male crocs have sometimes been seen helping too.

The only member of the turtle order known to show any form of parental care is the yellow mud turtle (*Kinosternon flavescens*), and its efforts are not exactly spectacular. Females simply stay by their newly laid eggs for a few days, occasionally urinating on them if the weather is dry.

So Ferrara, aided by Vogt and another INPA colleague, Renata Sousa-Lima, set out to see if arrau turtles went further. The team's three-year study included putting microphones near captive and wild adults and hatchlings. The results surprised everyone. In 308 hours, Ferrera recorded 2128 calls of 11 distinct kinds. Some were short pulses, others single calls, with frequencies that varied from 36.8 to 4500 hertz. Excitingly, some were the short and high-frequency vocalisations that the biologists recognised as characteristic of animal contact calls.

Baby turtles started making noises around a day before hatching. When the team released hatchlings into the wild close to females, the females appeared to respond to their calls and approached them. Similarly, when an adult female was put into a tank with recent hatchlings, the hatchlings made calls not heard under other circumstances and actually climbed onto her. When she swam, the hatchlings swam beneath her.

This co-swimming happens in the wild, too. By attaching radio transmitters to females, the researchers found that they leave

PETE OXFORD/CORBIS

Collecting eggs for safekeeping may deprive baby arrau turtles of motherly care

"The hatchlings swim with females. We think the females are guiding them to safe feeding sites"

the vicinity of nesting beaches only after the eggs have hatched and the hatchlings have entered the water. What's more, the hatchlings swim away with them.

Hatchlings with radio transmitters have been found swimming with adults several kilometres from the nest site. Most couldn't be relocated after the first sighting, either because the transmitter failed or because they were eaten, but one remained with a group of adults for at least 10 days. "We think the females are guiding young to safe feeding sites," says Vogt.

CLAUS MEYER/MINDEN/NGS

All this suggests that female arrau turtles do care for their young after they hatch, which is extremely rare in reptiles. Although a few snakes and lizards look after their eggs, crocodiles are the only reptiles known to care for the hatchlings as well. "The study revolutionises how we look at these turtles," says Ferrara. "They show social behaviour, including complex parental care, which was previously totally unknown in turtles."

But there is something odd about the turtles' case. Crocodiles nest alone and can be sure the hatchlings they care for are their own, but turtles nest en masse and the females don't appear to discriminate between their own offspring and those of others. Why should this be? Vogt thinks he has the answer. "Beaches are used by generations of females," he says. "Hatchlings and females may be close relatives."

So what do other turtle biologists make of all this? "That adult *Podocnemis* care for hatchlings is truly news," says Gerald Kuchling of the University of Western Australia in Crawley. "Until this study, we thought hatchlings were on their own, and navigated alone to the specific habitat where they can grow up." Yet although the study proves that adults and hatchlings interact after the young reach the river, Kuchling isn't sure whether this can really be called parenting.

Whatever you call it, the discovery is of more than academic interest, because of the practice of collecting newly laid eggs and incubating them elsewhere to protect them from people and predators. The hatchlings are often released far from the capture site to try to establish new breeding populations. But such actions could be depriving the young of adult assistance. "Instead of reducing hatchling mortality, well-intentioned conservationists may actually be increasing it," Vogt says.

It wouldn't be the first time. In the 1970s, Vogt found that turtles' sex-determination is temperature dependent. By keeping eggs in controlled environments, some conservation programmes inadvertently raised batches with highly skewed sex ratios. "One programme spent 20 years releasing nearly all males," recalls Vogt, who is convinced that breaking mother-hatchling vocal bonds could also harm conservation efforts.

That makes it important to find out if other species behave this way towards their young. Kuchling thinks such behaviour may well occur in other river turtles, especially in species that nest communally on sandbanks like arrau turtles. This could include some critically endangered turtle species in Asia.

Vogt thinks even some sea turtles could care for their young. His team has recorded calls in olive ridley sea turtles, both by hatchlings on the beach and by adults in the sea. "I think all turtles vocalise to some extent. This does not mean they have parental care, however," he says. "This remains to be studied."

Others are sceptical. T. Todd Jones of the Pacific Islands Fisheries Science Center in Hawaii thinks it very unlikely. Adult marine turtles swim a lot faster than their hatchlings, he points out, have different temperature requirements and often feed far from the nursery areas where hatchlings spend their early years.

Only further studies will settle the issue. But if many turtles do care for their young, some of the strategies intended to save them could be casting them alone and adrift from an early age. And what would a mother turtle have to say about that? ■

CHAPTER SIX

EXTREMES

Homeward bound

THE sand is still whipping through the air as the penguins come into view.

The Gentoo penguins emerge from the haze, their red-orange beaks and peachy feet flaring against the dreary beach of Sea Lion Island in the Falklands. The birds are hurrying home after a long day feeding at sea.

Penguins usually conjure up images of snow blizzards or ice sheets, but not these ones. The Gentoo penguins set up house on sandy or shingle beaches, with good open access to the sea.

Adults spend nearly the whole day hunting. Their diet consists mainly of krill or fish and occasionally squid. Awkward waddlers on land, these are the fastest birds underwater, swimming at speeds of up to 36 kilometres per hour.

"After a big sandstorm I was waiting near by the beach until afternoon when the penguins usually come back from their daily trip to the ocean to feed themselves," says photographer Michael Lohmann. He took this shot, *Returning from the Hunt*, after an assignment in the South Atlantic. The image bagged him the runner-up place in the bird category of the GDT Nature Photographer of the Year 2013 prize. Rebecca Summers

Photographer

Michael Lohmann
Gesellschaft Deutscher Tierfotografen

LIVING ON THE EDGE

Very few places on Earth are completely lifeless. No matter how extreme the conditions, there is almost always something that has evolved to exploit them.

Even though ice rips apart cell membranes and heat destroys cell machinery, extremes of temperature are no barrier to life. Some creatures even freeze completely and live to tell the tale. Other organisms can survive without water for decades, turning their cells to solid sugar, or live at enormous pressures that kill everything else.

Join **Caroline Williams** as she takes a tour of some of the toughest life forms on Earth, including some that defy death itself

FLIP NICKLIN/MINDEN PICTURES/FLPA

Frozen solid

Get below 5 °C, and enzymes, the biological catalysts that facilitate all of life's chemistry, work painfully slowly. Below freezing, matters get even worse. Ice crystals start to form in and around cells, sucking water out of them and cutting their membranes and contents to shreds.

Nevertheless, more than 80 per cent of the habitats on Earth are colder than 5 °C. And there is no shortage of species that can cope with the chill.

For once, microbes don't come out on top: they stop growing at around -15°C. More complex animals take this record, employing an array of tricks to survive the freeze.

Mammals and birds have a head start, as they generate their own heat as a by-product of metabolism. They also insulate their bodies with fur, blubber and, in the case of emperor penguins, by huddling en masse against the icy Antarctic winds that can bring the air temperature down to -60 °C.

Plenty of animals that lack their own internal heating can still survive such temperatures. Take the insect-like creatures called Arctic springtails (*Megaphorura arctica*). These lower the freezing point of their body fluids as winter approaches by synthesising antifreeze molecules and getting rid of anything that could act as a nucleation site for ice crystals to form around, such as gut contents and bacteria. They also manufacture cryoprotectants – sugars or glycols that protect cells from being damaged by the freezing process.

Some animals can even survive being frozen solid, including many insects, western painted turtle hatchlings (*Chrysemys picta bellii*) and several North American frogs, such as the wood frog, *Rana sylvatica*. These animals use

Polar cod have antifreeze in their blood

antifreeze to protect the body parts that matter most. In less crucial parts, such as their body cavity and the lenses of their eyes, they encourage controlled freezing by producing proteins that act as ice nucleation sites or encouraging the growth of ice-nucleating bacteria.

The woolly bear caterpillar, *Gynaephora groenlandica*, of Ellesmere Island, Canada, is an extreme example. It hibernates in temperatures of -70 °C, surviving by letting its gut contents, blood and any other extracellular liquid freeze. The Antarctic nematode, *Panagrolaimus davidii*, can go a step further, allowing freezing of its cells' cytoplasm – the liquid component – keeping only its cell nuclei and other organelles unfrozen. No one knows how they cope with this bizarre state, but they do synthesise a cryoprotectant that may smooth the edges of ice crystals, preventing damage.

Scalding hot

Heat is a major challenge for life. On land, too much heat means that water evaporates or boils away, and without water nothing can survive.

That is obviously not a problem under the sea. Temperatures can reach 400 °C in deep-sea hydrothermal vents, where water is heated by the Earth's interior. The upper temperature limit that organisms can endure becomes the point at which complex molecules, like DNA and proteins, start to break down; the surfeit of energy literally shakes apart their chemical bonds.

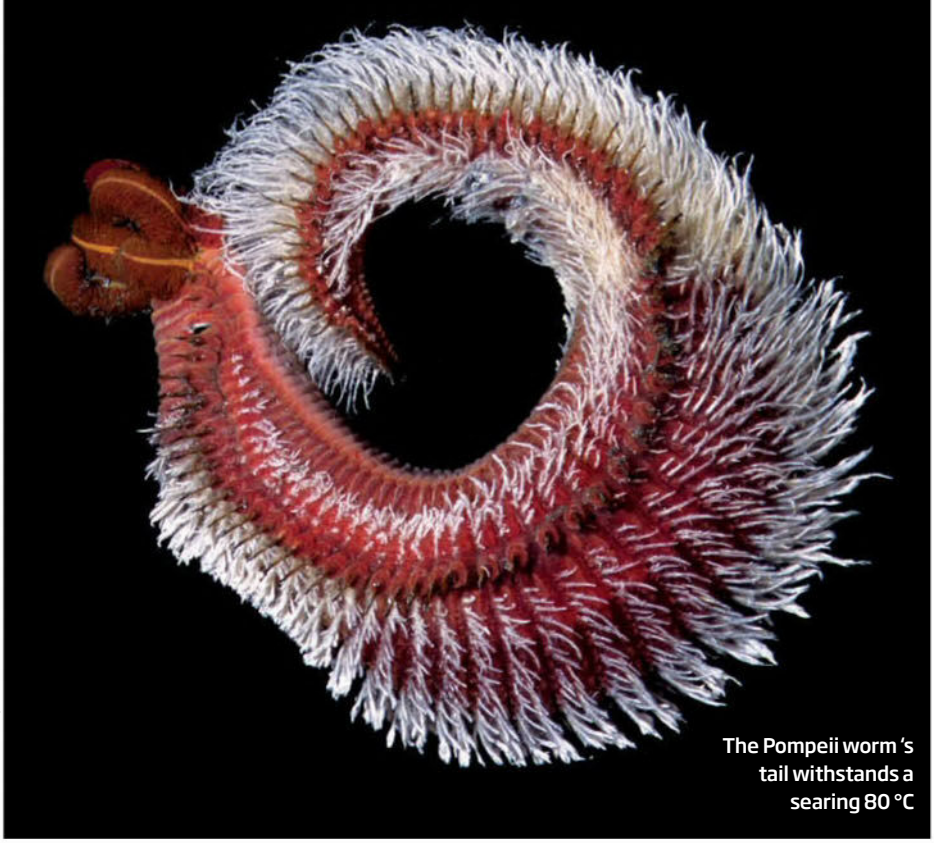
The hottest recorded temperature at which life has been able to grow is 121 °C. This record is held by a microbe called simply Strain 121, which normally lives at temperatures of around 100 °C in hydrothermal vents; it barely seemed to notice when it was heated to 121 °C in the lab, in 2003. Even at 130 °C the bacterium was still hanging in there, but it could not replicate until the temperature dropped.

Extreme "thermophiles" like Strain 121 have similar cellular chemistry to you and I. The difference is that their proteins and DNA are more tightly packed, so they can withstand more heat energy before unravelling. However, at temperatures over 100 °C, essential metabolites such as ATP break down in seconds. So the upper temperature limit on life is set by how quickly a cell can replace these chemicals.

Multicellular life finds it harder to stand the heat, although it is not really known why. Most such organisms hit problems above 40 °C, and no eukaryotes – organisms with a membrane-bound nucleus – live full-time above 60 °C, with one exception, kind of. The Pompeii worm, *Alvinella pompejana*, was discovered at hydrothermal vents off the coast of the Galapagos Islands in the 1980s. Unusually, their tails experience scalding water of up to 80 °C, as they are attached to the vent walls. The rest of their body is far enough away from the very hot water.

How the worms' tails cope is not understood, partly because the animals don't live very long in the lab. One factor may be their high level of collagen, a protein that is relatively stable at high temperatures. The hard tubes they build to live in and the symbiotic bacteria that grow in furry clumps on their bodies also offer some protection.

On land, the animal that can cope with the highest temperatures is a desert-dweller: the Saharan silver ant, *Cataglyphis bombycina*. This can withstand temperatures above 53 °C for a few minutes while foraging for other creatures that have perished in the midday sun. How do the ants escape heat exhaustion themselves? Before leaving the nest they stock up on heat shock proteins, which help other proteins keep their shape. While out they tend to climb up anything tall they find to cool off in the breeze, whether it be plants, or scientists there to observe them.



PETER BATSON/IMAGEQUESTMARINE.COM

The Pompeii worm 's tail withstands a searing 80 °C

The immortal jellyfish reverts to a juvenile stage when starved

STEFANO PIRAINO/BARCROFT MEDIA

Cheating death

Of all the limitations on Earth there is one that no life can escape: death. But some living things manage to outsmart their fate for longer than others.

For reasons that aren't well understood, animals rarely make it to their 100th birthday. But, as ever, there are exceptions. Besides sponges and coral colonies, which can live for thousands of years, the oldest living animal yet discovered is a clam (*Arctica islandica)* caught off the coast of Iceland. It was named Ming and sadly died when it was opened by researchers curious to find out more about it. According to Paul Butler, at Bangor University in the UK, Ming was 507 years old. Recently, a Greenland shark was estimated to be up to 512 years old – although it's probably closer to 400.

No one knows how clams like Ming manage to live such long lives. We do know that at some point in their lifespan, their death rate actually drops, making it unclear whether they experience ageing in the way we do.

Plants get around the ageing problem by allowing the cells in the oldest parts of the organism to die while continuing to produce new sections. The most extreme examples are so-called clonal trees, which reproduce by sprouting genetically identical colonies over vast areas, all sharing the same root system. A stand of clonal quaking aspens, *Populus tremuloides*, in Utah may be one of the oldest such examples. While the existing trees seem to be no more than 130 years old, parts of the roots have been dated to around 80,000 years old.

The oldest individual tree ever recorded was a bristlecone pine, or *Pinus longaeva*. Named Prometheus, it was around 5000 years old when it was felled in 1964. Again, though, the oldest parts of the tree were long dead, and the living part only tens or hundreds of years old.

Probably the oldest living things on the planet are bacteria found in the permafrost of Siberia, Canada and the Antarctic. These Actinobacteria are thought to have been alive for around 500,000 years. This could be because they have a very slow metabolism and super-efficient DNA-repair mechanisms that help them to cope with a serious lack of food while allowing them to live for a very, very long time.

But perhaps nothing can beat the "immortal jellyfish", *Turritopsis nutricula*, which can revert to an immature stage after becoming sexually mature and can go on ageing and "unageing" indefinitely – in theory. After all, there is nothing stopping it getting eaten before it reaches a ripe old age, and no way of measuring that age anyway.

"As the clams get older their death rate *drops*, so they may not even experience ageing as we know it"

Under pressure

Dip beneath the ocean and the pressure starts to rise, causing problems for anything adapted to living at the surface, like us.

The most obvious difficulty is that rising pressure puts the squeeze on the lungs and any other air spaces in the body. To combat the effects, diving mammals that reach depths of more than 1000 metres, such as elephant seals and sperm whales, allow their ribcage and lungs to collapse, squeezing the air out. So they can go longer without breathing, they have higher levels of oxygen-binding haemoglobin in their blood, plus more of a similar molecule called myoglobin in their muscles.

Still, at only a few hundred metres down, where pressure reaches a few tens of atmospheres, a whole host of other problems kick in. Nerves and heart muscle start to struggle as vital communication channels in the cell membranes are squeezed, and many proteins cannot fold into their correct three-dimensional shape properly, becoming physically deformed.

Yet the deep sea is full of life. Even the deepest parts of the ocean – with pressures up to 1000 times that at the surface – are buzzing with shrimp-like creatures called amphipods, as well as sea cucumbers, nematodes and other worms, and bacteria. Fish make it as far as 8730 metres down, just a couple of thousand metres shy of the deepest part of the ocean, although no one knows why they don't get any further.

To survive, these creatures have a number of clever cellular adaptations. Deep-sea organisms, from bacteria to fish, tend to have more flexible cell membranes, having replaced saturated fats with unsaturated versions. They use a compound called trimethylamine oxide to help proteins fold properly.

Once adapted, deep-sea creatures are as committed to a life in the depths as we are at the surface. Deep-sea crabs and amphipods suffer the same kinds of tremors and movement problems on the surface as we would under pressure, as their cell membranes become too flimsy for atmospheric pressure. Gas-filled spaces, such as fish swim bladders, will swell and burst as pressure is released on the way up. When it comes to pressure, the best plan is to stick to what you know.

General Sherman packs the largest trunk

JIM BRANDENBURG/MINDEN PICTURES/FLPA

Giant challenge

As any school child will tell you, the largest known animal now and in evolutionary history is the blue whale. At 30 metres long and weighing up to 190 tonnes, blue whales may be about as big as it is possible for this type of animal to get. Any larger and they would face overheating on exertion, with their metabolism generating heat faster than it could be dissipated through their surface area. The problem is compounded by their thick layer of blubber, essential for insulation when at rest.

While there might never be a larger animal than the blue whale, there are other kinds of organism that dwarf it. The largest of them all, dubbed the "humongous fungus", is a honey mushroom (*Armillaria ostoyae*). Although the exact size of the fungus is not known, it is currently munching its way through 965 hectares' worth of trees in Malheur National Forest in Oregon.

As for plants, the largest of the large today is General Sherman, a giant sequoia in Sequoia National Park, California, which has a trunk volume of around 1500 cubic metres. The tallest living tree is also found in California. Called Hyperion, this coast redwood clocks in at 115 metres. Only one tree has topped that, a fallen eucalyptus called the Robinson tree, found in Mount Baw Baw in Victoria, Australia, which was 143 metres high. Calculations suggest that this is near to the theoretical limit for tree height, set by the difficulty the top leaves have in drawing up water from the roots through capillary action.

The fat-tailed dwarf lemur sleeps through a drought

Drastically dry

Of all the limits on life, water is the least negotiable. All cells need water as a medium for their chemical reactions to take place in, and to keep their membranes intact.

For most animals, drying out means certain death. A few life forms, however, can survive by hunkering down and waiting for the rains to come. Tardigrades, rotifers, nematode worms and the larvae of some shrimps and one fly dry up, roll into a ball and sit out the drought. Most lichens and mosses, some fungi and bacteria, and hundreds of species of flowering plants also dry up and wait for conditions to improve, sometimes for years or decades.

All of these organisms survive drying by replacing water molecules in and around the cell with sugars, which maintain the cell's structure. As the sugar level in the cell increases it turns the cytoplasm from a liquid into a solid called sugar glass, freezing the cell in time.

It is a clever trick, but in the grand scheme of things, not a common one. Other methods of sitting it out are less drastic. For example, some toads and several species of frog, including the African bullfrog (*Pyxicephalus adspersus*), dig themselves into a hole, form a waterproof cocoon around their body leaving their nostrils free, and go into a state similar to hibernation until the rainy season comes. Countless other creatures, from snails to crocodiles, do something similar. Even a few mammals, including ground squirrels and one species of lemur, can sleep through the dry times.

For all these organisms, though, drying out and hiding are only temporary measures. Lack of water is the ultimate outer limit of life on Earth and, as most species have found, the best strategy is to avoid such areas in the first place. ■

"These animals replace water molecules with sugar, turning their cytoplasm into a solid called sugar glass"

DAVID HARING/DUPC/PHOTOLIBRARY

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New Scientist

Last march of the penguins

Emperor penguins rule Antarctica – but perhaps not for too much longer, reports **Alison George**

THE emperor penguin is an impossible bird. It breeds in the middle of winter in some of the coldest places on Earth, surviving temperatures as low as -50 °C and hurricane-force winds.

In March or April, just as the Antarctic winter begins, the birds waddle across the sea ice to their colonies, where they mate. After the egg is laid, the females head back to sea to feed, leaving the males behind to incubate it. By the time the females return in July or August, when the eggs hatch, the males will have spent almost four months huddling together in the bitter cold without eating, losing half of their body weight.

This extraordinary lifestyle has made the emperors famous. They have even been held up as role models by evangelical Christians. But these breathtaking birds will soon have to face the one thing they haven't evolved to cope with: warmth. Fast-forward a few decades, and many colonies will be on the road to extinction. Are we witnessing the last march of the emperor penguins?

Finding out what's going on with emperor penguins is a huge challenge as almost all of their colonies are exceedingly difficult to get to. In fact, it was only in 2012 that the first global census of the birds was published, based on an automated analysis of satellite images by the British Antarctic Survey. This revealed four previously unknown colonies, bringing the total to 46 (see map, far right), and put the number of adults at 600,000, nearly double earlier estimates. That might sound like good news, but saying whether the overall number of birds is rising or falling has been a nigh-on-impossible challenge. "It's simply that we now have a better method to find them – remote sensing," says team member Phil Trathan.

The most comprehensive insight into the highs and lows of emperor populations comes from just one colony, which happens to be next to the Dumont d'Urville research station on the Adélie coast of Antarctica. "After a snowstorm, [researchers] can see how many eggs have got frozen, and how many chicks have died," says biologist Stephanie Jenouvrier of the Woods Hole Oceanographic Institution in Massachusetts, who studies the birds. This

Most emperor penguins never set foot on dry land

relatively small colony of 2500 birds featured in the 2005 blockbuster documentary *March of the Penguins*.

The Dumont d'Urville emperor's have been closely monitored since 1962. During the 1970s and early 80s, the average winter temperature was -14.7 °C, compared with a more typical -17.3 °C. This "warm spell" reduced the extent of winter sea ice by around 11 per cent – and the penguin population by half. "When sea ice decreased, it caused strong mortality of emperor penguins," says Jenouvrier.

Why are emperors so sensitive to changes in sea ice? Well to start with, most never set foot on land. They aren't agile enough to scale the steep rocks and ice precipices that guard most of Antarctica's shoreline. All but two of the 46 colonies are on fast ice – sea ice stuck fast to the shore. So if the sea ice forms late or breaks up early, it won't last for the eight months or so these large birds need to breed and raise chicks.

"Early break-up of sea ice can cause catastrophic breeding failure," says Trathan. Emperors live around 20 years, so colonies can survive a few bad breeding seasons, but persistent changes can be disastrous.

What's more, emperors moult every year in January or February. The birds would freeze to death if they tried to swim during the 30 or so days it takes to grow new feathers, so they must find ice floes to shelter on that are large enough to survive this period. This may be an even more demanding period in the emperors' lives than the winter, because they have little time to fatten themselves up beforehand.

"The adults are reliant on stable sea ice for moulting, and for me, that's the greatest concern," says Gerald Kooyman of Scripps Institution of Oceanography, one of the world's leading emperor penguin biologists. "They don't have any options. They have to moult."

Last, but not least, the source of much of the penguins' energy, directly or indirectly, is krill – and krill also depend on sea ice. Young krill shelter and feed under it. "The sea ice is the basis of the Antarctic ecosystem," says Jenouvrier.

For now, there is still plenty of sea ice. In fact, the extent of Antarctic sea ice in winter has increased slightly over the last 30 years. This has been caused by stronger winds blowing sea ice further away from the land, with more ice forming in the open water exposed by this movement. The stronger winds are thought to be a consequence of ozone loss, rather than global warming.

> "The adults rely on stable sea ice for moulting, and for me that's the biggest concern. They have to moult"

INGO ARNDT/MINDEN PICTRES/NGS

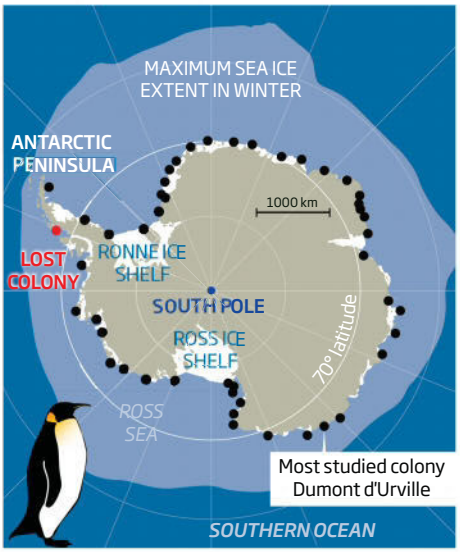
Lost colony

But unlike the Arctic Ocean, where thick sea ice used to survive from year to year, in Antarctica almost all the sea ice melts every year. That means the extent of winter sea ice changes rapidly in response to any change in conditions. This can be seen around the rapidly warming Antarctic Peninsula, where winter sea ice extent is falling 1 or 2 per cent each year. Here one small emperor colony, on the Dion Islands, has already died out. When it was discovered in 1948 it was home to 300 adults. By 1999, just 40 remained and 10 years later they were all gone. Though no one knows for sure what caused the colony's demise, it coincided with a decline in the duration of winter sea ice.

On the peninsula, populations of the other Antarctic native penguins, the Adélie and chinstrap, are also plummeting, probably because of the changing environment and declining krill. Matters haven't been helped by an invasion of non-native gentoo penguins, and other species like the king and macaroni penguins could follow.

Now you see them…

…but the 46 emperor penguin colonies that remain might not survive global warming



What's happening on the peninsula today could be happening all around Antarctica in the decades to come. "With a doubling of greenhouse gas concentrations over the next century, we estimate that the extent of Antarctic sea ice would decrease by about one third," says John Turner, a climatologist with the British Antarctic Survey.

In 2012, the emperor penguin was added to the IUCN's Red List for species threatened with extinction in the near future – "near" meaning in a century or two. When Jenouvrier's team used the observations at Dumont d'Urville to predict what will happen as the continent warms, they concluded that the colony is likely to decline by 81 per cent by 2100 and be heading towards extinction.

That is in line with a 2010 study by a team including Jenouvrier and David Ainley of the California-based ecological consultants H. T. Harvey and Associates. It predicted that all emperor colonies north of 70 degrees latitude – about 35 per cent of the total population – would decline or disappear if the world warms by 2 °C, although a few colonies south of 73 degrees might grow a little.

This might not sound too bad, but both these studies are based on what increasingly appear to be overly optimistic assumptions. If we continue as we are, the global temperature will climb above 2 °C before 2050, on course to a 5 or 6 °C rise by 2100. "If the earth warms by 5 or 6 degrees, I can't see that there's going to be much sea ice left anywhere on Earth," says Ainley. And if the sea ice vanishes, the emperor penguins will vanish too. ■

Ghosts of the Arctic

How does an animal the size of a domestic cat survive on the barren polar ice for months on end? **Garry Hamilton** investigates

SPRING 2008, and life seemed normal for one female Arctic fox living on Bylot Island in the far north of Canada. She had found a suitable den, teamed up with a mate, and together the pair had successfully raised a litter of 11 pups. Then, sometime around midsummer, a switch in her brain seemed to flip. She abandoned her home and headed north, off the island and onto the polar ice cap.

For most of the following winter she wandered the sea ice, enduring 24-hour darkness and temperatures that regularly dipped below -40 °C. As spring approached, she started moving south-west towards Baffin Island and eventually into a sweeping loop that took her more than 1000 kilometres in three weeks. She wasn't finished. In mid-May the miniature canine turned westward and covered another 1200 kilometres before eventually spending the summer traversing Somerset Island – a 25,000-square-kilometre

NORBERT ROSING/NATIONAL GEOGRAPHIC STOCK

Forget hibernating, migrating or holing up – Arctic foxes take winter on the chin

DMITRY DESHEVYKH/ALAMY

expanse of low-lying, barren rock. Within a year, her skinny legs had logged close to 5000 kilometres. Had she chosen to travel the same distance southwards, she could have been on a subtropical beach in southern Florida.

Polar explorers and scientist have long marvelled at the Arctic fox's formidable grit. These feisty little animals spurn the strategies to deal with winter used by other occupants of the far north. They don't hibernate. They don't migrate to more hospitable climes. They don't seek solace inside a den or under the snow. Instead they take the brutality of their frozen environment on the chin as they roam over a landscape with no permanent landmarks and often devoid of any signs of life. In this harsh environment, keeping track of the Arctic fox's wanderings is challenging, to say the least. Only recently, with advances in wildlife tracking technology, have we finally got an insight into these improbable journeys.

Seventeenth-century European seafarers searching for the North-West Passage through the Canadian Arctic were among the first to be struck by this astonishing lifestyle. These explorers frequently spent the winter aboard their vessels, locked in the sea ice, but no matter how far from land they were, they would find the fluffy white scavengers emerging from the ice fog like ghosts. The ability of these animals to navigate their way around a sheet of ice the size of Europe was well known even back then. More than once, rescue teams looking for lost explorers from previous expeditions fitted Arctic foxes with collars engraved with coordinates of supply dumps, reasoning that if the survivors were out there, the foxes would come across them.

As adventurers pushed into ever more remote corners of the Arctic, the mystique surrounding the species continued to grow. During his failed attempt to reach the North Pole on foot in the spring of 1895, Norwegian explorer Fridtjof Nansen encountered several sets of fox footprints on the ice north of the 85th parallel, several hundred kilometres from the nearest dry land, the remote Russian archipelago known today as Franz Joseph Land. Baffled by the sightings, he concluded he must have been much closer to land than he had thought. But it took Nansen another three-and-a-half months of exhausting slog to reach solid ground.

> "They roam across a landscape with no permanent landmarks and devoid of any signs of life"

Truly foxed

"What in the world was that fox doing up here?" he wrote in his journal the morning after seeing the first set of tracks. "It is incomprehensible what these animals live on up here, but presumably they are able to snap up some crustacean in the open waterways. But why do they leave the coasts? That is what puzzles me most. Can they have gone astray? There seems little probability of that." Since Nansen's day, polar explorers have recorded similar experiences, including one sighting less than 60 kilometres from the pole.

Early attempts to solve some of these riddles only added to the mystery. Robert Garrott, now at Montana State University in Bozeman, was part of a team that spent several years during the 1970s trying to track the winter movements of Arctic foxes near Prudhoe bay in northern Alaska. They fitted the animals with numbered ear tags, released them, and then waited to see where they turned up. Some were recovered more than 2000 kilometres away, deep into the high Arctic, but this technique could only record the animals' destination, and revealed nothing about how they got there.

In a valiant effort to learn more, Garrott ›

and his colleagues decided to try out radio telemetry, the technology that had revolutionised wildlife tracking in the early 1960s. A radio collar fitted to the animal being studied transmits a signal that can be picked up by researchers on foot or in a plane, allowing them to follow their target wherever it goes. Early in the spring of 1979, the researchers ventured 32 kilometres onto the ice off the north shore of Alaska, pitching tents near where the current had swept floes free from the shore-anchored ice. After fitting a fox with a radio collar, they set out to follow it using two planes – one to track the fox and the second as a back-up in case the first was forced down on the drifting pack ice.

"Shivering was finally observed after the foxes had been exposed to -70 °C for an hour"

"It was a great adventure," says Garrott. "But we learned absolutely nothing. The place is simply too big and the foxes are too mobile. We would catch one and put a collar on it and then we would never hear the signal again. They just disappeared – gone outside the ability of the plane to keep track of them."

If Arctic foxes were proving elusive in the wild, at least some of their secrets were surrendering to lab-based studies. As far back as the late 1940s, Laurence Irving and Per Scholander, two pioneers in comparative physiology working at the US navy's Arctic Research Laboratory in Barrow, Alaska, attempted to measure the cold tolerance of different species, using the point at which shivering begins to indicate environmental stress. Arctic ground squirrels succumbed at 8 °C and polar bear cubs at 0 °C, but when the scientists came to test Arctic foxes, their equipment could not generate temperatures cold enough to register a result. They eventually had two of the hardy animals flown to a more sophisticated facility in Washington DC, where shivering was finally observed after they had been exposed to -70 °C for an hour.

There is no question that these creatures are built for life in the cold. Another early study revealed that their furry pelt has unrivalled insulation capabilities. And their physiology is tuned to the task of balancing energy loss and intake – a must for any warm-blooded animal trying to survive in a world where food to fuel the inner furnace is both essential all year round and in short supply. For example, the Arctic fox's veins and arteries run closer to each other than in most other animals of similar size, forming a heat exchanger that uses heat from arterial blood to warm the blood flowing back through the veins. This saves energy by maintaining the outer extremities at a lower temperature than the body's core.

Ready or not, Arctic morsel, here I come

STEVEN KAZLOWSKI/SCIENCE FACTION/GETTY

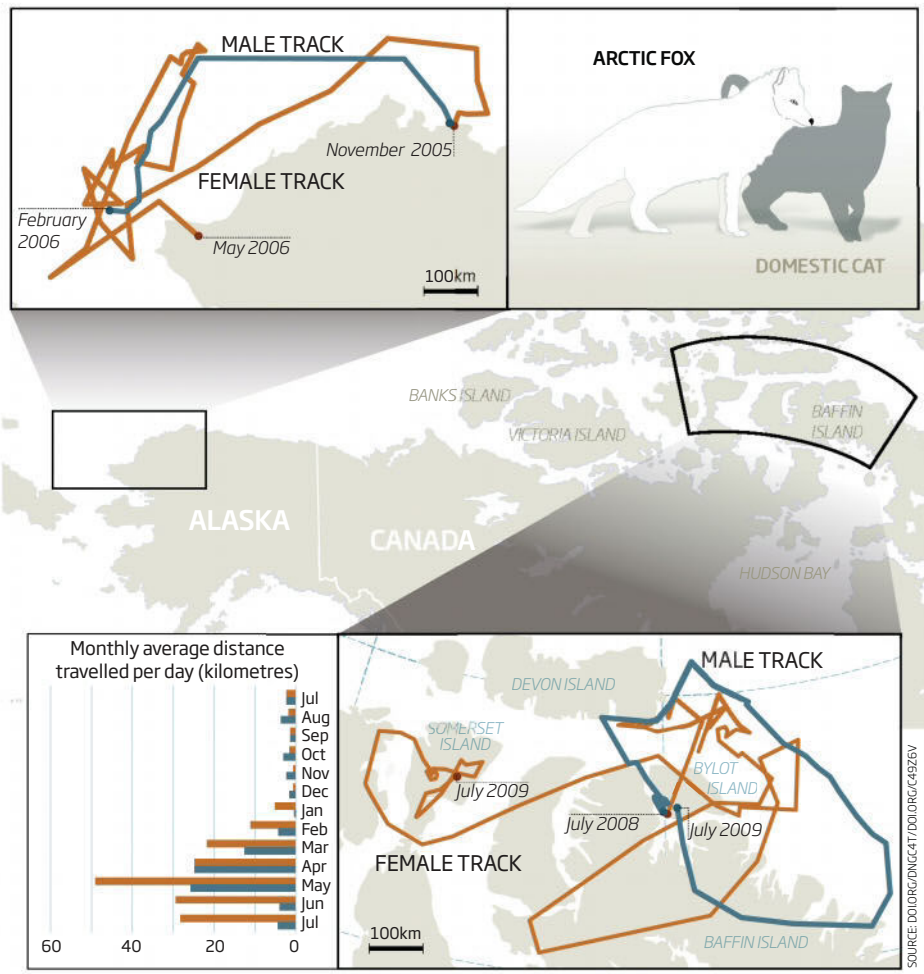
Why don't foxes' feet freeze?

Despite these specialist adaptations, the thought of an Arctic fox wandering around for months on end, under such harsh conditions, continues to raise many questions. What do they eat while they are out on the ice floes? Do they all undertake long-distance journeys? Are the journeys random, or do they follow some preordained pattern? If the latter, how do they find their way around an icescape that has no permanent landmarks, that drifts and spins at the mercy of the currents, melts and freezes according to the weather, and seemingly has little to offer in the way of a scent trail to follow for food?

Even the advent of satellite-based tracking in the early 1990s did not provide an immediate answer. The first collars, which required large batteries to keep them working for a year or more, were far too heavy for Arctic foxes. Lighter systems developed for birds draw power from a tiny solar cell – clearly not a solution in the round-the-clock darkness of an Arctic winter. Recently, the technology caught up, in the form of light, battery-powered collars tailored for the Arctic fox, including one equipped with an antenna laced with red pepper to discourage animals from gnawing it off. In 2010, a team from the University of Quebec at Rimouski published results of a satellite-tracking study of the Bylot Island foxes (see "Incredible journeys", lower part of diagram on page 115). This came hard on the heels of publication of a similar study by a team from the University of Alaska at Fairbanks, who followed foxes collared at two locations on the north shore of Alaska

Incredible journeys

Tracking technology has caught up with the Arctic fox, revealing that some individuals travel vast distances across the frozen landscape



(upper part of diagram, above).

The findings provided more evidence that Arctic foxes regularly travel enormous distances. A juvenile female in Alaska covered more than 2750 kilometres (top map) and a male from Bylot Island logged almost 2200 kilometres. The undisputed record holder, however, is our Bylot female, with her epic 5000-kilometre journey (lower map). Even that distance is almost certainly an underestimate of how far the animal actually travelled, says Nate Pamperin, who conducted the Alaskan study. He points out that the collars only transmit once every four days, and the distance calculations assume that the animals travel in a straight line between measurements. "On land, foxes move back and forth investigating every little feature," Pamperin says. "I'm sure it's the same on the ice where you have pressure ridges and such."

Marathon journeys are not the only aspect of Arctic foxes' lifestyle that satellite tracking is revealing. One long-standing mystery was whether animals found wandering on the ice were on brief forays from land, or extended trips. The new studies suggest the latter – that ice can indeed be a second home. One fox from Pamperin's study appears to have lived on the ice for more than five months in one stint.

> "One unexpected finding was that these extended treks are far from universal"

Both studies also found that the animals moved erratically, sometimes criss-crossing a large area, sometimes determinedly striking out in one direction for days on end. During her westward march, for example, the Bylot Island female travelled between 80 and 90 kilometres a day. The Canadian study also showed that while some foxes travel to land far from their original homes, this is not always the case. After covering nearly 2200 kilometres, the long-distance Bylot Island male was back close to the den he had left three months earlier. "It's not luck," says Dominique Berteaux, head of the Bylot team. "They know where they are. They have a very good sense of orientation, I'm sure."

One unexpected finding was that these extended treks are far from universal. In the Alaskan study, only three of the 17 collared foxes from an undeveloped location made long-distance ice journeys. The Canadians reported similar findings, with just two of 12 collared foxes venturing out for long distances. "What we've found is that it is not typical," says Berteaux. Why some foxes choose such a dramatically different lifestyle remains a mystery, but what is clear is that around human habitation the lure of garbage dumps and other tasty food sources keeps them as homebodies. Among the 20 foxes collared near the Prudhoe bay oilfields in 2005, none turned out to be ice travellers.

Another unanswered question is what the foxes do with their time out on the ice, and in particular how they feed themselves. There is good anecdotal evidence that they spend at least some time scavenging the remnants of seal carcasses left on the ice by polar bears. There is also evidence that Arctic foxes feed on invertebrates, mainly tiny crustaceans known as amphipods, which can be found clinging to the undersurface of the ice. And for a brief period in the spring they prey on ringed seal pups, winkling them out from their lairs in the thick layer of snow sitting on the ice.

Such bounties are rare and widely scattered, though, and hints are emerging that taking to the ice might have less to do with what can be gained there and more to do with having nothing to lose. In the first two years of tracking, the researchers on Bylot Island detected a link between the number of foxes on the ice and a shortage of lemmings, their favourite land-based prey, whose population undergoes dramatic swings from year to year. Although it is too early to say for sure, it is possible that foxes decide to go onto the ice based partly on how much food is available on land in the autumn.

Living the life of an ice nomad may well be a wise gamble. In Alaska, the three ice travellers all lived longer than the 14 collared foxes that stayed on land. In the Canadian Arctic, most young foxes that remained on Bylot Island perished before the end of their first summer, probably as a result of starvation. By comparison, our intrepid female was still going strong when the battery on her collar gave out after a year. Who knows: she may still be on the move. ■

NORBERT ROSING/NATIONAL GEOGRAPHIC CREATIVE

Brown is the new white

Can the snowshoe hare adapt its coat to diminishing snow cover, asks **Lesley Evans Ogden**

IT IS midsummer in Montana. Traipsing through the lush, dewy forest undergrowth, the morning mist is lifting and shafts of orange sunlight beam through the trees. To nature's soundtrack of a gurgling stream and birdsong, we check for quarry in live traps near Seeley Lake in the Rocky mountains. From the third one we visit, a young snowshoe hare stares up at us, silent, its whiskered nose twitching. This juvenile has unwittingly signed itself up for a cross-continental journey for science.

The snowshoe hare is one of 11 species worldwide that turns pure white in winter. The regrowth of its brown summer pelt has evolved to synchronise with average snowmelt times – dates that have been relatively stable for centuries. Not any more. In temperate regions, periods of snow cover are getting shorter – one of the strongest signals of climate change. Snowmelt times are changing so quickly that hares are being caught out of fashion – staying white when their snowy background has already melted. This young hare is destined to be transported across the country to North Carolina State University, where it will help my companion Marketa Zimova and her colleagues answer an important question: can the snowshoe hare adapt to shifting climate?

Scientists have long been intrigued by animal camouflage. The story of the peppered moth is a classic example of how background matching can, through natural selection, track human-imposed habitat changes. Before the industrial revolution, the vast majority of peppered moths were pale coloured, like the trees and lichen they rested on. Within 50 years, the darker-winged ones had become more prevalent as this provided better camouflage on the soot-covered trees.

However, early investigations into camouflage were often flawed because researchers based their work on their own vision, says Sami Merilaita at Åbo Akademi University in Finland. What's important, he says, is how the animals' predators see.

The snowshoe hare is the primary prey of the lynx and forms part of the diet of a host of other mammals and birds. Avian predators have good colour vision but mammals do not. "Mammals have dichromatic vision, like colour-blind people," says Merilaita. "They can't distinguish between green and orange very well, and probably green and brown as well." So, while speedy hops help snowshoe hares evade some predators, for others its camouflage is vital.

ERLEND HAARBERG/NATUREPL

Unlike hares, male rock ptarmigan know they stand out and use this to attract mates

But hares have other interests, such as finding food and mates, and these "may conflict with the need to maximise their background matching", says Merilaita. In fact, some species that turn white in winter appear to delay the change back on purpose.

Arctic-dwelling rock ptarmigan (above) have a white winter plumage and a mottled brown summer plumage. As snow melts in spring, females quickly moult and change colour, but males take almost a month to do so. Not surprisingly, the males experience higher mortality than females during this period.

Clues about why ptarmigan remain dangerously white have emerged from a 17-year field study by Bob Montgomerie at Queen's University in Ontario, Canada, and his team. Their observations suggest that the males flaunt their stark whiteness to woo females. Then, when hens are no longer fertile, the cocks deliberately soil their plumage with mud until they moult.

In an attempt to test this idea, the researchers dirtied the feathers of male ptarmigans in the mating season with a black "indelible" marker. It took the birds just 48 hours to completely remove the ink, says Montgomerie. "It was a strong clue that staying white was important, and that the birds were actively keeping themselves as clean as possible."

Hare-brained

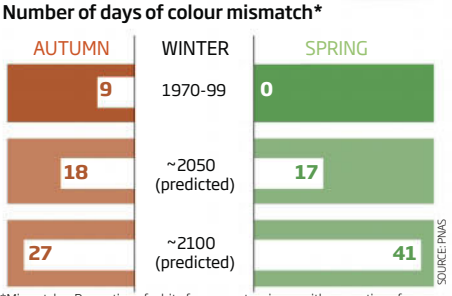
By contrast, snowshoe hares appear to be oblivious to whether or not they are camouflaged. "They do not act in any way to reduce colour mismatch, or to reduce the negative consequences of mismatch," says Zimova. When mismatched with their environment, they don't hide more, flee more or hang out in areas that match their coat. In short, these hare-brained creatures don't seem very smart.

If they can't adapt their behaviour, can they at least shift the timing of their moults? Zimova and her colleagues recorded coat-colour change in wild hares over three Montana winters starting in 2010. Locating radio-tagged hares weekly and noting what proportion of the fur cover was white, they examined the length of time individuals were mismatched with their background – defined as a difference of at least 60 per cent between coat whiteness and snow cover. On average, this came in at nine days a year. And mismatched hares paid a price; they were 7 per cent less likely to survive the week to the next assessment than hares whose pelts matched their environment.

Snowy mismatch

The snowshoe hare's coat changes from brown to white in autumn and back in spring to reflect varying snow cover. As climate change reduces the length of winter, it may be left wearing the wrong coat

Number of days of colour mismatch*



*Mismatch = Proportion of white fur cover at variance with proportion of snow cover by more than 60%

The study also revealed that the dates when moulting began in autumn and spring remained stable, despite large annual differences in snow duration. This suggests that the main trigger of moulting is the length of the day, not snow cover.

Other factors may also be involved. Looking closely at the two moulting seasons the team noticed that hares took about 40 days to change colour in autumn whatever the conditions. In spring, however, the rate of change was more flexible, with the moult lasting 16 days longer in the year with the longest period of snow cover compared with the shortest.

The source of this flexibility is unclear. Temperature and duration of snow cover appeared to have little effect in autumn. "[In spring] it might be the high reflectance of snow that enters the eye and triggers a hormonal cascade that slows down the change to brown," says Zimova.

The researchers can now test out their theories and investigate the genetics underpinning coat change at a futuristic-looking facility on the campus of North Carolina State University. In a series of stainless-steel-walled chambers, the young hare Zimova and I trapped, together with a dozen or so others, is being exposed to a variety of conditions to see how these influence the timing and length of moult. From a central control system, the researchers can manipulate day length, temperature and light conditions to mimic the reflectance of snow or bare ground – mechanisms that might drive the hares' twice-yearly wardrobe change.

"Snowshoe hares seem oblivious to whether or not they are camouflaged"

The team calculates that if the snowshoe hare fails to adapt, by 2099, reduced snow duration will increase mismatch to between 39 and 68 days a year. Theoretically, that could drive the species to extinction. It is unlikely to come to that, however. Given that individuals vary widely in the timing of their moult, and that those with the wrong colour fur face an increased risk of death, natural selection is likely to kick in.

"There is large potential for adaptation through evolutionary change," says Zimova. So as long as some snowshoe hares can stay hidden as snow cover decreases, the species isn't doomed. Natural selection will favour quick changers. Evolution can hop to it. ■

HUNT FOR THE SEA UNICORN

With its spiralled horn and elusive ways, it is the stuff of legends. **Isabelle Groc** goes in search of the mysterious narwhal

AUGUST 2012: even in the middle of summer, Tremblay Sound in the Canadian Arctic is an inhospitable place. As the small plane descends, I get my first glimpse of our destination. Remote and desolate, it consists mostly of piles of rocks and a little scrubby vegetation. During my two-week stay it will be cold, wet and windy almost all the time. Nobody comes to Baffin Island to get a tan.

Nevertheless, this is the third summer running that Jack Orr from Fisheries and Oceans Canada has visited and, together with a team of scientists, vets and Inuit hunters, he seems right at home. In no time at all they have transformed the site into a fully operational research station, complete with colourful sleeping tents, a kitchen tent and a science lab housed in a plywood shack. ›

PAUL NICKLEN/NATIONAL GEOGRAPHIC CREATIVE

"Narwhals spend all winter in the dense Arctic pack ice, in complete darkness"

HOW THE NARWHAL GOT ITS TUSK

For centuries people have wondered why male narwhals have a tusk. Today, most scientists see it as a sexual trait used to determine social rank and compete for females – much like the antlers of a stag. Another idea, suggested by Martin Nweeia at Harvard University, is that it acts as a sensor, detecting chemicals associated with prey, ice formation and salt concentration. Traditional explanations are often more colourful, and when I spoke to Nweeia he recounted a legend he had learned from Elisapee Ootuva, an Inuit elder from Baffin Island.

One day, a polar bear approached a house occupied by a woman, her daughter and her partially sighted son. The woman told her son to shoot the bear and, with help from his sister to position his bow and arrow, he struck it through the heart. His wicked mother pretended he had missed and, that night, while she and her daughter ate fresh bear meat, her son dined on dog food. But later, his sister told him the truth.

The next day, an old man came to the house predicting that the boy would encounter a giant bird on the lake and was to climb onto its back. He did so and the bird took him underwater three times. Each time he came up, he could see more clearly, until his eyesight was restored.

That summer, a pod of beluga whales swam close to shore. When the boy grabbed his spear, his mother eagerly asked if she could help. Quickly, he tied the end of the line from his harpoon around her waist so that she could hold the speared animal. Then he harpooned the biggest whale in the pod. The beluga pulled. As the woman entered the water, her body bloated and she morphed into a narwhal, while her long hair spun into its spiralled tusk. "The legend has it that it is a good sign to see a narwhal in the midst of belugas because that's the woman who was transformed," says Nweeia.

4.1 metres

Average size of a male
Females are smaller at 3.5 metres

Vital statistics: each tag comes with a health check

ISABELLE GROC

Finally, they set their trap. Having firmly anchored one end of a heavy-duty fishing net to the shore, Orr jumps in a boat and crosses the narrow inlet so he can sink the other end to the seabed with a bag of rocks. Six buoys keep the upper edge of the net afloat to create a hanging curtain. All we can do now is await our quarry. Its scientific name is *Monodon monoceros*, which derives from the Greek for "one tooth, one horn" in reference to the males' spiralled tusk, which can extend up to 3 metres. Many people simply know these creatures as sea unicorns.

There are some 90,000 narwhals in the frozen northern seas. A small population lives off the coast of Svalbard, Norway, but most inhabit seas around Greenland, or are found in the northern reaches of Hudson Bay and in the Canadian high Arctic. The Baffin Bay population is one of the largest. Each summer, hundreds of narwhals return to these fjords and inlets. Orr and his team aim to catch nine of them as they swim past, and fit them with satellite transmitter tags.

Orr is a veteran of this research, having tagged 300 whales over the past 30 years, mostly narwhals and belugas. It is hard, unpredictable, time-consuming work, but it is worth the effort to better understand this elusive animal. Narwhals are particularly tricky to study because they spend each winter in the dense Arctic pack ice, in complete darkness. Satellite tracking is invaluable in efforts to learn more about them.

Another researcher, Mads Peter Heide-Jørgensen from the Greenland Institute of Natural Resources has studied narwhals for more than two decades. Using satellite tracking he has found that they have strict migratory patterns. Year after year, each group undertakes the same migration in the spring and the autumn, moving between its winter feeding areas in the pack ice and coastal summering grounds (see map, page 122). The animals Orr studies leave northern Baffin Island in the autumn, migrating south to the Davis Strait where they spend the winter feeding on Greenland halibut, before returning the following summer. "They will go to the same places where they always go because they are programmed to do so," says Heide-Jørgensen.

Narwhals are experts at navigating and surviving in the extreme Arctic environment. In the winter, they traverse the pack ice following small cracks and leads. "I am mesmerised when I see how fast the ice changes," says Kristin Laidre at the University of Washington, Seattle. "In just an hour, a lead can close or completely freeze but the whales somehow know. They detect the change, and they are very good at navigating these dynamic areas." It turns out they are also one of the deepest diving whale species, with a record dive depth of 1800 metres, which may

5-20

Group size in winter
In summer groups can exceed 1000

PAUL NICKLEN/NATIONAL GEOGRAPHIC CREATIVE

Narwhal derives from the Old Norse "nar" meaning "corpse"

help them stay out of trouble.

Even so, a sudden freeze can catch them out. Between 2008 and 2010, there were several reports of narwhals becoming trapped in sea ice in Baffin Bay, unable to surface to breathe. At first, scientists thought changing sea ice conditions might be to blame, but then they discovered that the incidents coincided with seismic surveys of the bay. Narwhals are highly sensitive to noise; hunters in Greenland have known this for centuries and approach them in kayaks because if they use boats with noisy outboard engines the whales disappear. Heide-Jørgensen believes that the airgun noises from the survey may have interrupted the narwhals' migration, causing them to return to their summering grounds where they became trapped in the fast-freezing ice that now covered the sea surface.

90,000

Total number of narwhals
Conservation status is "near threatened"

Baffin Island in August never gets dark. We work 24 hours a day in 3-hour shifts to watch the net and keep a look out for polar bears. Often hundreds of narwhals swim past, yet none are caught. Waiting for a whale to hit the net is our main activity: when one becomes entangled it is crucial that we act quickly so that it doesn't drown. Bundled up against the cold, we watch and we wait.

In this meditative state, you notice things. The Arctic tundra is surprisingly colourful. There is bright orange lichen growing on rocks, yellow saxifrage and the tiny Arctic willow, the most northerly of all woody plants. The ground is also covered in animal bones, some seemingly very old. Bowhead whale remains, narwhal skull fragments, the pelvis of a ringed seal and caribou jaws and antlers dot the landscape like unexpected artworks.

At one point, a storm hits and we have to pull in the net – it would be unsafe to try to tow a whale to shore. The wind is so violent I am worried it will rip my tent. There is more waiting, but this time for the storm to pass.

The Arctic is changing rapidly. Since 1979, about 2 million square kilometres of year-round sea ice has melted. At this rate, the Arctic Ocean is expected to be ice free in summer by around 2050. Can the narwhal survive in a world without ice?

It doesn't look good. A study comparing the sensitivity of different Arctic marine mammals to the effects of climate change found the narwhal to be one of the most vulnerable species because of its restricted distribution, reliance on sea ice and ›

specialised feeding behaviour. One problem is that the loss of sea ice during the summer is opening new hunting territory for orcas (see "Invasion of the bowhead snatchers", page 56). With their large dorsal fins, orcas are poorly adapted for swimming in ice-covered waters, but areas in the eastern Canadian Arctic that were once off limits to them are now accessible. That puts narwhals at increased risk of becoming dinner.

A second concern is how the loss of sea ice and warming temperatures will affect the fish the narwhal eats. In Hudson Bay, for example, warming has led to an increase in capelin and a decrease in Arctic cod over the past three decades. Scientists don't know if the narwhal, which feeds on only a handful of species

3.1 metres

Maximum tusk length
It is actually a hollow canine tooth

including Arctic cod, can switch to other types of prey. There is some hope. Comparing the diets of narwhal populations in Baffin Bay, northern Hudson Bay and the east coast of Greenland, a team led by Cortney Watt, now at the University of British Columbia in Vancouver, Canada, found they eat different food types depending on where they are. "This suggests they may be able to adapt their foraging behaviour to the changing prey availability," she says.

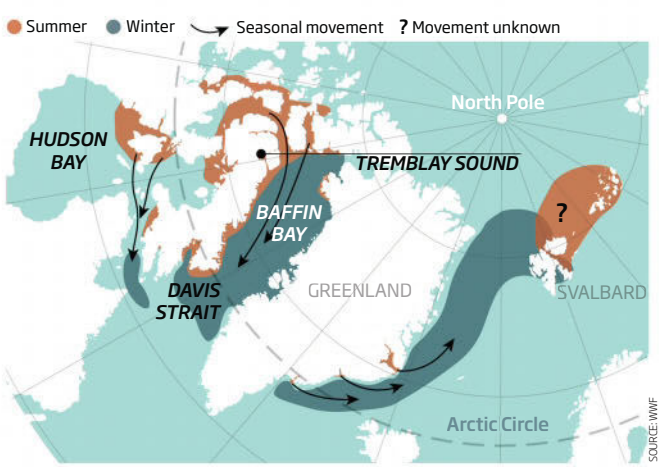
Sea ice loss also opens up opportunities for industrial development and commercial shipping in the region. Peter Ewins at WWF Canada and his colleagues have reported worrying overlaps between these activities and the distribution of three whale species – narwhals, belugas and bowhead whales. For example, a new iron mine in northern Baffin Island is expected to bring more shipping traffic into one of the most important summering areas for narwhals. Ewins is particularly concerned about oil pollution, ship strikes and acoustic disturbance. "There is a major likelihood of disruption to these habitats, which may become totally unsuitable to these animals," he says. The authors suggest a variety of measures to mitigate the impacts of human activities on whales, including careful planning of shipping lanes, the prevention of industrial activity in critical areas and regulation of seismic surveys.

After days of waiting, netting a sea unicorn seems like an impossible task. We play cards, wait, drink coffee, wait, drink more coffee and wait some more. Despite the tedium, it can

FLIP NICKLIN/MINDEN PICTURES

A chilly commute

Narwhals have strict migratory patterns, with each group returning to the same summering and wintering grounds every year



SOURCE: WWF

1800 metres

Maximum dive depth
They are among the deepest-diving whales

ISABELLE CROC

Tremblay Sound in summer is one of the best places on Earth to spot a narwhal

"In just an hour, a lead can close or completely freeze, but the whales somehow know"

5 - 6 months

Average time a narwhal tag transmits data
The record is 14 months

be nerve-racking. Because narwhals are often captured in the middle of the night, we never really sleep, always ready to spring into action as soon as we hear the alarm.

Eventually it comes. First the horn and then: "Whale in the net!" We all frantically pull on our dry suits, ready to jump into the freezing water. Three people hop into a boat and race to the end of the net to cut the anchor rope. Another boat crew pulls the net up to bring the whale to the surface so that it can breathe. A shore crew then manoeuvres the animal into shallow water where the real work can begin.

We have caught a large female, 4 metres long and anxious to get back to her calf. It's a team effort to calm and control her. While Orr attaches the tag to her dorsal ridge using two nylon pins, others collect a small piece of skin, which will undergo genetic testing later. The researchers monitor her heart rate, take blood and blowhole samples, record body measurements and assess her overall health, noting scars and signs of moulting. "We go as fast as we can, and we put a lot of effort into ensuring that there is as little stress to the animals as possible," says Orr. In less than 30 minutes she is ready to return to her calf.

More information is needed to plan for the long-term conservation of these extraordinary animals, but narwhals are tricky to study. "It takes years to learn even a small thing," says Laidre. And with changes coming so fast to the Arctic, time is of the essence. "We need the answers now but it takes a while to get them," says Heide-Jørgensen. Even with satellite tracking there are problems. One tag from a female caught in Tremblay Sound was still transmitting data 14 months later, but that is highly unusual; on average the tags last five to six months. We caught five whales during our trip, fewer than Orr had hoped for. One of the tags malfunctioned within the first few weeks, and contact was lost with the remaining whales after about four months. This is the reality of using high-tech equipment in the Arctic. Anything can happen, from programming glitches to tagged narwhals being killed by hunters or orcas.

As scientists work to understand the mysterious narwhal, it remains a paradox. Despite being long-lived – they can live at least 50 years – slow breeding and lacking genetic diversity, the species is remarkably resilient. It has survived for thousands of years in an extreme environment and through several periods of dramatic flux. But how much more can the narwhal take? ■

We've discovered some astonishingly small animals recently, but can they get even smaller? **Henry Nicholls** gets out his magnifying glass

SIZE ZERO

MAIN: MARK MOFFETT/GETTY. INSET: RALF BRITZ

Small fry: a carp from Sumatra makes the chameleon *Brookesia mimima* look big

WALKING back to camp as night fell in Papua New Guinea, Christopher Austin heard a high-pitched, insect-like call coming from the forest floor. He and his companions were there to hunt for new species, so they started searching through the leaf litter.

"But we didn't find anything," says Austin. "We repeatedly did that during the night and weren't able to find out what was making the call. So we ended up just grabbing a whole handful of leaf litter and throwing it into a plastic bag."

Back in camp, with the benefit of better lighting, they slowly went through their haul. It soon became clear why they hadn't been able to find anything out in the rainforest. The creatures that were making the noise were just 7.7 millimetres long. Yet they were not insects but fully grown frogs. "It was obvious that they were adult male frogs, as they were calling to attract a mate," says Austin.

This minute amphibian (*Paedophryne amanuensis*, pictured page 126), found in 2009, is the latest in a string of miniature vertebrates discovered in the past few years. The discoveries sparked something of a race to find the world's smallest – and although they had no idea at the time, Austin's frog is a leading contender for that title. It could well be smaller than the previous record holder, a tiny freshwater carp from Sumatra in Indonesia described in 2006 (pictured left).

So are there even smaller vertebrates out there waiting to be found? What are the limits on how small a vertebrate can get? And what made these animals so small in the first place?

Many ordinary-sized species, from monkeys to deer, are still being discovered each year, so it is perhaps not surprising that the most diminutive vertebrates have eluded us for so long. The recent rash of discoveries might be partly due to growing awareness of their existence, and partly to new tools. "I used my digital camera as an impromptu microscope, allowing me to quickly recognise this frog as a distinct species," says Austin, who is based at Louisiana State University in Baton Rouge.

Back in the lab, DNA analysis often reveals that very similar looking animals are separate species. And we know the smallest fish were slipping through the net; when a couple of ichthyologists from Singapore happened to use a finer mesh, they started catching miniature fish. Other collectors soon followed suit.

Whatever the reasons, the discoveries are coming in thick and fast. In most groups, from fish and frogs to lizards and snakes, biologists have now found examples of extreme miniaturisation. ›

"Miniature fish aren't just larvae whose development has frozen. Many have also evolved unique features"

Different factors may have driven the evolution of different kinds of animals. Many of the tiny fish live in swamps, for instance, and it is thought their size enables them to survive in small pools during dry periods.

In the case of the frogs, they may have evolved simply because there was a niche available for a tiny predator. "We think one of the major driving factors in the evolution of small body size in these frogs is an abundance of really, really small prey, like mites in the leaf litter that aren't being preyed on heavily by anything else," says Austin. "That food resource, that guild, that ecological niche is something that has caused the independent miniaturisation of frogs throughout the world."

This may help explain why most miniature vertebrates are found on islands rather than on continents. "Not everything makes it out to an island," says Blair Hedges, an evolutionary biologist at Temple University, whose work in the Caribbean has resulted in the discovery of some of the smallest vertebrates there. "That means there are open niches and the species that do make it out can expand their ecological space a bit more than they normally would on the continent," he says. "Sometimes that means being really small."

Missing bones

The simplest way to become small is to stop growing earlier. The tiniest animals go a step further: they often stop developing early too, meaning some adult features never form. Mini frogs, for instance, have a somewhat simplified skeleton, probably because bones that appear late in development in larger species never form. "With really small frogs you often get a reduction in the number of digits on the hands and feet," says Christopher Raxworthy, a herpetologist at the American Museum of Natural History in New York, who has helped discover several species of diminutive frogs in Madagascar.

TOP: OLIVER SMART/ALAMY. BOTTOM: CHRISTOPHER AUSTIN/AP/PA

The smallest bird, the bee hummingbird, is a giant compared to this dime-sized frog discovered in 2009

Some of these frogs also bypass one or more steps during early development. Many are "direct developers", that's to say, they skip the tadpole stage entirely and hop straight out of the egg. This may be because they live in environments where there isn't a lot of standing water and the aquatic stage is very dangerous, especially for animals that produce few offspring.

The story is similar for the Sumatran carp described in 2006. They look somewhat like fish larvae, but features such as the presence of eggs in females show they are indeed fully grown adults. When Ralf Britz, an ichthyologist at the Natural History Museum in London, studied their skeletons, he found that compared with close relatives these tiny fish have dozens of bones missing. Most of them are bones that normally appear late on in development, making the fish another example of so-called developmental truncation.

However, midget fish aren't just larvae whose development has frozen. Many have also evolved unique features, such as the male mini-carp's bizarrely modified pelvic fins, which have been transformed into two drumstick-shaped appendages with various hooks and flanges attached. "When I saw them I couldn't really believe my eyes," says Britz. They are unlike anything found in any of the other 3000 or so members of the carp family.

In rare footage of the mating ritual of these fish captured by an amateur aquarist, the male actually seems to use these appendages like drumsticks, flipping upside down to rap out a rhythm on the underside of a floating leaf. This may play a role in attracting the female, says Britz, but nobody has yet looked at their precise function.

Britz thinks the fishes' truncated development opened up new evolutionary possibilities. "Becoming larval has given them more freedom developmentally to do things with their skeleton that others cannot do," he says. It's like building a house. "The more floors you have the less freedom you have to put something on top, but if you go all the way back to the foundation stage then you can do whatever you want."

There is a limit to how much a body can shrink, though. Many of the constraints derive from the fact that for any given shape, the ratio of surface area to volume increases with decreasing size. This is a major issue for warm-blooded birds and mammals: the smaller they get, the faster they lose heat, so they have to generate heat faster to compensate. Minute

DENIS PALANQUE/BIOSPHOTO/FLPA

Baby it's cold outside: staying warm is hard for the Etruscan shrew

birds and mammals push their metabolism to the absolute limits. "The classic evidence of this size limitation is in the smallest shrews, where they are constantly eating to renew the energy that is being rapidly lost through their skin," says Hedges.

This is why the smallest recorded bird, the 30-millimetre-long bee hummingbird of Cuba (pictured left), and the smallest known mammal, the 40-mm Etruscan pygmy shrew found across Europe, north Africa and south-east Asia (above), are much larger than the smallest known reptile, a dwarf gecko from the Caribbean that measures just 14 mm from snout to anus. An impossibly cute chameleon from Madagascar was hailed as a contender for the title of tiniest reptile earlier this year, but Hedges says it is a fraction longer than the gecko, which he and a colleague discovered.

While heat loss isn't an issue for cold-blooded creatures, water loss is. This is a special problem for amphibians, says Raxworthy. "If a really tiny frog gets out into dry air it could dry out in a matter of minutes," he says.

> "You can't have half a baby. The only way to go is to have smaller offspring but smaller offspring would struggle to survive"

This was something Austin was careful to avoid when testing the jumping abilities of his pint-size Papua New Guinean frogs. "With this incredibly porous skin and this really large surface area to volume ratio, it makes desiccation a real issue." This is probably why the frogs stay in moist leaf litter.

Fish would appear to have things easier. Being cold-blooded and aquatic, heat loss and desiccation are not a problem. There are other constraints that kick in at such sizes, though. Losing a few bones here or there might not make much difference to a very small animal, but all its parts still have to work. It still has to be able to see and hear and so on. And there are fundamental limits on how far organs can be scaled down. One is that organs are made of cells, a certain number of which are needed to make complex organs like brains and eyes. The upshot is that an organ in a small animal is usually larger relative to its size than in a big animal.

As vertebrates get really petite, then, it becomes increasingly tricky to fit everything they need inside the body – especially offspring. "You can't have half a baby. The only way you could go is to have smaller offspring but smaller offspring would struggle to survive," Hedges says. So a reduction in size leads to reduction in the number of offspring.

This is evident for the world's smallest snake, the 100-mm-long Barbados threadsnake described by Hedges in 2008. The female produces only one egg at a time, and even then it's a squash, taking up half of the body cavity. "The female has to fill up this tubular spaghetti-shaped body cavity with her offspring," says Hedges. "The egg that's laid is this long sausage that's 10 times as long as it is wide."

Smallest of them all?

In fact, most miniature amphibians, reptiles and mammals that go in for internal fertilisation have room only for one, relatively large offspring, a clear indication that they are about as little as they can be.

Body shape, then, may account for the fact that the smallest known amphibians are shorter than their reptile counterparts, despite the problem of water loss. "The frog is more like a sphere with limbs," says Hedges, and this makes it easier to pack in the organs while still leaving room for an egg.

All these considerations suggest that while there might be even smaller vertebrates still out there waiting to be discovered, they are unlikely to be much smaller. In the meantime, biologists are still arguing about which of the known vertebrates holds the record.

Frogs have an obvious advantage in this competition. "Frogs don't have tails. Fish do," says Austin. With the smallest of his specimens from Papua New Guinea measuring just 7 mm from snout to anus, he says it surely beats Britz's carp, where the shortest mature individual was 7.9 mm long from its snout to start of the tail fin, which is how ichthyologists measure body length.

Britz brushes aside this amphibian challenge. This is not comparing like with like, he says. "If I were to use the amphibian metric [of snout to anus] we would have the smallest by far," says Britz. "It would be less than 5 millimetres."

Austin is having none of it. "Smallest clearly refers to a length measurement and tails count in measurement of fish length as any angler knows," he says. "This is no fault of the frogs, fish or scientists. Rather it is a biological and anatomical reality."

Still, perhaps we should wait a few years before awarding any prizes. The frog might be least, but it's probably not the last. ■

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