THE DARK SIDE OF LIGHT

The world is lit at night like never before. A clutch of experiments is tracking how ecosystems are faring.

BY AISLING IRWIN

It's a summer night near a forest lake in Germany and something unnatural is going on. Beyond the dark waters lapping at the shores, a faint glow emanates from rings of light hovering above the surface. Nearby, bobbing red torchlights — the least-disruptive part of the visible spectrum — betray the presence of scientists on the shoreline. They are testing what happens when they rob the lake creatures of their night.

This experiment near Berlin is the most ambitious of several projects going on in dark patches of countryside around Europe, set up in the past few years to probe what light pollution is doing to ecosystems. Researchers are growing increasingly concerned about the problem. Although many studies have documented how artificial light harms individual species, the impacts on whole ecosystems and the services they provide, such as crop pollination, is less clear. Several field studies hope to provide answers, by monitoring how plant and animal communities respond to both direct light and the more diffuse unnatural luminance of the night sky, known as skyglow.

Ecologists face challenges such as measuring light accurately and assessing how multiple species behave in response. But early results suggest that light at night is exerting pervasive, long-term stress on ecosystems, from coasts to farmland to urban waterways, many of which are already suffering from other, more well-known forms of pollution. It's an important blind spot, says Steve Long, a plant biologist at the University of Illinois at Urbana–Champaign and editor of the journal *Global Change Biology*. "We know a great deal now about the impacts of rising CO_2," he says. "But how extensive are the impacts of light pollution? We're gambling with our future in what we're doing to the environment."

In the 1950s, Dutch physiologist Frans Verheijen began to study how

KAMIEL SPOELSTRA/NIOO-KNAW

In mini-ecosystems in the Netherlands, researchers test the effects of artificial light.

lights attract animals and interfere with their behaviour. And during the 1970s, more biological observations of the impacts of light started popping up in the literature. But it took two lateral-thinking biogeographers — Catherine Rich, president of the Urban Wildlands Group in Los Angeles, California, and Travis Longcore, now at the University of Southern California in Los Angeles — to see the links between them and organize a conference in 2002, followed by a book, *Ecological Consequences of Artificial Night Lighting* (Island, 2006), pointing out how far the tendrils of the illuminated night extend.

For the vast majority of organisms — whether human, cockroach or wisp of plankton — the cycle of light and dark is an influential regulator of behaviour. It mediates courtship, reproduction, migration and more. "Since life evolved, Earth has changed dramatically, but there have always been light days and dark nights," says Christopher Kyba, a physicist at the German Research Centre for Geosciences in Potsdam. "When you change it, you have the worry that it could screw up a lot of things".

The pace of that change is increasing. Striking images from space over the past two decades reveal the extent to which the night is disappearing. Estimates suggest that more than one-tenth of the planet's land area experiences artificial light at night[1] — and that rises to 23% if skyglow is included[2]. The extent of artificially lit outdoor areas spread by 2% every year from 2012 to 2016 (ref. 3). An unexpected driver of the trend is the widespread installation of light emitting diodes (LEDs), which are growing in popularity because they are more energy efficient than other bulbs (see page 274). They tend to emit a broad-spectrum white light that includes most of the frequencies important to the natural world.

The trend has had profound impacts on some species; lights are well known to disorient migrating birds and sea turtles, for example. Scientists have also found that disappearing darkness disturbs the behaviour of crickets, moths and bats, and even increases disease transmission in birds.

The most lethal effects are perhaps on insects — vital food sources and pollinators in many ecosystems. An estimate of the effects of street lamps in Germany suggested that the light could wipe out more than 60 billion insects over a single summer[4]. Some insects fly straight into lamps and sizzle; some collapse after circling them for hours.

Fewer studies have examined plants, but those that have suggest that light is disrupting them, too. In a study in the United Kingdom[5], scientists took a 13-year record of the timing of bud opening in trees, and matched it up with satellite imagery of night-time lighting. After controlling for urban heat, they found that artificial lighting was linked with trees bursting their buds more than a week earlier — a magnitude similar to that predicted for 2 °C of global warming. A study of soya-bean farms in Illinois[6] found that the light from adjacent roads and passing cars could be delaying the maturation of crops by up to seven weeks, as well as reducing yield.

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ECOSYSTEM EFFECTS

Now, the results of some ambitious experiments are coming in. One of the largest is a field experiment in the Netherlands, where eight locations in nature reserves and dark places host several rows of street lamps. The rows are different colours — green, red, white and a control row turned off — and run from a grassland or heath field into a forest[7]. For six years now, scientists and volunteers have used camera traps to monitor the activity of small mammals; automatic bat detectors to record echolocation calls; mist nets for trapping birds; and nest boxes to assess the timing and success of breeding. Botanists are studying the vegetation underneath the lamps.

The team has found physiological evidence of the detrimental effects of light pollution on the health of wild animals. Songbirds roosting around the white light were restless through the night, slept less and had metabolic changes that could indicate poorer health[8]. The project also looked at how light affects bats, which have had mixed fortunes under the explosion of artificial illumination. Some species, such as the common pipistrelle (*Pipistrellus pipistrellus*), feast on the buffet of insects that they find circling lamps. Other, light-shy, bats have lost habitat and have disappeared from some places. In the Netherlands study, red light had no effect on any of the bat species[9], which means it could be deployed instead of white.

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But the experiment has yielded some puzzling findings. Several urban studies had found that artificial light at night triggers songbirds to sing earlier in the day. Because females tend to select early-singing males, the shifted dawn chorus might be affecting which birds get to reproduce. But the team in the Netherlands found no effect on any of 14 songbird species[10]. It's possible that the lighting was too weak to elicit an effect — it is calibrated to reflect the level on country roads and cycle paths, rather than the glare of an urban park.

Both kinds of result are useful for local governments, says Kamiel Spoelstra, a biologist at the Netherlands Institute of Ecology (NIOO-KNAW) in Wageningen, who leads the project. His team's findings are being incorporated into Dutch regulations on outdoor lighting. For instance, he says, some areas seeking to support local bat populations have switched to red light, a trend that he expects to increase.

Coloured light also graces grasslands in southwest England, where a project known as Ecolight is looking for evidence of 'cascade effects', in which the influences of light on one species have knock-on effects on the ecosystem.

The glowing cubes used by Ecolight might be mistaken for an art installation. Scientists led by Kevin Gaston, a biodiversity and

This grassland experiment supports the idea that red light is relatively benign to wildlife.

conservation specialist at the University of Exeter, UK, have just finished researching 54 artificial communities of grassland. In some of the cubes, beetles, slugs, pea aphids and 18 species of plant muddled along for 5 years, isolated from the outside world. Other boxes were simpler — containing just plants and herbivores, or plants alone. At night, some were illuminated with white light, some with amber, and some just saw the raw sky.

The effects of light on grasslands are important, partly because roadside grass provides refuges and corridors for wildlife in built-up areas. The scientists discovered that amber light and, to a lesser extent, white, suppressed flowering in the trefoil (*Lotus pedunculatus*)[11]. And there was a cascade effect in the amber-lit boxes. During August, when pea aphids switch from eating shoots to feasting on flower heads, their numbers fell, presumably because their food was less abundant. "I think this is the first experimental evidence of a strong, bottom-up effect of exposure to artificial light," says Gaston. In its latest, unpublished, work, the team reveals further effects, cascading onto the predators in the systems.

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Another elaborate experiment, in a dark-skies reserve in Westhavelland Nature Park in Germany, has shown that these cascade effects can spill over into neighbouring ecosystems. Street lamps erected near water-filled ditches lure aquatic insects out of the water[12], says Franz Hölker, an ecohydrologist at the Leibniz Institute of Freshwater Ecology and Inland Fisheries in Berlin. The insects flock to the lamps, exhaust themselves and become food for nearby predators. Meanwhile, the hinterland, which might otherwise have received insect visits, is deprived of an important source of food, he says.

Studies such as these, which lay such relationships bare in well-controlled, small-scale studies, mean that "those impacts are more likely to be taken seriously in the field and by regulators considering impacts from lighting", says Longcore.

Artificial light can also have impacts on ecosystem services — the benefits that ecosystems provide to humans. A study published in *Nature* last year found that illuminating a set of Swiss meadows stopped nocturnal insects pollinating plants[13]. A team led by Eva Knop of the Institute of Ecology and Evolution at the University of Berne, found that insect visits to the plants dropped by nearly two-thirds under artificial light and that daytime pollination couldn't compensate: the plants produced 13% less fruit. Knop's team forecast that these changes had the potential to cascade to the daytime pollinator community by reducing the amount of food available. "This is a very important study, which clearly demonstrates that artificial light at night is a threat to pollination," says Hölker.

LIGHT SKIES

Much of Earth remains free of direct artificial light, but skyglow — light that is scattered back to Earth by aerosols and clouds — is more widespread. It can be so faint that humans can't see it, but researchers say it could still threaten the 30% of vertebrates and 60% of invertebrates that are nocturnal and exquisitely sensitive to light.

Skyglow "almost certainly" has an impact on biodiversity, Gaston says, because the level is well above the thresholds for triggering many biological responses. And yet, he says, "it's actually quite hard to do the definitive study".

That's where the forest-lake experiment comes in. Glowing circles of light hover above cylinders sunk into Lake Stechlin, recreating skyglow. They are the work of Leibniz physicist Andreas Jechow, who had to find a way to produce low-level, even illumination without blocking daylight or impeding access for scientists. He and his team achieved this using state-of-the-art photonics tools such as an advanced ray-tracing model. "We were too ignorant as biologists about the complexity of light as a physical phenomenon," says Mark Gessner, director of the project, known as The Lakelab, and co-leader of its artificial-light project, called ILES (Illuminating Lake Ecosystems). In the past, some experiments have even failed to account for the fact that the Moon moves across the sky, he adds.

The idea for ILES was to extend findings from a well-known study of zooplankton, which live in deep, dark water during the day and migrate up into shallower waters at night to graze on algae. This movement is thought to be the biggest migration of biomass in the world. A study[14] in lakes near Boston, Massachusetts, in the late 1990s suggested that skyglow reduces the zooplankton's ascent by 2 metres, and the number of organisms that ascend by 10–20%. This behavioural change may be an unacknowledged driver of fundamental lake processes such as algal blooms.

At ILES, the 24 cylinders — each 9 metres in diameter — look from the surface like a fish farm. Lighting them with different levels of 'skyglow' and measuring the distribution of the tiny plankton using video cameras, the scientists found that skyglow had no massive effect on the movement of zooplankton. "We may have a changed migration pattern but I'm not yet certain about this," says Gessner. "If there is an effect, though, it looks like it's not the profound one we were expecting."

The surprise result is typical of these difficult studies. Gessner points out that their experiment has only completed its first season. "Maybe we don't need to be worried or maybe we need to be less worried — we don't know, at least as far as the effects of skyglow on lakes is concerned," he says.

BRIGHT FUTURE

It's slow, meticulous work, but the field is coalescing as evidence accumulates, says Gaston. "The last two or three years has seen a dramatic improvement in the level of our understanding," he says.

Nonetheless, there are improvements to make. Even measuring exposure is hard. In the field, the light an organism receives can be difficult to measure; a bird could retreat to the shadow of a nearby tree to avoid illumination, for example. So some scientists have tried strapping light meters to birds to get a better idea of dosage.

As the results seep out, one thing that both frustrates and inspires ecologists is that the remedy is at hand.

Longcore is now gathering published data on how different species, such as shearwaters and sea turtles, respond to different parts of the spectrum, and matching the results to the spectra emitted by different types of lighting. He wants to inform decisions about lighting — for example, which type of lamp to use on a bridge and which at a seaside resort.

Engineers and ecologists know that well-considered lighting can perform its task without "spraying light into the sky", as Kyba puts it. LEDs can be tweaked to shine in certain parts of the spectrum, to dim and to switch off remotely. "My vision," says Kyba, "is that in 30 years' time, the streets will be nicely lit — better than today — but we'll use one-tenth of the light."

That would be great news for ecological systems, says Hölker, because darkness is one of the most profound forces to shape nature. "Half of the globe is always dark," he says. "The night is half the story." ■

Aisling Irwin *is a science journalist based in Oxford, UK.*

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CORRECTION

The News Feature 'The dark side of light' (*Nature* **553,** 268–270; 2018) erred in saying that differing levels of skyglow had no effect on algae. In fact, it was zooplankton that were analysed. It also cited the wrong journal in reference 9: it should have referred to *Proc. R. Soc. B.*