Noise, Blazes and Mismatches

EMERGING ISSUES OF ENVIRONMENTAL CONCERN

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EMERGING ISSUES OF ENVIRONMENTAL CONCERN

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Foreword

Humanity has altered the planet in many detrimental ways, from the warming of our climate to the ever-diminishing wildernesses on land and in the sea. But in such a complex system as the Earth, science must always keep searching – for both solutions to problems already identified and new threats coming our way.

UNEP's Frontiers Report does this by identifying and exploring areas of emerging or ongoing environmental concern. The 2022 edition delves into three issues: noise pollution in cities, the growing threat of wildfires and shifts in seasonal events – such as flowering, migration and hibernation, an area of study known as phenology.

As cities grow, noise pollution is identified as a top environmental risk. High levels of noise impair human health and well-being – by disrupting sleep or drowning out the beneficial and positive acoustic communications of many animal species that live in these areas. But solutions are at hand, from electrified transport to green spaces – which must all be included in city planning with a view to reducing noise pollution.

Meanwhile, recent years have seen devastating wildfires across the world, from Australia to Peru. The trends towards more dangerous fire-weather conditions are likely to increase, due to rising concentrations of atmospheric greenhouse gases and the attendant escalation of wildfire risk factors. The next decade will be critical in building greater resilience and adaptive capacity to wildfires – including on the wildland-urban interface. In particular, further research should address vulnerable groups' exposure to hazards before, during and after extreme wildfires and action taken to increase efforts to prevent and prepare for wildfires.

Although wildfires are a striking impact of climate change, phenological shifts are equally worrying. Plants and animals often use temperature, the arrival of rains and daylength as cues for the next stage in a seasonal cycle. Yet climate change is accelerating too quickly for many plant and animal species to adapt, causing disruption to the functioning of ecosystems. Rehabilitating habitats, building wildlife corridors to enhance habitat connectivity, shifting boundaries of protected areas and conserving biodiversity in productive landscapes can help as immediate interventions. However, without strong efforts to reduce greenhouse gas emissions, these conservation measures will only delay the collapse of essential ecosystem services.

This report helps us understand that learning from ecosytems and how to live within them in harmony are objectives that we all need to adopt. We cannot have a healthy society without a healthy environment. And we need good science to inform responsible policies that back a healthy environment, which the Frontiers Report provides.

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Listening to cities

From noisy environments to positive soundscapes

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Scroll down page

1. Surround sound: our acoustic environment

Sounds are complex physical phenomena originating in the vibration from a source that propagates energy into a medium as an acoustic wave. Sounds happen continuously and are everywhere: there is no such thing as 'silence' on the planet. As physical phenomena, sounds are neither positive nor negative. They acquire meaning and produce an effect only when considered from the perspective of a listener. When sounds are unwanted, they become noise. When noises are too loud and persist too long, they become noise pollution.

Today, noise pollution is a major environmental problem, cited as a top environmental risk to health across all age and social groups and an addition to the public health burden. Prolonged exposure to high levels of noise impairs human health and well-being, which is a growing concern for both the public and policymakers.[1] Across the European Union, at least 20 per cent of citizens are currently exposed to road traffic noise levels that are considered harmful to health. This estimate is an average, with urban areas showing a far higher percentage.[2] Noise pollution comes from conventional sources, such as roads, railways, airports, and industry; however, high noise levels may also come from domestic or leisure activities. Traffic and other urban noises affect not only human well-being, but also disturb and endanger the survival of species crucial to the urban environment.[3]

Decibels (dB) are the units of measure for indicating the intensity or loudness of a sound that help predict thresholds when a noise starts to annoy people or when sleep disturbance emerges. While the loudness of noise is important, the frequency, in terms of high or low pitch, and temporal patterns of sound also determine the physical and psychological effects it has on the listener.[4]

Physically, proximity to very loud abrupt sounds, such as a gunshot over 140 dB, could rupture the ear's tympanic membrane, causing immediate hearing loss. Listening to music with earphones at the maximum volume – ranging between 90 and 100 dB at the eardrum – could start to cause hearing damage after only 15 minutes per day.[5] Regular exposure to over 85 dB for an 8-hour day or longer can cause permanent hearing damage. Long-term exposures, even at relatively lower noise levels that are common in urban areas, can also damage both physical and mental health.

Sound quality cannot be judged only by its physical properties, however. The definition of noise as unwanted sound implies a psychological concept.[6] While it is necessary to reduce noise levels when they are physically harmful to people, it may not be a sufficiently broad evaluation. It is becoming more relevant to consider soundscapes that contribute to people's physical as well as psychological well-being, especially in the urban environment.[7]

Yet, most people would agree that a silent world is not desirable because sounds can enrich our lives, restore feelings of health and well-being, and convey meaning to our everyday experiences.[7] They help define the characteristics of places and cultures and shape the quality of life. Some urban sounds may be unique to a community and add to its cultural identity, up to the point of becoming historical acoustic landmarks.[9] The sounds of Big Ben in London or the calls to prayer from the Masjid al-Haram in Makkah, for example, are evocative experiences. In its broader understanding, acoustic comfort should not be seen merely as the absence of noise, but rather as a situation where environmental sounds offer ample opportunities for people to thrive and look after both their physical and mental well-being.

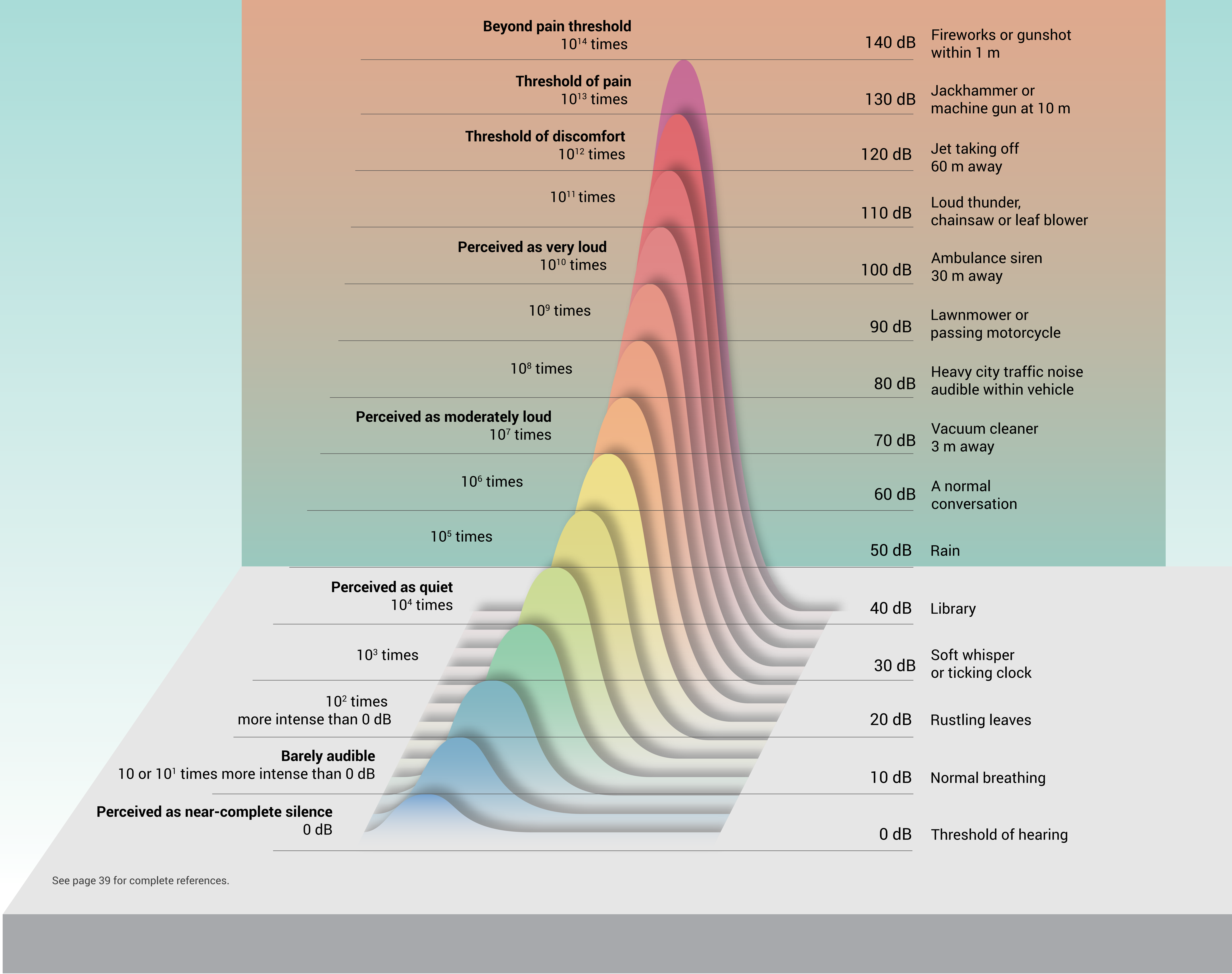
What is a soundscape?

The International Organization for Standardization (ISO) defines a soundscape as "[the] acoustic environment as perceived or experienced and/or understood by a person or people, in context".[10] In other words, soundscape encompasses the way people perceive, experience and respond to the full range of sounds in a place at a given time.[11] As an emerging discipline, soundscape studies try to look at the issue of urban acoustic environments more holistically, taking a listener-centred perspective.[12] The soundscape approach tends to focus on context, on wanted rather than unwanted sounds, and on individual preference rather than discomfort.[13]

Noise measurement

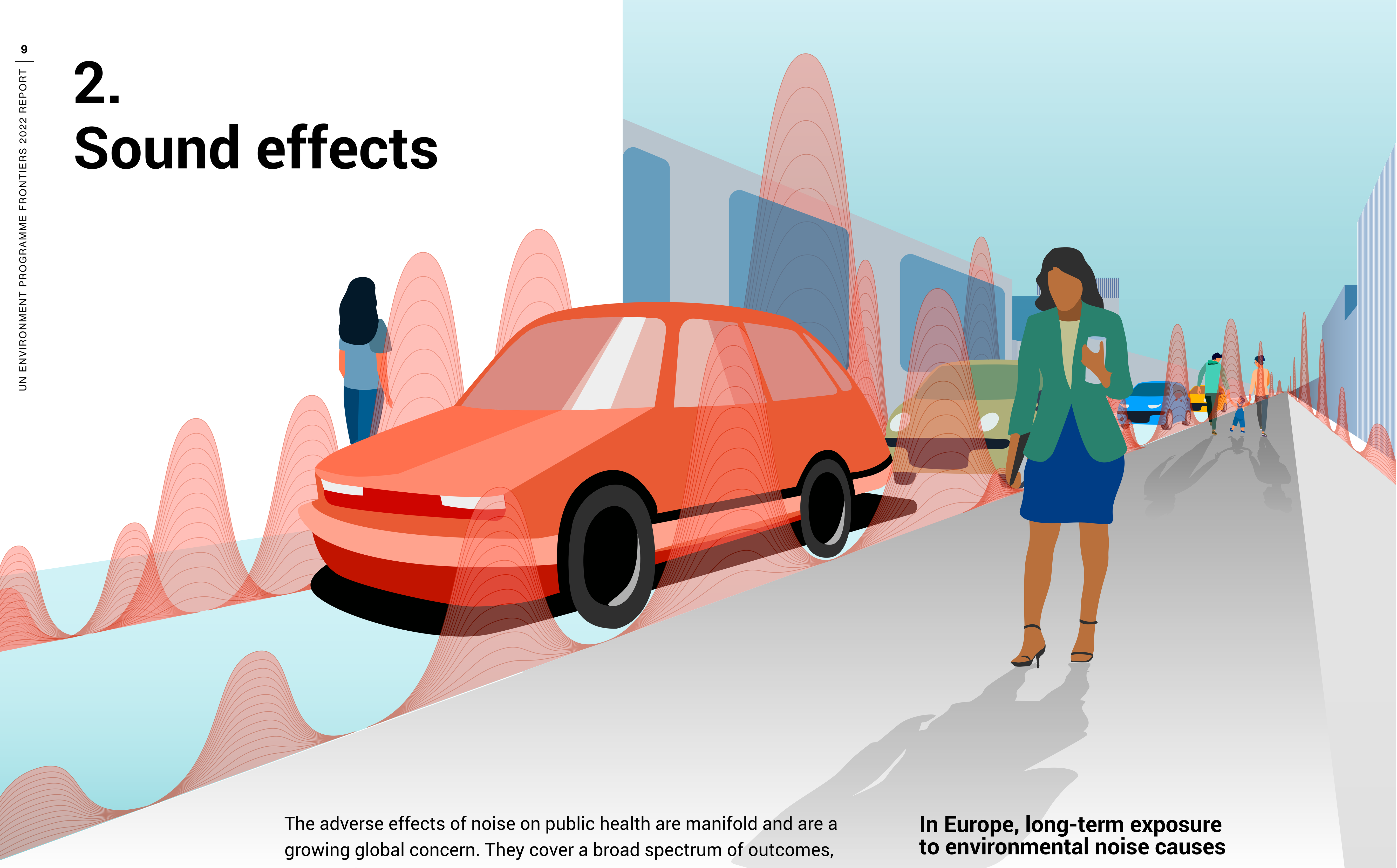
The pressure or intensity of sound is commonly expressed in decibels, or dB. Since the range of sound pressure that the human ear can detect is so large, the decibel scale is logarithmic: a scale based on powers of 10.

On the dB scale, the lowest audible sound, perceived as near-complete silence, is 0 dB. A sound 10^1 times greater in pressure than 0 dB is assigned a sound level of 10 dB. But this increment of 10 dB is generally perceived as a doubling of loudness by the ear. A sound 100 times more intense than 0 dB, or 10^2, is assigned 20 dB, and so on. That is, each increase of 10 dB is equivalent to an increase of sound pressure by another factor of 10.



See page 39 for complete references.

2. Sound effects



The adverse effects of noise on public health are manifold and are a growing global concern. They cover a broad spectrum of outcomes, ranging from mild and temporary distress to severe and chronic physical impairment. Night-time noise disturbs sleep and affects well-being the following day. Estimates suggest that in Europe 22 million and 6.5 million people suffer from chronic noise annoyance and sleep disturbance, respectively.[2] The elderly, pregnant woman and shift workers are among those at risk of noise-induced sleep disturbance.[2,14]

Noise-induced awakenings can trigger a range of physiological and psychological stress responses because sleep is necessary for hormonal regulation and cardiovascular functioning.[14,15] There is increasing evidence that traffic noise exposure is a risk factor for the development of cardiovascular and metabolic disorders such as elevated blood pressure, arterial hypertension, coronary heart disease and diabetes.[16] A conservative estimate indicates that long-term exposure to environmental noise contributes to 48,000 new cases of ischemic heart disease and causes 12,000 premature deaths annually in Europe.[2]

Two 15-year-long studies of long-term residents of Toronto, Canada found that exposure to road traffic noise elevated risks of acute myocardial infarction and congestive heart failure, and increased the incidence of diabetes mellitus by 8 per cent, and hypertension by 2 per cent.[17,18] These studies have already taken into account the confounding effects of traffic-related air pollution that are associated with the same outcomes. An analysis of national health and noise data from Korea estimated that for every 1 decibel increase in daytime noise exposure, cases of cardio- and cerebrovascular diseases increase by 0.17 to 0.66 per cent.[19]

The World Health Organization (WHO) Regional Office for Europe conducted systematic reviews to assess the associations between noise and health outcomes to develop guidelines and provide recommendations for protecting human health from exposure to environmental noise originating from various sources.[1] The health outcomes include annoyance; cardiovascular and metabolic effects; cognitive impairment; effects on sleep; hearing impairment and tinnitus; adverse birth outcomes; and quality of life, mental health and well-being. The noise sources considered in these reviews include road traffic, railways, aircraft, wind turbines, and leisure activities such as attending sporting or concert events, listening to music through personal devices, and other recreational pastimes.

Based on these reviews, the WHO recommends certain exposure thresholds to avoid adverse health effects. The thresholds are reported in terms of a day, evening and night noise level combined; and a night only noise level. These are time-averaged noise indicators for the relevant time period, expressed in dB and monitored at the receiving end on the most exposed side of a building. The limits recommended for the night period are always lower compared to the full 24-hour period, since specific noise sources and events may be more noticeable with less activity, leading to sleep disturbance and more awakenings.[1,20] Scientific evidence used in the WHO review, from studies representing numerous regions on different continents, provides the basis for the recommended exposure thresholds. This comprehensive coverage supports adoption of these thresholds to inform noise control policies around the world.

In contrast, some sounds bring health benefits, particularly sounds from nature. A number of systematic reviews documented empirical research from both clinical and physiological and subjective psychological studies of well-being in response to acoustic environments.[21,22] The reviews reported the positive influence of natural sound and quietness on physical and mental health. The importance of natural sounds to general well-being may also be associated with evolutionary advantages. Natural sounds may signal a safe environment, reduce anxiety and offer mental recuperation, while a lack of natural sound may provoke a more alert and vigilant state, especially for those from vulnerable groups.[23,24]

In Europe, long-term exposure to environmental noise causes

12,000

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48,000

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22 million

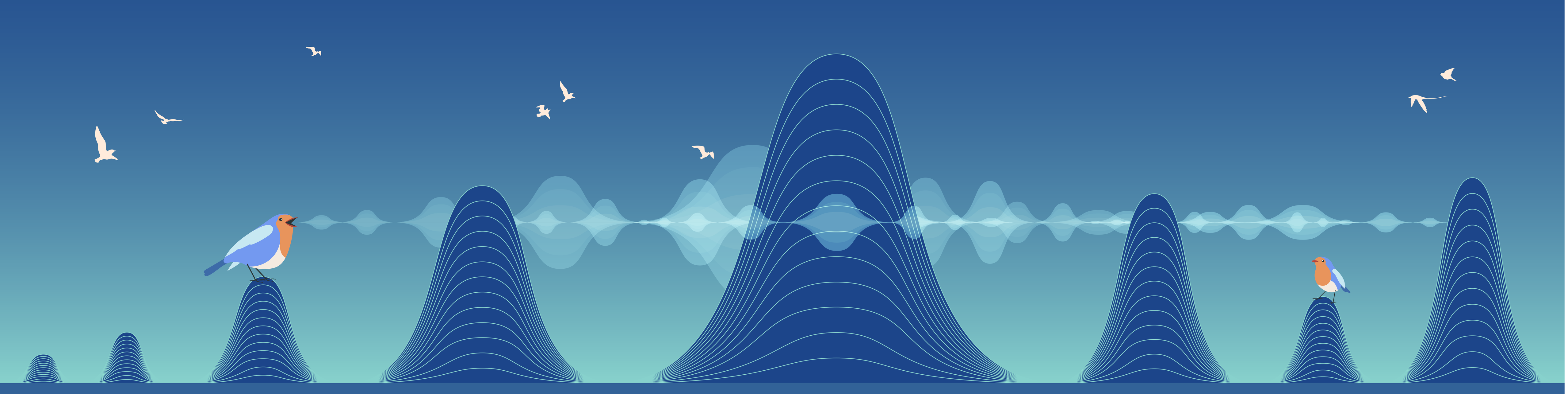
people in Europe suffer from chronic noise annoyance.

WHO recommendations on noise levels

Noise exposure should be kept below the following levels to avoid any harmful health effects.[1]

Noise source	Maximum level of day-evening-night noise exposure L_{den}	Maximum night-time noise exposure L_{night}
Road traffic	53 dB	45 dB
Railways	54 dB	44 dB
Aircraft	45 dB	40 dB
Wind turbine	45 dB	(Insufficient evidence to recommend a limit)

Drowned out by noise: Creatures of the city



Acoustic communication is vital for many animal species. Acoustic signals are used in a variety of communication contexts, including territory defence, warning of danger, locating or attracting a mate, and caring for offspring. While abrupt and unpredictable sounds may be perceived as a threat by animals, chronic acoustic disturbance such as traffic noise can interfere with acoustic communication and alter behaviours in a range of species.[1,25-27]

Abandoning noisy sites may seem the obvious response, but some animals adapt to noisy conditions instead, by altering their vocalization timing or pattern to avoid having their signal masked. In European cities, robins seem to sing more at night to avoid high acoustic interference during the day, while in the city parks in Bogota, Colombia, rufous-collared sparrows start the dawn chorus earlier in the morning at a site with heavy daytime traffic.[28,29] Some frogs exhibit gap-calling behaviour as they time their calls to breaks in noise.[30]

Other species modify their signals by switching their vocal frequency, or pitch, and amplitude to counteract low-frequency traffic noise. Many city bird species with natural low-frequency vocalizations sing at higher frequencies in areas of urban noise.[31-33] Studies in 30 city-forest paired locations in continental Europe, Japan and the United Kingdom have found that urban great tits sing higher-pitched songs than their forest-dwelling counterparts.[34-36] Zebra finches and white-crowned sparrows slow down their tunes in response to city noise.[37,38] These types of vocal modification have also been observed in frogs and insects, such as grasshoppers, living next to noisy highways.[39-42]

These changes certainly help animals to be heard in noisy environments, but sometimes altered vocalization patterns are considered less attractive by potential mates, therefore affecting reproductive success.[3,30] And if species are not behaviourally flexible in producing or receiving signals, the inability to communicate may eliminate them from their habitats, with possible significant ecological implications.[3,27]

Sound check:
How noisy are cities?

The illustration presents traffic-related noise levels (dB, LAeq) measured for a specific daytime duration in different cities. The data are compiled from various published studies, which utilized different methodologies. According to the 1999 WHO guidelines for community noise, the recommended limits are 55 dB LAeq for outdoor residential areas and 70 dB LAeq for traffic and commercial areas.[19] The latest 2018 WHO guidelines established a health-protective recommendation for road traffic noise levels of 53 dB based on the Lden indicator, an average noise level during day, evening and night that differs from the LAeq indicator.

New York

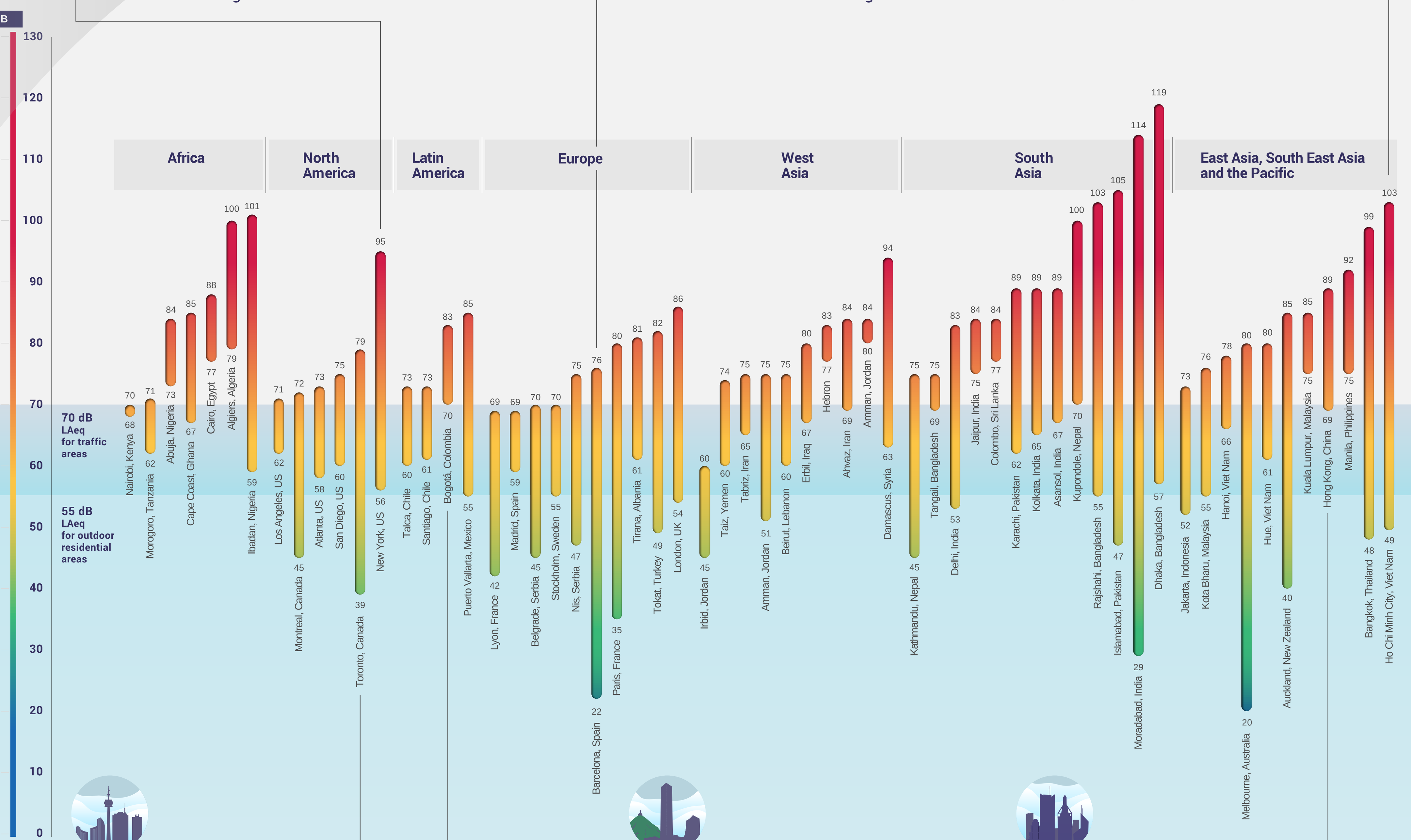
Over 2 million people commute by public transportation in the New York metropolitan areas. 9 in 10 mass transit users in New York City are exposed to noise levels exceeding the recommended limit of 70 dB, and may be at risk of irreversible hearing loss.

Barcelona

Over 72% of the city's residents are exposed to noise levels of over 55 dB. More than half of the residents of large European cities live in areas where noise levels may adversely affect their health and well-being.

Ho Chi Minh City

A study that followed cyclists riding over 1,000 km within the city showed that cyclists were exposed to noise levels of over 78 dB, which could damage hearing.



Toronto

Two 15-year-long studies of long-term residents of Toronto found that exposure to road traffic noise elevated risks for acute myocardial infarction and congestive heart failure, and increased the incidence of diabetes mellitus by 8% and hypertension by 2%.

Bogota

A study of the dawn chorus of rufous-collared sparrows living in public parks of the city of Bogota found that the birds changed their singing behaviour in anticipation of the morning rush hour by starting to sing earlier at a site with heavy daytime traffic.

Hong Kong

2 in 5 residents of Hong Kong are exposed to road traffic noise above the permissible limit. City morphology and building design play a key role in noise distribution. Residents with lower income and poor housing are more exposed to traffic noise compared to wealthier residents.

See page 19 for complete references.

Soundscape management:
From noise mitigation to desirable soundscape

Exposure to environmental noise sources such as road traffic, air traffic, railways, machinery, industry and recreational activities has well-documented negative impacts on physical and mental well-being. Noise abatement is a public health issue and it has become imperative for urban planners to increasingly create and preserve quiet spaces to deliver pleasant urban soundscapes.

Soundscape

Soundscape encompasses the way people perceive, experience and respond to the sounds of a given place at a given time. Soundscape planning aims to deliver pleasant acoustic environments that enhance appreciation of places by people. Soundscape design considers contextual characteristics of the place, including perceived acoustic parameters, physical features, natural factors, purpose, usage and user community.

Sight and sound

Both sight and sound influence human perception of surroundings. Landscape affects soundscape, and vice versa. Visual surroundings are a vital consideration in soundscape planning and design.

Green solutions

Vegetation in urban environments can absorb acoustic energy, diffuse noise and reduce street amplification. Tree belts, shrubs, green walls and green roofs have positive visual effects in addition to helping amplify natural sounds by attracting urban wildlife.

Tree belts

Roadside tree belts can shield noise when planted in sufficiently high biomass density. Noise attenuation can be enhanced by the correct choice of species, trunk size, length and depth of the belt, distance from noise source, and planting scheme.

Green roofs

Vegetated roofs attenuate sound by absorbing propagation over rooftops from street to quiet sides.

Electric vehicles

Even electric vehicles emit noise when driven at speeds above 50 km/hr from tyre contact with the road. Solutions such as porous asphalt surfaces can lower noise emission at higher speeds.

Pathway intervention

Engineering solutions aim to obstruct the pathway between source and receiver. Measures such as noise barriers along highways or railways, earth berms, gabions, and use of acoustic insulation materials and architectural features in buildings can break the chain of noise propagation.

Mitigation at source

Noise mitigation measures differ in effectiveness. Emission reduction at source is the most effective, including restriction of traffic flow or speed, quieter vehicle engines and low-noise road surfaces.

Noise barriers

Barriers placed near source or receiver can significantly reduce noise. Both traditional and innovative materials, made from recycled materials such as plastic and car tyres, have proved effective. Fibreglass from decommissioned wind turbine blades in Denmark have shown a barrier effect reduction of traffic noise levels by 6-7 dB.

Vegetated noise barriers

Vegetation increases the absorption and reduces the propagation of sound. Customized placement of tree rows behind traditional highway noise barriers or layers of vegetation on rigid noise walls can reduce noise levels by up to 12 dB.

Ecosystem services

The mental health benefits from natural sounds and general quietness are considered psychological ecosystem services provided by nature. Exposure to natural sounds contributes to relaxation, stress recovery and psychological restoration.

Green space

Urban green space and vegetation produce positive psychological effects. Public parks, gardens and other small green areas provide pleasant sounds from nature, such as rustling leaves, swaying tree branches and chirping birds. Natural sounds support stress recovery and attention restoration.

Quiet space

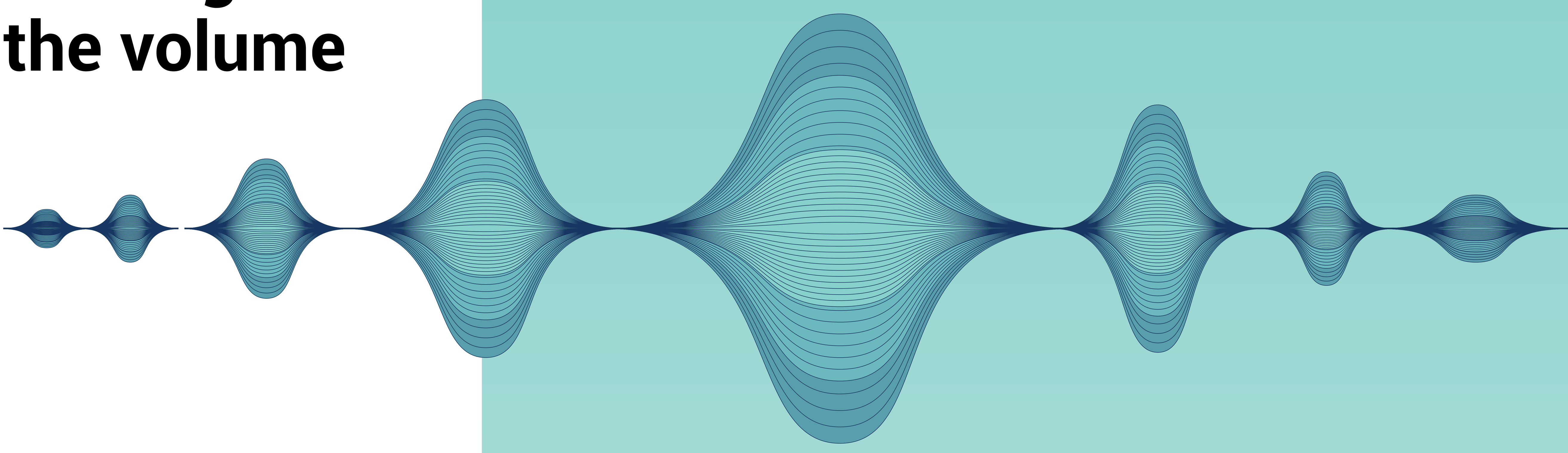
Quiet urban areas offer acoustic relief to city inhabitants from noisy surroundings, a prerequisite for mental restoration and well-being. Natural sounds found in urban parks, gardens, and other green spaces positively contribute to peaceful and quiet soundscapes.

Place-making

Everyday sounds of a particular place that are immediately recognizable help create the identity of the place. When these sounds are unique and convey a distinct sense of place, with a significance beyond the local community, they become acoustic landmarks, termed soundmarks.

See page 21 for complete references.

3. Turning down the volume



> "When general noise reduction is difficult to achieve overall, it is important to guarantee local access to quietness for people in public spaces."

> "Quiet areas are more generally understood as places with pleasant soundscapes or where unwanted sounds are mostly absent."

Like most sources of pollution, noise is an issue that must be managed. Regulatory frameworks and legal requirements are in place in many countries and are sometimes coordinated multilaterally, such as in the European Union.[43,44] Common measures usually address the sources of noise as they are the most cost-effective and straightforward to enforce. Source interventions include management of road, rail and air traffic flow, use of low-noise road surfaces and rail tracks, improved aerodynamics and components for aircraft, and shifts away from internal combustion engines to quieter propulsion systems.[2]

Public bodies, industry, and research have focused mainly on these kinds of technological developments. The alternative receiver-oriented measures, like installing noise barriers, are typically less cost-effective and only solve a problem locally, with potential negative landscape impacts as an additional drawback.

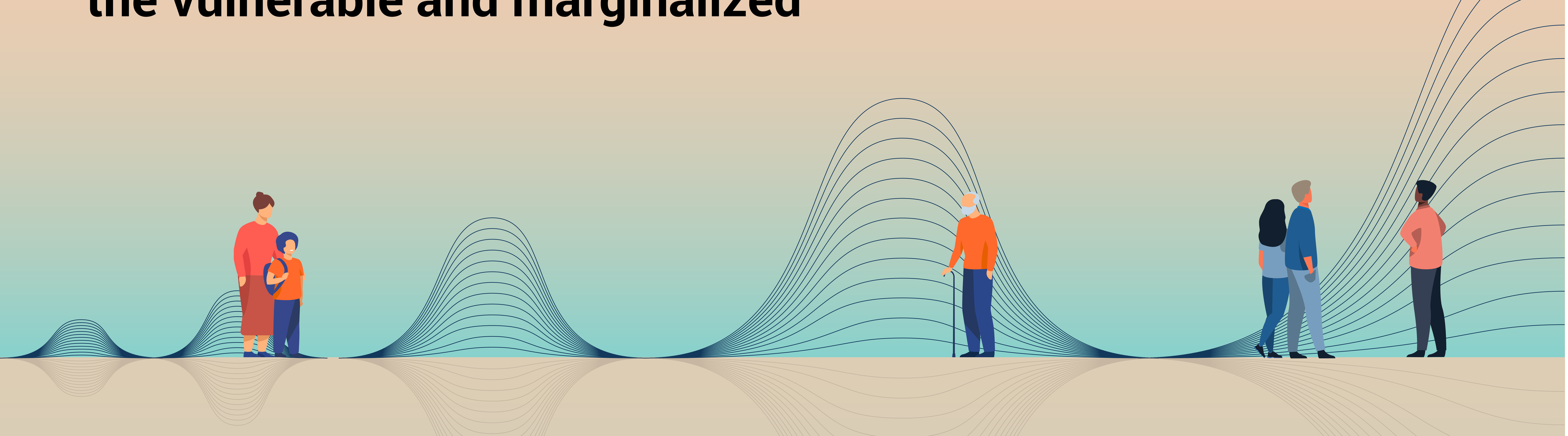
Noise mitigation in cities can also be achieved with indirect approaches. In the national plan to combat noise and reduce its sources, the Government of Egypt has incorporated measures with environmental co-benefits. These include encouraging the use of bicycles, and adopting building energy standards to reduce noise emission from air conditioning systems.[43,45] In Berlin, Germany, new cycle lanes on wide roads have been used as an indirect noise abatement strategy aimed at reducing the available driving space for motorized vehicles. More than 500,000 residents were originally exposed to night noise levels higher than 50 dB, so many city roads with two lanes per direction and volumes of transit up to 20,000 daily units were narrowed to single-lane roads, releasing space for bicycles and pedestrians. This moved the source of the sound emission towards the middle of the roads, away from residential settings. Overall, it achieved a reduction in night noise levels for more than 50,000 residents.[2]

In April 2019, the Ultra-Low Emission Zone came into effect in Central London and expanded in late 2021 to include an area encompassing 3.8 million people.[46,47] While the scheme was mainly driven by a desire to improve air quality, encouraging the use of electric and hybrid vehicles has noise-reduction benefits as these vehicles are much quieter compared with internal combustion engine vehicles, especially at low speeds.[48] However, the detectability of quiet vehicles may become a safety concern for pedestrians and consequently a new challenge.[49,50]

Looking at cities with complex vertical development and tight road networks, Hong Kong stands out as a challenging case where land use and urban morphology are key factors affecting the spatial distribution of noise sources in the built environment.[51,52] With over one million residents exposed to road traffic noise at levels higher than the 70 dB limit, the authorities adopted a relatively aggressive policy centred on infrastructure design and land-use planning, with limited success.[53-55]

The WHO noise guidelines also emphasize that policy attention should not simply focus on areas with high noise levels, but also on where positive soundscapes exist or can be created.[1,56,57] Many environmental noise policies and local authorities' actions acknowledge that when general noise reduction is difficult to achieve overall, it is important to guarantee local access to quietness for people in public spaces.[57] The focus in most urbanized contexts has, therefore, been on identifying and protecting areas of quietness, and restoration of environmental assets that are embedded in the city fabric.[45] Quiet urban parks, converted canal towpaths and rail spurs, pocket green and blue areas within apartment blocks, in courtyards, gardens and other leisure areas are places where people can escape city noise. Access to nearby quiet areas contributes to the health and well-being of local communities.[58] While noise level is an important aspect, soundscape quality is also contextual and influenced by non-acoustic factors, including the feeling of safety, which may be a notable concern for women and for parents.[23,58,60] Quiet areas are more generally understood as places with pleasant soundscapes or where unwanted sounds are mostly absent; they are often combined with positive landscaping elements, like greenery and water features.[59-61] Providing or protecting these spaces is a more passive, yet still valuable, way of regulating against noise in urban areas.

Amplified effects on the vulnerable and marginalized



The effects of noise on health are not uniform among individuals or across population groups. Specific individual differences can increase a person's vulnerability. An individual's sensitivity to noise is considered a relatively stable and partly genetic trait, independent of exposure level.[62] Noise sensitivity manifests as a heightened degree of vigilance and physiological reactivity to sounds. High sensitivity to noise can exacerbate stress responses and may be associated with an individual's general ill-health.[63]

Age also seems to shape our reaction to sounds, with the very young and the elderly at higher risk from the effects of particular noises.[64-66] Evidence of gender differences in vulnerability to noise is mixed, where differences may be rooted in the way men and women perceive and deal with stressors in general.[67,68]

At the population scale, some social groups are more vulnerable than others.[69] Poorer individuals have fewer housing choices, often forcing them to live near environmental stressors such as waste dumps, industrial areas, and roads with high traffic density.[70,71]

Subsequent long-term exposure to such environmental stressors can compromise the underlying health conditions of individuals living in these communities.[72] Studies from many major cities suggest that marginalized communities are more exposed to higher environmental noise levels, with indications that noise exposure inequalities also divide along ethnic lines in certain multiracial societies.[73-79]

Having access to public green spaces and local quiet areas can improve soundscape quality and buffer the negative impact of noise. Evidence suggests that the positive health effects of green spaces and neighbourhood greenness are strongest in communities of the most socioeconomically deprived groups.[80] However, the access to high-quality public green spaces for marginalized communities is limited compared to that available for affluent communities.[80-84]

4. Healthy decisions for positive soundscapes

> "Noise pollution should be considered within a broader range of environmental challenges through integrated policies, particularly for the combination of noise and air pollution."

Over the past several decades, policymakers have achieved some progress in addressing noise pollution as an environmental and public health issue. However, two major shortcomings have emerged. First is the inherent limitation of using a reactive approach — when the primary focus is retroactively reducing noise levels. The second is thinking of sound only in terms of discomfort, such as transport and industrial noise, rather than investigating how to promote sounds that provide comfort. These two points need to be urgently addressed to achieve livable cities and support for research-informed interventions is crucial in this process.

To overcome the first shortcoming, in any urban development strategy, environmental sounds should be considered at the earliest possible stage of planning and design to prevent them from becoming an afterthought – one that could involve significant expense. According to data from Europe, more than 50 per cent of actions intended to manage noise focus on the source, which is often effective but will not necessarily provide soundscape quality.[2] A very limited percentage of measures dealing with environmental sounds resort to land use or urban planning, while growing evidence from research indicates that this approach would be the most sustainable path.[85,86] Therefore, it is crucial that experts in environmental acoustics and urban soundscapes are involved in urban development processes and that they communicate with local stakeholders.[87]

Furthermore, noise pollution should be considered within a broader range of environmental challenges through integrated policies, particularly for the combination of noise and air pollution. Many countries surveyed by the European Environment Agency report successful policies that provide co-benefits, including traffic calming measures, green vehicle fleets, energy-efficient buildings, tree and shrub plantings to create and link green corridors, and incorporating downcycled materials into engineered noise control solutions.[2]

To address the second shortcoming, there needs to be an extension of the scope of policymaking through a shift from only managing environmental sounds when they cause noise pollution to considering environmental sounds as opportunities for promoting healthy living environments for all age, gender and social groups. The Government of Wales aspires to preserve or cultivate positive soundscapes, defined as "where natural sounds such as flowing water, birdsong, the wind in the trees and human conversation are more prominent than background traffic noise".[57]

For positive soundscapes to thrive, while keeping noise pollution within acceptable bounds, new approaches need to account for people's perception rather than just their exposure; this will complement and augment the dB measure to characterize soundscapes. Although desirable for some contexts like urban parks or residential areas, simple silence or quiet cannot be the standard for assessing the quality of every urban space. We need our cities to be aurally diverse and inclusive, to support mixed uses; this is something silence alone cannot deliver.

> "We need our cities to be aurally diverse and inclusive, to support mixed uses; this is something silence alone cannot deliver."

The link between time spent in natural environments and general well-being is accepted by more people after their pandemic experiences.[97] The COVID-19 lockdowns brought new appreciation for urban green spaces of every kind.[98,99] Urban planners are looking to 'build back better' after the pandemic by including more green space, and some are particularly concerned that those green spaces, and their benefits, are delivered to often-ignored poorer neighbourhoods and those housing marginalized groups.[100,101] Policymakers, urban planners, community members and other stakeholders involved in creating more livable cities need to keep the sounds of the new and renewed spaces under consideration.

Lockdown soundscapes

When the SARS-CoV-2 virus spread at the end of 2019, governments around the world responded with measures to contain the infection rates.[88] The halt of most non-essential commercial and social activities, local commuting, and other travel led to less pollution, including noise.[89]

Many research groups and governmental agencies reported decreasing noise levels, particularly in urbanized areas.[90] In Paris, monitoring detected an average reduction of 7.6 dB for road traffic noise over the whole network with the first lockdown on 17 March 2020.[91] Air traffic noise in the Charles de Gaulle airport area also decreased significantly, with reductions reaching 20.4 dB.

In Madrid, the reduction of road traffic and the absence of people on the streets led to sound level reductions in the 4–6 dB range.[92] In a study conducted in London across 11 locations, comparing data from the peak of local lockdown measures, an average reduction of 5.4 dB was observed.[93] In San Francisco, the sudden drop in human noise meant people could hear more natural sounds, such as birdsong.[94] In Mumbai, noise levels were monitored at different locations during the Ganesh Chaturthi festival celebrations under COVID-19-related municipal restrictions in 2020. Compared with measurements in 2018 and 2019, noise level reductions ranged between 27.5 and 28.5 dB.[95] This general pandemic-related quieting could be detected at a global scale via seismologic investigations that reported substantial decreases in noise during lockdown.[96]

The long-term environmental implications of the COVID-19 crisis are still unclear and current global research should provide further insights. The unexpected silence from human sound sources triggered a debate among academic communities and the public on how modern cities could sound and whether we are doing enough to achieve positive soundscapes.

Although there is consensus that the limitations imposed by lockdown measures led to lower noise levels in many cities, the maximum observed reductions for traffic noise were still typically in the region of only 6–10 dB. While this would be perceptually noticeable in most situations, it is not always enough to bring noise pollution to safe levels according to WHO recommendations. For cities to improve their soundscape quality, different strategies for planning and infrastructural changes would develop healthier acoustic environments.

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Sound check: How noisy are cities?

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Soundscape management: From noise mitigation to desirable soundscape

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Wildfires under climate change

A burning issue

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1. Waves of extreme wildfires

On 11 July 2012, more than 25,000 hectares of boreal forests were burning across central and eastern Siberia, Russia. Uncontrolled wildfires were alight from Yugra in the west to Sakhalin in the east. This satellite image shows fires raging near the Aldan River in Yakutia on 10 July 2012.

Source: NASA Earth Observatory

Recent years have seen devastating wildfires in many regions of the world, following heatwaves and droughts. Much news coverage focuses on Northern hemisphere wildfires destroying towns, such as during the extraordinary 2020 fire season in the western United States.[1] The extensive 2021 evacuations from the Greek island of Euboea brought haunting images of what researchers suggest will become more frequent events in Mediterranean countries.[2]

Catastrophic wildfires rage in the global South as well. In 2019/2020, Australia experienced the unprecedented Black Summer fires, with news stories and shocking images broadcast internationally.[3] Despite being a country shaped by fire in many ways, the sheer scale and intensity of the Black Summer fires brought into focus how global warming is adding to wildfire risk.[4-7] The fires burned over 24 million hectares, thousands of homes were destroyed and 33 people lost their lives.[3] The 2019-2020 massive fires destroyed critical habitats for hundreds of species, including those already threatened with extinction.[8]

In Latin America, the rapid and widespread deforestation of savannahs and tropical rainforests, compounded by droughts and the limitations of existing fire management policies, has led to disastrous wildfires in recent decades.[9-11] In 2019, more than 6 million hectares burned in the Chiquitania, Cerrado and Amazon regions in Bolivia, Brazil, Colombia, Paraguay and Peru, mostly within protected areas of native vegetation.[12,13] During the dry season of 2020, another long and destructive wave of wildfires swept through the area.[14,15] Across Africa, fires are visible in satellite imagery throughout the year, adding up to vast burned areas in observation and monitoring records.[15]

“The observed trends towards more dangerous weather conditions for wildfires are projected to continue increasing, due to mounting concentrations of atmospheric greenhouse gases, with escalating risk factors.”

Over continents and biomes, there are similarities among these extreme wildfire events in the form of underlying risk factors, hazards and consequences for society and the environment. Long-term effects on physical and mental health are not limited to those fighting wildfires, evacuated, or suffering great loss.[16-20] Smoke and particulate matter from wildfires deliver significant consequences for human health in downwind settlements, sometimes thousands of kilometres from the source.[21-23] Research suggests that the most vulnerable – women, children, elderly, disabled and the poor – suffer the worst ongoing damage from their wildfire exposure, echoing the acknowledged understanding of this same result as the common outcome from most disasters.[24,25]

The observed trends towards more dangerous fire weather conditions for wildfires are likely to continue increasing, due to mounting concentrations of atmospheric greenhouse gases and attendant escalation of extreme-wildfire risk factors.[4,6,26-34] Beyond changing climate, the heightened intensity of some wildfires can be attributed to land-use change and fire management approaches that do not appreciate the close relationships, evolved over millennia, between vegetation and fire.[11,35-38]

With compounding effects of a heating climate that extends fire seasons and can deliver more natural ignition events, of changes in land use that introduce more combustible fuel and ignition risks, and of more communities built at the wildland-urban interface, significant challenges lie ahead as we learn more about how to live with the fire component of the ecosystems we occupy.

Burned areas in the last two decades

This chart illustrates global burned area patterns from 2000 to March 2021, using the remote sensing data set from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS).

From 2002 to 2016, approximately 423 million hectares of the Earth's land surface burned annually, the majority (67%) on the African continent.[39] A related analysis estimated that from 2003 to 2016 over 13 million individual fires occurred globally, each lasting 4–5 days.[15] On average, each ignition burned an area of 440 hectares globally, while in Australia individual fires burned up to 1,790 hectares.[15]

The data includes all types of burned areas detected – including cropland, pasture, and natural vegetation – regardless of the ignition source, fire types, or reason for burning.

Data source: The monthly MODIS Burned Area Product (MCD64A1 v006) is publicly available for download from Global Forest Watch (https://globalforestwatch.org/topics/fires)

* South Sudan gained independence from Sudan on 9 July 2011. The burned area data prior to the date have been mapped to the present border demarcations of both countries.

See page 38 for complete references.

2. Human influences on wildfires

Wildfires are a natural feature of the Earth system, necessary for the functioning of many ecosystems. Interactions between vegetation and climate over extended periods establish a particular pattern of wildfire recurrence in a defined ecosystem, known as its fire regime.[40] Deviations from the prevailing fire regime – the timing, frequency, size and intensity of wildfires – can drive significant ecological changes in both fire-dependent ecosystems that need fires to thrive and fire-sensitive ecosystems where fires bring more negative than positive effects.[37,41-45]

Humans directly and indirectly alter fire regimes by modifying landscapes and their vegetation, by starting fires as a land management practice where natural fires rarely occur, by suppressing and preventing fires to protect human communities, and by changing the climate.[42] Land clearing, deforestation, agricultural expansion, resource extraction and urban and rural development are all major land-use changes that can interfere with natural fire regimes.[41]

Fire-sensitive tropical rainforests seldom burn naturally, because fire ignitions are rarely sustained in such a humid environment with moist vegetation.[45] Now wildfires have become more common in some regions where they were not expected to occur, including due to climate change as well as other factors such as land-use change and deforestation. In the Amazon rainforest fires are set by humans: native vegetation is cut down, the more valuable timber is selected and removed, and the remains are left to dry until the debris is deliberately set alight to open space for farms and grazing land.[10,11] Forest fragmentation and the eventual breakdown into savannah and grassland create favourable conditions for future wildfires, resulting in the permanent loss of tropical forest ecosystems.[46]

Growing urbanization, as cities expand into wildland, is another important form of land-use change and landscape transformation. Recent decades saw a rapid expansion of cities towards forest areas in many regions.[47] This wildland-urban interface is the area where wildfire risks are most pronounced.[48]

Inappropriate fire management policies, including aggressive fire suppression, and the low recognition of traditional fire management practices and indigenous knowledge, can generate a cascade of challenges.[11,49-51] In some other cases, attempts to eliminate fire from ecosystems, including fire-dependent ones, can lead to build-up of fuel loads and an associated increase in ignition risks.[52-55] Fire management policies such as these can result in fire regime shifts with large and frequent wildfires becoming prevalent.[37,56]

In recent decades, a growing recognition of the need for a system and whole-of-landscape approach that is integrated with the cultural and ecological significance of indigenous land management is helping to promote ecological health and prevent larger, more destructive uncontrolled fires in ecosystems.[57,58] For example, fire management initiatives in Australian savannahs have measured and monitored the effects of prescribed burning that incorporates indigenous wildfire management techniques, with positive results.[57] This approach has provided inspiring examples for other countries, including in Brazil's Cerrado and Botswana's savannah ecosystems.[59]

On 13 June 2020, a vehicle fire ignited vegetation near a highway in Phoenix, Arizona, USA, resulting in a burned area of nearly 26,000 hectares in 3 days.

The satellite image acquired by the Operational Land Imager (OLI) on Landsat 8 shows the burn scar and some active fire fronts as they appeared on 14 June 2020. The combination of natural colour with the infrared signature of active burning enhances detection of ongoing fires through the smoke.

Source: NASA Earth Observatory

Wildfires in the Anthropocene

Fire ecology

What is a wildfire?

A wildfire is a free-burning vegetation fire, including fires that can pose significant risk to social, economic, or environmental values. It may be started maliciously, accidentally, or through natural means.[38]

A wildfire can be short in duration and small in area but more commonly burns for an extended period of time and over a wide area. The behaviour of a wildfire can be largely benign around its perimeter but will sometimes be characterized by periods of rapid spread and intense behaviour at its front, against which suppression and other risk mitigation efforts may be ineffective. The impacts of a wildfire may be immediately and directly apparent or may materialize some time after the fire is extinguished.[38]

While wildfires can occur naturally, most are a result of human actions such as clearing land after industrial deforestation and for agriculture or human settlement, managing pastures for grazing livestock, and negligence.[38]

Depending on the interactions between vegetation and climate, wildfires generally behave according to a pattern specific to the surrounding ecosystem, known as the *fire regime*. The attributes of a fire regime include frequency, burn extent, intensity, severity and seasonality.

Wildfires can occur naturally when three elements combine:

Ignition
heat from the sun or lightning strike to ignite a fire

\+ **Fuel**
sufficient combustible materials to feed the flames

\+ **Weather**
conditions such as temperature, wind, or relative humidity to enable spread

Wildfire and ecosystems

Wildfires play a key role in maintaining ecological functions and biodiversity. Many ecosystems evolved to incorporate wildfire recurrence and depend on them to maintain ecosystem health. For instance, some plants need recurring fires to trigger germination and burn off competing vegetation. Because species in a given habitat have adapted to a specific fire regime, any change can impact both species and ecosystem as a whole.

Types of wildfires

Depending on biomass fuel and weather conditions, there are three types of wildfire. A single fire event may exhibit all or a combination of these three fire types.

Crown fires
These ascend from ground to tree crown and can spread through the forest canopy. Common in Mediterranean-climate woodlands and boreal forests. The most intense and dangerous wildfires, often the most difficult to suppress. Spread generally requires heavy fuel loads and strong winds.

Surface fires
These burn through leaf litter, dead material and vegetation on the ground. Predominant and frequent in grasslands and savannahs where productivity is high. Also common in woodlands and forests where litter is the main fuel. Surface fires can spread vertically by igniting bushes and shrubs to become crown fires.

Ground fires
These burn decomposed organic subsurface layers of soil and usually do not produce visible flames. Difficult to fully suppress, ground fires can smoulder over winter and may re-emerge in spring. Most common in peatlands and bogs, and can develop into surface fires.

Fire-dependent plants

In fire-prone ecosystems, many plant species depend on recurring fires in their life cycle. Fires trigger flowering, seed dispersal, or seed germination.[36]

Some species common to boreal forests and Mediterranean-climate regions store seeds in cones for years until a fire event triggers their release.

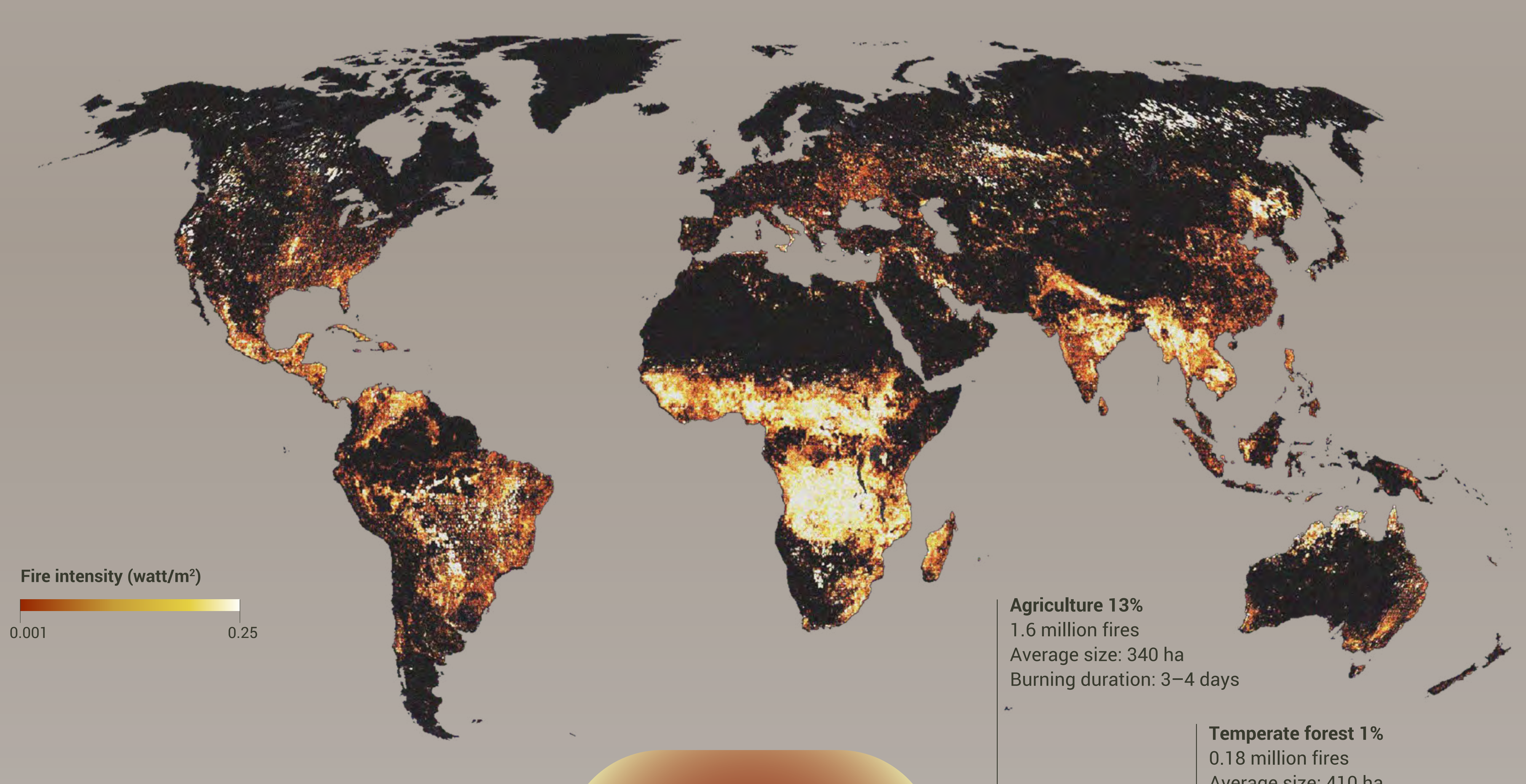
Wildfire events stimulate flowering in bulb-producing plants such as orchids and lilies, and in perennial grasses.

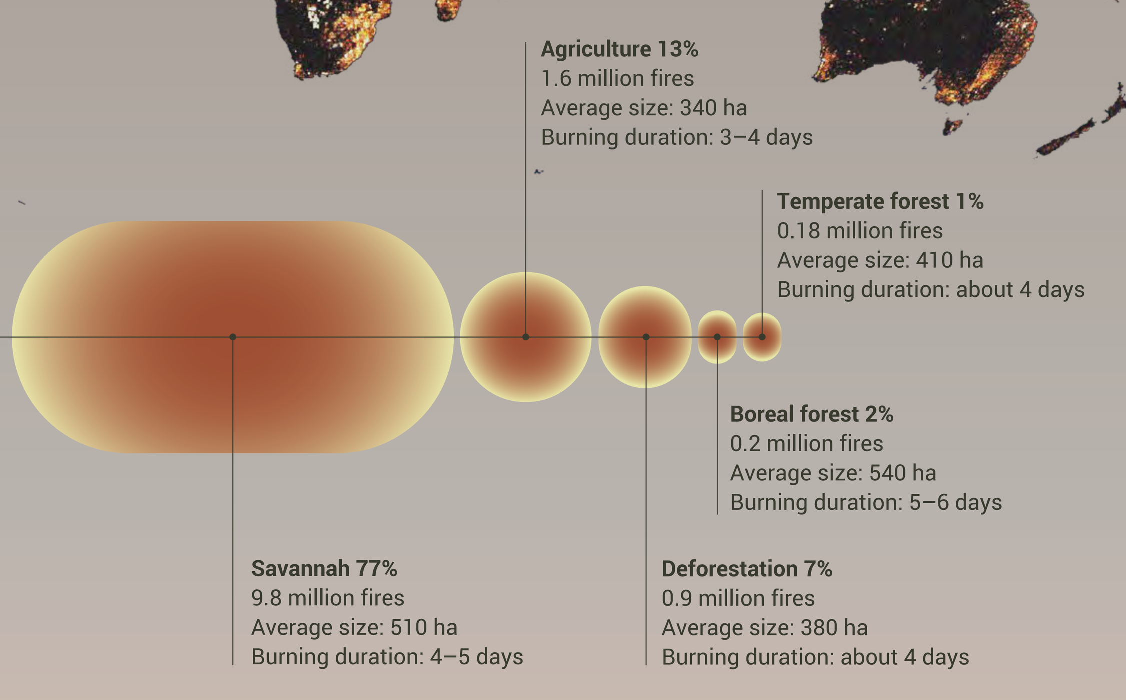
Smoke and charred wood can also induce seed germination in many species in fire-prone shrublands.

Where fires burn

The map shows active fires of all types observed from 1 January to 20 September 2021. The image was created by merging still frames extracted from NASA's time-lapse video of active fires. For best viewing of the dynamic changes in fire intensities over time, go to NASA Scientific Visualization Studio.

See the timelapse ▸





Number of fires detected from 2003–2016

From 2003 to 2016, over 13 million individual fires occurred globally with mean durations lasting from 4 to 5 days, varying by continent and fire circumstance.[15] Average burned area of each fire was 440 hectares.[15]

Fire regimes are changing

Changing fire regimes in selected biomes

The table adapted from Bowman *et al.* (2011)[35] summarizes how regimes in selected biomes from low to high latitudes have changed following global industrialization.

Biome	Tropical rainforest	Tropical savannah	Mid-latitude desert	Mid-latitude North American seasonally dry forests	Boreal forest
Pre-industrial fire regime	Very infrequent low-intensity surface fires with negligible long-term effects on biodiversity	Frequent fires in dry season causing spatial heterogeneity in tree density	Infrequent fires following wet periods that enable fuel build-up	Frequent low-intensity surface fires limiting recruitment of trees	Infrequent high-intensity crown fires causing replacement of entire forest stands
Post-industrial fire regime	Frequent surface fires associated with forest clearance causing a switch to flammable grassland or agricultural fields	Reduced fire due to heavy grazing causing increased woody species recruitment	Frequent fires due to the introduction of alien flammable grasses	Fire suppression causing high densities of juveniles and infrequent high-intensity crown fires	Increased high-intensity wildfires associated with global warming causing loss of soil carbon and switch to treeless vegetation

Source: Adapted from Bowman *et al.* (2011)[35]. Published with permission from John Wiley & Sons Ltd.

Photo credit for mid-latitude North American seasonally dry forest: kenkistler / Shutterstock.com

Land-use change

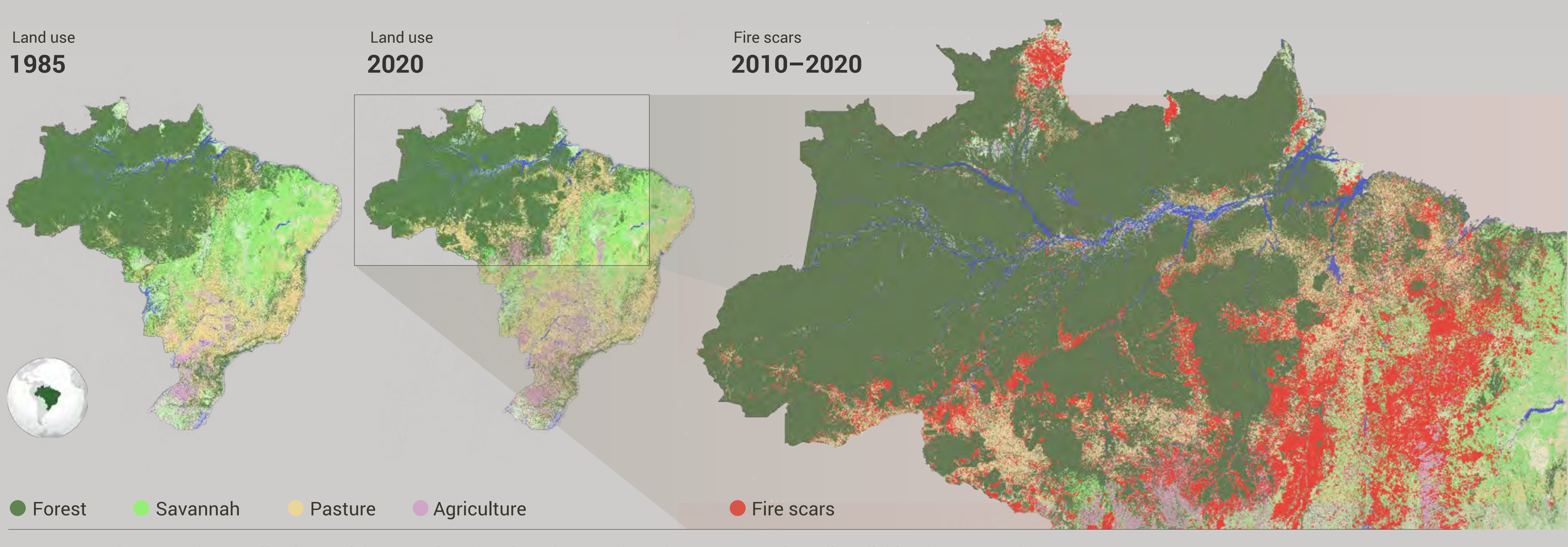
Land-use changes associated with agriculture, deforestation and urban development are driving substantial changes to fire patterns in a wide range of ecosystems.[35]

People frequently use fires to manage land where wildfires are rare, or suppress fires where wildfires are common. Land conversion from native vegetation changes fuel properties that may lead to higher severity or frequency of wildfires.

Around the Mediterranean, reduction in pastoral activities has converted grasslands into highly flammable shrublands.[36]

In tropical rainforests where most species have not evolved to recover rapidly from fire, wildfire is often used to convert forests to ranches and farmlands. This land clearing changes fire regimes at local scale, which becomes ecosystem conversion at larger scale.[41]

In Brazil, land-use changes such as deforestation and agriculture have resulted in an increase in fires across the country, including in the Amazon rainforest region where fires were previously rare.



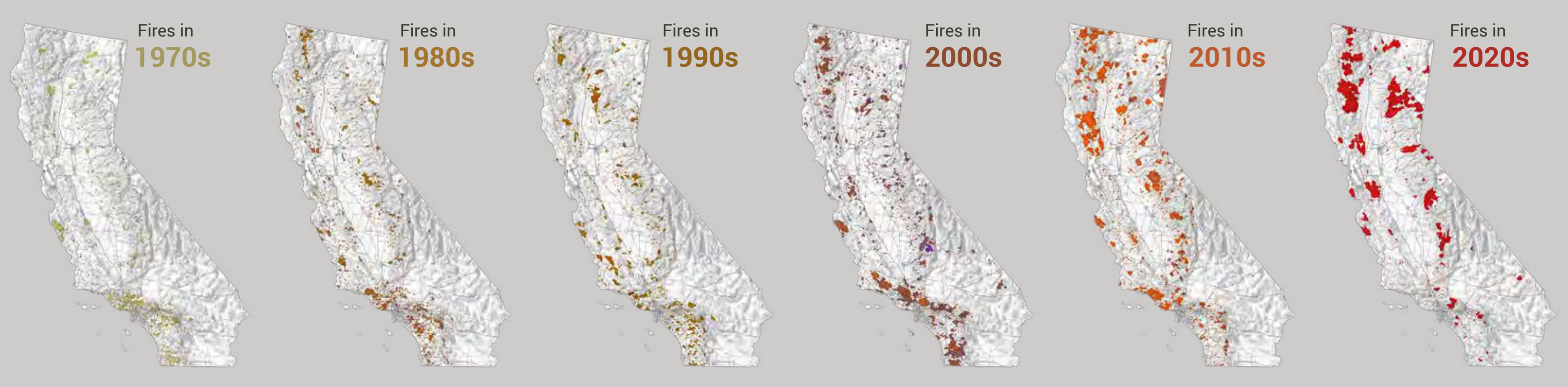
Source: MapBiomas Project - Collection 6 of the Annual Series of Land Use and Land Cover Maps of Brazil available at http://mapbiomas.org.
MapBiomas Project is a multi-institutional initiative to generate annual land use and land cover maps from automatic classification processes applied to satellite imagery.

Expanding wildland-urban interface

Urban development at the wildland-urban interface requires that fire risks be managed and aggressively suppressed, resulting in changes to natural fire regimes.[42]

Land development not only modifies vegetation, but the fire suppression and exclusion policies, intended to protect human lives and properties, also lead to fuel accumulation and severe fires when they do burn.[35,37]

The burned area and average size of wildfires in California, USA, have increased in the last decades. Rapid urbanization along the forest edges, accumulation of biomass fuels from decades of fire suppression and extreme drought and heat exacerbated by climate change contribute to the surge in large fires.



Source: NASA Earth Observatory (https://earthobservatory.nasa.gov/images/148908/whats-behind-californias-surge-of-large-fires)

Fire and invasive species

Human activity is largely responsible for introducing invasive species that can alter fire regimes by changing the vegetation structure within the ecosystem, changing fuel quantity and properties.[37]

Altered fire regimes can create conditions unsuitable for native vegetation to recover after a wildfire, but suitable for invading fire-tolerant species to flourish.

Across many ecoregions of the USA, invasion by certain non-native grasses has increased fire occurrence by 230% and fire frequency by 150%.[44]

Many invasive grasses have high fuel biomass and low moisture, creating conditions favourable for wildfires. Some of the most successful invasive grasses germinate seeds when cued by heat and smoke.

3. Changing climate, changing fire weather

In November 2019, numerous bushfires were burning north of Sydney, Australia, with thick smoke blowing towards the coastal cities of Coffs Harbour and Port Macquarie. Air quality in the affected cities reached hazardous levels. Record-breaking temperatures, strong winds and a persistent lack of rainfall enabled massive bushfires across the state of New South Wales.

Source: NASA Earth Observatory.

Globally, many types of extreme weather events are now more intense and occurring more frequently than in the past due to anthropogenic climate change.[27,28] Long-term warming trends show that most years are now hotter than those observed before 1950 in 41 out of the world's 45 regions.[28] Hotter temperatures, coupled with more droughts, lead to longer fire seasons and more likelihood of dangerous fire weather conditions.[1,26-34,60,66]

Research focusing on western North America shows that heatwaves and multi-year droughts are not only fostering more wildfires, but the wildfires are increasing in severity and burning larger areas.[30,34,61] In South America, severe and prolonged droughts and higher air temperatures are associated with increased fire incidence and severity in humid tropical areas and seasonally flooded wetlands, including areas where wildfires were unprecedented.[14,62-65] In the temperate climate region of Australia, rainfall in the period leading to the fire season has declined by over 10 per cent since the late 1990s.[67] Based on over 100 years of data, 2019 was Australia's hottest and driest year on record.[5,66,67] In Chile, New Zealand and parts of Africa, research has also shown the influence of climate change in increased drought conditions and forest fire activity.[62,68-71] In Southern Europe and around the Mediterranean Sea, climate change is likewise driving more dangerous fire weather conditions as the entire Basin transitions into a more arid system.[2,28,35,72,73]

> "Globally, many types of extreme weather events are now more intense and occurring more frequently than in the past due to anthropogenic climate change. Hotter temperatures, coupled with more droughts, lead to longer fire seasons and more likelihood of dangerous fire weather conditions."

Lightning is an important natural ignition source for wildfires and frequency of lightning strikes in some parts of the world are projected to increase with a changing climate.[74-81] In recent years climate-driven lightning ignitions account for the majority of burned areas in the North American boreal forests.[82] An increased frequency of dry lightning – a type of lightning that occurs with little or no precipitation – has also been documented in some parts of southeast Australia in recent decades, while some areas experienced a decline.[83] Of the total area burned by wildfires, a significant proportion can be attributed to lightning ignitions, because they can occur variably over time and space and they spread in remote regions that are difficult to reach with response capabilities.[74]

Another phenomenon that has become more frequently reported in Australia and North America in recent decades is the fire-generated thunderstorm.[4,6,84-89] A characteristic of more extreme fire events, these thunderstorms form in wildfire smoke plumes, generating what are known as pyrocumulonimbus clouds. The frequency of weather conditions associated with the occurrence of fire-generated thunderstorms is increasing over time in parts of southern Australia, with these increases projected to continue.[4,77,86,90] Fire-generated thunderstorms can contribute to more dangerous conditions for fires on the ground, including more erratic wind speeds and changes in direction, as well as generating lightning that can ignite new fires far beyond the fire front.[85] They illustrate the risk of dangerous feedback loops between the fire and atmospheric processes.

Available biomass fuel is a key factor driving fire intensity under the uncertain influence of climate change. Fuel loads may increase due to the CO_2 fertilization effect when higher carbon dioxide concentrations at ground level encourage certain plant types to thrive.[91-93] While the bulk of organic material could increase, lower relative humidity would turn the greater bulk into dry fuels for wildfires. Fuel load has also increased due to the practice of wildfire exclusion in some cases.[26,94] Better comprehension of fire-dependent ecosystems, and fire ecology as a whole, is fostering the shift toward integrated fire management including the use of controlled and prescribed burning at appropriate times and under the correct conditions to reduce fuel loads.[42,95]

While climate change is already influencing wildfires, wildland fires may likewise be influencing climate change.[28,96,97] Loss of the Amazon rainforest and thawing of Arctic permafrost are considered two possible tipping elements that could potentially accelerate climate change.[28,98,99] Recent research has indicated deforestation in the Amazon is shifting the region from a carbon sink to a carbon source and permafrost thaw is accelerating in the Siberian Arctic, with fires as contributing factors in both cases.[87,88,100]

Climate change:
Fire weather is becoming more extreme

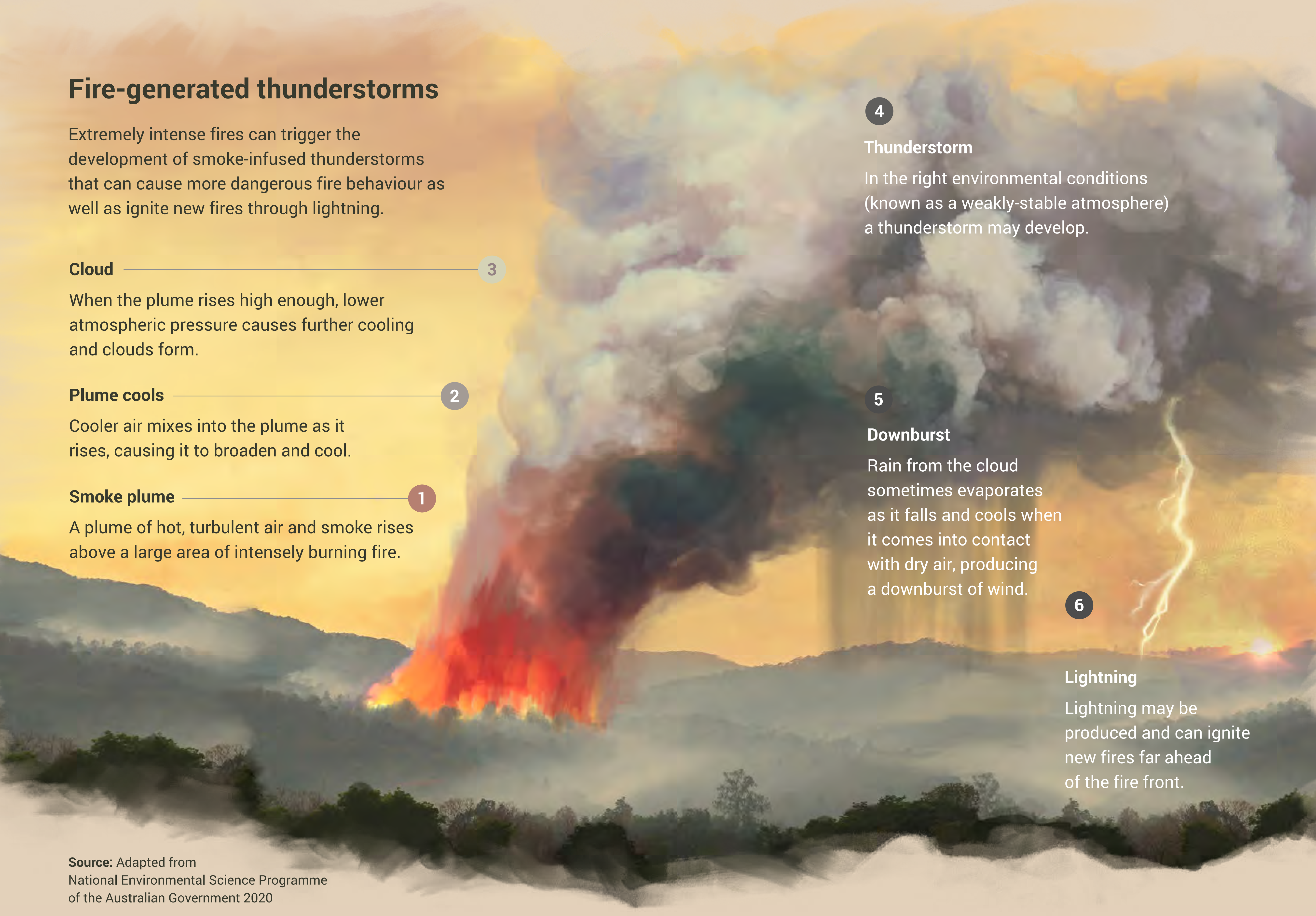
Climate change is increasing the risk of large and more intense fires.[5,6,42] Climate directly affects the production and condition of biomass, and weather that supports fire ignition and propagation. In the months preceding fire season, prolonged warm and dry weather reduces vegetation moisture, increasing risks of fire ignitions that may develop into wildfires and spread. In contrast, unusually high rainfall increases plant growth that then may serve as fuel in the next dry season. Large fires in woody ecosystems occur during prolonged drought events, such as in regions affected by El Niño variability.[5,36]

Lightning ignition

Lightning is an important natural ignition source for wildfires. Lightning strikes are projected to increase in frequency in some parts of the world as climate changes. Lightning ignition is the predominant driver of massive wildfires in the boreal forests of North America and northern Siberia.[60]

Fire-generated thunderstorms

Extremely intense fires can trigger the development of smoke-infused thunderstorms that can cause more dangerous fire behaviour as well as ignite new fires through lightning.



Cloud 3

When the plume rises high enough, lower atmospheric pressure causes further cooling and clouds form.

Plume cools 2

Cooler air mixes into the plume as it rises, causing it to broaden and cool.

Smoke plume 1

A plume of hot, turbulent air and smoke rises above a large area of intensely burning fire.

4 **Thunderstorm**

In the right environmental conditions (known as a weakly-stable atmosphere) a thunderstorm may develop.

5 **Downburst**

Rain from the cloud sometimes evaporates as it falls and cools when it comes into contact with dry air, producing a downburst of wind.

6 **Lightning**

Lightning may be produced and can ignite new fires far ahead of the fire front.

Source: Adapted from National Environmental Science Programme of the Australian Government 2020

Impacts of extreme wildfires on the Earth's system

Atmospheric pollution

Large wildfires emit vast amounts of atmospheric pollutants, such as black carbon, particulate matter, and greenhouse gases. These pollutants may be transported a long distance and deposited over remote landscapes, including glaciers.

Changed albedo

Atmospheric transport and deposition of soot reduces surface albedo and enhances snow and ice melt. Soot deposits from Amazon basin wildfires are found to increase the melting of the Andean glaciers.

Carbon sink turns into carbon source

Large and frequent wildfires in boreal and tropical forests may transform terrestrial carbon storage into major sources of greenhouse gases.

Water pollution

Following severe wildfires, elevated sediment levels in rivers increase turbidity, alter water temperatures, and affect fish abundance.

Post-wildfire erosion brings a range of nutrients and contaminants into water bodies, affecting water quality and aquatic species.

Nutrients such as nitrogen and phosphorous released into water bodies can cause eutrophication and reduce the levels of dissolved oxygen, posing a risk to aquatic organisms.

See page 40 for a complete reference.

Erosion

Wildfires increase the susceptibility of soil to erosion when exposed to postfire precipitation. Erosion normally occurs before vegetation has redeveloped. Slope failures can lead to catastrophic debris flows and landslides in some environments.

Ocean fertilization

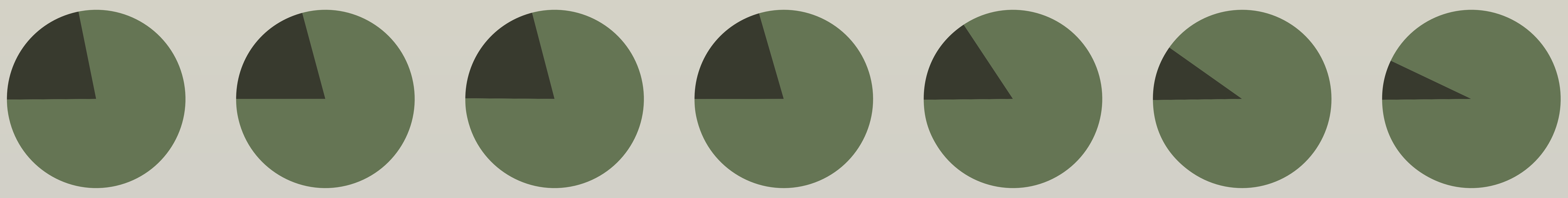
Large, intense wildfires release enormous amounts of aerosols, including bio-essential trace metals such as iron. Atmospheric transport of iron-rich aerosols from the 2019/2020 Australian extreme wildfires caused large-scale algal blooms in the South Pacific over a 4-month period.

Biodiversity loss

More frequent and more intense wildfires can produce a long-term change in plant species composition and structure of forest ecosystems. Reburns may also become more common, potentially reducing post-fire regeneration. Depending on the original forest type, reburns could possibly result in a shift to non-forest vegetation.

Species under threat of altered fire regimes

Percentage of species threatened by altered fire regimes including fire exclusion per habitat



Savannah	Grassland	Rocky areas	Shrubland	Forest	Wetlands	Desert
28.0%	26.3%	26.0%	25.7%	18.7%	10.9%	7.6%
463 species	1,315 species	822 species	1,768 species	7,629 species	4,469 species	144 species

Source: Kelly *et al.* (2020). See page 40 for a complete reference.

4. Wildfire management improvements in the face of further climate changes

As the loss and damages from extreme wildfires mount, needs for both prevention and response management approaches are gaining attention. The threats will only increase as anthropogenic climate change intensifies, including in cases where land-use changes fail to follow best practices to conserve ecosystem resilience and landscape integrity.

While developed country practices have often emphasized fire exclusion, many developing countries lack capacity to manage fires, beyond responding once the disaster becomes an immediate threat to life and property. Effective fire management is important in fire-dependent ecosystems, such as savannahs and grasslands, where fuel loads build up and increase fire risks, especially in the peak of the dry season.[53] Whether ignited by lightning or humans, fuel loads that have accumulated over years or decades can result in uncontrollable wildfires. In contrast to total fire exclusion approaches, recognition of indigenous practices that maintain manageable fuel loads and productive ecosystems through periodic controlled burns is now a common practice in some regions.[50,57,59,107,110] However, certain countries still follow wildfire suppression policies, where attempts to exclude fire completely from the landscape can add to the intensity and severity of dry season wildfires.[55]

Community-owned solutions in Latin America

Divinópolis, Minas Gerais, Brazil **Credit:** Christyam de Lima / Shutterstock.com

The absence of adequate fire management policies in Latin America dates back some centuries.[55,101,102] Yet increasing extreme wildfire events have demanded special attention from rural, traditional and indigenous communities, who are not only directly affected by such disturbances, but are also restrained in managing their own territories in some cases.[10] These peoples have therefore implemented ancient fire management practices that deliver the safest outcomes by protecting themselves, conserving the natural ecosystems essential to their livelihoods, producing crops, and preventing wildfires spreading.[10,50,103]

In the last decade some Latin American governments have recognized traditional fire knowledge and learn from these ancient fire management techniques to adjust their wildfire prevention strategies.[55,103] In 2014, a pilot programme of integrated fire management was initiated in Brazil, encouraged by the Brazilian-German Cooperation Project "Prevention, Control and Monitoring of Bushfires in the Cerrado", and inspired by a successful Australian abatement and carbon sequestration accounting methodology.[104,105]

The programme started in 3 Cerrado protected areas and after 5 years scaled up to 74 areas distributed across all Brazilian biomes.

This integrated fire management reduced the area burned by late dry season wildfires by up to 57% and mitigated 36% of the associated greenhouse gas emissions.[50,106] In addition, more than 2,000 local, traditional and indigenous fire brigade members are being hired and trained annually to operate in preventive and suppression activities, as well as to collect data for assessing the effects of different fire regimes on plant and animal species.[107,108] A concerted effort to hire and train indigenous women from the Xerente community includes focus on equipment, mobilization and controlled fire techniques, safety, as well as general environmental education.[108]

The programme's reach is still limited to some protected areas, and most of the Brazilian territory is still highly vulnerable to catastrophic wildfires, such as those experienced in 2019 and 2020. Nevertheless, there is great potential for rural landowners and the government to scale up these successful management practices to reduce repeated annual wildfire losses and risks.

Longer fire seasons as influenced by climate warming can hamper the practice of controlled burns since the conditions for safely undertaking these fuel reduction burns are specific. Rising temperatures and increasing fuel availability, through longer growing seasons and hotter, drier weather, may change opportunities for safe controlled burns, which has consequences for the long-term management of wildfire risk.[91]

Long-range planning depends upon various cooperative components among countries and world regions, including the sharing of resources such as aircraft and firefighters between the Northern and Southern Hemispheres. This worked well when fire seasons did not overlap. Now, with longer fire seasons and more intense demand on firefighting resources during extreme wildfires, this sharing of capabilities will become increasingly difficult.[3,34]

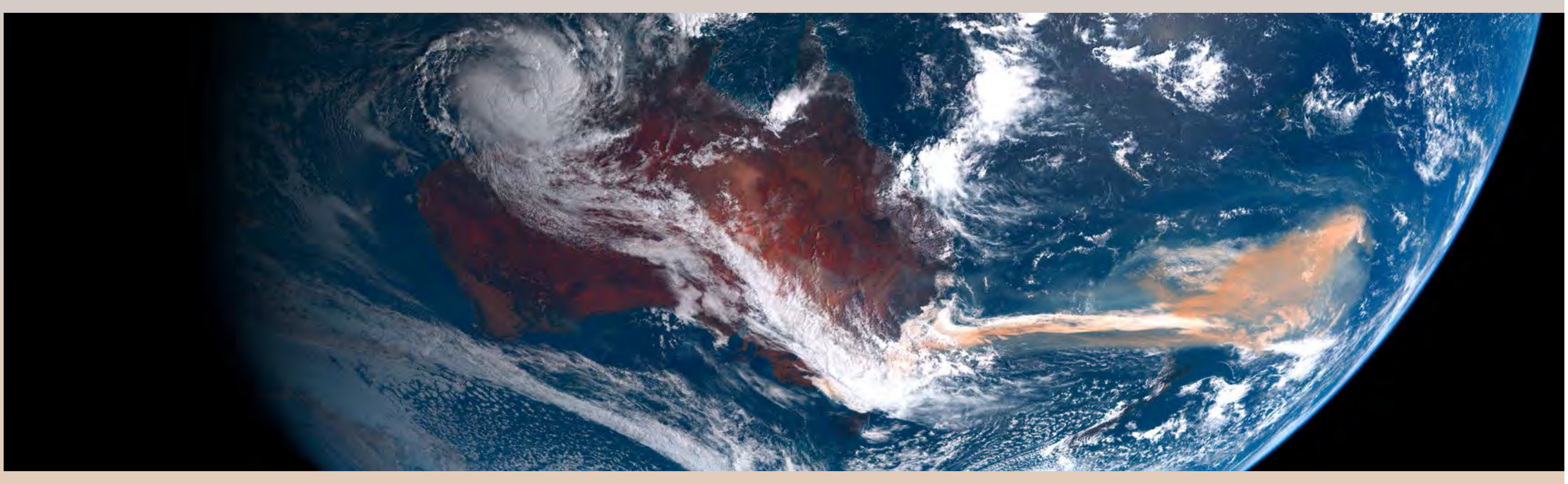
The Royal Commission investigating Australia's 2019/2020 fires presented a wide-ranging set of recommendations, comprehensively covering improved planning, policies, and practices; increased fire-fighting capabilities; enhancing community resilience; and land management strategies that include indigenous practices of controlled burning.[3] The recommendations supported improved design standards for buildings and infrastructure at the wildland-urban interface. This could provide a practical means to incorporate climate change science into routine practices for enhanced resilience, using knowledge of how risk factors have already changed and are likely to continue changing.

The next decade will be critical in building greater resilience and adaptive capacity to wildfires. Use of participatory approaches and involvement of vulnerable groups in all phases of preparedness and response is necessary.[109] Implications for children, women, elderly, people with disabilities, and other at-risk groups can affect whole communities and society at large, both at the time of the extreme event and for years afterwards. Local knowledge can help address questions of ecological integrity and social justice.[110] Calls for further research should address vulnerable groups' exposure to hazard risks before, during and after extreme wildfires.

Additional and improved research on reducing fire risk should include cost assessments integrated with social science and environmental assessments of how effective different actions might be.[110] Enhanced scientific understanding of extreme wildfires should examine how land-use change or land management affects these events. Further research should explore how lightning and vegetation conditions may change in the future, noting considerable uncertainty due to the limitations of currently available climate modelling methods, especially through observations and data collection on extremes including wildfire-generated thunderstorm systems.[84]

Pressure will become more pronounced with further loss and damage that climate changes bring. To avoid the disastrous impacts of worsening extreme wildfires, our ability as communities to prepare for, respond to and manage these extreme fire events must match or exceed the rate of climate change influence accelerating their threat.

Building resilience: new tools and approaches to wildfire management



The image taken on 6 January 2020 shows the long-range atmospheric transport of aerosols from the unprecedented wildfires along the south-eastern coast of Australia towards the broad South Pacific. The oceanic deposition of wildfire aerosols stimulated large-scale phytoplankton blooms. **Source:** Japan Meteorological Agency and NASA

The increased frequency and intensity of natural disasters are posing a greater challenge to existing approaches to disaster risk reduction. New tools offer an enhanced ability to address systemic disaster risk. Globally, refinements in modelling and observations data, including from remote sensing capabilities – satellites, ground-based radar, lightning detection, and data processing – facilitate improved systems for monitoring, predicting and managing wildfires.

The monitoring and data handling power offered by systems such as the European Union's Copernicus programme on Earth observations and the US National Aeronautics and Space Administration are supporting efforts worldwide.[112] The Latin-American Regional Network for Remote Sensing and Forest Fires enables joint efforts and resolutions for fire management operations in Latin America.[113] Brazil's National Institute for Space Research promotes research and enhances monitoring capacity throughout the region with the Queimadas Programme, developing innovative tools for wildfire risk detection and frequently updated heat source information.[114]

South Africa uses a nested model for fire prevention and management, through the Working on Fire programme, in which provincial fire protection associations coordinate with district and local counterparts to develop community skills and employment focused on fire management and firefighting.[115]

Australia now has long-range prediction capability for fire weather conditions, providing guidance to fire agencies to help with decision-making over a broad range of timescales. Climate change projections are also provided to emergency management groups, including fire agencies and planners. This aids evidence-based decision-making on climate hazards related to environmental management, energy, infrastructure, health and finance sectors.[116]

The *Australian National Disaster Risk Reduction Framework*, endorsed into national policy in March 2020, identifies climate change as a fundamental driver for building disaster resilience and taking a systems approach to managing the complexity inherent in disaster reduction and response.[117] It recognizes the importance of developing resilient communities through social and economic networks that cooperate and share responsibility in responding to disasters and adapting to climate change.[118,119] In recent years, the country's approach to disaster management has included an emphasis on strengthening resilience and capacity before disaster strikes.[117] Establishing a network and national capability of knowledge and skills through partnerships, education and professional programmes across sectors is fundamental not only for wildfire management, but also for broader resilience to natural disasters.[120]

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Phenology

Climate change is shifting the rhythm of nature

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1. Timing is everything for ecosystem harmony

Timing is critical in the natural world. Birds' chicks must be hatched when there is food to nourish them, pollinators must be active when their host plants flower, and snow hares must change their colour from white to brown as the snow disappears. Phenology examines the timing of recurring life-cycle stages, driven by environmental forces, and how interacting species respond to changes in timing within an ecosystem.[1,2] Plants and animals often use temperature, daylength, the arrival of rains, or other physical changes as cues for the next stage in their seasonal cycle. When spring arrives earlier, many birds react by breeding sooner, matching the advanced emergence of food for their nestlings as temperatures warm. Because temperature is such a strong influence on these cues, phenological shifts over the past decades are among the most visible consequences of global climate change, at least in temperate and polar regions of the world.

Temperature is not the only environmental variable that affects phenology. At higher latitudes, another critical variable is photoperiod, or daylength, varying at different times of year.[3-5] While photoperiod itself is not affected by climate change, the degree to which temperature affects phenology can depend on it: in some systems, high temperatures will cue the next stage during a long photoperiod, but not during a shorter one.[3,6,7] At higher latitudes, some plants and insects also need a spell of low temperature, called winter chilling, to respond well to warmer temperatures once they arrive.[8-10] Some species depend on fire to cue life-cycle stages, such as fire-stimulated seed release from cones and seed germination.[11,12] An aquatic example is the influence of rain on river discharges that in turn influence the timing and duration of the migration of fishes, along with water temperature and photoperiod factors.[13-15]

Understanding phenology in tropical regions is more complicated than in regions that have clear annual seasonal cycles, due to less variations in temperature and daylight.[16-18] Tropical species show diverse phenological strategies, individuals within a population may not synchronize, and cycles can be shorter than 12 months. Different factors, including rain, drought, moisture availability and abundant exposure to sunlight, can trigger the next life-cycle stage in tropical regions.[17-21]

A major concern with phenological changes in response to climate change is that not all interdependent species in a particular ecosystem shift in the same direction or at the same rate.[16,22-26] The reason for varying shifts is that each organism is sensitive to different environmental drivers, or shows different levels of sensitivity to a single environmental driver.[5,17,27,28] Within food chains, plants may shift their development more quickly than animals that feed on them, leading to phenological mismatches. Detailed studies on various life-cycle stages across a wide range of plant and animal species have detected significant phenological mismatches.[16,22,30-34] These mismatches between predator and food source within a food web will affect individuals' growth, reproduction and survival rates, with eventual repercussions for whole populations and ecosystems.

Image credit: Meyers Lexicon book from 1908 and Nicku / Shutterstock.com.

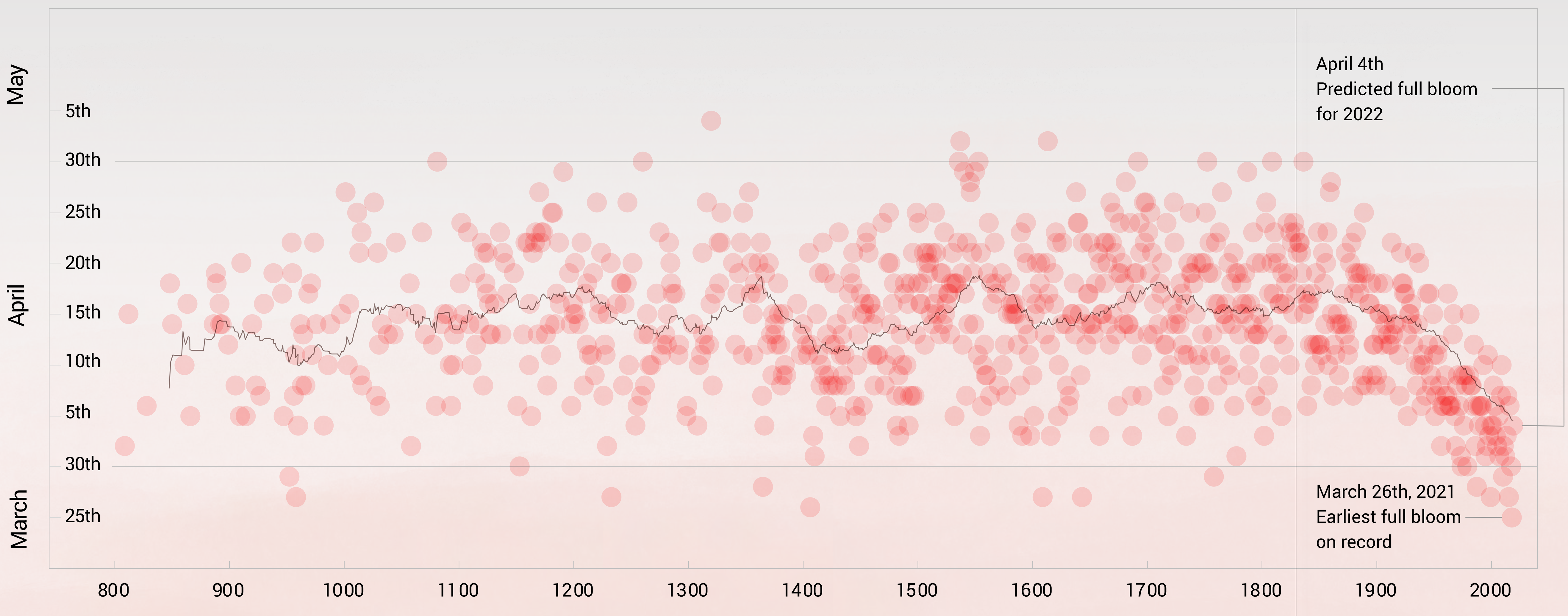
Phenology in the tropics

A key feature of tropical climates is the lack of distinct seasonal temperature variations.[18] In contrast, changes in rainfall and the switch between dry and wet seasons define clearer phases within annual cycles of the tropics.[16,18] The frequency and intensity of rainfall, or its absence, is a crucial driver of phenological changes in tropical plants, as well as sunlight, humidity, and the subtle temperature changes.[16-21] Given the high species diversity in tropical ecosystems, phenological responses to those drivers are various and complex, within species and communities.[19,35]

Rainfall patterns in tropical regions are highly influenced by the El Niño/La Niña Southern Oscillation (ENSO), characterized by its alternating warm and cool phases of sea surface temperature in the equatorial Pacific Ocean.[36] These anomalies occur every 2-7 years and typically last for 9-12 months.[36] Tropical plant communities respond to ENSO events, such as El Niño-induced mass flowering or drought-affected fruiting.[17,18,20,37] More frequent and more intense extreme weather events, delivered by ENSO and climate change, are likely to further disrupt the timing of leafing, flowering and fruit production.[17,18] Such phenological changes will have cascading effects on dependent herbivores, nectarivores and frugivores, as well as other functional groups within the ecosystems.[17,19] Long-term observations of phenological change in the tropics are still scarce, and predicting the magnitude of phenological shifts and mismatches remains a challenge.[18]

Blooming of cherry blossom over 1,200 years

Trendline is 50-year moving average



Data source:
Historical data courtesy of Dr. Yasuyuki Aono, Osaka Prefecture University, Japan, available at http://atmenv.envi.osakafu-u.ac.jp/aono/kyophenotemp4/

Data from 1950 courtesy of Japan Meteorological Agency, available at http://www.data.jma.go.jp/sakura/data/index.html

The blooming of cherry blossom (*Prunus jamasakura*) marks the arrival of springtime in Japan and is central to Japanese culture. Celebration of cherry blossom has been traced back to around 712 A.D.[38] Phenological observations in Kyoto have been historically recorded in old diaries and chronicles.[39-41] Researchers have assembled a phenological data series of full-flowering dates of cherry blossom from these documents, dating back as early as 812 A.D.[39-41]

Over 1,200 years, the full-flowering dates started as early as late March and as late as early May.[42]

Blossoming has advanced progressively to earlier dates since 1830s, which also coincided with rising temperatures based on meteorological observations, with the bias effects of urban heat already eliminated.[41,42]

2. Disruption in ecosystem harmony

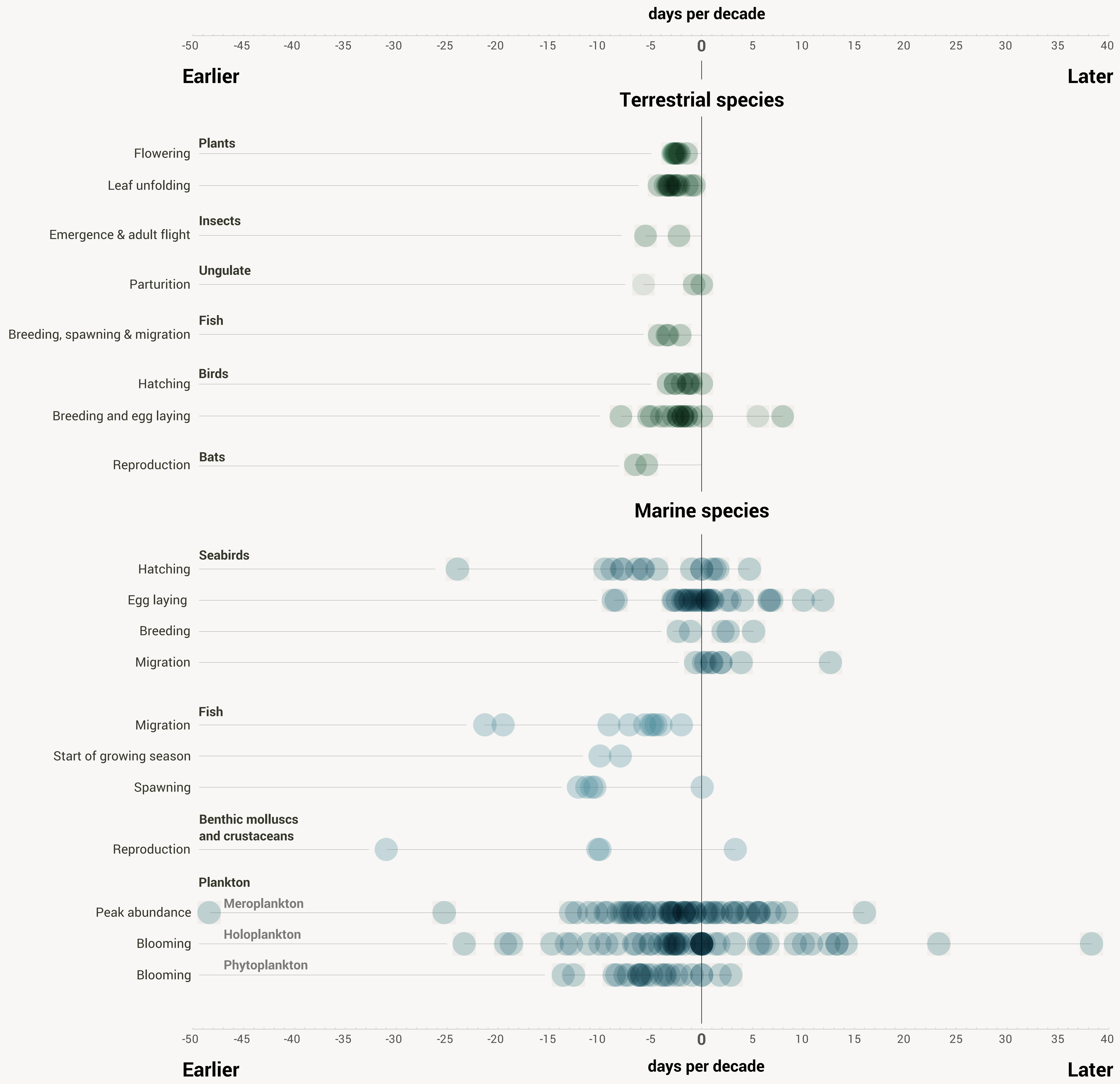
Shifts in phenology due to climate change have been detected at a variety of stages: reproduction, flowering, leaf-out, onset of larval development, moult, hibernation, migration, and others. Supporting data come from studies comparing phenological shifts among large sets of species – plants, insects, fish, amphibians, birds and mammals, for which phenological events have been recorded over the long term through observations in both hemispheres.[16,23,29-33,43-51] Researchers have also tracked an increasing probability of phenological mismatches across multiple regions, including through 10,000 data sets on plants and animals across the United Kingdom, terrestrial species in the Alps, over 1,200 time series of phenological trends in the southern hemisphere, and marine species across different oceans, among others.[16,19,23,32,43,51]

Identifying shifts, tracking trends

In the early 2000s, researchers published a few pioneering broad-scale assessments of phenological shifts that became models for ongoing work.[22,29,30] A synthesis of those databases indicate that the life stages of 203 plant and animal species advanced by about 2.8 days per decade.[30] Since then, additional ecosystems and biomes have been assessed for phenological trends. The visualization below presents the observed phenological shifts within taxonomic groups tracked in recent assessments.[31-33,49]

Each circle represents a quantified rate of phenological response of a particular species as it shifts a life-cycle stage to earlier or later by a number of days per decade. Circles appear as overlapping when two or more species in the same taxonomic group shift at similar rates.

See page 57 for complete references.



Hungry birds and early caterpillars

A long-standing, well-known example of phenological mismatch is between the great tit (*Parus major*) and its caterpillar food.[54,55] This small hole-nesting songbird is found across Asia and Europe and produces unusually large broods. The parents must provide large amounts of nourishment for fast-growing nestlings in the 18 days it takes for their full development. Adults may deliver caterpillars at the rate of almost one per minute during that period.[72] To ensure this level of food supply, the birds use temperature as a cue to time their breeding so the nestlings arrive at the peak abundance of caterpillars on oak trees. For similar reasons, the hatching of caterpillar eggs is timed with the emergence of oak trees' young foliage.[73]

Field observations show varying phenological responses in these two interacting species across different sites.[54,55,74,75] The great tit population in the Netherlands has advanced its egg-laying in response to warming trends, but the shift is not enough to match the peak of the caterpillar population.[54,55,74] Forecasts indicate that the caterpillars' phenology will continue to advance faster than the birds' in the coming decades, further increasing the mismatch.[76] In contrast, a 47-year population study in the United Kingdom found that both birds and caterpillars shift their timing at approximately the same rate, keeping the interaction in synchrony.[75] Similar results were found in Belgium and the Czech Republic.[77,78] These findings demonstrate the complexity in phenological responses among species and populations in different environments.[27,80]

Studies on birds provide ample evidence of mismatches affecting successful breeding. Species such as pied flycatchers (*Ficedula hypoleuca*) and great tits (*Parus major*) need their chicks to hatch when their normal food supply of caterpillars is most abundant.[52-55] This peak food-supply period is short, covering only a few weeks, so the correct timing is crucial. Other birds, like the common murres (*Uria aalge*), need to precisely time their reproduction to the inshore migration of their main prey, small forage fish.[56]

Within the annual cycle, different life stages need to synchronize. For migratory species, annual cycles involve stages of moving to breeding grounds, reproducing, moulting and returning to wintering grounds. Some life-cycle stages, like reproduction, are highly temperature-sensitive. With warming temperatures, reproductive phenology is shifting, while other stages, like moult, are more sensitive to photoperiods, so they are not occurring in synchrony.[57,58]

Phenological responses differ throughout marine ecosystems and seasonal cycles, leading to mismatches between species and among groups in the food web.[31,32,43,59] Research shows that phenological responses to climate change happen faster in marine environments than on land.[31,32] The different marine groups, from plankton to higher-up predators, all shift their phenology at different rates, indicating that climate change can cause mismatches in whole oceanic communities as well.[31,32,60,61]

Differences in the rates of phenological responses to warming across terrestrial, freshwater and marine ecosystems could ultimately affect species that depend on different ecosystems to host phenological transitions to the next life-cycle stage. Examples include fish that migrate between marine and freshwater ecosystems, and many insects, amphibians and birds whose life-cycle stages depend on both terrestrial and aquatic ecosystems.[24,62-64] Mismatched phenological shifts could cause widespread food-web disruptions and ecological consequences.[26]

While phenological responses to climate change are well-documented, remaining questions about links to populations and consequences for ecosystems deserve greater attention.[34,51] In the Arctic, after snowmelt, the vegetation that caribou (*Rangifer tarandus*) mothers and calves depend on has advanced significantly due to higher temperatures. Now caribou calves are born too late, leading to a 75 per cent decrease in offspring.[65] In roe deer (*Capreolus capreolus*), the increased mismatch between birth date and food availability also decreases calves' survival chances.[66]

Asynchronous changes in the phenology of a broad range of interacting species have the potential to disrupt the functioning of whole ecosystems and the provision of ecosystem services on which human systems depend.[34,61] Shifts in the phenology of commercially important marine species and their prey have significant consequences for all aspects of fisheries.[47,67-69] Phenological responses in crops to seasonal variations will be challenging food production in the face of climate change. For example, fruit trees that bloom early and then experience late-season frosts result in large economic losses for orchards.[70] Phenological shifts are already complicating climate-smart agricultural adaptation for major crops around the world.[71]

Incredible journeys:

The challenge of mistimed migration

Migration is a behavioural adaptation to seasonality.[81] Periodic movements of animals between habitats allows them to optimize resources in multiple locations at different times of year. Migration is also necessary when seasonal air or water temperatures become unfavourable for breeding or rearing offspring. Most migratory species are therefore from high-latitude regions where changes in season and available resources are most marked.[81] Diverse species of insects, crustaceans, reptiles, fish and mammals migrate, and many cover remarkable distances. Some avian migrants nest in the high Arctic and escape its winter to lower latitudes; cetaceans migrate between the equator and polar feeding grounds; and migrating herbivorous mammals follow seasonal changes in vegetation across continents.[81,82]

Long-distance migrants are particularly vulnerable to phenological change caused by climate warming effects, which are not uniform across regions. Local climatic cues that normally trigger migration may no longer accurately predict conditions at both destination and stopover sites along the route. The challenge is even greater for migrants returning to polar regions where the speed and magnitude of climate change are greatest.[83,84] Consequently, many migratory species struggle to arrive when quality food is still abundant, weather is suitable for specific life-cycle stages, predation or competition pressure is lower, or parasites and pathogens are fewer.[34,81,85,86] Advancing spring phenology in high latitudes has caused increasing degrees of ecological mismatch for migratory species, with potential demographic consequences.[81,86,87]

Species have demonstrated the ability to modify their migratory behaviour, from adjusting the timing to changing routes and locations.[81,85,88,89] But their adaptive capacity in response to climate change is already compromised by other ongoing threats. Ecological degradation, fragmentation and loss of feeding, breeding and resting habitats, hunting, pollution, plus other hazards on long journeys, are threatening migratory species with increasing pressure to adapt to rapid environmental changes.[88,90]

Provisions to maximize adaptive potential and build resilience in species populations require a reduction in conventional threats and modification of existing conservation policies and strategies in light of climate change.[81,91] An extensive network of diverse critical sites and protected habitats could maximize the adaptation potential of migratory species.[88] It is also imperative to ensure and enhance the connectivity of land and marine habitats critical for dispersal, now and in the future.[88,92] Increasing habitat connectivity will help maintain adaptive genetic variation and population viability needed for species survival.

European migratory birds

Analysis of spring arrival times of 117 European migratory bird species over 5 decades suggests increasing levels of phenological mismatch to spring events. This has contributed to population decline in some migrants, particularly those wintering in sub-Saharan Africa.[87]

White stork *(Ciconia ciconia)*

The white stork is a long-lived migratory bird that overwinters throughout Africa.[93] They adapt their migratory timing to advance arrival at breeding grounds in different parts of Europe and nest early to avoid mismatch with food supply.

Early breeding exposes hatchlings to unfavourable conditions, such as strong wind and heavy rainfall. With extreme weather events expected to become more frequent under changing climate, white stork hatchling mortality may increase in the future.[94,95]

Monarch butterfly *(Danaus plexippus)*

The North American monarch butterfly is renowned for its 4,300 km journey between summer breeding grounds across southern Canada and northern United States, and overwintering sites in central Mexico.[96]

Shortened daylength and lower temperatures in autumn usually prompt them to fly south. Analysis over 29 years shows that they have delayed migration by 6 days/decade due to warmer-than-normal temperatures. Late-season migrants appear less likely to reach overwintering sites than those migrating earlier in the season, possibly from encountering mismatches in food availability along the way.[97]

Barnacle geese *(Branta leucopsis)*

Flocks of barnacle geese usually migrate from their wintering ground on North Sea coastlines to spring breeding grounds in northern Russia and Svalbard. Adjusting for climate changes, they have begun migrating earlier to avoid mismatches with food at destination, and to accelerate the journey, they tend to skip stopover feeding sites along the Baltic Sea.[98] Despite arriving early, they cannot lay until they have built sufficient reserves for egg production. Consequently, their goslings hatch late and often do not survive.

Sea turtles

A range of migratory sea turtles have responded to rising seawater temperatures by shifting their timing of nesting. Loggerhead sea turtles (*Caretta caretta*) are found to nest earlier, while leatherback sea turtles (*Dermochelys coriacea*) have delayed nesting.[99-102]

However, the observed shifts in nesting phenology are likely insufficient to track optimal environmental conditions.[101-103] Beach temperatures during incubation influence hatching success and directly determine the sex of hatchling – females are produced in higher temperatures. In a rapidly changing climate, hatching success and biased sex ratio will have implications for sea turtle populations.

Baleen whales

Most baleen whales migrate seasonally between low-latitude calving grounds and higher-latitude feeding grounds, where they prey on dense concentrations of krill or forage fishes.[85,104,105]

Many baleen species are known to shift migratory timings, depending on prey availability. In the past 27 years, fin and humpback whales have advanced their arrival by 1 day/year at the Gulf of St. Lawrence feeding grounds off eastern Canada. This is likely due to earlier ice break-up and rising sea surface temperature, which triggers earlier plankton bloom and influences prey abundance.[85] Shorter-distance migrants like fin whales may reduce migration due to temperature changes and less winter sea ice, but it is harder for long-distance migrants like humpback whales to correctly time their arrival for abundant prey.[85]

Colombia's Gorgona National Natural Park is an important breeding and calving ground for Eastern South Pacific humpback whales. Their arrival has shifted up to 1 month earlier over the last 3 decades. This is likely due to changes in sea ice formation in Antarctic feeding grounds affecting krill availability, and less prey being a cue to return to tropical waters.[105]

Eastern North Pacific blue whales are also known to alter migration, arriving at their feeding grounds off California approximately 42 days earlier than 10 years ago. This shift was associated with at least a 2°C increase in sea surface temperature, and the resultant krill abundance.[106]

Although phenotypic plasticity – the ability to adapt in response to changing environmental signals – allows these species to adjust migratory timings, modifying the timing of a life stage can negatively affect another within the annual life cycle. Remaining longer on feeding grounds can cut reproduction time, and vice versa.[106] Adaptation in human activities, including fisheries, maritime traffic, and exploratory seismic testing, is also needed to accommodate whales' changing sojourns within and outside protected areas.[105]

3. Evolving toward new synchronies

Climate change attribution for observed mismatches depends upon long-term research on the phenology of interacting species within an ecosystem. Long-term studies are essential, but the major challenge is proving causality. Climate change may influence temperatures and rainfall, but other factors may simultaneously influence species responses, such as land-use change, resource overexploitation, invasive species, and other ecological stressors. Uncertainty around causality can be partly addressed by minimizing variables: observing responses either in different locations, comparing populations in areas with a lot of warming to those with a little, or in different time periods, comparing populations in years with rapidly increasing temperatures to years with slower increases.[76,107] These approaches allow a better estimate of the specific effect of temperature increase on species' phenology, although they do not solve issues involving other environmental factors influenced by temperature. For instance, in many regions, precipitation patterns change dramatically with varying climatic conditions, altering the timing, frequency and intensity of rainy seasons.[108,109] As data accumulate, researchers realize that combinations of phenological mechanisms – temperature, photoperiod and precipitation, for instance – may need to align for the phenological cue to take effect.

A strong phenological shift in a population in response to environmental change indicates a large proportion of the individuals have the ability to change timing in the same direction, known as phenological plasticity.[110] Empirical evidence suggests that this plasticity is the main source of observed climate-related phenological shifts.[111] But individual or population plasticity may not be able to keep up with the rapid environmental changes we are experiencing.[112] Species also require genetic change to adapt successfully, which is more likely in species with short generation time, like insects, than in trees that regenerate over decades.[113] There are a handful of examples where genetic change, as a response to climate change, can be recognized as microevolution, mainly in insects and some birds.[114,115] Overall, genetic changes are happening at a much slower rate than the climate is changing.

Phenological microevolution, the process of natural selection where genetic changes shift the phenology of species to better fit the changed climate, most likely played an important role in species and ecosystem adaptation to past warming periods.[113] Still, as the rate of warming is much faster now – perhaps by as much as a factor of 100 – even microevolution will likely emerge too slowly for current rates of climate change.[116]

In practice, conservation and ecosystem management measures could be taken to encourage favourable conditions for microevolution.[117] One measure is to support and nurture the genetic diversity of populations, as this is the crucial prerequisite for microevolution and natural selection. Increasing ecological connectivity through habitat corridors would enable plant colonization and movement of animal species with novel genetic material within a particular ecosystem, promoting genetic diversity and increasing the chances of successful adaptation.[118]

Out of reach

The red knot (*Calidris canutus*) is a medium-sized shorebird in the sandpiper family. The global population is in decline and considered Near Threatened. The 6 subspecies of red knot migrate remarkably long distances from the high Arctic breeding grounds to wintering grounds across different continents.[119]

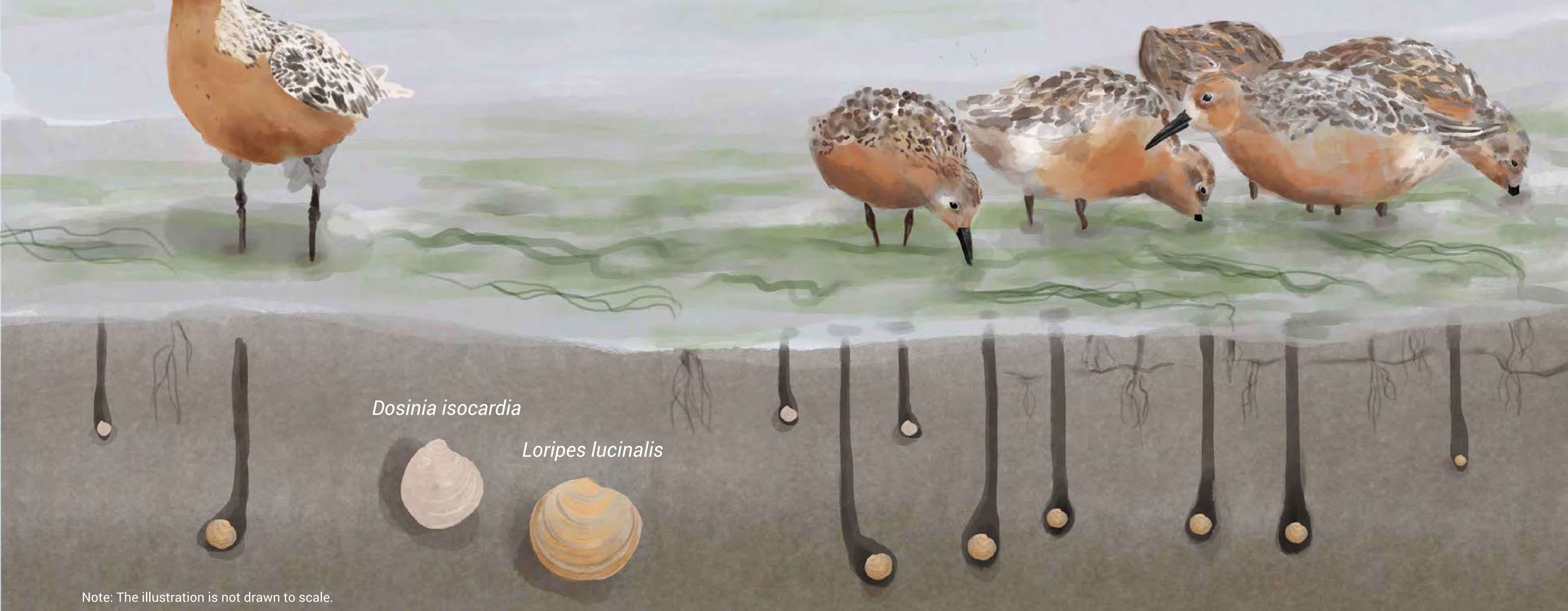
A subspecies, *Calidris canutus canutus*, breeds in central and northern Siberia, and migrates to warmer areas along the coast of Mauritania, notably Banc d'Arguin National Park. As the snow starts to melt, they mate and lay eggs. Red knot chicks feed on insects that seasonally emerge from thawing tundra permafrost, in preparation for the long voyage to Africa.[120]

In the last 3 decades, snowmelt duration in the high Arctic has progressively advanced by 0.5 days/year, resulting in the early emergence and abundance of insects. This shift in insect phenology causes a series of consequences for the red knots in later life stages.[120,121]

Since the birds have not adjusted their breeding phenology, offspring miss the peak of their food abundance. Poor food resources mean poor growth. Juvenile red knots become smaller and have shorter bills during summers with early snowmelt.[120]

Once in West Africa, their main food source changes to mollusc buried in intertidal sediments. These shorter-billed birds have less access to highly abundant bivalve species (*Loripes lucinalis*) buried deeper in the sediments. Instead, they can only consume shallowly buried rhizomes of seagrass (*Zostera noltii*) and rare species of bivalve (*Dosinia isocardia*).

This knock-on effect leads to increased mortality of the short-billed red knots, which demonstrates the complex implications of a mismatch in one location and one part of the life cycle with another part that takes place halfway across the globe.[120]



Note: The illustration is not drawn to scale.

4. Bridges to new harmonies

Phenological shifts can only be determined from long-term records. Data collection is conducted by scientific institutions, universities, governments, and NGOs. Initiatives such as the African Phenology Network, Australia's TERN project, India's SeasonWatch, the UK Nature's Calendar, and the USA National Phenology Network include observations by citizens to track plants, insects, birds and mammals. These comprehensive data sets allow scientists to single out species and locations most at risk. They also provide data for IPCC estimates of tolerable warming rates for ecosystems, underpinning governmental objectives to reduce global warming to limits set by the Paris Agreement.[122]

Phenological monitoring and citizen science

Farmers, gardeners and nature-lovers have been applying their understanding of phenological stages all around the world, for centuries. Regional and local networks allow participants to exchange knowledge and advice on diverse environments and ecosystems. With modern communication tools, identifying and tracking the development of plants and animals has become a common pastime in many countries.[123]

Formal phenological gardens contain a selected array of plants to monitor their responses to changing local conditions. Scientists working with national botanical gardens and other long-established efforts set up areas within those confines to grow the same selection of plants across different latitudes, longitudes and elevations, and collect data to compare phenological responses over time. These large-scale plant-behaviour observation systems offer data sets for other researchers to establish baselines and track trends for their own work.[124]

By studying the phenology and adaptive changes of keystone species, the collected data provide solid biological evidence of climate changes and adaptive responses from living collections that supports long-term monitoring of climate change biology.[125]

Less formal phenological gardens are an important teaching tool about the crucial timing in the life cycles of species, but they too must follow certain protocols for data quality. The Global Learning and Observations to Benefit the Environment (GLOBE) Program offers guidelines for thousands of participating schools in 125 countries.[126] After three decades, the GLOBE Program is now expanding its methods, protocols, and databases to also include citizen scientists' observations.[127] Citizen science contributions to phenological knowledge span from noting flowering dates in their gardens to observations of migrating herds for verifying aerial and satellite images.[128] An enduring citizen science project, the Christmas Bird Count initiated by the US National Audubon Society in 1900, covers most of North America and has provided solid data on the decline of bird populations over more than a century.[129]

A selection of phenology citizen science projects and activities

Global coverage

- Earthdive
- Global Phenological Monitoring Programme
- GLOBE Program Phenology Protocols
- International Waterbird Census
- WorldBirds

Regional coverage

- The African Phenology Network
- e-Butterfly
- Hummingbird Conservation Network
- International Phenological Gardens of Europe
- MonarchWatch
- Pan European Phenology Project

National coverage

- Centro de Informação en Saúde Silvestre
- Chinese Phenological Observation Network
- ClimateWatch, Australia
- Farmers' Wildlife Calendar, Ireland
- Nature Today, Netherlands
- NatureWatch, Canada
- Phaenonet, Switzerland
- PhenoRangers, Switzerland
- SeasonWatch, India
- UK Environmental Change Network
- USA National Phenology Network

Phenological shifts and mismatches, attributed to climate change, have been affecting agricultural ecosystem services for decades.[1,71,130-132] To ameliorate problems of advanced growing seasons, growing stages curtailed by heat or drought, and other climate-change repercussions, farmers have been selecting more climate-resilient cultivars.[133] Adopting new techniques, trying new seeds, sharing seed banks, and exploiting extension services are all aspects of climate-smart agriculture, promoted by the Food and Agriculture Organization of the United Nations, many NGOs, and national and sub-national agencies.[134]

Limited research has studied how phenological shifts and mismatches affect natural resource management and biodiversity conservation, with managers often unclear on how to incorporate the data into practice.[135,136] Phenological data could inform climate response, optimize implementation of monitoring, and support climate change vulnerability assessment.[135] This is especially important in less-studied areas, such as many southern hemisphere locations.[18,19] Managers need to consider how phenological changes affect their current strategies. For example, fisheries managers typically survey fish populations annually, targeting dates when populations were most abundant in an area historically. Phenological shifts could result in surveys conducted at the wrong time of the year, which would skew population estimates and catch allowances.[60]

Recent reviews of multiple specific case studies have mapped out examples of phenology, phenological shifts, and phenological mismatches in extended coverage.[27,32,33,49] This wider perspective considering larger numbers of species, ecosystems and regions and diverse phenological mechanisms at work can inform the approaches needed to help human communities and ecosystems adapt to climate-changed conditions.

Larger-scale efforts to strengthen the integrity of biological diversity will build resilience and adaptability throughout ecosystems.[137] Rehabilitating habitats, building habitat corridors to enhance ecological connectivity and genetic diversity, adjusting protected-area boundaries as species' ranges shift, and conserving biodiversity in productive landscapes are all necessary immediate management interventions.[138,139]

In conclusion, anthropogenic climate change leads to phenological shifts in both terrestrial and aquatic ecosystems. These shifts can lead to mismatches, with major consequences for individuals, populations, communities and whole ecosystems. Climate change is accelerating too quickly for many species to adapt through their natural phenological capacity.[140] Preserving the integrity of functioning biological diversity, ending habitat destruction, and pursuing ecosystem restoration will bolster the natural systems upon which we depend. However, without continued efforts to drastically reduce greenhouse gas emissions, these conservation measures will only delay the loss of those essential ecosystem services. For species and ecosystems to match accelerated rhythms set by climate change, time and opportunity to achieve new harmonies will be needed.

Food production and phenology

All season-dependent activities are inherently risky, from hot spells causing a poor wheat harvest or marine heatwaves affecting local fish stocks, to unseasonal weather impinging on travel and tourism. But food production is the most critical socioeconomic activity affected by phenological shifts as climate change accelerates.[2]

Warming trends have shifted the phenological stages of a variety of staple crops over decades and across continents.[71,141-145] The change in growth stages has consequences on crop yields and quality.[144-147] The shifts have been observed in crops ranging from cereals such as barley, maize, rice, rye, sorghum, soybean and wheat, to cotton, grapevines, and fruit trees such as apple, cherry, pear and mango.[71,143,148-154] At the same time, crop management decisions on sowing date and cultivar choice have direct effects on crop phenology.[71,155] They are often used as adaptation strategies to counteract climate-induced phenological changes.[71]

With the constant introduction of new varieties and variations in the sowing calendar, farming practices and climate have a combined influence on diverse changes in crop phenology.[71,151,155-160]

Many highly productive regions suffer more frequent, extreme climate-related events that also interfere with critical growth stages.[161] Climate-scenario crop models project that many global regions will experience reductions in yields, with additional challenges from soil degradation, unsustainable farming, pests, and water scarcity.[162]

Adaptation practices focus on implementing sustainable management, including organic fertilizer use, combining legumes with grasses, optimizing irrigation, breeding plants selectively, and choosing more resilient cultivars.[71] Projections of agricultural productivity often incorporate adaptation to climate change in their predictions, with the call for more observational evidence on the effectiveness of adaptation practices.[161]

Fisheries

Successful growth to maturity and production of fish stocks is strongly affected by any climate-induced changes to the phenology and distribution of both fish and prey.[67] For many marine fish species, spawning phenology is sensitive to temperature cues.[69,163] Spawning time, subsequent transport of fish larvae during the planktonic stage, and abundance of suitable food are critical factors for early development and survival.[43,67,164,165] Reduced survival at early life stages leads to fewer additions to the adult stock.[59] Changes in the timing of reproduction and migration and resulting phenological mismatches with prey availability have been observed in and projected for species that are important to inland and marine fisheries in some regions.[166]

Shifting species' phenologies and environmental conditions under climate change present challenges for fisheries management.[166] With observed shifts in timing of critical life stages and geographic distribution, common practices used by fisheries authorities, such as closed fishing seasons and areas, may not provide adequate protection.[59,163,166] Management measures and restrictions should consider existing and emergent critical habitats, and changes in spawning sites, nursery grounds and migratory corridors. An ecosystem-wide approach that is adaptive to both climate and environmental changes is essential for sustainable fisheries management within resilient ecosystems.[166]

Inland fisheries

Patterns of rainfall and snowfall altered by climate change affect the availability, quality and flow regime of fresh water. These are important phenological cues for species in freshwater habitats, and modifications in water flow and levels, as well as flood events, affect the timing of migration and spawning.[166-168]

Marine heatwaves

The 2012 intense marine heatwave warmed north Atlantic waters by 1-3°C, inducing a phenological response in lobsters and majorly affecting fisheries in the Gulf of Maine. Cued by rising temperatures, lobsters migrated inshore earlier, moulted faster, and reached legal fishing size sooner. The longer fishing season, overharvesting, and unmet market demand led to a price collapse.[169]

The Sardine Run

A seasonal mass migration of sardines (*Sardinops sagax*) from the temperate waters of the Agulhas Bank towards the sub-tropical waters off the northern coast of KwaZulu-Natal, South Africa, occurs annually. From May to July, the phenomenon attracts many opportunistic marine predators, as well as fishing activities and tourism.[170]

Records over 60 years show a progressive delay in arrival of sardines off Durban by 1.3 days/decade. This delay coincided with a change in the threshold thermal range for sardines as the 21°C isotherm shifted south.[170] If the shifting trends continue, the sardine run may no longer extend as far north, or the run may collapse in the long term, with implications for predators, fisheries and tourism.[170,171]

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Identifying shifts, tracking trends

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