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WHY DAYLIGHT SHOULD BE A PRIORITY FOR URBAN PLANNING

Carlo Volf / Bruno Bueno / Peter Edwards / Richard Hobday / Stephan Maeder / Barbara S. Matusiak / Katharina Wulff / Werner Osterhaus / Gabriele Manoli / Christina Della Giustina / Jasmin Joshi / Jerome H. Kaempf / Kevin Vega / Christoph Kueffer

Daylight is essential for ecosystems and for the physical and mental well-being of people. In densely populated cities, only a small proportion of total daylight is available to support urban greenery and most people have little daily exposure to natural daylight. Despite this, many cities have followed a strategy of densification as a way of preventing urban sprawl and reducing energy consumption. In this article, we review the biological importance of daylight and show that urban densification leads to a reduction in the daylight available for both people and nature. We conclude that daylight in cities should be treated as a limiting resource that needs to be planned and managed carefully, much like water or energy. We suggest elements for a policy framework aimed at optimizing urban daylight, including how to determine daylight needs, how to determine the maximum viable urban density, and policy options for built and unbuilt areas.

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1. Introduction

The importance of daylight for physical and mental well-being has long been known (Daylight Academy, 2017). In the 1850s, Florence Nightingale recommended that hospital patients be exposed to sunlight and fresh air as an effective way to speed recovery and prevent the spread of infections (Nightingale, 1863). Social reformers in 19th century England encouraged outdoor sports for children in inner cities, partly so that they could benefit from natural daylight. The life reform movement of the early 20th century promoted access to light, daylight and fresh air as central for a healthy urban life (Buchholz et al., 2001). In most countries, buildings codes make recommendations concerning how to optimize natural lighting in buildings, for example by specifying ratios for window to floor area.

The EU Workplace (Health, Safety and Welfare) Regulations (1992), for example, requires that "Every workplace shall have suitable and sufficient lighting" and that this lighting "shall, as far as is reasonably practicable, be by natural light". An important area of architectural practice is 'daylighting', which describes designs aimed at utilizing sunlight for internal lighting. Supported by technical developments such as high-performance glazing, daylight responsive electric lighting controls, tubular daylight devices and building information modeling (BIM), such designs can greatly improve the daylight received within buildings (Kota et al., 2014).

Despite this recognition of the importance of daylight, dating back centuries, an increasing number of people living in large cities receive less daylight than they require for good health and well-being. One indicator for this is a high prevalence of vitamin D deficiency in large cities (Bailey et al., 2012), including in tropical regions (Bi et al., 2016). In this forum article, we argue that ensuring adequate daylight for urban residents should become a priority for urban planning. Furthermore, because people receive daylight both indoors and outdoors, any policy framework for daylight should cover both the design of buildings, which is the concern of architects and engineers, and the provision of urban green spaces, which is the province of ecologists and landscape architects.

We begin by reviewing briefly the biological and medical importance of daylight and then consider how urban densification affects people's exposure. These considerations lead us to argue that daylight in urban areas should be regarded as a limiting resource much like water or energy, which must be planned and managed in an integrative manner. We conclude by proposing a policy framework for managing daylight and suggest various practical steps by which it could be implemented.

2. The importance of daylight

Light from the sun is essential for life. It is the energy source for photosynthesis, upon which most organisms are directly or indirectly dependent, and is a source of information that steers many biological processes (Daylight Academy, 2017). Not surprisingly, plants and animals are usually closely adapted to the light climate they encounter in their natural habitat, with its characteristic fluctuations in light intensity and spectral composition. Especially important are the daily and seasonal rhythms of daylight, since these provide information for the internal coordination and synchronization (entrainment) of many biological processes (Helm et al., 2017).

Daylight is also essential for regulating biological rhythms in humans (Daylight Academy, 2017). Many physiological processes are entrained by exposure to bright light (Turner et al., 2010); and an absence of daylight interferes with the biological rhythms of processes such as thermoregulation, growth and digestion, which increases the risk of somatic and mental diseases. On the other hand, too much artificial light at night suppresses the brain hormone melatonin, which disturbs sleep and eventually impairs brain health.

Another vital role for daylight is in the synthesis of vitamin D, which is formed when the skin is exposed to ultraviolet radiation (Weller, 2016). This vitamin plays a pivotal role in the auto-immune system, protecting the body against numerous chronic and acute conditions including cardiovascular disease, internal hormone cancers, neurological disorders, diabetes, and infectious diseases (Holick, 2017). In pale-skinned people, a daily exposure to sunlight of 30 min is sufficient to prevent vitamin D deficiency, while in dark-skinned people somewhat longer is needed (Wu & Chen, 2022). Besides enabling the synthesis of vitamin D, UVB radiation also acts as a natural disinfectant that inactivates pathogens such as the SARS-CoV-19 virus. UVA radiation is necessary for the production of nitric oxide in the skin, which is protective against bacterial and viral infections and can also reduce systolic blood pressure and the risk of coronary disease (Liu et al., 2014).

Daylight also has powerful effects on mental well-being, including alertness, mood and general quality of life, which can be linked to its role in maintaining a healthy sleep-wake cycle (Nagare et al., 2021; Walker et al., 2020). These effects may also explain why exposure to sunlight in hospitals reduces recovery times of patients (Beauchemin & Hays, 1998; Gbyl et al., 2016; Park et al., 2018) and is restorative for health-care workers (Zadeh et al., 2014). Even just looking out a window is very effective for circadian entrainment and has important health benefits (Raanaas et al., 2012).

Artificial lighting differs from natural daylight in both spectral composition and temporal fluctuations and does not produce the same range of biological effects. Indeed, exposure to artificial lighting, especially during the hours of darkness, disrupts circadian entrainment and can have negative consequences for human health (Cain et al., 2020). It may have significant negative impacts upon animals, plants and whole ecosystems (light pollution, Sanders et al., 2021).

3. Daylight in urban areas and the effects of densification

As cities grow, the numbers of inhabitants per unit area usually increases. This densification occurs partly for economic reasons, since high land costs in large cities increase the pressure to develop remaining green spaces and construct bigger buildings (Bettencourt, 2013). In addition, densification has been actively promoted since the 1950s (Teller, 2021; Wicki et al., 2022) as a way to contain urban sprawl, increase infrastructure efficiency, reduce traffic and facilitate social and cultural exchange (Jabareen, 2006; Lin et al., 2015). More recently, concerns about urban sustainability have provided another argument for densification, since compact cities use relatively less energy for heating, cooling, travel and transport.

Though well intentioned, efforts to make cities more compact and energy efficient can create new social, health and environmental problems. For example, Berghauser Pont et al. (2021) review some of the negative health effects of high density, which include increased heat vulnerability, increased air pollution, lower fertility rates and more stress-related problems and depression. Here, we describe four main ways in which densification tends to reduce exposure to daylight and can therefore be harmful not only for people's physical and mental health but also for urban ecosystems (Fig.1). Furthermore, artificial lightining indoors or outdoors tends to worsen the situation because it leads to additional light pollution instead of a substitution of natural daylight.

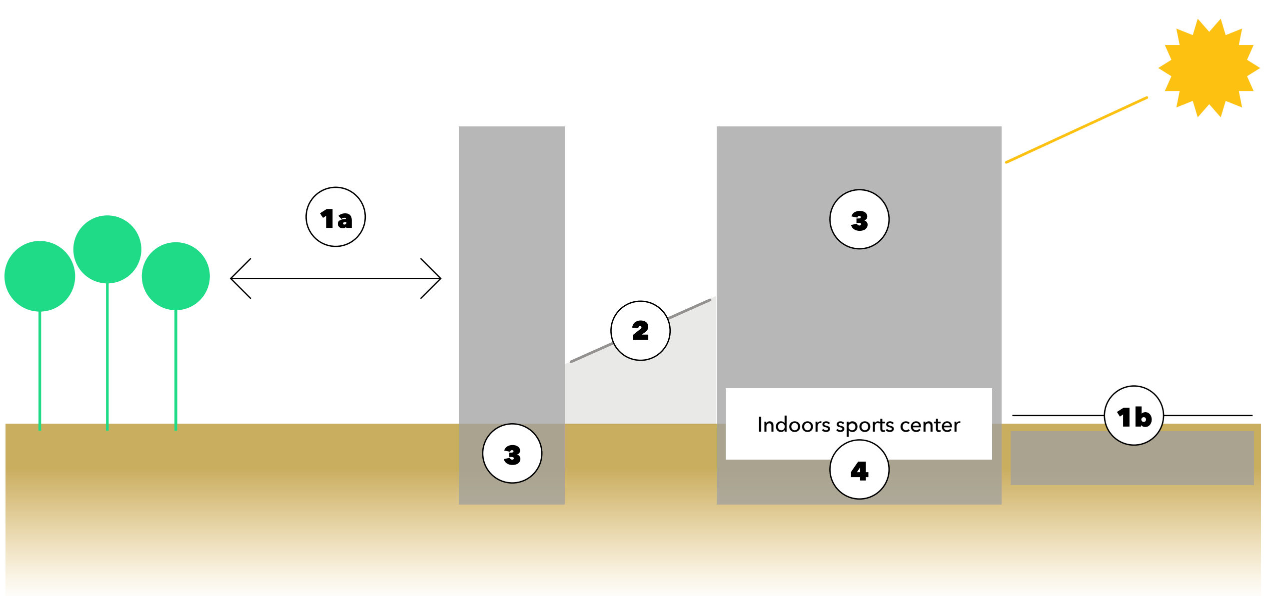
3.1. Less green space and less unsealed, intact soil

Time spent outdoors is the most effective way to get enough daylight. Easily accessible urban parks and green corridors offering attractive places for recreation and relaxation are therefore important in urban areas, while having enough green spaces is central to the ecological functioning of cities (Edwards, 2020). Urban ecosystem services such as primary production or climate cooling depend on enough daylight-exposed surfaces with unsealed and intact soil. As population density increases, however, the per capita allocation of green space declines dramatically (Fuller & Gaston, 2009), with compact cities often having very low allocations. Fuller and Gaston (2009) suggest that as cities grow, interactions between people and nature depend increasingly on landscape quality outside formal green space networks, such as street plantings and private gardens, and the same is probably true for people's access to daylight. Unfortunately, opportunities for street plantings in compact cities are often limited, because open areas are sealed or overlie underground structures such as car parks (Cavender & Donnelly, 2019). Green roofs can only provide the same social and ecological benefits as green spaces if they are easily accessible, not used for other purposes such as the production of solar energy, and have deep enough soil to support a high plant biomass. The lack of sufficient access to open and green spaces is more pronounced in poorer neighborhoods (Chen et al., 2022). In short, densification reduces the space where humans, plants, animals and ecological processes, including in the soil, can interact with daylight.

3.2. Less daylight reaches ground level

In a dense city with tall, closely packed buildings, only a small fraction of daylight reaches ground level. This geometric constraint to daylight exposure in the three-dimensional built environment is especially pronounced at higher latitudes and in winter in temperate regions. In addition, structures such as balconies that are designed to increase the porosity of facades have the negative side-effect of reducing daylight at lower levels and indoors. As a consequence, dependence upon artificial lightning increases with urban density, thus exacerbating the problem of light pollution for humans and wildlife. Another effect of densification is that many windows offer a restricted view, so that peo-

Fig. 1.



We describe four main ways in which densification tends to reduce exposure to daylight and can therefore be harmful for people's physical and mental health and for urban ecosystems. First, the per capita allocation of green space declines with less open space in the vicinity of buildings and longer distance to the nearest green spaces (1a). Increased proportion of sealed surfaces reduces potential for plant growth (1b). Due to geometric constraints shading of ground level and surrounding buildings (2) and the proportion of windowless and underground rooms (3) increase through tall, voluminous and closely packed buildings. Ultimately, densification promotes indoor lifestyles by replacing outdoor spaces with indoor spaces (4). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ple are less likely to profit from the positive health and mental effects of a view into a green and daylit environment (White et al., 2021). As for ecological processes, the capacity of a city to support green spaces with healthy populations of plants and animals is impeded by the dual constraints of shading and sealed or degraded soils.

3.3. Less daylight penetrates indoors

The daylight received indoors declines with density for many reasons. These include shading by neighbouring buildings, increasingly more windowless rooms in large buildings, and more development underground. Indeed, many work places in cities receive no daylight, either because they are underground or in large buildings without windows, such as factories and shopping malls.

A further reason for insufficient daylight penetrating indoors is the use of building technologies developed to improve thermal comfort, increase energy efficiency or reduce external noise. Guided by regulations aimed at maximising energy performance, cities are increasingly dominated by large, hermetically closed buildings, typically with simple, cubic and closed facades, small envelopes and low height to floor area ratios. In warm climates, the introduction of air conditioning has led to radical changes in the design of buildings, with sealed, often darkened glazing replacing the former open balconies. However, highly insulated, airtight buildings, together with mechanical ventilation and extensive use of triple-pane windows, reduce not only indoor daylighting but also easy access and sensorial connections to the outdoor environment.

3.4. Urban residents live indoor lifestyles

People living in large cities spend less time on average outdoors than do those in rural areas (Gao et al., 2022; Matz et al., 2015). This difference can be explained by various factors. Firstly, urban lifestyles may provide little incentive or even opportunity to go outside. Consider, for example, someone who lives in a small flat in a high-rise, mid-town building, travels to work in the metro, works in a large office and spends most of his/her spare time in shopping malls or visiting the gym; such a person might only spend a few minutes per day outdoors. Secondly, gaining access to public green spaces can be difficult and even dangerous. This is especially the case for the frail and elderly, but also children, who may be unable to cross busy highways to visit parks or other green spaces. Thirdly, economic forces tend to encourage indoor lifestyles. For example, large developments such as shopping malls and entertainment centres are often heavily promoted through advertising, which is essential to ensure their profitability. There are amplifying feedbacks between the expansion of indoors lifestyles and the loss of outdoors urban qualities. In essence, densification through construction replaces outdoors space with indoors space, and is associated with strong economic forces encouraging people to spend their time indoors.

3.5. Daylight as a limiting resource

Taken together, these effects mean that many people living in large cities receive far less daylight than they need for good health and well-being. One consequence is a high prevalence of vitamin D deficiency in many cities, including equatorial cities like Singapore (Bi et al., 2016; Ting & Devnani, 2016). Another is that bone disease rickets, which was a serious problem among factory workers in 19th century cities due to prolonged sunlight deprivation and deficiency of vitamin D, has re-emerged as a global health issue (Holick, 2006). A lack of sun exposure also increases susceptibility to myopia and to certain metabolic diseases, including obesity (Gorman et al., 2017). Similarly, urban biodiversity may be impaired by exposure to artificial light, reducing its capacity to provide social, health and environmental benefits for humans (Daylight Academy, 2017; Sanders et al., 2021).

An important conclusion from these observations is that declining access to daylight sets an upper limit to densification, if a city is tobe healthy and sustainable. New technologies may keep pace with a city's growing demands for energy, clean water and waste disposal, or else these resources and services can be imported to cities from their hinterlands. In contrast, artificial lightning or other technologies cannot provide an adequate substitute for natural daylight, which is limited in supply and cannot be imported. Which raises an important question: what is the maximum urban density beyond which the biological and social needs for daylight can no longer be met? The answer will vary according to the geographical context and latitude, but many urban neighbourhoods, especially in poorer regions of the world, already exceed this maximum density.

> "Given its importance for human health and well-being, we propose that daylight in urban areas be treated as a limiting resource that, like water or energy, is carefully planned and managed."
> (Volf, C. et al., 2024, p.9)

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4. Towards a policy framework for urban daylight

Given its importance for human health and well-being, we propose that daylight in urban areas be treated as a limiting resource that, like water or energy, is carefully planned and managed. For the planner, this means adding daylight to the list of essential things that the city provides, along with clean water, clean air, recreation facilities and green spaces. The goal of an urban daylight policy should be to ensure that people, animals and plants receive the daylight they need to thrive, while preventing the harmful effects of excessive exposure. This goal must be seen in the larger context of managing the urban radiation budget, which may also entail measures to reduce urban warming and the use of exposed surfaces to generate solar power. Such a unified approach is necessary because the supply of solar radiation per unit area is limited and there is a real risk that daylight conditions for people and nature will continue to deteriorate as cities grow denser and planners seek to optimize other aspects of the urban environment.

4.1. Active and passive components of daylight

Human needs for daylight can be met, in principle, both indoors and outdoors. We designate the fraction of daylight received indoors as the 'passive' component, since people obtain it without having to take any particular action. The architectural practice of daylighting is aimed at optimizing this component of daylight. In contrast, the daylight received outdoors represents the 'active' component, because people only obtain this benefit when they go outside. Urban greening influences the supply of both components; people can obtain the daylight they need by visiting green spaces (active component), but the arrangement of these spaces is important for how much daylight reaches surrounding buildings (passive component). For this reason, planning policies for daylight and green spaces must be closely linked.

4.2. Enough daylight for everyone under all circumstances

A particular challenge in implementing an urban daylight policy is ensuring that everyone, including the poorest and most frail, receive the daylight they need. In general, the poor are more likely to live in small apartments with inadequate daylight, have limited access to private or public outdoor spaces with greenery, work in spaces with little or no daylight, and have fewer opportunities to leave the city for recreation (Cole et al., 2021). And the elderly and bed-ridden, but often also children, are similarly restricted in their access to daylight.

4.3. Daylight in a densifying city

The distinction between the active and passive components of daylight is particularly helpful in the context of densification. As buildings become taller and more closely packed, it becomes increasingly difficult for planners and designers to ensure adequate daylight indoors (i.e. passively), especially on the lower floors and underground, and they need to focus more upon the active component of daylight. In practice, this means protecting and extending the area of open and green spaces, and making them as accessible as possible. Given limited space in a dense city, it may be necessary to restrict further development to ensure that the growing population has access to open spaces. This can only be achieved by increasing the number of persons per building, which means reducing the floor area per inhabitant or work space. Such a strategy of protecting and creating new open spaces improves access to daylight in two ways. First, residential buildings are surrounded by easily accessible green spaces that can be used for recreation and active mobility. Second, widely spaced, high-rise buildings offer better opportunities for daylighting (passive component), being less shaded than more closely packed buildings, especially when they are adjacent to a green space. In addition, it may be possible to establish green infrastructure such as roof gardens and skyways, which also allow residents to benefit actively from the daylight intercepted by buildings. Such a strategy can ensure good access to daylight even in rapidly densifying cities. For example, in the 50 years between 1965 and 2015 Singapore's population increased three-fold, but through careful planning of the city could actually increase the proportion of vegetation. The new urban district of Punggol in Singapore is an impressive example of high density public housing set in a landscape with parks, gardens, green connectors and waterways (Holmes, 2018).

4.4. Determining daylight needs

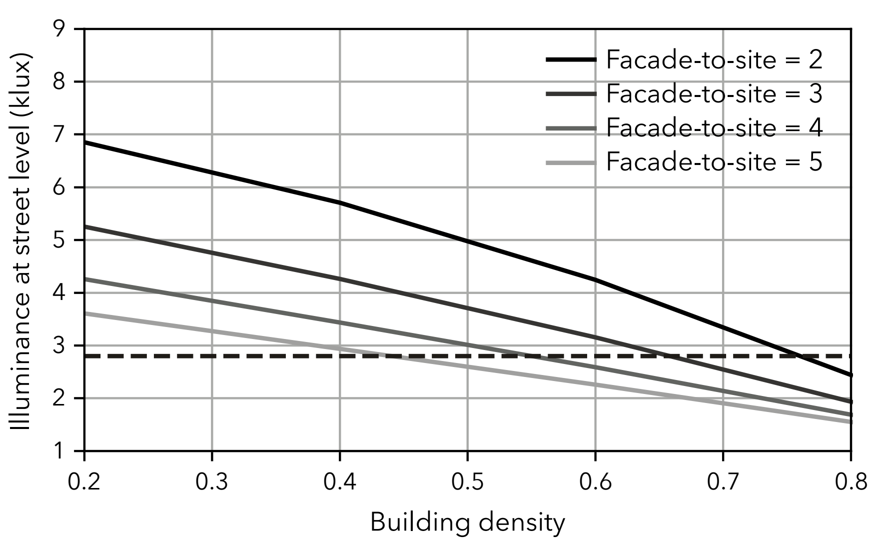
To guide planning of daylight in densifying cities, metrics are needed by which to assess whether the supply is adequate. Clearly, the critical levels of these metrics would be different when considering the differing needs of people and nature, and the use of solar radiation for energy production. At present, minimum exposure levels for daylight based upon human physiological and psychological needs cannot be precisely specified, although various approaches seem possible. One would be 30 min of daylight daily, which is the estimated exposure needed to prevent vitamin D deficiency. Another approach would be to establish minimum illuminance levels that must be reached at street level to enable circadian entrainment (Turner et al., 2010).

Establishing target values would be a first step in ensuring that city inhabitants receive sufficient daylight to meet their physiological needs. Modelling studies could then be used to determine how particular urban designs perform in terms of meeting threshold values. Fig. 2 provides an example of how such models could be used, showing the illuminance at street level at noon during equinox at Central European latitude 47 N, e.g. Zurich, for different urban densification parameters. Similar graphs could be generated for different latitudes and times of the year in order to establish daylight-driven limits for urban densification. The dashed line in Fig. 2 indicates a minimum threshold of 1800 lux needed for circadian entrainment. It should be noted that this is a very tentative limit, because circadian entrainment is mainly driven by contrast of light intensity between day and night, which also means that urban design must enable inhabitants to receive high levels of daylight exposure, at least at street level for a few hours a day. However, even this simple model is useful in suggesting where the limits to urban density may lie.

5. Daylight-inspired urban planning and design in context

New societal demands and challenges have always been a stimulus for innovation in architecture and planning, as is well illustrated by recent responses to the challenges of designing for urban nature (e.g., biophilic design, Zhong et al., 2022), climate adaptation (e.g. water-sensitive urban design, Richards & Edwards, 2018), densification (Schröpfer, 2020), globalization (Adam, 2013) or multiculturalism (Beynon, 2009). There is good reason to suppose, therefore, that new thinking and design ideas will emerge as the importance of daylight as a fundamental and far-reaching constraint in urban development becomes more widely recognized. It is impossible to say what those future designs will be, but there is a rich diversity of possible solutions

Fig. 2.



Illuminance at street level for different urban densification parameters of an urban site (neighbourhood, town). Urban densification parameters are 1) the building density, defined as the ratio between the building footprint and the total horizontal area of the urban site, and 2) the façade-to-site ratio, defined as the ratio between the area of all vertical surfaces in the urban site and the total horizontal area of the urban site. For each combination of building density and façade-to-site ratio, the graph provides the illuminance at street level, assuming a CIE overcast sky at 12:00LT on the 21st of March in Zürich. The underlying simulations have been carried out with the raytracing tool "Radiance". The dashed line indicates that certain combinations of building density and facade-to-site ratios lead to scenarios where a minimum threshold of 1800 lux of daylight for circadian entrainment is not guaranteed for the given time.

that could be applied to improving individual exposure to daylight in cities.

To illustrate how the needs and opportunities for daylight-inspired planning and design vary according to the urban context, we consider here four contrasting scenarios of urban densification: (1) relatively sparse, low density development, (2) moderate density with predominantly low-rise buildings, (3) high density but predominantly low-rise buildings, and (4) high density, including a significant proportion of high-rise buildings.

In the first scenario - low density development – it would be easy to conclude that daylight is unimportant compared to other design considerations, such as protecting landscape aesthetics or optimizing traffic. However, this would be to ignore the small but significant fraction of the population that is bed-ridden or, for some other reason, confined indoors. Thus, even at the lowest densities, internal daylighting solutions may be needed to ensure that all urban residents receive the daylight they require.

In the second scenario – moderate density – a higher proportion of the population is at risk of receiving too little daylight, whether because of lifestyle or poor light conditions in their residences and workplaces (e.g., people living in basement flats or working in large, windowless offices). In these cases, measures such as installing balconies or improving internal daylight may be helpful, though they will often prove insufficient. The focus of planning therefore should be upon strengthening the active component of daylight, for example by developing easily accessible open and green spaces. Strengthening public awareness of the importance of daylight is also important, for example by communicating that further urban development could reduce life quality and the value of existing property.

The third scenario – high density with many low-rise buildings – is common in many large cities, especially in low- and middleincome countries (e.g., Jakarta, Manila, Mumbai), and is typically associated with poverty and informal settlements. In such conditions, insufficient daylight is only one of a suite of often intractable problems that architects and planners must address, such as insecure land tenure, frequent flooding, poor sanitation and the lack of electricity, running water and waste collection. There have been many initiatives to develop affordable housing in cities, including innovative designs and construction methods (World Economic Forum, 2019), but daylight needs have rarely if ever been considered.

In contrast, the fourth scenario – high density with many high-rise buildings – is associated with greater affluence, with densification being driven mainly by high land prices. As density increases, an increasing proportion of the population is likely to receive too little daylight, which is reflected in the high incidence of vitamin D deficiency in many urban populations. Fortunately, there are many opportunities to improve daylight conditions in this scenario, including roof gardens, skywalks, elevated walkways, having taller buildings with increased setbacks, and using podium constructions to increase the daylight reaching the upper, residential parts of highrise buildings. An inspiring example of a city that has adopted all of these strategies and more is Singapore (Centre for Liveable Cities, 2016), which since 1970 has actually slightly increased the total area covered by vegetation (to 49%), despite its population increasing over threefold in this period. It should be noted, however, that the guiding principle for implementing these strategies was not to improve daylight conditions, but to make Singapore a 'garden city' (later modified to be a 'city in a garden' and more recently a 'city in nature'). While many of the measures are also relevant for improving daylight, there is also an important difference, which deserves to be emphasised. Progress towards creating a 'city in nature' can be assessed through global goals such as the total area of green spaces, or the number of street trees, or the lengths of blue and green corridors; in contrast, daylight planning has the goal of ensuring that all urban residents receive the daylight they need. This focus upon the needs of the individual makes daylight planning different from most other urban planning priorities.

6. Concluding remarks

A growing number people in cities lack sufficient exposure to daylight, making them susceptible to conditions ranging from obesity, myopia, viral infections to mental illness, and equally urban ecosystems suffer from disturbed light regimes. For this reason, we argue that daylight should be explicitly recognized as a planning priority, with the aim of ensuring that all urban residents receive the daylight they need for optimal health. Such a recognition would have important implications for the development of cities. For example, it would set an upper limit to densification, beyond which adequate daylight could not be provided for everyone. It would also be a factor to consider in the design of buildings and in the use of technologies aimed at maximising energy efficiency. And it would be an argument to be considered when deciding between competing claims for open spaces, such as between constructing green roofs or installing photovoltaic panels.

Making daylight a priority poses new challenges for those involved in the design and construction of cities. For the planner, daylight should be seen as an overarching theme that bridges concerns as diverse as architectural aesthetics, healthy cities, biophilic design, urban climate adaptation and renewable energy systems. For the architect, the challenge will be to maximize daylight within buildings, while meeting stringent requirements for energy efficiency. The topic of 'daylighting' dates back centuries, but it now needs to be linked with efforts to make buildings sustainable in other ways. Landscape architects and ecologists face the challenge of including daylight as one of the essential services provided by open spaces, along with designing a range of ecosystem services, access to nature and recreation.

Meeting this challenge may require redesigning green spaces to make them more easily accessible and safe, even for the most frail.

We hope the ideas presented here will encourage urban planners to recognise the importance of both daylight and urban greenery for sustainable cities, and inspire designers to develop innovative solutions capable of maximising their benefits. In addition, there is a need to increase public awareness of the benefits of daylight, since many people have been taught that exposure to sunlight is harmful and that it is healthier to remain indoors or wear long clothes. Finally, much research is needed to determine the levels of daylight needed for both humans and nature, and to find ways to meet these needs, even in the densest cities.

Authors contributions
Christoph Kueffer (CK) together with Carlo Volf and Bruno Bueno (BB) led the project, Peter Edwards and CK led the writing process, all coauthors contributed to the development of ideas and the writing. Figure 1 was designed by CK and Figure 2 by BB.

Declaration of competing interest
The authors are mostly members of the Daylight Academy (DLA) of Velux Stiftung (https://daylight.academy/) that "promotes international and interdisciplinary cooperation among scientists, architects and other professionals involved in daylight research or with a strong interest in daylight related topics." The authors do not have any other potentially competing interests.

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Switzerland
office@daylight academy

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Figure 1 (page 6): "Four main ways in which densification tends to reduce exposure to daylight" from the original article of this reprint, https://doi.org/10.1016/j.jum.2024.02.002

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Figure 2 (page 10): "Illuminance at street level for different urban densification parameters of an urban site (neighbourhood, town)" from the original article of this reprint, https://doi.org/10.1016/j.jum.2024.02.002

Daylight Academy
A VELUX STIFTUNG initiative
Kirchgasse 42
8001 Zürich
Switzerland

www.daylight.academy
office@daylight.academy