modules, using particular combinations of materials converted directly to electricity in solar photovoltaic generation. Alternatively, solar energy can also be taken advantage of the transmission properties of glass. In Sun’s energy to heat fluids or produce energy, which also solar energy include technological systems that collect the (~10,000 nm). More commonly recognized applications of solar shading and daylight redirection. Dynamically or attached to windows to achieve the double function of solar shading and daylight redirection. Dynamically controlling the admission of solar heat gains and daylight in buildings can maintain thermal and visual comfort in workspaces, while simultaneously mitigating demand for heating, cooling, and lighting.

The solar radiation passing through windows offers another advantage by warming surfaces in buildings: It is familiar to experience these surfaces releasing heat by convection and long-wave radiation, thus providing warmth. Such “passive” solar heating does not usually come to mind as an application of solar energy. But this commonplace phenomenon is the consequence of the spectral characteristics of glass transmitting incident short-wavelength solar radiation (up to 3,000 nm), while trapping long-wavelength radiation which has been emitted from solar-heated interior surfaces (~10,000 nm). More commonly recognized applications of solar energy include technological systems that collect the Sun’s energy to heat fluids or produce energy, which also take advantage of the transmission properties of glass. In solar energy, a fluid flowing through a metal absorber typically transfers solar heat for applications ranging from domestic hot water up to electrical power generation. Alternatively, solar energy can also be converted directly to electricity in solar photovoltaic modules, with particular combinations of materials that absorb solar radiation at wavelengths corresponding to quantized electron energy gaps, in order to produce an electrical current.

Conclusions
Daylight, though ubiquitous, is rarely understood holistically. The interaction of daylight with organic and physical systems, as illustrated in Figure 2, has diverse consequences, from daylight through windows, to photosynthesis in plants, to vitamin D produced by exposure of our skin to the Sun.

In this publication, architects, vision scientists, botanists, physicians, physicists, engineers, and material scientists have contributed to an eclectic range of perspectives on daylight, each of which captures only part of the complex interplay of factors implicit in this apparently simple phenomenon. The insights from these very different perspectives are brought together here to provide a cross-disciplinary narrative intended to enhance our understanding of this fascinating subject.

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Acknowledgments
The authors wish to recognize the work of Brian Norton and Jean-Louis Scartezzini in editing this chapter.
Plants are sessile organisms that need to endure and respond to day-to-day uncertainties.

Information conveyed by light about recurring events

The direct effects of sunlight on energy transformation have been widely explored at various organizational levels: from the cell to the organ, as well as within food webs and ecosystems. However, the transfer and integration of information are not well understood, mainly at higher ecosystem levels. Evidence exists on the molecular, cellular, and individual levels that light information and how it is used is of central importance for understanding the processes and functions of life. We will also explore the temporal and spatial information conveyed by light and how it may increase the adaptability and plasticity of ecosystem responses, with implications for both agricultural and wild vegetation. The impact of human activity upon our planet is becoming ever more apparent, leading scientists to propose a new ecological epoch: the Anthropocene. Therefore, we also address the various ways that humans disturb or transform the information conveyed by light, and how the processing of light information in ecosystems has been and may be affected in the Anthropocene.

Plants are sessile organisms that need to endure and respond to day-to-day uncertainties. Temperature, precipitation, and other environmental factors affecting a plant’s existence show only a limited degree of predictability. However, there is one environmental factor that varies predictably and has shown to be a function of time of year and geogaphical latitude: the photoperiod. Ecologists have long studied the mechanisms by which plants respond to and cope with unpredictable environmental changes. The adaptations and strategies they use to take advantage of predictable, photoperiodic changes have been much less explored.

Plants can anticipate photoperiodic changes through an elaborate set of light sensors (2). They can anticipate dawn and dusk transitions, and can also more broadly "tell the time" and anticipate noon, midnight, and other times of day. Anticipation of the light regime is important, because it allows the plant to prepare its metabolism in advance for the upcoming demands (e.g., to prepare for photosynthesis before dawn), to temporally couple or uncouple processes that are associated or incompatible, and, over the course of the year, to respond to changes in the seasons. The mechanism by which plants tell time is the circadian clock.

We have known for quite some time that not only gene expression, but also carbon and water fluxes at the leaf level, are regulated by the circadian clock (6). But we are only now beginning to understand the implications of this finding—and its evolutionary consequences—at the scale of the vegetation canopy and the global carbon cycle. Information conveyed by light, and how the processing of light information in ecosystems has been and may be affected in the Anthropocene.

Circadian regulation is also responsible for part of the seasonal variation in stomatal conductance that is consistent with a model of stomatal conductance that is consistent with a model based on maximizing carbon assimilation also leads to less conservative water use. This is particularly true for plant species that are less centrally organized than animals. Research on the circadian regulation of photosynthesis and transpiration on the ecosystem scale in a field setting has received limited attention, mainly due to experimental limitations. The effect of the circadian clock is normally assessed under constant light and/or dark conditions, which is difficult if not impossible to achieve for whole ecosystems and under field settings. However, the few studies that have been published and that used either statistical filtering approaches or elaborated field infrastructure give some initial indications that circadian regulation may act as an adaptive memory to adjust ecosystem function based on environmental conditions from previous days (17, 12). Still, we do not know if these clock-triggered mechanisms significantly affect the carbon and water balance of ecosystems, and whether the clock-regulated regulation of gas exchange is common to all plant species or whether the clock over gas exchange is suppressed under certain conditions, such as in the understorey (the vegetation layer(s) below the main forest canopy).

The processes regulating flux and function at the individual plant scale will not necessarily be the same as those found in the canopy or at the ecosystem scale, because not all processes relevant at one scale will be equally important at other scales (10). This is particularly true for plants that are less centrally organized than animals. Research on the circadian regulation of photosynthesis and transpiration on the ecosystem scale in a field setting has received limited attention, mainly due to experimental limitations. The effect of the circadian clock is normally assessed under constant light and/or dark conditions, which is difficult if not impossible to achieve for whole ecosystems and under field settings. However, the few studies that have been published and that used either statistical filtering approaches or elaborated field infrastructure give some initial indications that circadian regulation may act as an adaptive memory to adjust ecosystem function based on environmental conditions from previous days (17, 12). Still, we do not know if these clock-triggered mechanisms significantly affect the carbon and water balance of ecosystems, and whether the clock-regulated regulation of gas exchange is common to all plant species or whether the clock over gas exchange is suppressed under certain conditions, such as in the understorey (the vegetation layer(s) below the main forest canopy).

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Dependent on temperature and water availability, thus photoperiod is not the only important cue. As global warming advances, we are more often encountering an advancement of life-cycle events. However, such advancement has been slower than predicted based on temperature changes alone (13).

Photoperiod signals, which do not change with warming, could thus provide a buffer against such phenological advancements.

Information conveyed by light from/about the local environment

Light provides information on the structure and quality of the environment and neighborhood within an ecosystem. This is important not only for animals and their spatial orientation, but also for sessile plants. Chlorophyll, the major light-absorbing pigment of plants, is activated predominantly by blue (400 nm–500 nm) and red (650 nm–700 nm) light, causing a depletion of these wavelengths further down in the vegetation canopy. Moreover, far-red light (700 nm–800 nm) is reflected by the leaves. This reflection also occurs downwards into the canopy, leading to an enrichment of far-red light. Thus, the ratio of red to far-red light will be reduced in dense canopies. Within complex, multilayer-canopy ecosystems such as forests and grasslands, the spatial distribution of light as well as its quality and wavelength composition allow for a 3D interpretation of available space and competitor location, and an optimization of shade-avoidance strategies (14). Due to the different absorption and reflectance properties of different objects, plants can differentiate between the shade of a nonliving object (e.g., a rock) and that of another plant: In the shade of a plant, far-red light is relatively enriched compared to the red light, whereas natural nonliving objects will not change the red-to-far-red ratio. Phytochrome is used by plants to measure the ratio of red to far-red light, and thus to detect whether the plant is in the shade of a competitor or not. In addition to red-light depletion, absorption of light by chlorophyll and other pigments also causes reduction of blue light in the shaded parts of dense canopies. Blue-light intensity and its change is detected through two classes of blue-light photoreceptors called “cryptochromes” and “phototropins” (15). These different photoreceptors regulate the concentration and allocation of various phytohormones, such as gibberellins, auxins, and brassinosteroids, which in turn affect growth patterns.

Because of their ability to sense light quality, plants can thus alter their growth strategy accordingly (so-called “photomorphogenesis”), for example by enhancing height growth to reduce competition for light. The red-to-far-red ratio also provides important information to plants about their location in the system. If sensed vertically, the red-to-far-red ratio of incoming radiation indicates how far it is to the top of the canopy (i.e., the lower the red-to-far-red ratio, the further the distance), albeit not in meters, but in terms of “competing leaf surface.” By contrast, if sensed horizontally, plants can determine how far away the nearest plants are that might compete for light. Depending on

their life-history strategy, plants can adjust their growth accordingly, for example by growing away from their neighbors to avoid competition, or growing toward them so as to outcompete them.

Plants have developed different combinations of life-history traits such as growth and development rates, size and age at maturity, and life span in order to respond to changing environmental factors that may impact fitness. Organisms seek to maximize their fitness, which is determined by both reproductive success and survival. Because light is an important environmental factor, plant species have evolved strongly diverging morphological and eco-physiological traits to improve their fitness under differing and changing light conditions. Trees have evolved upright stems to get access to direct sunlight, with some species growing taller than others (e.g., giant sequoias in the Southwest of North America or some species of the Dip terocarpaceae family in Southeast Asia). Plant species such as some tall tropical forbs tend to grow extremely large leaves to collect sunlight. In contrast, the development of shade tolerance allows certain plant species to become established and survive under dense forest canopies or beneath multiple layers of herbs in grasslands. All of these traits affect the response of individual species to light, according to the information it provides on their position within the canopy and relative to their competitors.

Many open questions remain with respect to the orientation of plants within the complex canopies of forests and grasslands. For example, plants need to determine if they are shaded by parts of their own organism, such as leaves, or by competitors; and growth reactions need to be adjusted accordingly. Even though wavelength-specific reflectance and absorption patterns of different plant species may vary, conspecific competition cannot be distinguished from self-shading by sensing light quality alone. Light intensity and carbon assimilation may provide additional organism-integrating information, because the whole plant is a source-sink continuum for

leaves to collect sunlight.
Sunlight not only provides energy for almost all processes in the biosphere, but is also an important source of information for living organisms and ecosystems.

Sunlight provides energy for almost all processes in the biosphere, but is also an important source of information for living organisms and ecosystems. In ecosystems, sunlight is important as a source of energy for photosynthesis, which is the process by which plants convert light energy into chemical energy. This energy is then transferred through the food web, providing energy for all other organisms in the ecosystem.

Challenges related to light information in the Anthropocene

The term ‘Anthropocene’ encompasses all major anthropogenic changes in ecosystems, biodiversity, and biogeography, among other factors, through climate change and light. The change in light as a source of information, which is important for ecosystem processes and function, can occur via direct effects such as the increasing abundance of artificial light, often referred to as light pollution. Moreover, rapid environmental change induced by mankind may interfere with circadian resonance, which normally serves to tune a plant’s endogenous rhythms to match environmental cues. These impacts may compromise the evolved mechanisms of plants and vegetation and disrupt their ability to predict conditions in the (near) future based on hitherto reliable environmental cues (e.g., day-night or seasonal rhythms).

It is not only animals, which have often adapted their behavior to the day and night rhythm, but also plants, height and whole ecosystems that are affected by artificial lighting. While light intensity may be only locally close to the light source sufficient to induce photosynthesis at night, circadian clocks and photoperiodism are likely to be more strongly affected at lower light intensities via phytochrome- and cryptochrome-sensing. Changes in the natural photoperiod as a consequence of artificial light are known to affect plant phenology in various ways, including changing the timing of flowering as well as leaf shedding of deciduous trees in autumn. As the photoperiod’s natural, reliable cue is altered, it may no longer provide an adaptive advantage to enable the plant to cope with environmental conditions, but rather turn maladaptive. As an example, delayed leaf senescence in trees close to street lamps might increase the risk of early frost damage (16).

Under natural conditions (i.e., in the absence of artificial light), diurnal and seasonal light-related triggers remain largely constant as climate is usually more stable, and thus, the phenology of photoperiod-sensitive species may no longer be in resonance with current climatic conditions. The abovementioned buffer effect provided by temperature-insensitive photoperiod signals may therefore be diminished or may even turn negative, thus restricting its herbivore in the adaptation of light-related environmental cues when the change in environmental conditions becomes more extreme. Our understanding of the role of light in the development of individuals and species (including adaptation by migration) and of whole ecosystems (e.g., synchronization among species, including phytoplankton) is largely lacking, reducing our ability to predict impacts and devise response strategies. We do not yet know if the evolved ability of plants to predict future conditions based on aspects of the natural light regime is an advantage or a disadvantage with respect to global climate change and human-induced changes of the external light–dark cycle. In general, it is assumed that prediction of conditions in the (near) future that take advantage of reliable environmental cues (day-night and seasonal rhythms) optimizes resource use and provides acclimation and adaptation advantages. Circadian resonance has been repeatedly shown to be adaptive in promoting growth and survival (17). However, such binding to daylength rhythmicity, both on a diurnal and seasonal scale, may hamper species distribution and plant adaptation to even local climate change. It may thus happen that the potential distribution range of a species—as defined by temperature and precipitation—moves north due to climate change, but that the photoperiod cues at this new latitude do not match the evolutionary demands of that species. As the climate changes faster than ever, it is unlikely that plants will have sufficient time to adapt, especially trees and shrubs with long generation times.

Conclusions

Sunlight not only provides energy for almost all processes in the biosphere, but is also an important source of information for living organisms and ecosystems. In plants, light quality-sensing and light-energy harvesting are closely interlinked and determine the growth strategies within complex canopy environments. Yet, how various sources of information are coprocessed remains unknown. The information provided by the highly reliable photoperiod allows a plant to substantially increase photosynthesis, growth, and survival when the circadian clock period and the external light–dark cycle are matched. However, whether the circadian clock plays a role in modulating canopy and ecosystem water and carbon fluxes is still unknown. If ecosystem responses are also driven by antecedent environmental conditions via the circadian clock, Earth system models may be unable to fully capture the effect of global climate change on the Earth’s biogeochemical cycles. Taking light and photoperiod as surrogates for other, less reliable environmental cues, such as temperature and precipitation, may prove to be an insurmountable evolutionary burden for some species, particularly when light and other environmental cues no longer match, preventing migration, for example. Neither species distribution models nor mechanistic dynamic global vegetation models normally take into account the impacts of natural light as a source of information. Thus, we need better mechanistic representations of the impacts of light information on ecosystem processes in order to include these in models that allow for the projection of future species distributions as well as ecosystem and biome function.

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