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Optics of sunlit water drops on leaves: conditions under which sunburn is possible

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Summary

- It is a widespread belief that plants must not be watered in the midday sunshine, because water drops adhering to leaves can cause leaf burn as a result of the intense focused sunlight. The problem of light focusing by water drops on plants has never been thoroughly investigated.
- Here, we conducted both computational and experimental studies of this phyto-optical phenomenon in order to clarify the specific environmental conditions under which sunlit water drops can cause leaf burn.
- We found that a spheroid drop at solar elevation angle $\theta \approx 23°$, corresponding to early morning or late afternoon, produces a maximum intensity of focused sunlight on the leaf outside the drop's imprint. Our experiments demonstrated that sunlit glass spheres placed on horizontal smooth *Acer platanoides* (maple) leaves can cause serious leaf burn on sunny summer days.
- By contrast, sunlit water drops, ranging from spheroid to flat lens-shaped, on horizontal hairless leaves of *Ginkgo biloba* and *Acer platanoides* did not cause burn damage. However, we showed that highly refractive spheroid water drops held 'in focus' by hydrophobic wax hairs on leaves of *Salvinia natans* (floating fern) can indeed cause sunburn because of the extremely high light intensity in the focal regions, and the loss of water cooling as a result of the lack of intimate contact between drops and the leaf tissue.

Introduction

It is a widely held belief in horticulture that plants must not be watered in the midday sunshine. The most frequent explanation for this is that in direct sunshine water drops adhered to plants can scorch the leaves as a result of the intense light focused on to the leaf tissue. Seventy-eight per cent of the relevant topical websites surveyed by us (Supporting Information, Table S1) answered the question 'Do sunlit water drops burn leaves?' in the affirmative. This attests to the fact that laymen and professionals alike commonly believe water drops on plants after rain or watering can cause leaf burn in sunshine. (We add that morning dew on plants can also persist into the daylight hours and might thus cause leaf burn.) This is a long-standing environmental optical problem, the solution of which is not trivial at all.

An analogous issue is whether or not human skin covered by water drops can be damaged by focused sunlight during sunbathing. Eighty-nine per cent of the surveyed dermatological and cosmetics websites (Table S2) answered the question 'Can sunlit water drops burn the human skin?' in the affirmative. Similarly, in the forestry literature the prevailing opinion is that forest fires can be sparked by intense sunlight focused by water drops on dried-out vegetation (Table S3).

The closest atmospheric optics problem is the refraction of sunlight by falling raindrops, which produces a rainbow. Although the literature of rainbow optics is extensive (Des-Cartes, 1637; Airy, 1838; Nussenzweig, 1977; Können & de Boer, 1979; Lee, 1998), these studies were all limited to the spherical or semi-spherical shapes of falling water drops.

The problem of light focusing by water drops adhered to plants has never been thoroughly investigated, either theoretically or experimentally. In order to fill this gap and determine the specific conditions under which sunlit water drops can cause leaf burn, we conducted both experimental and computational studies. First, we exposed horizontal leaves covered with glass spheres or water drops to sunlight, considering plants of different wettabilities and surface properties (smooth or hairy). Next, we performed an optical modeling study of realistic water drops derived from digital photographs. Using computer ray tracing, we calculated the spatial distribution of sunlight intensity focused by a rotation-symmetric water drop onto a horizontal leaf. This, in turn, allowed us to determine the location and magnitude of maximum light intensity on a leaf as a function of drop shape and solar elevation angle θ. Accounting for the θ-dependent solar spectrum and the absorption spectrum of green plant tissue, we could finally determine the particular drop shape and solar elevation that maximized the probability of leaf burn by focused sunlight.

Materials and Methods

We performed three experiments in sunshine with various leaves covered by glass spheres or water drops.

Experiment 1

We tested whether maple (*Acer platanoides*) leaves covered with glass spheres of different diameters (ranging from 2 to 10 mm) can suffer sunburn when exposed to direct sunlight for various periods. The experiment was performed on three sunny, cloudless, warm, and calm days in a garden in Göd (47°43′N, 19°09′E), Hungary. Ten circular grey plastic trays were put on a table (Fig. S1), each containing a single fresh-cut maple (*A. platanoides*) leaf with a smooth hairless surface. In trays 1–9, the leaves were covered with a single layer of tightly packed glass spheres (index of refraction $n_{glass} = 1.50$), the diameter of which systematically increased from 2 to 10 mm from trays 1 to 9. In tray 10 the leaf remained free of glass spheres, functioning as a control. The glass sphere-covered leaves were then exposed to direct sunlight for three different time periods: long (from 08:00 to 17:00 h local summer time = UTC + 2 h, on 8 July 2007), medium (from 10:30 to 13:30 h on 14 July 2007), and short (from 16:00 to 17:00 h on 17 July 2007). During exposure the trays were continuously sunlit encountering no shade. After the experiment, the maple leaves were scanned by a Canon Arcus 1200 scanner in the laboratory to document their sunburn (Fig. 1).

Experiment 2

Experiment 2 was devoted to determining whether or not sunlit water drops on horizontal *Ginkgo biloba* and *A. platanoides* leaves with smooth hairless surfaces can cause sunburn in the leaf tissue at any solar elevation angles (Table 1). It was performed on 26 July 2007 at the same place as Expt 1. The weather was sunny, cloudless, warm, and calm. One pair of fresh-cut *G. biloba* and one pair of *A. platanoides* (maple) leaves with smooth hairless surfaces were fixed flat on to rectangular (10 cm × 10 cm) glass panes with colourless transparent tape at a few points along the leaf edges. In each pair of leaves, one leaf had its upper surface and the other its lower surface facing upward. The glass panes with the flat leaves were placed horizontally on a table at a height of 10 cm above the tabletop (Fig. 2a). The table was covered with a bright green matte cloth. Several large drops (7–8 mm in diameter) of clean tap water were placed on to all four leaves (Fig. 2). To produce these large drops, four smaller droplets of the same size were dripped from an eye-dropper on to a given location on a leaf blade. Thus, the sizes of the large aggregate drops were practically the same on each leaf. The function of the glass panes was to ensure the orientation of the flat leaf blades was horizontal, and to allow the prepared leaves to be illuminated from below by the diffuse light reflected from the underlying green matte surface, thereby imitating the ground-reflected light received by vegetation under natural conditions.

The leaves holding numerous water drops were then exposed to direct sunlight in three different sessions. The first exposure began at low solar elevations at 07:55 h (Table 1) and lasted until all water drops evaporated from the leaves. Then, two more exposures were performed using newly cut pairs of *Ginkgo* and *Acer* leaves prepared as described earlier, with the third and last exposure finishing in the early afternoon. The experiments were not continued into the late afternoon because of cloudy weather, which is typical of the Hungarian summer. Under cloudy conditions the exposure by continuous sunlight could not be ensured. After the experiment the leaves were scanned in the laboratory to determine their possible sunburn.

The time, solar elevation angle, and air temperature at the start and end of a given exposure, as well as the number of water drops on the leaves, are summarized in Table 1, separately for each exposure. The start time of a given exposure was the same for all four leaves but the end times were determined by the duration of evaporation of the water drops, which, in turn, depended on leaf albedo and the shape of water drops, both varying with leaf type (see Figs 4a, 5a, 6a).

Experiment 3

Experiment 3 was conducted to test whether or not sunlit water drops held by hydrophobic wax hairs of floating fern leaves (*Salvinia natans*) can induce sunburn. It was performed in the Botanic Garden of Eötvös Loránd University in Budapest (47°28′N, 19°05′E) on 30 July 2007 on a sunny, cloudless, warm, and calm day. Floating ferns (*S. natans*) with a large number (120) of leaves were put into two small water-filled containers (Fig. 3a), which were then exposed to direct sunlight for 2 h from 13:00 to 15:00 h local solar time (UTC + 2 h). Before exposure, numerous (five to 20) water drops of varying sizes (0.5–8 mm in

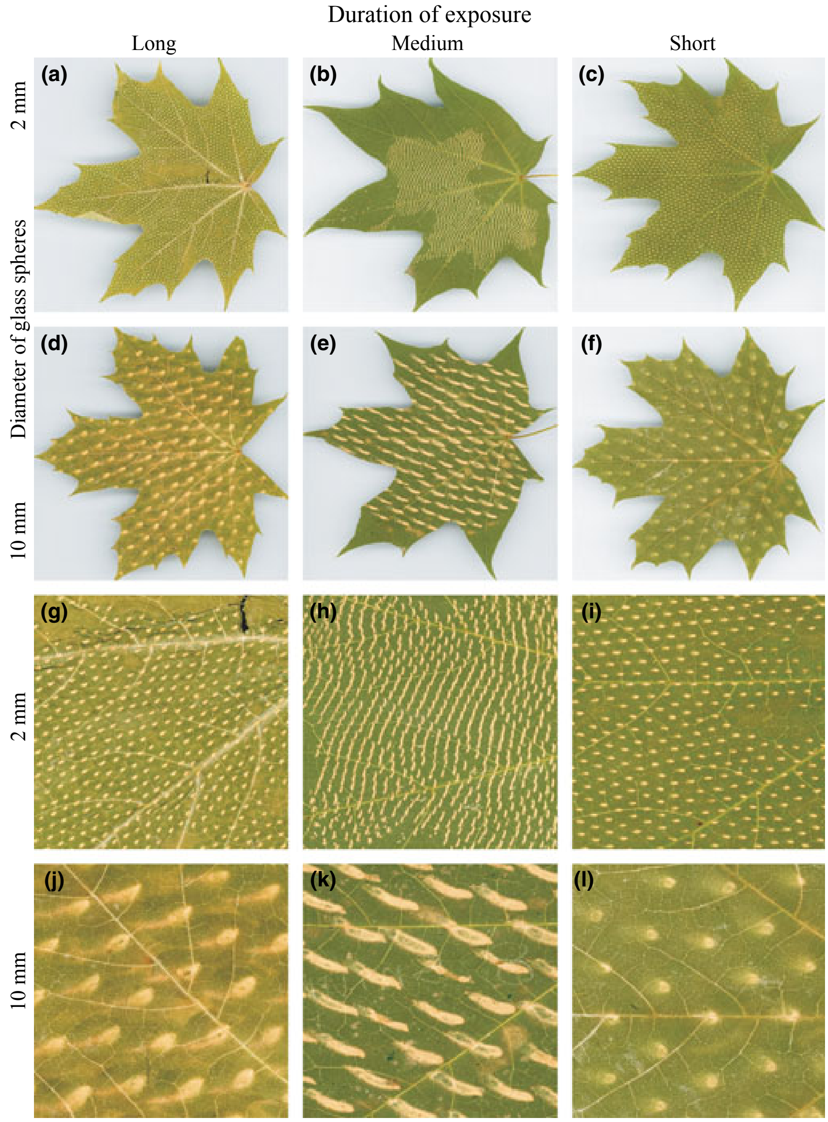

Fig. 1 (a–f) Sunburnt maple (*Acer platanoides*) leaves exposed to direct sunlight for long (left column), medium (middle column), and short (right column) periods covered by glass spheres of 2 and 10 mm diameter in Expt 1. The grid pattern of sunburnt brown patches caused by intense focused sunlight is clearly visible on the green leaves. (g–l) As (a–f) but with a fourfold enlargement.

diameter) were dripped/sprayed on to the hairy *Salvinia* leaves (Fig. 3b,c) with an eye-dropper/water-sprayer. Throughout the experiment the positions and orientations of the *Salvinia* leaves floating on the water surface did not change. After the 2 h exposure, smaller water droplets completely evaporated, while larger drops did not. The experiment was concluded by cutting and scanning several *Salvinia* leaves – still holding water drops – in the laboratory in order to document their sunburn (Fig. 3d–i).

Computer ray tracing

To better understand sunlight focusing by water drops, we also performed a computer ray tracing. First, we determined the rotational-symmetric shape of water drops of different sizes on various horizontal leaves (rowan, *Sorbus aucuparia*; plane tree, *Platanus hybrida*; maple, *A. platanoides*) with zdifferent water repellencies. Then, we computed the paths of rays refracted by these water drops when they were illuminated by parallel rays of sunlight at different solar elevation angles, θ. These calculations enabled us to determine the two-dimensional distribution of the light-collecting efficiency of water drops along horizontal leaf blades as functions of drop shape and θ. Finally, we calculated the intensity of focused sunlight absorbed by the leaf tissue, which is the parameter that ultimately determines leaf-damage potential. Further details of these computations can be found in the online Supporting Information (Notes S1A and S1D, Figs. S2, S3, S4).

Results

In Expt 1 using glass spheres, all maple (*A. platanoides*) leaves suffered serious sunburn (Fig. 1), regardless of the

Exposure	Leaf (exposed surface)	Start		End		T (°C)		N
		t	θ (°)	t	θ (°)	Start	End	
First	*Acer* (lower)	7:55	27.5	9:40	44.9	24.0	27.0	25
	Acer (upper)	7:55	27.5	9:35	44.1	24.0	27.0	21
	Ginkgo (lower)	7:55	27.5	10:30	52.6	24.0	29.0	8
	Ginkgo (upper)	7:55	27.5	10:00	48.1	24.0	28.0	11
Second	*Acer* (lower)	10:30	52.6	11:28	60.1	29.0	31.0	24
	Acer (upper)	10:30	52.6	11:20	59.2	29.0	30.5	29
	Ginkgo (lower)	10:30	52.6	12:00	63.0	29.0	32.0	18
	Ginkgo (upper)	10:30	52.6	11:31	60.4	29.0	31.0	21
Third	*Acer* (lower)	12:00	63.0	13:11	64.4	32.0	34.0	29
	Acer (upper)	12:00	63.0	13:01	64.7	32.0	33.5	31
	Ginkgo (lower)	12:00	63.0	13:45	62.3	32.0	34.5	19
	Ginkgo (upper)	12:00	63.0	13:17	64.1	32.0	34.0	21

Table 1 Local solar time (*t*UTC + 2 h), solar elevation angle θ, and air temperature T (°C) at the start and end of the three exposures of *Acer platanoides* and *Ginkgo biloba* leaves in Expt 2 (Fig. 2), and the number N of water drops on the sun-facing lower or upper leaf surfaces

(a) **(b)** *Ginkgo biloba* *Acer platanoides*

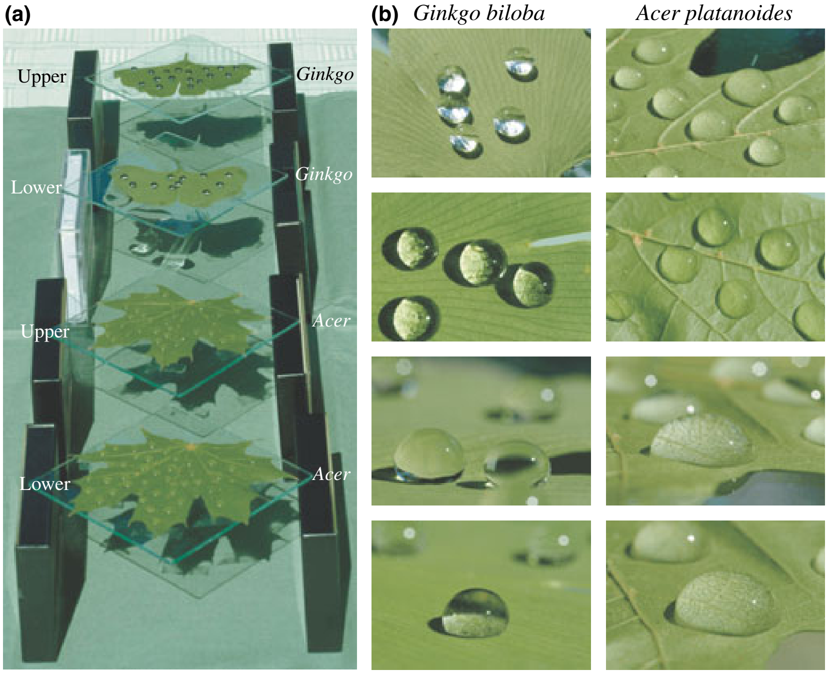

Fig. 2 (a) Setup of Expt 2 with two water-covered maple (*Acer platanoides*) leaves (bottom) and two *Ginkgo biloba* leaves (top) on glass panes. In each case, both upper and lower leaf surfaces were exposed to sunlight. (b) Close-up photographs of water drops on *Ginkgo* (left column) and *Acer* (right column) leaves.

length of sunlight exposure (long, medium, or short) and diameter of the spheres (2–10 mm). From this we concluded that sunlight focused by glass spheres (refractive index n_{glass} = 1.5) can burn the leaf tissue any time of day (morning, midday, or afternoon).

However, the effect of water drops may be different from that of glass spheres because the drop shape is usually not spherical; the refractive index of water (n_{water} = 1.33) is smaller than that of glass (n_{glass} = 1.50); and water cools the leaf tissue, if there is an intimate contact between a water drop and the leaf. Thus, we performed a second, more realistic experiment, in which horizontal and smooth *G. biloba* and *A. platanoides* leaves covered with water drops (*c.* 5–7 mm in diameter) were exposed to sunlight (Table 1, Fig. 2). In contrast to glass spheres, water drops did not cause any visible sunburn (browning).

In Expt 2, water drops were sitting directly on the leaf surface, and consequently their focal regions fell far below the leaf blade, explaining the lack of sunburn together with water cooling. If a water drop were further away from the leaf blade, it could not cool the leaf, and its focal region may fall on to the leaf surface, thus possibly inducing sunburn (browning) in the leaf tissue. This could be the situation for hairy leaves, where hydrophobic wax hairs can hold a water drop at a distance from the leaf surface. In order to study such a situation, we conducted Expt 3, in which highly water-repellent hairy leaves of floating fern (*S. natans*) holding water drops were exposed to sunlight (Fig. 3a–c). The hairs of *S. natans* are composed of bundles of thin, hydrophobic wax fibres, which can hold even large water drops. Fig. 3d–i shows pictures of *Salvinia* leaves after exposure, where brown sunburnt patches are clearly visible.

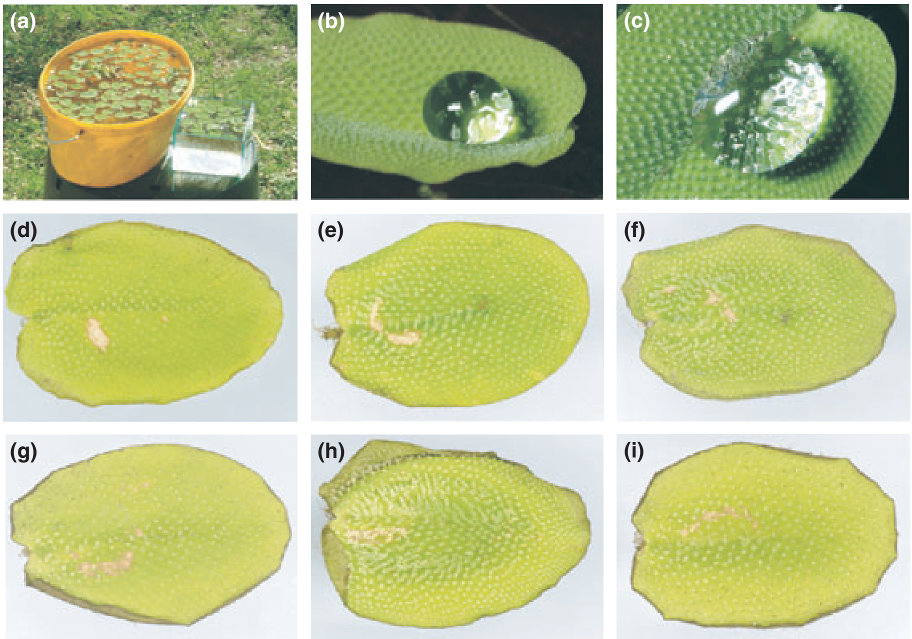

Fig. 3 (a) Setup of Expt 3 with leaves of floating fern (*Salvinia natans*) in two water-filled containers. (b, c) Water drops on green water-repelling hairy *Salvinia* leaves. (d–i) Brown sunburnt patches on *Salvinia* leaves after 2 h exposure to sunlight.

In conclusion, hairy leaves can suffer sunburn after raining/watering because the focal region of water drops held by water-repellent wax fibres falls right on to the leaf surface, which is not cooled by water because of the lack of intimate contact between drops and leaf.

Let us now turn to our optical modeling results. Fig. 4a shows a typical water drop on a horizontal rowan (*S. aucuparia*) leaf, which is approximately spheroid as a result of the large contact angle, $\chi \approx 145°$, between water and leaf blade. Fig. 4b represents the ray tracing through this spheroid water drop along its vertical main cross-section for various solar elevation angles, θ, while Fig. 4c shows the resulting two-dimensional distributions of the light-collecting efficiency Q vs θ. According to Fig. 4c, the focal region is mostly within the drop's imprint and is thus cooled by water for $\theta > 50°$. For $\theta < 40°$, however, the focal region is not cooled by water as it falls outside the drop's imprint, increasing the probability of tissue damage by sunburn. Figs 5 and 6 show the same result for a flat water drop on a maple leaf (*A. platanoides*) and a hemispherical drop on a plane tree leaf (*P. hybrida*).

Fig. 7 shows the intensity $I(\theta)$ of drop-focused sunlight that is actually absorbed by the green tissue of maple, plane tree, and rowan leaves (Figs 4–6) at a given solar elevation θ. Apparently, the θ-dependence of $I(\theta)$ is driven by that of the light-collecting efficiency $Q(n_{\text{water}},\theta)$ (see Fig. S5). Therefore, $I(\theta)$ monotonically increases with decreasing solar elevation for both the flat drop on the maple leaf and the hemispherical drop on the plane tree leaf (Fig. 7a,b). For these two plants, absorbed sunlight intensity I is largest at sunrise/sunset but with quite different peak intensities: $\log_{10}I$ reaches 4.37 for plane tree and 2.85 for maple at $\theta = 5°$, corresponding to a factor of $10^{4.37-2.85} = 10^{1.52} \approx 33$ difference (Fig. 7a,b).

Fig. 7c and Fig. S5c show that both the light-collecting efficiency $Q(n_{\text{water}},\theta)$ and the intensity $I(\theta)$ of absorbed sunlight have two maxima in the case of a spheroid water drop on a rowan leaf. This is because such a nonspherical drop has two different focal regions as a result of astigmatism: one at $\theta_1 = 13°$ (further from the drop) with $\log_{10}I = 4.7$, and one at $\theta_2 = 23°$ (nearer to the drop) with $\log_{10}I = 5.1$. These are formed by refracted rays crossing the drop along its horizontal and vertical main cross-sections, respectively. As a result, the first focal region is elongated parallel to the antisolar meridian, while the second is perpendicular to the antisolar meridian (see Fig. 4c, panel 6 for $\theta_1 = 13°$, and Fig. 4c, panel 4 for $\theta_2 = 23°$), and they show a factor of $10^{5.1-2.7} = 10^{2.4} \approx 251$ and $10^{4.7-2.8} = 10^{1.9} \approx 79$ increase in absorbed intensity compared with a flat drop. Therefore, the chance of leaf tissue sunburn caused by the spheroid water drop in Fig. 7c is significantly higher than that for either the flat drop in Fig. 7a or the hemispherical drop in Fig. 7b. However, as we showed in Expt 2, even these most intensely focusing spheroid water drops fail to cause sunburn (at least on Ginkgo leaves). Further results can be found in the online Supporting Information (Note S1B, Figs. S5–S8).

Discussion

Leaf surface characteristics are important in determining wettability, foliar permeability/penetration, water retention,

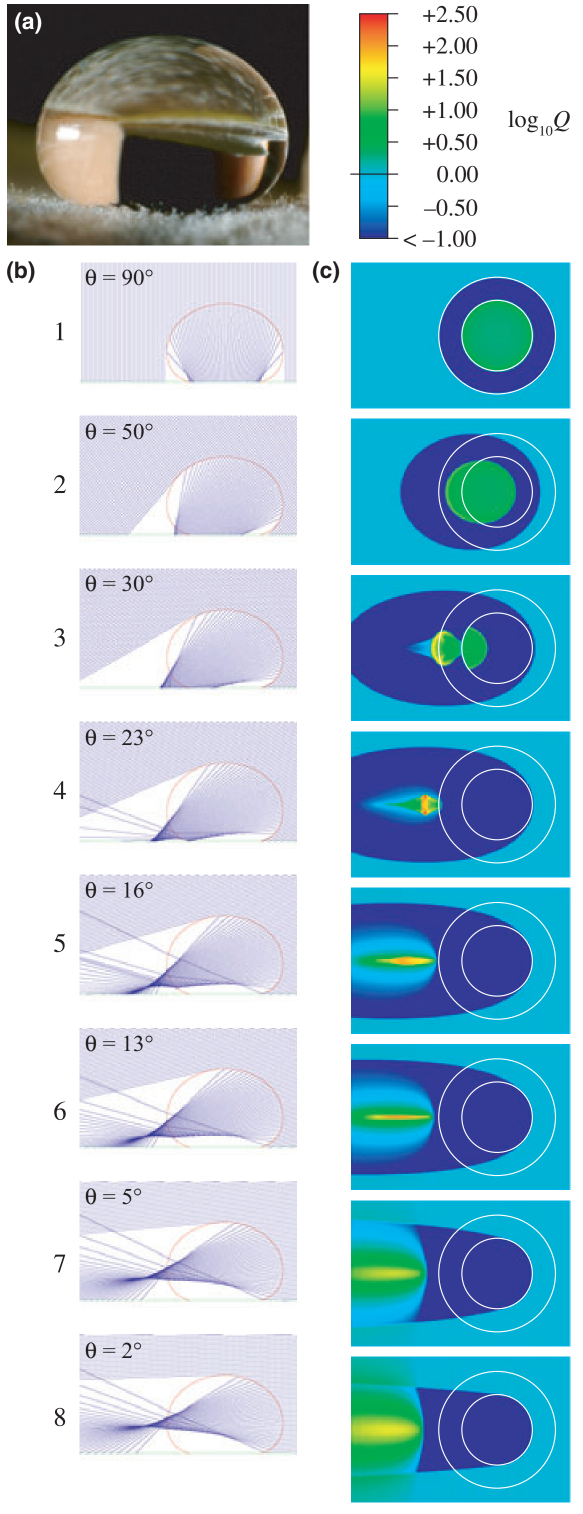

Fig. 4 (a) Side-view photograph of a spheroidal water drop on a horizontal rowan (*Sorbus aucuparia*) leaf. (b) Ray tracing through the vertical main cross-section of the water drop (the contour of which is shown by the red curve) vs solar elevation angle θ. (c) Two-dimensional distribution of the light-collecting efficiency Q of the water drop on the leaf. The area where the water drop contacts the leaf is shown by the inner circle, while the contour of the drop as seen from above is indicated by the outer circle.

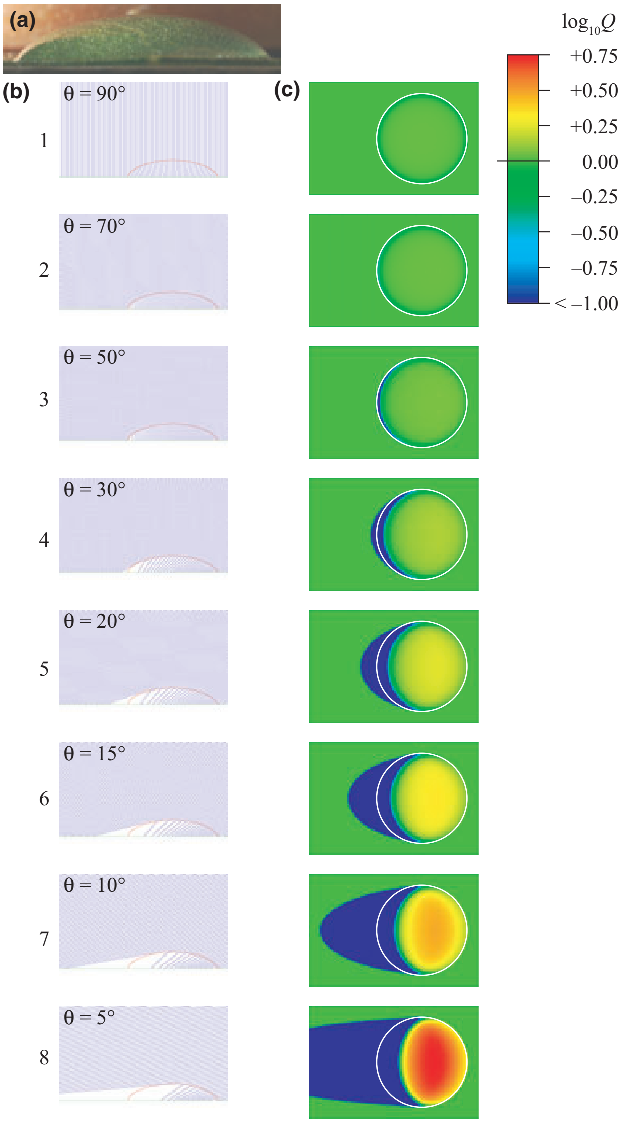

Fig. 5 As Fig. 4 but for a flat water drop on a maple (*Acer platanoides*) leaf. In panel (c), the circles mark the water drop's imprint on the leaf.

as well as exchange rates of gas, water and dissolved substances between plant and atmosphere (Fogg, 1947; Holloway, 1969; Martin & Juniper, 1970; Juniper & Jeffree, 1983). If, after rain, leaf blades were covered by a water film, they could not breathe, because gas exchange through the stomata would be blocked. To avoid this, plants evolved efficient water-repelling and water-channeling structures which build up and roll off rain drops (de Gennes *et al.*, 2004). A general rule is that the more hydrophobic the leaf surface (i.e. the greater the leaf-water contact angle), the smaller is its water-holding capacity. For example, water drops easily roll off the highly hydrophobic leaves of lotus, *Ginkgo* (Fig. 2b), and floating fern (Fig. 3b,c) if leaves are tilted or shaken.

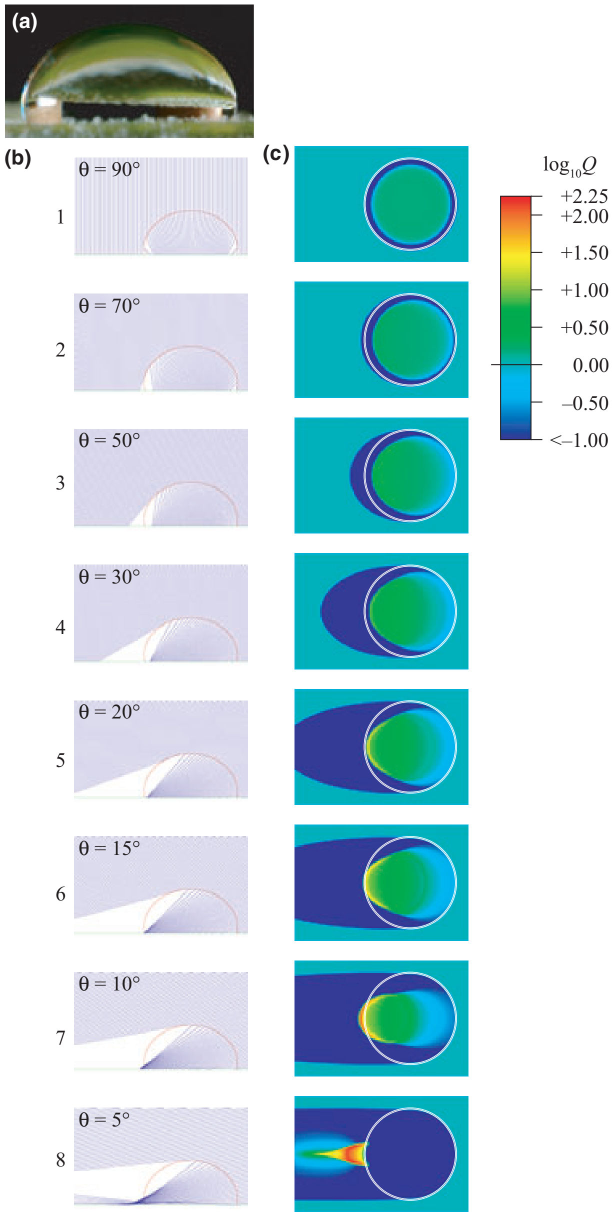

Fig. 6 As Fig. 5 but for a hemispherical water drop on a plane tree (*Platanus hybrida*) leaf.

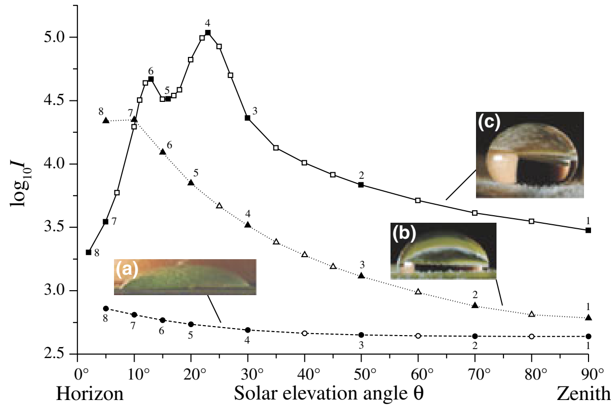

Fig. 7 $\text{Log}_{10}I$ vs solar elevation angle θ, where $I = Q(n_{\text{water}} = 1.33, \theta)\cdot a(\theta)$ is the maximum sunlight intensity absorbed by green leaf tissue in the focal region of a water drop on a horizontal maple (a), plane tree (b) and rowan (c) leaf with decreasing wettabilities from (a) to (c). Here, $Q(n_{\text{water}} = 1.33,\theta)$ is the maximum light-collecting efficiency of water drops in the focal region (Fig. S5), and $a(\theta)$ is the solar absorption factor of leaves (Fig. S4c). Insets show side-view photographs of water drops. Data corresponding to panels 1, 2, … 7, 8 in Figs 4–6 are marked by filled circles, triangles, and squares, respectively.

In Expt 1, we showed that glass spheres on smooth horizontal leaves can cause sunburn (Fig. 1), because their focal region falls on or near the underlying leaf surface for a wide range of solar elevation θ. Water drops, however, have a smaller index of refraction than glass spheres (n_{water} = 1.33 vs n_{glass} = 1.50) and thus have smaller refractive power as well. In addition, the shape of water drops on leaves is usually ellipsoidal (Figs 2, 3b,c, 4a, 5a, 6a), which further decreases their refractive power. As a result, the focal region of water drops falls far below the leaf at higher solar elevations and can fall on to the leaf only at lower solar elevations, when the intensity of light from the setting sun is generally too small to cause sunburn. Furthermore, water drops, especially flatter ones, contact the leaf surface over much larger areas than glass spheres and can thus produce significant water cooling. The intimate contact between a water droplet and a hairless leaf considerably increases the thermal mass in the contact region, which inevitably has the effect of greatly reducing any damaging temperature rise of the underlying leaf surface, and thus preventing sunburn. These factors explain our experimental finding that sunlit water drops on horizontal leaves without waxy hairs (Fig. 2) cannot cause sunburn regardless of solar elevation and drop shape.

In Expt 3 with *Salvinia*, however, the water drops were not residing on but were held above the leaves by hydrophobic wax hairs (Fig. 3b,c). This separation resulted in the focal region of drops falling on the leaf surface, and the loss of cooling by contact. In addition, the water drops had a high refractive power because of their spheroidal shape. As a consequence of these factors, the *Salvinia* leaves did get burnt in sunshine (Fig. 3d–i).

A more water-repellent leaf surface entails a greater contact angle between water and leaf cuticle, a lower water-holding capacity, and a more spheroid water drop. Because of their greater curvature, spheroid water drops have larger refractive power and, thus, greater light-focusing ability than flat ellipsoid drops; therefore, they are more likely to cause thermal damage in the leaf tissue. However, spheroid water drops (Fig. 4a) easily roll off highly hydrophobic leaves which are tilted or shaken by wind, practically eliminating the possibility of sunburn. By contrast, water drops can stick to wettable leaves, such as those of *Acer*, for an extended period of time (Fig. 5a). However, this is counterbalanced by the weak light-focusing ability (refractive power) of drops, which tend to be rather flat on a wettable leaf because of the small contact angle of water. In conclusion, water drops cannot cause sunburn, either on water-repellent or on wettable leaves with smooth, hairless surfaces, as clearly corroborated by Expt 2.

As shown in Expt 3, sunlit water drops can cause sunburn (Fig. 3d–i) but only if they are held at appropriate heights above the leaf surface. This is the case for the superhydrophobic leaves of lotus (Cheng & Rodak, 2005) and floating fern (Fig. 3b,c), where wax hairs can hold highly refractive spheroid drops 'in focus'. Note that sunburn potential is the net result of competing factors, the relative strengths of which depend on drop size. Although smaller water droplets have greater curvature and thus larger focusing capability than larger drops, they also evaporate more rapidly, reducing the exposure to focused sunlight and the chance of sunburn. Furthermore, the amount of light focused by smaller droplets is also smaller than that collected by larger drops, because light-collecting efficiency is proportional to effective cross-section perpendicular to incident sunlight. As a result, sunburn tends to favor larger drops over smaller droplets. However, sunburn caused by tiny droplets could potentially be more injurious than that caused by a few large drops, as they cover a leaf more extensively.

At the start of this paper, we quoted the oft-stated advice that plants must not be watered in the midday sunshine in order to avoid tissue damage as a result of intense sunlight focused by water drops on leaves (Table S1). We have shown that this widely held belief is only correct for hairy leaves. Based on the computed light-collecting efficiency of water drops (Figs 4–7), we have also determined that the risk of sunburn of smooth, hairless leaves is theoretically the highest at a solar elevation of $\theta \approx 23°$, corresponding to early morning or late afternoon. In practice, however, the light intensity from such an oblique position of the sun is too weak to be a factor, as was confirmed by Expt 2.

We believe that completely unrelated types of leaf damage might be partly responsible for the widespread belief about sunburn caused by water drops. For example, drops of acid rain, salty sea/tap water, chlorinated water, and concentrated solutions of nutrition, fertilizers, and chemicals can all cause sunburn-like brown patches via osmotic dehydration of leaf tissue (Boize *et al.*, 1976; Haines *et al.*, 1980, 1985; Appleton *et al.*, 2002). In addition, guttation and chlorophyll deficiency can also be associated with a brownish/pale appearance of leaves. Finally, spraying cold water on to plants in hot, sunny weather might also induce physiological stresses with damaging consequences, such as withering or browning of leaves, to name but a few possibilities.

These results also enable us to comment on the analogous issue of whether human skin covered with water drops can be damaged by focused sunlight during sunbathing, as is often claimed on dermatological and cosmetics websites (Table S2). If the skin is not oily, the contact angle of water relative to the skin surface is small, and consequently water drops are flat and their focal region falls far below the skin surface, eliminating the possibility of sunburn. Nevertheless, such drops may still increase the risk of skin cancer by focusing and enhancing ultraviolet (UV) radiation in deeper skin layers, but this effect will also depend on the UV absorption properties of the drops. However, a situation similar to floating fern (*S. natans*) leaves is plausible for humans as well. Most of us have tiny hairs covering our skin (except on our lips and the undersides of our hands and feet), and tiny water droplets with greater curvature and larger focusing capability could rest on this layer of fluffy hairs, potentially causing skin burn. Hence, this problem appears rather complex and should be investigated for a definitive answer. By contrast, if the skin is oily (e.g. because of sunscreen), the water drops formed are spheroidal and can easily roll off the water-repelling skin, thereby minimizing the possibility of both sunburn and skin cancer. Further discussion can be found in the online Supporting Information (Note S1C).

Conclusions

In sunshine, water drops residing on smooth, hairless plant leaves are unlikely to damage the underlying leaf tissue, while water drops held above leaves by plant hairs can indeed cause sunburn, if their focal regions fall on to the leaf blade. The same phenomenon can occur when water drops are held above human skin by body hair. However, sustained exposure of a given patch of skin to intense focused sunlight would require that a sunbather's position remained constant relative to the sun; otherwise, the water drops receive sunlight from a continuously changing direction, and therefore focus it on to different skin areas. Therefore, we treat claims of sunburn resulting from water droplets on the skin with a healthy dose of skepticism.

Lastly, a similar phenomenon might occur when water droplets accumulate on dry vegetation (e.g. straw, hay, fallen leaves, parched grass, brush-wood) after rain. If the focal region of drops falls exactly on the dry plant surface, the intensely focused sunlight could theoretically spark a fire. However, the likelihood of this is considerably reduced by the fact that after rain the originally dry vegetation becomes wet, and as it dries water drops also evaporate. Thus, claims of fires induced by sunlit water drops on vegetation should also be treated with a grain of salt.

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References

Airy GB. 1838. On the intensity of light in the neighbourhood of a caustic. *Transactions of the Cambridge Philosophical Society* **6**: 379–403.

Appleton B, Greene V, Smith A, French S, Kane B, Fox L, Downing A, Gilland T. 2002. *Trees and shrubs that tolerate saline soils and salt spray drift*. Petersburg, Virginia, USA: Publications of the Virginia State University No. 430-031, 1–7.

Boize L, Gudin C, Purdue G. 1976. The influence of leaf surface roughness on the spreading of oil spray drops. *Annals of Applied Biology* **84**: 205–211.

Cheng YT, Rodak DE. 2005. Is the lotus leaf superhydrophobic? *Applied Physics Letters* **86**: 144101.

DesCartes R. 1637. *Oeuvres de Des Cartes. La Géometrie*. Leyden: Livre 2, J. Maire.

Fogg GE. 1947. Quantitative studies on the wetting of leaves by water. *Proceedings of the Royal Society of London. Series B, Biological Sciences* **134**: 503–522.

de Gennes PG, Brochard-Wyart F, Quéré D. 2004. *Capillarity and wetting phenomena: drops, bubbles, pearls, waves*. Heidelberg: Springer-Verlag, Germany.

Haines B, Stefani M, Hendrix F. 1980. Acid rain: threshold of leaf damage in eight plant species from a southern Appalachian forest succession. *Water, Air, and Soil Pollution* **14**: 403–407.

Haines BL, Jernstedt JA, Neufeld HS. 1985. Direct foliar effects of simulated acid rain II. Leaf surface characteristics. *The New Phytologist* **99**: 407–416.

Holloway PJ. 1969. The effects of superficial wax on leaf wettability. *Annals of Applied Biology* **63**: 145–153.

Juniper BE, Jeffree CE. 1983. *Plant surfaces*. London, UK: Arnold.

Können GP, de Boer JH. 1979. Polarized rainbow. *Applied Optics* **18**: 1961–1965.

Lee RL. 1998. Mie theory, airy theory, and the natural rainbow. *Applied Optics* **37**: 1506–1519.

Martin JT, Juniper BE. 1970. *The cuticles of plants*. New York, NY, USA: St Martin's Press.

Nussenzweig HM. 1977. The theory of the rainbow. *Scientific American* **236**: 116–127.

Supporting Information

Additional supporting information may be found in the online version of this article.

Notes S1 (a) Computer ray tracing, (b) supplementary results, (c) supplementary discussion, (d) supplementary references.

Fig. S1 The 10 circular grey plastic trays with maple (*Acer platanoides)* leaves covered by glass spheres used in our first experiment.

Fig. S2 Ray-tracing geometry of a ray of light incident on, passing through, and leaving a water drop above a horizontal surface.

Fig. S3 Angles of incidence (α, δ) and of refraction (β, γ), and unit direction vectors ($\underline{e}_0$, $\underline{e}_1$, $\underline{e}_2$) of incident and refracted rays of light at the air–water interface.

Fig. S4 (a) Relative irradiance of unpolarized direct sunlight for solar elevation angles θ = 60, 40, 20, 10, 5, 4, 3, 2, 1 and 0°, computed using the 1976 US Standard Atmosphere; (b) absorption spectrum $A(\lambda)$ of green plant leaves averaged for bean, spinach, Swiss chard and tobacco; and (c) the solar absorption factor of plant leaves vs θ.

Fig. S5 $\mathrm{Log}_{10}Q$ vs solar elevation angle θ computed for a water drop on a horizontal maple (a), plane tree (b) and rowan (c) leaf with decreasing wettabilities.

Fig. S6 As Fig. 4 but for a glass sphere with a refractive index of n_{glass} = 1.5.

Fig. S7 (a) $\mathrm{Log}_{10}Q$ vs solar elevation angle θ computed for a glass sphere contacting a horizontal surface; (b) logarithm of the maximum intensity $I(\theta) = Q(n_{glass} = 1.5, \theta) \cdot a(\theta)$ of sunlight absorbed by a green leaf tissue in the focal region of a glass sphere on a horizontal leaf surface.

Fig. S8 Logarithm of light intensity I absorbed by the leaf tissue as a function of the ratio H/R, computed for incident angles θ = 60° and 90° in the focal region of a spherical water drop with radius R placed at distance H from the leaf surface.

Table S1 Survey of horticultural websites discussing the possibility of leaf damage caused by sunlight focused by water drops

Table S2 Survey of dermatological and cosmetics websites considering the possibility of sunburn of human skin caused by sunlight focused by water drops during sunbathing

Table S3 Survey of websites discussing the possibility of forest fires caused by sunlight focused by water drops

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