Physiological Effects of Kaolin Particle Film Technology: A Review

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ABSTRACT

Particle film applications (i.e. spraying canopies with a suspension of particles of various kinds of clay, including kaolin, leaving a film on the leaves) has long been used to limit the impact of water and heat stress on crops. Earlier work has focused primarily on crop yield and suggests that particle film applications, in some crops and under some conditions, increases yield. More recent and detailed work has been carried out using new kaolin products. Such work suggests that, besides other effects on fruit colour and size, kaolin generally reduces photosynthetic rates of individual leaves except under high temperature and/or heat stress. This is probably because kaolin films increase the albedo thus reducing leaf temperature and the consequent heat stress, but also reducing the light available for photosynthesis, possibly offsetting benefits of lower temperature, depending on the level of heat stress and incident irradiances. The few studies on the effects of kaolin applications on canopy photosynthesis report either an increase, or no effect, despite a reduction in photosynthetic rates of individual leaves. This is probably due to improved light distribution within the canopy, which increases the radiation use efficiency more than compensating for the slight reduction in canopy light absorption. In conclusion, kaolin applications appear to have the ability to reduce the effects of water and/or heat stress and, possibly to enhance canopy photosynthesis, at least under certain circumstances. These effects alone might not necessarily justify kaolin applications economically. However, when the kaolin film technology is adopted for pest management or for other purposes, it can be concluded that there are possible additional benefits.

Keywords: photosynthesis, stomatal conductance, surround, transpiration, yield

INTRODUCTION

Particle film applications (i.e. spraying canopies with a suspension of particles of various kinds of clay, including kaolin, leaving a film on the leaves) have long been used to limit the impact of water and heat stress on crop physiology and productivity. Results have often been inconsistent as such applications resulted at times in increased yield and at other times in no effect or reduction of yield.

Recently, the application of a particular kaolin product (Surround WP, Engelhard, Iselin, N.J.), containing 95% kaolin, was found to be beneficial in pest control on fruit tree species (Glenn et al., 1999; Unruh et al., 2000; Thomas et al., 2004). Kaolin is a naturally occurring mineral (a clay), which main constituent is kaolinite (Al₂Si₂O₅(OH)₄). Kaolin applications were also found to be beneficial against certain plant diseases (Puterka et al., 2000; Thomas et al., 2004), including viruses (Creamer et al., 2005) and even to protect plants from frost damage (Wisniewski et al., 2002; Walters, 2006). Kaolin films were also found, in some cases but not always, to protect crops from sunburn (Glenn et al., 2001; Schupp et al., 2002; Wand et al., 2006), while the effects on fruit colour has been variable (Schupp et al., 2002; Glenn et al., 2003). Providing details on these results is not in the scope of this review.

Because of these recent findings, a revival of studies aims at understanding the physiological effects of kaolin applications has occurred with, again, contradictory results. In this review I will summarize the results of several studies concerned with the effect of kaolin applications on the crop

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yield and physiology, particularly the gas exchange and water status at the leaf and the canopy level. In the “Rationale section” I will attempt to provide a general understanding of the physiological effects of kaolin applications that might explain the apparently contradictory results available in the literature.

Kaolin and temperature

Most of the literature is consistent in showing that kaolin applications decrease the temperature of leaves and canopies. For instance, Tworkoski et al. (2002) found a significant reduction in the leaf temperature of greenhouse bean leaves from 27.4°C in the leaves of the control plants, to 26.8°C in the leaves of kaolin treated plants, when using a 3% suspension in water and methanol of M96-018 (Engelhard Corporation, Iselin, NJ) kaolin product. Jifon and Syvertsen (2003) found that the leaf temperature of “Ruby Red” grapefruit trees, treated with a 6% kaolin (Surround WP) suspension in water, was about 3°C lower than leaves of control trees during midday, while there was no difference early in the morning and late in the afternoon. Lombardini et al. (2004), using the same product on pecan, found a reduction in leaf temperature up to 4°C. Rosati et al. (2006) found a 2-3°C reduction in the leaf temperature of Surround WP on walnut and almond. Similar results were obtained by other authors (Abou-Khaled et al. 1970; Singh and Sahay 1989; Kadbane and Mungse 1999; Makus 2000; Glenn et al. 2001, 2003). In summary, kaolin applications appear to reduce the leaf temperature by about 1-4°C. This reduction is minor compared to the increase in leaf or canopy temperature with water stress. For instance, kaolin applications failed to lower the leaf temperature of water stressed walnut trees to the temperature of the leaves of well irrigated trees (Rosati et al. 2006). Additionally, kaolin (i.e. 8.7% Surround WP + surfactant) did not reduce significantly pepper leaf temperature (33.3 and 32.9°C, respectively for control and kaolin treatments) at midday on clear days in Georgia (Ruso and Diaz-Pérez 2005). In rare cases, whitening the leaves resulted in increased leaf temperature (Baradas et al. 1976).

Kaolin, stomatal conductance, transpiration and water status

The effect of kaolin application on stomatal conductance ($g_s$) and transpiration ($E$) has been inconsistent, with few findings reporting increased $g_s$ and/or $E$. Rao (1985) reported decreased stomatal resistance (i.e. increased conductance) in the fruit developmental stage of tomato plants treated with kaolin like 5% (no further details given), with values ranging for different cultivars from 22.7 to 25.7 s cm$^{-1}$ in the control and from 16.5 to 17.0 s cm$^{-1}$ for the kaolin treated plants. Jifon and Syvertsen (2003) reported reduced midday depression of $g_s$ in grapefruit, during hot days (up to 35°C) with high incident irradiance (up to 2000 µmol m$^{-2}$ s$^{-1}$). Under such conditions, $g_s$ was about 0.15 mol m$^{-2}$ s$^{-1}$ for leaves of control plants, the difference being statistically significant. In the morning, $g_s$ was higher (between 0.17 and 21 mol m$^{-2}$ s$^{-1}$) and not different between treatments. Thomas et al. (2004), using various amounts of Surround WP in apple found that $g_s$ increased significantly from 40.5 mmol m$^{-2}$ s$^{-1}$ in control leaves up to 64.6 mmol m$^{-2}$ s$^{-1}$ in the most heavily treated plants on 20 July, and from 27 to 57 mmol m$^{-2}$ s$^{-1}$ on 21 August. $E$ increased similarly from 2.39 to 3.68 mmol m$^{-2}$ s$^{-1}$ on 20 July, and from 1.35 to 2.64 mmol m$^{-2}$ s$^{-1}$ on 21 August. These were the two hottest days out of nine measurement days; no significant differences were found on the other days. $E$ was similarly increased in cotton, again using Surround WP (Makus 2000).

Other works reported reductions in $g_s$ and/or $E$. In water stressed cotton, Moreshet et al. (1979) found decreasing $g_s$, with time after kaolin application (i.e. down to 58% of the control) on plants treated with a 25% suspension of fine grade kaolin (speswhite, English China Clay Sales Co. Ltd., St. Austell, England) to which 0.3% sodium hexametaphosphate was added. Tworkoski et al. (2002) found reductions in both $g_s$ and $E$ of greenhouse bean leaves: $g_s$ decreased (though not significantly) from 608 to 528 mmol m$^{-2}$ s$^{-1}$; $E$ decreased significantly from 6.5 to 5.8 mmol m$^{-2}$ s$^{-1}$. Similar results were found in groundnut (Khush and Morely 1980, 1983) and mungbean (Kadbane and Mungse 1999).

No effect of kaolin application on either $g_s$ or $E$ were found in other works. For instance, Russo and Diaz-Pérez (2005) found $g_s$ values of 220 and 257 mmol m$^{-2}$ s$^{-1}$ and $E$ values of 5.9 and 6.0 mmol m$^{-2}$ s$^{-1}$ respectively for control and kaolin treated plants with no significant differences. In walnut and almond kaolin applications did not affect $g_s$; which remained at about 0.5 mol m$^{-2}$ s$^{-1}$ for both control and kaolin treatments in almond, and varied from 0.3 to 0.6 mmol m$^{-2}$ s$^{-1}$ in irrigated walnut and from 0.2 to 0.02 mol m$^{-2}$ s$^{-1}$ in water stressed walnut, with no difference between kaolin and control trees (Rosati et al. 2006). Similar results were obtained in pecan (Lombardini et al. 2004), and in apple (Wünsche et al. 2004).

Moreshet et al. (1979) hypothesized that kaolin particles could block or reduce the use of leaves reducing stomatal conductance, but this hypothesis has not been confirmed. Later reports suggest that stomata are not blocked but rather less dense: in chili (cv. “Sindhurr”), Mahalakshmi et al. (1999) found that the number of stomata per square millimeter was reduced from 45 to 19 with a 5% kaolin application. Subramanian et al. (1992) found similar results in cotton with a 3% kaolin application. Lower stomatal density might explain why $g_s$ and $E$ are found to decrease in some studies and not in others: it takes some time for new growth to respond to kaolin with decreased stomatal density and consequently decreased $g_s$ and $E$. When stomatal conductance and transpiration are measured soon after kaolin application, the effect of kaolin cannot involve lower stomatal density and stomatal conductance and transpiration might be less affected if at all.

Plant water status (i.e. leaf, $V_{c}$ or stem, $V_{s}$, water potential and/or leaf relative water content, $RWC$) was not affected by kaolin in some experiments. In grapefruit $V_{c}$ did not vary (P = 0.92) between kaolin and control leaves, reaching -1.77 and -1.76 MPa for kaolin and control leaves respectively (Jifon and Syvertsen 2003). In walnut and almond kaolin applications did not affect $V_{c}$, which ranged during the day between -0.4 and -0.8 MPa in irrigated almond, between -0.6 and -1.4 MPa in droughted almond, between -0.1 and -0.4 MPa in irrigated walnut and from -0.6 to -1.3 in water stressed walnut, independent of kaolin application (Rosati et al. 2006). Similarly, no effect of kaolin on $V_{s}$ was observed in pecan (Lombardini et al. 2004).

Kaolin applications slowed down the decrease in $V_{c}$ with the onset of drought in water stressed cotton, resulting in higher (less negative) values towards the end of the crop cycle (Moreshet et al. 1979). Rao (1985) reported higher $V_{s}$ with kaolin in the fruit developmental stage of tomato plants, with values ranging for different cultivars from -0.44 to -0.49 MPa in the control and from -0.33 to -0.39 MPa for the kaolin treated plants. In chilli pepper Mahalakshmi et al. (1999) found for two seasons that foliar application of 5% kaolin induced higher RWC (80.8 and 83.0%, respectively for the first and second season) compared to controls. Similarly, RWC was improved in Phaseolus aureus and Vigna catjang (Pawar and Patil 1982) and cotton (Singh and Sahay 1989).

Kaolin and photosynthesis

In some cases kaolin applications were found to improve light-saturated photosynthesis ($A_{max}$). For instance Glenn et al. (2001) found increased $A_{max}$ in apple in seven of the eight trials carried out in Chile and USA. Thomas et al. (2004), using various amounts of Surround WP in apple
found that $A_{\text{max}}$ increased significantly only in the two hottest test days (i.e. leaf temperatures of control trees of 38.4 and 40.1°C) out of nine measurement days. $A_{\text{max}}$ increased from 8.6 μmol m$^{-2}$ s$^{-1}$ in control leaves up to 14.7 μmol m$^{-2}$ s$^{-1}$ in the most heavily treated plants on 20 July, and from 3.9 to 6.1 μmol m$^{-2}$ s$^{-1}$ on 21 August. In citrus, Jifon and Syvertsen (2003) found increased $A_{\text{max}}$ (from about 4 to about 6 μmol m$^{-2}$ s$^{-1}$) but only at midday under high temperature (not shown), while leaf-to-air vapour pressure difference (i.e. about 4 kPa in the control). In the morning, $A_{\text{max}}$ was about 7-8 μmol m$^{-2}$ s$^{-1}$ and not different between kaolin and control trees. Other authors found no effect of kaolin applications on photosynthesis. In greenhouse beans Tworkoski et al. (2002) found $A_{\text{max}}$ values of 17.8 μmol m$^{-2}$ s$^{-1}$ in kaolin treated plants and 17.7 μmol m$^{-2}$ s$^{-1}$ in control plants, with no significant difference. Similarly, Russo and Díaz-Pérez (2005) found no difference in field-grown pepper where $A_{\text{max}}$ was 37.6 μmol m$^{-2}$ s$^{-1}$ in the kaolin treatment and 33.1 μmol m$^{-2}$ s$^{-1}$ in the control, with no significant differences, while leaf temperatures were about 33°C for both treatments. Similar results were found in pecan (Lombardini et al. 2004).

More often a reduction in $A_{\text{max}}$ with kaolin applications has been found. In cotton, Moreshet et al. (1979), found decreasing $A_{\text{max}}$ with time after kaolin application, down to 76.1% of the control. In walnut and almond, $A_{\text{max}}$ was decreased anywhere between 1 and 4 μmol m$^{-2}$ s$^{-1}$, except in late afternoon in water stressed walnut when $A_{\text{max}}$ was as low as 4 μmol m$^{-2}$ s$^{-1}$ (Rosati et al. 2006). Similar results have been found in apple by several authors (Schupp et al. 2002; Grange et al. 2004; Wünsche et al. 2004). Most of these authors agree that the decrease in $A_{\text{max}}$ is due to the shading effect of kaolin, which reduces the light available for photosynthesis due to the 20 to 40% increased reflection and decreased absorption with particle films as discussed below. The shading effect of kaolin films on leaves is confirmed by the reduction in the apparent quantum yield (Ω) as found by Grange et al. (2004) and by Rosati et al. (2006). The latter authors showed that kaolin applications reduced Ω from 0.05 to 0.03 mol mol$^{-1}$ which implied a 37% decrease in light absorption. Increasing incident photosynthetically active radiation (PAR) well above that of a sunny day, the difference in $A_{\text{max}}$ between kaolin treated and a control leaves disappeared.

The effects of kaolin applications on canopy photosynthesis have been rarely measured: Wünsche et al. (2004) found that kaolin did not affect canopy photosynthesis despite a reduction in photosynthetic rates of individual leaves. Indeed, Glenn et al. (2003) found an increase in canopy photosynthesis under high air temperature.

**Kaolin, light reflection and absorption**

The ability of kaolin applications to increase the albedo of the vegetation has long been established. Doraiswamy and Rosenberg (1974) found that kaolinite increased total reflection in the visible (380-750 nm) wavelength interval of a soybean canopy by 87-312%, depending on canopy and sky condition and time of day. Kumar et al. (1992) found that a reflectant layer of kaolin + detergent + gum adhesive sprayed at 20-d intervals increased crop albedo by 44%. Khan and Morey (1980) and Pawar and Patil (1982) found similar results respectively in groundnut (Arachis hypogaea) and in summer mung (Phaseolus aureus) and cowpeas (Vigna radiata) (Ingawale et al. 1988; Kumar et al. 1988). However, other times the yield was lower or unaffected: “Fuji” apple yielded 32.31 kg per tree with kaolin and 31.45 kg per tree with water (Velasco et al. 1990), peach (Prunus persica) ('Varuna' (Damor and Vegada 1984), pearl millet (Pandey et al. 1988; Kaushik and Gautam 1991).Kaolin, plant growth and yield

Kaolin application have been often found to increase crop yield. In sorghum Stanhill et al. (1976) found that crop spraying of a 25% kaolin suspension increased average annual yield by 11% over 3 years, the most effective spraying being that applied from 7 weeks after seedling emergence to just before ear emergence. A foliar spray of 6% kaolinite clay suspension applied 45 days after sowing increased yields by 27.7 and 16.5% in a dry and a wet year, respectively, in dryland wheat (De and Giri 1978b). In cotton, Moreshet et al. (1979) found a 12% increase in gross yield (from 1830 to 2060 kg ha$^{-1}$) in one of two years. Also in cotton, Subramanian and Sheriff (1992) found that foliar sprays of 3% kaolin gave average kapas yields of 2.13 t ha$^{-1}$ compared with 1.00 t ha$^{-1}$ in the untreated control while Singh and Sahay (1989), using a 6 or 12% kaolin suspension increased yield one month after the cessation of monsoon rains, found cotton yields of 1.79 and 1.89 t ha$^{-1}$, respectively, compared with 1.68 t ha$^{-1}$ with water spray and 1.66 t ha$^{-1}$ in the untreated control. Similar results were found in rapeseed (De and Giri 1978a), tomato (Rao 1985), peanuts (Khan and Morey 1980; Soundara Rajan et al. 1981; Joshi et al. 1987), wheat (Dhiman et al. 1979; Singh et al. 1981), barley (Uppal and Cheema 1981; Solanki et al. 1987), sunflower (Jambhale and Thorat 1988), chilli pepper (Mahalakshmi et al. 1999), apple (Glen et al. 2001), pear (Puterka et al. 2006), Vigna radiata (Ingawale et al. 1988; Kumar et al. 1992), highbush blueberry (Spiers et al. 2003), Polianthes tuberosa (Al-Moftah 2005), olive (Saour and Makee 2003), Cyanopsis tetragonoloba (Sen and Daiya 1983), Brassica juncea “Varuna” (Damor and Vegada 1984), pearl millet (Pandey et al. 1988; Kaushik and Gautam 1991). Despite such reduction in PAR absorption at the leaf level, at the canopy level the reduction is lower, ranging in the order of 7% of incident PAR in almond and walnut orchards (Rosati et al. 2007) or 8% of global radiation (Doraiswamy and Rosenberg 1974). This implies that a great part of the PAR reflected by the kaolin film at the leaf level is re-intercepted and eventually absorbed within the canopy.

**Kaolin and light distribution within the canopy**

Little data is available on the effect of kaolin application on light distribution within the canopy. However, early work (Doraiswamy and Rosenberg 1974; Lemeur and Rosenberg 1976) showed that a kaolinite reflectant increased the radiation penetration into a soybean canopy. By placing small PAR sensors on individual leaves, Rosati et al. (2007) showed that kaolin application increased light penetration within walnut and almond canopies, resulting in increased incident PAR on inner canopy leaves, compared to non-sprayed trees, even after considering the shading effect of the film.
RATIONAL

In the following paragraphs, possible explanations for the different and apparently contrasting results will be discussed.

Kaolin and temperature

The general reduction in leaf and canopy temperature with kaolin (Abou-Khaled et al. 1970; Moreshet et al. 1979; Singh and Sahay 1989; Kadbane and Mungse 1999; Makus 2000; Glenn 2001; Tworkoski et al. 2002; Glann 2003; Jifon and Svyyterven 2003; Lombardini et al. 2004; Rosati et al. 2006) can be explained considering the increased albedo (Doraiswamy and Rosenberg 1974; Khan and Morey 1980; Pawar and Patil 1982; Kumar et al. 1992; Cottrell et al. 2002; Wünsche et al. 2004; Rosati et al. 2006): since a smaller fraction of the incident radiation is absorbed, the leaves remain cooler than control ones, at least the most sunlit leaves. However, the shade provided by the film often decreases the leaf photosynthesis (Moreshet et al. 1979; Schupp et al. 2002; Grange et al. 2004; Wünsche et al. 2004; Rosati et al. 2006) and consequently stomatal conductance and transpiration (Moreshet et al. 1979; Khan and Morey 1980; Rao 1985; 1986; Rao and Bhatt 1990; Kadbane and Mungse 1999; Tworkoski et al. 2002). In rare cases, the decreased transpiration may compensate for the decrease in incident radiation, so that leaf temperature remains similar or even increases as infrequently found (Baradas et al. 1976). In most cases, however, transpiration is not reduced enough (if at all) and kaolin coated leaves remain cooler than non-sprayed leaves.

Kaolin, gas exchange and water status

As discussed earlier, the increased albedo with kaolin applications reduce the light available for leaf photosynthesis, thus reducing it. The reduction in leaf photosynthesis often results in a parallel reduction of g, and E. Lower E is also explained considering the lower leaf temperature with kaolin, which reduces the leaf to air vapour pressure difference, further reducing transpiration at any g. Lower E results in better conservation of soil water in non irradiated crops. This explains why most of the experiments where kaolin applications improved yield were carried out on water stressed crops as in sorghum (Stanhill et al. 1976) wheat (De and Giri 1978b; Dhiman et al. 1979), cotton (Moreshet et al. 1979; Singh and Sahay 1989), Cynamopsis tetragonoloba (Sen and Daitya 1983), Brassica juncea “Va-runa” (Novar and agardha 1984); barley (Solanki et al. 1987), pearlmandy (Pamelt et al. 1988; Kaushik and Gau-tam 1991), groundnut (Lourdrad et al. 1996), and Capsicum annum (Mahalakshmi et al. 1999), where kaolin reduced Amax and E, resulting in improved plant water status and in a slower rate of soil water depletion as in barely (Ali and Prasad 1975), cotton (Singh et al. 1982), and tomato (Rao 1985). This delays the onset of severe water stress, with positive impact on yield. Many authors have already concluded that kaolin applications are more or only beneficial in water stressed conditions (De and Giri 1978b; Khan and Morey 1980; Singh et al. 1981; Uppal and Cheema 1981; Lombardini et al. 2004; Al-Moftah and Al-Humaid 2005).

However, in well irrigated plants, photosynthesis can be limited by heat stress, making the excessive incident radiation detrimental by increasing leaf temperature. Under such conditions, where high temperature, and not light, limits leaf photosynthesis and this is very low, kaolin applications can improve Amax as it was shown in citrus at mid-day (Amax < 5 μmol CO₂ m⁻² s⁻¹; Jifon and Syvertsen 2003) or apple (Amax < 8 μmol CO₂ m⁻² s⁻¹; Glenn et al. 2001). At higher Amax kaolin reduces leaf photosynthesis as was observed in citrus in the morning (Amax = 8 μmol CO₂ m⁻² s⁻¹; Jifon and Syvertsen 2003) and in apple (Amax < 15 μmol CO₂ m⁻² s⁻¹; Grange et al. 2004; Wünsche et al. 2004). This hypothesis has been confirmed recently by Grange et al. (2004) who showed that kaolin applications on apple trees reduced Amax in all cases except in outer-canopy leaves exposed to high irradiance under high temperature and high vapour pressure difference. Similar results were found in walnut, where kaolin reduced leaf photosynthesis except in water stressed plants, later in the day, when photosynthesis was as low as 4 μmol CO₂ m⁻² s⁻¹ (Rosati et al. 2006). It may be concluded that in species, or under conditions where Amax is low and/or saturates at relatively low PAR levels, the kaolin-induced reduction in PAR absorption is less important, so that the beneficial mitigation of the heat stress may result in improved Amax. At higher Amax, as in non-stressed situations, the PAR reduction associated with kaolin is more likely to reduce leaf photosynthesis at any incident irradiance.

Gas exchange and PAR absorption

The above considerations explain the positive effect of kaolin applications in water and/or heat stressed plants with non-limiting light conditions. Under well irrigated conditions, and mild temperature leaf usually reduces leaf photosynthesis, but this does not appear to reduce canopy photosynthesis (Wünsche et al. 2004). Indeed, Glenn et al. (2001) found an increase in canopy photosynthesis, although only under high air temperature. Wünsche et al. (2004) speculated that this is due to improved light distribution within the canopy. Previous work had already suggested that kaolin increases light penetration (Doraiswamy and Rosenberg 1974; Lemeur and Rosenberg 1976). Rosati et al. (2007) showed that kaolin applications do indeed alter the light distribution within the canopy, increasing incident radiation on inner canopy leaves. This increase partially compensates for the reduction in PAR absorption of individual leaves with kaolin so that, for the whole canopy, PAR absorption is reduced much less than at the leaf level. In other words, the 20-40% loss of PAR absorption at the leaf level (Abou-Kaled et al. 1970; Moreshet et al. 1979; Wünsche et al. 2004; Rosati et al. 2006), due to increased PAR reflection, is in great part re-intercepted and eventually absorbed within the canopy. In walnut and almond, whole canopy PAR absorption was reduced by 7%, despite estimated reductions of 37% PAR absorption at the leaf level (Rosati et al. 2007). The small loss in PAR absorption by the canopy was more than compensated by an increase in photosynthetic radiation use efficiency (PhRUE), which was positively affected by the altered light distribution. In fact, skewing the light distribution towards inner-canopy leaves, results in improved canopy PhRUE, as was found in Prunus under water stress (Lampinen et al. 2004), due to increased PAR absorption with diffuse light, which penetrates the canopy better than direct radiation (Spitters 1986; Sinclair et al. 1992). Thus, even in well irrigated trees under mild temperatures, canopy photosynthesis may benefit from kaolin applications.

If this is the case, the question arises as to why the plants did not make white leaves in the first place. The answer might be that the benefits of kaolin applications on canopy photosynthesis and crop yield have been documented in environments high incident irradiance, which were probably different from those where the species had evolved. With more cloudy weather (i.e. lower light and temperature) the documented benefits might not occur. For instance, in a light limited environment such as a greenhouse, kaolin application reduced the yield of beans (Tworkoski et al. 2002), and the plants showed typical symptoms of shade-grown plants such as altered shoot-to-root ratio and decreased stomatal density. Lower stomatal density was also found in other works (Subramanian and Sheriff 1992; Mahalakshmi et al. 1999), confirming the shade effect of kaolin. Additionally, in crops where the vegetation is less shaded in the inner canopy, as in small trees or in vegetable crops with discontinuous canopy cover, the positive effect of the altered distribution of light within the canopy might not occur.
CONCLUDING REMARKS

Under conditions of high incident radiation (i.e. sunny conditions), hot weather and water stress, kaolin applications appear often beneficial in terms of plant physiology and yield. However, whether or not these benefits alone make kaolin applications economically and environmentally via-
ble is not clear. Stanhill et al. (1976), for instance, report that kaolin increased sorghum yield at a rate of two kg of grain per kg of kaolin, which does not appear very interesting economically. In non-stressed conditions, the benefits of kaolin applications in terms of plant photosynthesis and yield are probably very marginal when present at all.

It seems possible to conclude that, when used for pest and disease control or to prevent sunburn or else, kaolin application might additionally improve plant physiological activity under hot and dry conditions, and water stress and high incident irradiance. Under scarce incident irradiance, kaolin application might decrease plant productivity.

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