Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: a review

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Abstract

Temperature increase and the effects of greenhouse gases are among the most important issues associated with climate change. Studies have shown that the production and quality of fresh fruit and vegetable crops can be directly and indirectly affected by high temperatures and exposure to elevated levels of carbon dioxide and ozone. Temperature increase affects photosynthesis directly, causing alterations in sugars, organic acids, and flavonoids contents, firmness and antioxidant activity. Carbon dioxide accumulation in the atmosphere has directly effects on postharvest quality causing tuber malformation, occurrence of common scab, and changes in reducing sugars contents on potatoes. High concentrations of atmospheric ozone can potentially cause reduction in the photosynthetic process, growth and biomass accumulation. Ozone-enriched atmospheres increased vitamin C content and decreased emissions of volatile esters on strawberries. Tomatoes exposed to ozone concentrations ranging from 0.005 to 1.0 μmol / mol had a transient increase in β-carotene, lutein and lycopene contents.

Keywords: global warming; carbon dioxide; air temperature; ozone; firmness; sugars; photosynthesis.

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1. Introduction

Climate on Earth has changed many times during the existence of our planet, ranging from the ice ages to periods of warmth. During the last several decades increases in average air temperatures have been reported and associated effects on climate have been debated worldwide in a variety of forums. Due to its importance around the globe, agriculture was one of the first sectors to be studied in terms of potential impacts of climate change (Adams et al., 1990). Many alternatives have been proposed to growers aimed at minimizing losses in yield. However, few studies have addressed changes in postharvest quality of fruits and vegetable crops associated with these alterations. Nowadays, climate changes, their causes and consequences, gained importance in many other areas of interest for sustainable life on Earth. The subject is, however, controversial.

According to studies carried out by the Intergovernmental Panel on Climate Change (IPCC), average air temperatures will increase between 1.4 and 5.8 ^{o}C by the end of this century, based upon modeling techniques that incorporated data from ocean and atmospheric behavior (IPCC, 2001). The possible impacts of this study, however, are uncertain since processes such as heat, carbon, and radiation exchange among different ecosystems are still under investigation. Less drastic estimates predict temperature increase rates of 0.088 ^{o}C per decade for this century (Kalnay & Cai, 2003). Other investigators forecast for the near future that rising air temperature could induce more frequent occurrence of extreme drought, flooding or heat waves than in the past (Assad, Pinto, Zullo-Junior & Ávila, 2004).

Higher temperatures can increase the capacity of air to absorb water vapor and, consequently, generate a higher demand for water. Higher evapotranspiration indices could lower or deplete the water reservoir in soils, creating water stress in plants during dry seasons. For example, water stress is of great concern in fruit production, because trees are not irrigated in many production areas around the world. It is well documented that water stress not only reduces crop productivity but also tends to accelerate fruit ripening (Henson, 2008).

Exposure to elevated temperatures can cause morphological, anatomical, physiological, and, ultimately, biochemical changes in plant tissues and, as a consequence, can affect growth and development of different plant organs. These events can cause drastic reductions in commercial yield. However, by understanding plant tissues physiological responses to high temperatures, mechanisms of heat tolerances and possible strategies to improve yield, it is possible to predict reactions that will take place in the different steps of fruit and vegetable crops production, harvest and postharvest (Kays, 1997).

Besides increase in temperature and its associated effects, climate changes are also a consequence of alterations in the composition of gaseous constituents in the atmosphere. Carbon dioxide (CO_2) and ozone (O_3) concentrations in the atmosphere are changing during the last decade and are affecting many aspects of fruit and vegetable crops production around the globe (Felzer, Cronin, Reilly, Melillo & Wang, 2007; Lloyd & Farquhar, 2008).

Carbon dioxide concentrations are increasing in the atmosphere during the last decades (Mearns, 2000). The current atmospheric CO_2 concentration is higher than at any time in the past 420,000 years (Petit et al., 1999). Further increases due to anthropogenic activities have been predicted. Carbon dioxide concentrations are expected to be 100% higher in 2100 than the one observed at the pre-industrial era (IPCC, 2007). Ozone concentration in the atmosphere is also increasing. Even low levels of ozone in the vicinities of big cities can cause visible injuries to plant tissues as well as physiological alterations (Felzer, Cronin, Reilly, Melillo & Wang, 2007).

The above mentioned climate changes can potentially cause postharvest quality alterations in fruit and vegetable crops. Although many researchers have addressed climate changes in the past and, in some cases, focused postharvest alterations, the information is not organized and available for postharvest physiologists and food scientists that are interested in better understanding how these changes will affect their area of expertise.

In the present article we review how changes in ambient temperature and levels of carbon dioxide and ozone can potentially impact the postharvest quality of fruit and vegetable crops.

2. Harvest and postharvest

Harvest of fruit and vegetable crops occurs in different times of the year depending on cultivar, water regime, climate conditions, pest control, cultural practices, exposure to direct sunlight, temperature management and maturity index, among other important pre-harvest factors.

After crops are harvested, respiration is the major process to be controlled. Postharvest physiologists and food scientists do not have many options to interfere with the respiratory process of harvested commodities, since they are largely dependent on the product specific characteristics (Saltveit, 2002).

In order to minimize undesirable changes in quality parameters during the postharvest period, growers and entrepreneurs can adopt a series of techniques to extend the shelf life of perishable plant products. Postharvest technology comprises different methods of harvesting, packaging, rapid cooling, storage under refrigeration as well as modified (MA) and controlled (CA) atmospheres and transportation under controlled conditions, among other important technologies. This set of strategies is of paramount importance to help growers all over the world to withstand the challenges that climate changes will impose throughout the next decades.

3. Effects of temperature

Fruit and vegetable growth and development are influenced by different environmental factors (Bindi, Fibbi & Miglietta, 2001). During their development, high temperatures can affect photosynthesis, respiration, aqueous relations and membrane stability as well as levels of plant hormones, and primary and secondary metabolites (Bewley, 1997).

Most of the physiological processes go on normally in temperatures ranging from 0 ºC to 40 ºC. However, cardinal temperatures for the development of fruit and vegetable crops are much narrower and, depending on the species and ecological origin, it can be pushed towards 0 ºC for temperate species from cold regions, such as carrots and lettuce. On the other hand, they can reach 40 ºC in species from tropical regions, such as many cucurbits and cactus species (Went, 1953).

A general temperature effect in plants involves the ratio between photosynthesis and respiration (Went, 1953). High temperatures can increase the rate of biochemical reactions catalyzed by different enzymes. However, above a certain temperature threshold, many enzymes lose their function, potentially changing plant tissue tolerance to heat stresses (Bieto & Talon, 1996).

Temperature is of paramount importance in the establishment of a harvest index. The higher the temperature during the growing season, the sooner the crop will mature. Hall, McPherson, Crawford and Seager (1996) and Wurr, Fellows and Phelps (1996) reported that lettuce, celery, cauliflower and kiwi grown under higher temperatures matured earlier that the same crops grown under lower temperatures.

3.1 Rapid cooling

Fruit and vegetable crops are generally cooled after harvest and before packing operations. Cooling techniques have been used since the 1920's to remove field heat from fresh produce, based on the principle that shelf life is extended 2- to 3-fold for each 10 ^{o}C decrease in pulp temperature. Rapid cooling optimizes this process by cooling the product to the lowest safe storage temperature within hours of harvest. By reducing the respiration rate and enzyme activity, produce quality is extended as evidenced by slower ripening/senescence, maintenance of firmness, inhibition of pathogenic microbial growth and minimal water loss (Talbot & Chau, 2002).

Rapid cooling methods such as forced-air cooling, hydrocooling and vacuum cooling demand considerable amounts of energy (Thompson, 2002).

Therefore, it is anticipated that under warmer climatic conditions, fruit and vegetable crops will be harvested with higher pulp temperatures, which will demand more energy for proper cooling and raise product prices.

3.2 Fruit Ripening

High temperatures on fruit surface caused by prolonged exposure to sunlight hasten ripening and other associated events. Ripening of ‘Hass’ avocados was also affected by exposure to high temperatures during growth and development (Woolf, Ferguson, Requejo-Tapia, Boyd, Laing & White, 1999).

Tomato ripening occurred normally in terms of color development, ethylene evolution, and respiratory climacteric after three days at temperatures above 36 °C. However, ripening was slower than freshly harvested fruit (Lurie & Klein, 1991).

The immediate effects of heat treatments have generally been to inhibit respiration and ethylene production, reduce protein synthesis, and increase protein breakdown (Eaks, 1978; Lurie & Klein, 1990, 1991; Ferguson, Lurie & Bowen, 1994).

Eaks (1978) determined the respiratory rate of mature 'Hass' avocado fruits at 20 to 40 °C. Typical climacteric patterns occurred at 20, 25, 30 and 35 °C with the climacteric maximum increasing with temperature, but only a decreasing respiratory rate with time was observed at 40 °C. The exposure to exogenous ethylene or propylene hastened the ripening response up to 35 °C. However, at 40 °C the respiratory rate was increased, but ethylene production and normal ripening did not occur.

Although there are few reports in the literature on other specific effects of exposure to high temperatures during the growing season and subsequent changes in ripening behavior, extrapolations can be made from reports on postharvest ripening (Woolf & Ferguson, 2000). High temperatures on fruit surface caused by pronounced exposure to sunlight can hasten ripening and other associated events. The above studies suggest that changes in ripening behavior are likely to occur when fruit and vegetable crops are exposed to higher temperatures prior to harvest. Chan, Tam and Seo (1981) and Picton and Grierson (1988) observed that high temperature stresses inhibited ethylene production and cell wall softening in papaya and tomato fruits. On the other hand, cucumber fruits showed increased tolerance to high temperature stress (32.5 ^{o}C) with no change in *in vitro* ACC oxidase activity (Chan & Linse, 1989).

3.3 Quality parameters

Extensive work has been carried out for more than three decades focusing quality properties of fruit and vegetable crops exposed to high temperatures during growth and development. Flavor is affected by high temperatures. Apple fruits exposed to direct sunlight had a higher sugar content compared to those fruits grown on shaded sides (Brooks & Fisher, 1926). Grapes also had higher sugar content and lower levels of tartaric acid when grown under high temperatures (Kliewer & Lider, 1968, 1970).

Dry matter content is used as a harvest indicator for avocados due to its direct correlation with oil content, a key quality component (Lee, Young, Shiffman & Coggins, 1983). For example, the State of California produces about 80% of the avocados grown in the USA (Mexican and Guatemalan strains and their hybrids) and requires a minimum oil content from 19% to 25% depending upon the cultivar (Kader & Arpaia, 2002). Avocados with higher dry matter content take longer to ripen which could pose a serious problem for growers planning to market their fruits immediately after harvest (Woolf, Ferguson, Requejo-Tapia, Boyd, Laing & White, 1999, 2000). Thus, fruit and vegetable growers, packers and shippers must pay close attention to ambient temperatures during growth and development as well as maturity indices to assure harvest at the appropriate time.

3.4 Antioxidant activity

Antioxidants in fruit and vegetable crops can also be altered by exposure to high temperatures during the growing season. Wang and Zheng (2001) observed that ‘Kent’ strawberries grown in warmer nights (18 to 22 ^{o}C) and warmer days (25 ^{o}C) had a higher antioxidant activity than berries grown under cooler (12 ^{o}C) days. The investigators also observed that high temperature conditions significantly increased the levels of flavonoids and, consequently, antioxidant capacity. McKeon, Warland, and McDonald (2006) also addressed the effects of climate changes in functional components. They verified that higher temperatures tended to reduce vitamin content in fruit and vegetable crops.

3.5 Physiological disorders and tolerance to high temperatures

Exposure of fruit and vegetable crops to high temperatures can result in physiological disorders and other associated internal and external symptoms.

Exposure of tomato fruits to temperatures above 30 ^{o}C suppresses many of the parameters of normal fruit ripening including color development, softening, respiration rate and ethylene production (Buescher, 1979; Hicks, Manano-Mendez & Masters, 1983). It is also well known that exposure of fruit to temperature extremes approaching 40 ^{o}C can induce metabolic disorders and facilitate fungal and bacterial invasion.

In general, visible evidence of heat injury on tomatoes appears as yellowish-white patches on the side of fruits (Mohammed, Wilson and Gomes, 1996). Electrolyte leakage in harvested ´Dorado´ tomatoes exposed to direct sunlight (34 ± 2 ^{o}C) for 5 h was 73% higher than fruits held in shaded (29 ± 2 ^{o}C) conditions. Although no significant changes in firmness were observed for either treatments following storage at 20 ^{o}C for 18 days, the percentage of infected fruits was 35% higher in fruits exposed to direct sunlight (Mohammed, Wilson & Gomes, 1996).

Frequent exposure of apple fruit to high temperatures, such as 40 ^{o}C, can result in sunburn, development of watercore and loss of texture (Ferguson, Volz & Woolf, 1999). Moreover, exposure to high temperatures on the tree, notably close to or at harvest, may induce tolerance to low temperatures in postharvest storage. Avocado fruit grown in New Zealand and exposed to direct sunlight had pulp temperatures at harvest that frequently exceeded 35 °C (Woolf, Bowen & Ferguson, 1999). During subsequent storage at 0 °C (below the recommended temperature), these fruit had lower incidences of chilling injury than fruit harvested from shaded parts of the tree.

Practical effects of climate change have already been experienced in some parts of the globe. For example, increased temperatures in Sambalpur, India, have delayed the onset of winter. As a consequence, cauliflower yields have dropped significantly (Pani, 2008). Where growers commonly harvested 1-kg heads, inflorescences are now smaller, weighing 0.25 – 0.30 kg each. Reductions in yield drive up production costs, an effect also observed for tomato, radish and other native Indian vegetable crops. In Brazil, the Brazilian Agricultural Research Corporation (Embrapa) has estimated a 50% reduction in soybean yield in the center-west region ("cerrado") by 2020, assuming an average increase of 0.3 and 0.5 ^{o}C per year (unpublished data).

4. Effects of carbon dioxide exposure

The Earth's atmosphere consists basically of nitrogen (78.1%) and oxygen (20.9%), with argon (0.93%) and carbon dioxide (0.031%) comprising next most abundant gases (Lide, 2009). Nitrogen and oxygen are not considered to play a significant role in global warming because both gases are virtually transparent to terrestrial radiation. The greenhouse effect is primarily a combination of the effects of water vapor, CO_2 and minute amounts of other gases (methane, nitrous oxide, and ozone) that absorb the radiation leaving the Earth´s surface (IPCC, 2001). The warming effect is explained by the fact that CO_2 and other gases absorb the Earth's infrared radiation, trapping heat. Since a significant part of all the energy emanated from Earth occurs in the form of infrared radiation, increased CO_2 concentrations mean that more energy will be retained in the atmosphere, contributing to global warming (Lloyd & Farquhar, 2008). Carbon dioxide concentrations in the atmosphere have increased approximately 35% from pre-industrial times to 2005 (IPCC, 2007).

Besides industrial activities, agriculture also contributes to the emission of greenhouse gases. In 2007 the agricultural sector in the United States was responsible for the emission of 413.1 teragrams of CO_2 equivalents (Tg CO_2 Eq.), or 6% of the total production of greenhouse gas emissions. Methane and nitrous oxide were the primary sources emitted by USA agricultural activities (EPA, 2009).

4.1 Growth and physiological alterations

Many papers published during the last decade have clearly associated global warming with the increase in carbon dioxide concentration in the atmosphere. Changes in CO_2 concentration in the atmosphere can alter plant tissues in terms of growth and physiological behavior. Many of these effects have been studied in detail for some vegetable crops (Cure & Acock, 1986; Bazzaz, 1990; Idso & Idso, 1994). These studies concluded, in summary, that increased atmospheric CO_2 enhances net photosynthesis, biomass production, seed yield, light, water, and nutrient use efficiency and plant water potential.

As noted previously in the present review, this theme remains controversial. Clark (2004), working on tropical forests, argued that increasing atmospheric CO_2 has no or little result in biomass production rates. In other words, she stressed the growth of tropical forests is not carbon limited and, additionally, that since higher temperatures increase respiration and other metabolic processes, that increased atmospheric CO_2 can reduce forest productivity.

4.2 Quality parameters

Högy and Fangmeier (2009) studied the effects of high CO_2 concentrations on the physical and chemical quality of potato tubers. They observed that increases in atmospheric CO_2 (50% higher) increased tuber malformation in approximately 63%, resulting in poor processing quality, and a trend towards lower tuber greening (around 12%).

Higher (550 μmol CO_2 / mol) concentrations of CO_2 increased glucose (22%), fructose (21%) and reducing sugars (23%) concentrations, reducing tubers quality due to increased browning and acryl amide formation in French fries. They also observed that proteins, potassium and calcium levels were reduced in tubers exposed to high CO_2 concentrations, indicating loss of nutritional and sensory quality.

Bindi, Fibbi and Miglietta (2001) studied the effects of high atmospheric CO_2 during growth on the quality of wines. These authors observed that elevated atmospheric CO_2 levels had a significant effect on fruit dry weight, with increases ranging from 40 to 45% in the 550 mmol CO_2 / mol treatment and from 45 to 50% in the 700 mmol CO_2 / mol treatment. Tartaric acid and total sugars contents increased around 8 and 14%, respectively, by rising CO_2 levels up to a maximum increase in the middle of the ripening season. However, as the grapes reached the maturity stage, the CO_2 effect on both quality parameters almost completely disappeared.

Overall wine quality was not significantly affected by elevated CO_2. Furthermore, no significant differences were detectable among plants grown in the two enriched treatments, and the effects of elevated CO_2 concentration were similar in the two growing seasons. The researchers concluded that the expected rise in CO_2 concentrations may strongly stimulate grapevine production without causing negative repercussions on quality of grapes and wine.

5. Effects of ozone exposure

5.1 Formation and distribution

Ozone in the troposphere is the result of a series of photochemical reactions involving carbon monoxide (CO), methane (CH_4) and other hydrocarbons in the presence of nitrogen species (NO + NO_2) (Schlesinger, 1991). It forms during periods of high temperature and solar irradiation, normally during summer seasons (Mauzerall & Wang, 2001). It is also formed, naturally during other seasons, reaching the peak of natural production in the spring (Singh, Ludwig & Johnson, 1978). However, higher concentrations of atmospheric ozone were found during summer due to increase in nitrogen species and emission of volatile organic compounds (Mauzerall & Wang, 2001).

5.2 Visible injury and physiological effects

The effects of ozone on vegetation have been studied both under laboratory and field experiments. Stomatal conductance and ambient concentrations are the most important factors associated with ozone uptake by plants. Ozone enters plant tissues through the stomates, causing direct cellular damage, especially in the palisade cells (Mauzerall & Wang, 2001). The damage is probably due to changes in membrane permeability and may or may not result in visible injury, reduced growth and, ultimately, reduced yield (Krupa & Manning, 1988).

Visible injury symptoms of exposure to low ozone concentrations include changes in pigmentation, also known as bronzing, leaf chlorosis, and premature senescence (Felzer, Cronin, Reilly, Melillo & Wang, 2007). Since leafy vegetable crops are often grown in the vicinity of large metropolitan areas, it can be expected that increasing concentrations of ozone will result in increased yellowing of leaves. Leaf tissue stressed in this manner could affect the photosynthetic rate, production of biomass and, ultimately, postharvest quality in terms of overall appearance, color and flavor compounds.

Using modeling tools, Fuhrer, Skarby and Ashmore (1997) concluded that ozone concentrations higher than 40 nmol O_3 / mol can result in a 10% yield reduction in different tree species in Southern Europe. In open field studies a 2-fold increase in CO_2 concentration caused a 15% increase in soybean yield, whereas a 20% increase in the atmospheric ozone offset the yield increasing effect of CO_2 (Henson, 2008).

Grulke and Miller (1994) and Tjoelker, Volin, Oleksyn and Reich (1995) observed that higher ozone concentrations can affect both the photosynthetic and respiratory processes. They verified that branches within the upper canopy of sugar maple (*Acer saceharum* Marsh.) submitted to ozone concentrations of 95 nmol O_3 / mol (twice-ambient concentrations) showed reduced light-saturated rates of net photosynthesis by 56% and increased dark respiration by 40%. These researchers also observed that ozone reduced net photosynthesis and impaired stomatal function, with these effects depending on the irradiance environment of the canopy leaves.

The present review of the pertinent literature related to plant responses to ozone exposure reveals that there is considerable variation in species response. Greatest impacts in fruit and vegetable crops may occur from changes in carbon transport. Underground storage organs (e.g., roots, tubers, bulbs) normally accumulate carbon in the form of starch and sugars, both of which are important quality parameters for both fresh and processed crops. If carbon transport to these structures is restricted, there is great potential to lower quality in such important crops as potatoes, sweet potatoes, carrots, onions and garlic.

Exposure of other crops to elevated concentrations of atmospheric ozone can induce external and internal disorders, which can occur simultaneously or independently. These physiological disorders can lower the postharvest quality of fruit and vegetable crops destined for both fresh market and processing by causing such symptoms as yellowing (chlorosis) in leafy vegetables, alterations in starch and sugars contents fruits and in underground organs. Decreased biomass production directly affects the size, appearance and other important visual quality parameters. Furthermore, impair stomatal conductance due to ozone exposure can reduce root growth, affecting crops such as carrots, sweet potatoes and beet roots (Felzer, Cronin, Reilly, Melillo & Wang, 2007).

5.3 Quality parameters

Skog and Chu (2001) carried out a set of experiments to determine the effectiveness of ozone in preventing ethylene-mediated deterioration and postharvest decay in both ethylene-sensitive and ethylene-producing commodities, when stored at optimal and sub-optimal temperatures. On mushrooms, which have no known site of ethylene activity (Abeles, 1984), effects from ozone would be antimicrobial only. Ozone at the concentration of 0.04 μL / L appeared to have potential for extending the storage life of broccoli and seedless cucumbers, both stored at 3 ^{o}C. When mushrooms were stored at 4 ^{o}C and cucumbers at 10 ^{o}C, response to ozone was minimal.

Quality attributes and sensory characteristics were evaluated on tomato fruits cv. Carousel after ozone exposure (concentration ranging from 0.005 to 1.0 µmol / mol) at 13 °C and 95% RH. Soluble sugars (glucose, fructose), fruit firmness, weight loss, antioxidant status, CO_2 / H_2O exchange, ethylene production, citric acid, vitamin C (pulp and seed) and total phenolic content were not significantly affected by ozone treatment when compared to fruits kept under ozone-free air. Sensory evaluation revealed a significant preference for fruits subjected to low-level ozone-enrichment (0.15 µmol / mol) (Tzortzakisa, Borlanda, Singletona & Barnes, 2007).

The quality of persimmon (*Diospyros kaki* L. F.) fruits (cv. Fuyu) harvested at two different harvest dates was evaluated after ozone exposure. Fruits were exposed to 0.15 µmol / mol (vol/vol) of ozone for 30 days at 15 °C and 90% relative humidity (RH). Astringency removal treatment (24 h at 20 °C, 98% CO_2) was performed and fruits were then stored for 7 days at 20 °C (90% RH), imitating commercial conditions. Flesh softening was the most important disorder that appeared when fruit were transferred from 15 °C to commercial conditions. Ozone exposure was capable to maintain firmness of second harvested fruits, which were naturally softer that first harvested fruits, over commercial limits even after 30 days at 15 °C plus shelf-life. Ozone-treated fruit showed the highest values of weight loss and maximum electrolyte leakage. However, ozone exposure had no significant effect on color, ethanol, soluble solids and pH. Furthermore, ozone-treated fruits showed no signs of phytotoxic injuries (Salvador, Abad, Arnal & Martínez-Jávega, 2006).

6. Conclusions

Understanding how climate changes will impact mankind in the decades to come is of paramount importance for our survival. Temperature, carbon dioxide and ozone directly and indirectly affect the production and quality of fruit and vegetable crops grown in different climates around the world. Temperature variation can directly affect crop photosynthesis, and a rise in global temperatures can be expected to have significant impact on postharvest quality by altering important quality parameters such as synthesis of sugars, organic acids, antioxidant compounds and firmness.

Rising levels of carbon dioxide also contribute to global warming, by entrapping heat in the atmosphere. Prolonged exposure to CO_2 concentrations could induce higher incidences of tuber malformation and increased levels of sugars in potato and diminished protein and mineral contents, leading to loss of nutritional and sensory quality. Increased levels of ozone in the atmosphere can lead to detrimental effects on postharvest quality of fruit and vegetable crops. Elevated levels of ozone can induce visual injury and physiological disorders in different species, as well as significant changes in dry matter, reducing sugars, citric and malic acid, among other important quality parameters.

7. References

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