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Review

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

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A B S T R A C T

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.

Contents

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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 °C by the end of this century, based upon modeling techniques that incorporated data from ocean and atmospheric behavior (IPCC. Climate change, 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 °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).

In most tropical regions temperature effects were so far lower, but important changes in rain distribution has occurred in Australia, Asia and Africa. In such events monsoon weakening was observed across Asia and Africa, playing an important role by making rain more scarce and irregular, at a point that climate changes are pointed as one of the most important causes of recent famines in areas such as the Sahel region of Africa (Henson, 2008).

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), also known as the most important greenhouse gas, 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 et al., 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, primary and secondary metabolites. Seed germination can be reduced or even inhibited by high temperatures, depending on the species and stress level (Bewley, 1997).

Most of the temperature effects on plants are mediated by their effects on plant biochemistry. That is, of course, for well water supplied plants, for which the Q_{10} for growth is very high. For plants that are subjected to water deficit, temperature is a physical facilitator for balancing sensible and latent heat exchange at the shoot, which is modulated by relative humidity and by wind.

Most of the physiological processes go on normally in temperatures ranging from 0 °C to 40 °C. 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 °C for temperate species from cold regions, such as carrots and lettuce. On the other hand, they can reach

40 °C 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. For a high yield, not only photosynthesis should be high but also the ratio photosynthesis/respiration should be much higher than one. At temperatures around 15 °C, the above mentioned ratio is usually higher than ten, explaining why many plants tend to grow better in temperate regions than in tropical ones (Went, 1953).

Higher than normal temperatures affect the photosynthetic process through the modulation of enzyme activity as well as the electron transport chain (Sage & Kubien, 2007). Additionally, in an indirect manner, higher temperatures can affect the photosynthetic process increasing leaf temperatures and, thus, defining the magnitude of the leaf-to-air vapor pressure difference (D), a key factor influencing stomatal conductance (Lloyd & Farquhar, 2008).

Photosynthetic activity is proportional to temperature variations. 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 1920s to remove field heat from fresh produce, based on the principle that shelf-life is extended 2- to 3-fold for each 10 °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. One of the classical examples is that of grapes, where berries exposed to direct sunlight ripened faster than those ripened in shaded areas within the canopy (Kliewer & Lider, 1968). Ripening of 'Hass' avocados was also affected by exposure to high temperatures during growth and development. For fruits exposed to direct sunlight, pulp temperatures reached 35 °C and required 1.5 days longer to ripen than those than grew in the shade (Woolf et al., 1999). 'Fuerte' and 'Hass' fruits exposed to direct sunlight were firmer than fruits of the shaded areas. Cell wall enzyme activity (cellulose and polygalacturonase) was negatively correlated with fruit firmness, indicating that sun exposure, i.e., higher temperatures during growth and development, can delay ripening. However this delay did not occur via a direct effect on the enzymes associated with cell wall degradation (Chan & Linse, 1989).

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; Ferguson, Lurie, & Bowen, 1994; Lurie & Klein, 1990; Lurie & Klein, 1991). However, in apples, treatments of 38 and 40 °C for 2–6 days did not have marked effects on respiration, although ethylene production was reduced (Liu, 1978; Porritt & Lidster, 1978).

Eaks (1978) determined the respiratory rate of mature 'Hass' avocado fruits at 20–40 °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 °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; Kliewer & Lider, 1970). Coombe (1987) observed that a 10 °C increase in growth temperature caused a 50% reduction in tartaric acid content. Kliewer and Lider (1970) and Lakso and Kliewer (1975) verified that malic acid synthesis was more sensitive to high temperature exposure during growth than was the synthesis of tartaric acid.

Fruit firmness is also affected by high temperature conditions during growth. 'Fuerte' avocados exposed to direct sunlight (35 °C) were 2.5 times firmer than those positioned on the shaded side (20 °C) of the tree. Changes in cell wall composition, cell number, and cell turgor properties were postulated as being associated with the observed phenomenon (Woolf, Wexler, Prusky, Kobiler, & Lurie, 2000).

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

Table 1
Symptoms of heat and solar injury of fruit and vegetable crops[a].

Crop	Symptoms
Snap bean	Brown and reddish spots on the pod; spots can coalesce to form a water-soaked area
Cabbage	Outer leaves showing a bleached, papery appearance; damaged leaves are more susceptible to decay
Lettuce	Damaged leaves assume papery aspect; affected areas are more susceptible to decay; tipburn is a disorder normally associated with high temperatures in the field; it can cause soft rot development during postharvest
Muskmelon	Characteristic sunburn symptoms: dry and sunken areas; green color and brown spots are also observed on rind
Bell pepper	Sunburn: yellowing and, in some cases, a slight wilting
Potato	Black heart: occur during excessively hot weather in saturated soil; symptoms usually occur in the center of the tuber as dark-gray to black discoloration
Tomato	Sunburn: disruption of lycopene synthesis; appearance of yellow areas in the affected tissues
Apple	Skin discoloration, pigment breakdown and water-soaked areas
Avocado	Skin and flesh browning; increased decay susceptibility
Lime	Juice vesicle rupture; formation of brown spots on fruit surface
Pineapple	Flesh with scattered water-soaked areas; translucent fruit flesh

[a] Adapted from Kader, Lyons and Morris (1974), Sargent and Moretti (2002), Wolf and Ferguson (2000).

the cultivar (Kader & Arpaia, 2002). 'Hass' avocados grown under high ambient temperatures (45 ± 2 °C), had higher moisture content at harvest than fruit grown under lower temperatures (30 ± 2 °C) (Woolf et al., 1999). They also noted that higher temperature influenced oil composition, where the concentration of certain specific fatty acids increased (e.g., palmitic acid by 30%) whereas others did not (e.g. oleic acid). 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, 2000; Woolf et al., 1999). 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.

Mineral accumulation was also reported to be affected by high temperatures and/or direct sunlight. 'Hass' avocado fruits exposed to direct sunlight showed higher calcium (100%), magnesium (51%) and potassium (60%) contents when compared to fruits grown under shaded conditions (Woolf et al., 1999). The authors suggested that these changes might be related to water movement through the fruit.

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 (18–22 °C) and warmer days (25 °C) had a higher antioxidant activity than berries grown under cooler (12 °C) days. The investigators also observed that high temperature conditions significantly increased the levels of flavonoids and, consequently, antioxidant capacity. Galletta and Bringhurst (1990) verified that higher day and night temperatures had a direct influence in strawberry fruit color. Berries grown under those conditions were redder and darker. 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 (Table 1).

Exposure of tomato fruits to temperatures above 30 °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 °C can induce metabolic disorders and facilitate fungal and bacterial invasion. Although symptoms of heat injury and disease incidence are easily observed at the end of storage, the incipient incidence of these disorders is often not recognized in time to effect corrective treatment.

In general, visible evidence of heat injury on tomatoes appears as yellowish-white patches on the side of fruits (Mohammed, Wilson, & Gomes, 1996) (Table 1). Electrolyte leakage in harvested 'Dorado' tomatoes exposed to direct sunlight (34 ± 2 °C) for 5 h was 73% higher than fruits held in shaded (29 ± 2 °C) conditions. Although no significant changes in firmness were observed for either treatments following storage at 20 °C for 18 days, the percentage of infected fruits was 35% higher in fruits exposed to direct sunlight. Exposure of tomato fruit to elevated temperatures affected quality determining characteristics. Titratable acidity and soluble solids content were 20% higher and 10% lower, respectively, in those tomatoes exposed to direct sunlight (Mohammed et al., 1996).

Frequent exposure of apple fruit to high temperatures, such as 40 °C, can result in sunburn, development of watercore and loss of texture (Ferguson, Volz, & Woolf, 1999) (Table 1). 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.

Other workers have investigated the increased tolerance to high temperatures after harvest of fruit and vegetable crops grown under high temperatures. Brooks and Fisher (1926), for apples, and Schroeder (1965) for avocados, observed this particular characteristic. Woolf, Bowen and Ferguson (1999) and Woolf and Ferguson (2000) observed that avocados grown under direct sunlight, with pulp temperatures frequently around 40 °C, had a significant tolerance to high temperature stresses during postharvest operations.

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

Table 2
Physiological and quality parameters of fruit and vegetable crops affected by exposure to increased CO_2 levels.

Physiological or quality parameter	Effect of high CO_2	Product	Reference
Photosynthesis	↑	Potato; spinach	Katnya et al. (2005), Jain, Pal, Raj and Khetarpal (2007)
Respiration	↓	Asparagus; broccoli; mungbean sprouts; blueberries; tomatoes; pears	Beaudry (1993), Peppelenbos and Leven (1996)
	↑	Potatoes; lettuce, eggplants; lemons; cucumbers; mango	Pal and Buescher (1993), Fonseca, Oliveira, and Brecht (2002), Bender, Brecht, and Campbell (1994)
	=	Apples	Peppelenbos and Leven (1996)
Ripening	↓	Tomato	Klieber, Ratanachinakorn, and Simons (1996)
Stomatal conductance	↓	Spinach	Leakey, Bernacchi, Ort, and Long (2006), Jain, Pal, Raj, and Khetarpal (2007)
Firmness			
	=	Tomato	Klieber et al. (1996)
	↑	Strawberry; raspberry	Siriphanich et al. (1998), Haffner, Rosenfeld, Skrede, and Wang (2002).
Color intensity	↑	Grape	Bindi et al. (2001)
Dry matter	↑	Potato	Vorne et al. (2002)
Starch	↑	Potato	Vorne et al. (2002)
Alcohol	↑	Grape; mango; pear	Bindi et al. (2001), Bender et al. (1994)
Titratable Acidity	=	Grape	Bindi et al. (2001)
Citric Acid	↓	Potato; tomato	Donnelly et al. (2001), Islam, Matsui, and Yoshida (1996)
Malic Acid	↓	Potato; tomato	Vorne et al. (2002), Islam et al. (1996)
Ascorbic acid	↑	Potato; strawberry; orange; tomato	Vorne et al. (2002), Wang, Bunce, and Maas (2003), Idso et al., (2002), Islam et al. (1996)
Reducing sugars	↑	Potato	Vorne et al. (2002); Högy and Fangmeier (2009))
	↑	Tomato	Islam et al. (1996)
Total phenolics	↑	Grape; strawberry	Bindi et al. (2001); Wang et al. (2003)
Flavonoids	↑	Grape	Bindi et al. (2001)
Anthocyanins	↑	Grape; strawberry	Bindi et al. (2001), Wang et al. (2003)
Glycoalkaloids	↓	Potato	Vorne et al. (2002)
pH	=	Grape	Bindi et al., 2001
Nitrate	↓	Potato; celery; leaf lettuce; Chinese cabbage	Vorne et al. (2002), Jin et al. (2009)
Volatile compounds	↓	Mango	Lalel, Singh, and Tan (2003)
Antioxidant capacity	↓	Scallion; strawberry	Levinea and Paré (2009), Shin et al. (2008)

("cerrado") by 2020, assuming an average increase of 0.3 and 0.5 °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 Earth́s 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), 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 (Bazzaz, 1990; Cure & Acock, 1986; Idso & Idso, 1994). These studies concluded, in summary, that increased atmospheric CO_2 alters net photosynthesis, biomass production, sugars and organic acids contents, stomatal conductance, firmness, seed yield, light, water, and nutrient use efficiency and plant water potential (Table 2).

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 CO_2 levels (550 µmol CO_2/mol) increased the occurrence of common scab by 134% but no significant changes in dry matter content, specific gravity and underwater weight were observed.

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 (Table 2).

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 (Table 2).

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 (550 and 700 mmol CO_2/mol), and the effects of elevated CO_2 concentration were similar in the two growing seasons. The absence of any further stimulation of the highest CO_2 treatment (700 mmol/mol) on grapevine growth and yield quality (i.e. grapes and wine) may be explained as a result of transport and/or sink limitations. 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 are found during summer due to increase in nitrogen species and emission of volatile organic compounds (Mauzerall & Wang, 2001). Concentrations are at maximum values in the late afternoon and at minimum values in the early morning hours, notably in industrialized cities and vicinities. The opposite phenomenon occurs at high latitude sites (Oltmans & Levy, 1994). Another potential source for increased levels of ozone in a certain region is via the movement by local winds or downdrafts from the stratosphere.

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 et al., 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 (Table 3). Additionally, Percy, Legge, and Krupa (2003) observed that ozone exposure causes reduction in photosynthesis and increased turnover of antioxidant systems. Furthermore, Reich (1987) verified that a reduction in photosynthesis reduced growth in conifers by 3%, in hardwoods by 13%, and by 30% in other crops (Table 3).

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

Table 3
Physiological and quality parameters of fruit and vegetable crops affected by exposure to increased O_3 levels.

Physiological or quality parameter	O_3 effect	Product	Reference
Respiration	↑	Blueberry; broccoli; carrot	Song et al. (2001)
Dark respiration	↑	Sugar maple	Tjoelker, Volin, Oleksyn, and Reich (1993)
Photosynthesis	↓	Strawberry; conifers; hardwoods	Amthor and Cumming (1988), Reich (1987)
Visible injury	↑	Black cherry	Chappelka, Renfro, Somers, and Nash (1997)
Viscosity	↑	Potato	Donnelly et al. (2001)
Starch	=	Potato	Vorne et al. (2002)
Reducing sugars	↓	Potato	Vorne et al. (2002)
Citric acid	↑	Potato	Piikki, Vorne, Ojanperä, and Pleijel (2003)
	=	Tomato	Tzortzakisa et al. (2007)
Electrolyte leakage	↑	Persimmon	Salvador, Abad, Arnal, and Martínez-Jávega (2006)
Malic acid	↓	Potato	Piikki et al. (2003)
Ascorbic acid	↓	Potato	Vorne et al. (2002)
	=	Tomato	Tzortzakisa et al. (2007)
N, P	=	Potato	Heagle, Miller, and Pursley (2003)
K, Mg	↑	Potato	Piikki et al. (2003)
Nitrate	↑	Potato	Vorne et al. (2002)
Color (L)	↑	Broccoli;	Skog and Chu (2001)
	↓	cucumber	
		Mushroom	Skog and Chu (2001)
Browning index	↑	Mushroom	Skog and Chu (2001)
Firmness	↑	Cucumber	Skog and Chu (2001)
Isocumarin	↑	Carrot	Hildebrand, Forney, Jun, Lihua, McRae (2008)
Sucrose	=	Potato; carrot	Hildebrand, Forney, Jun, Lihua, McRae (2008)

the photosynthetic and respiratory processes (Table 3). 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 (Table 3).

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 of fruits and in underground organs. Decreased biomass production directly affects the size, appearance and other important visual quality parameters. Furthermore, impaired stomatal conductance due to ozone exposure can reduce root growth, affecting crops such as carrots, sweet potatoes and beet roots (Felzer et al., 2007) (Table 3).

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, 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 °C. When mushrooms were stored at 4 °C and cucumbers at 10 °C, response to ozone was minimal (Table 3).

Ozone also showed the capability of removing ethylene from the environment, inside cold rooms. At concentrations of 0.4 μL/L, ozone was effective in removing ethylene (1.5–2.0 μL/L) from an apple and pear storage room. Apples and pears submitted to ozone-enriched atmospheres showed no difference on fruits quality.

Strawberries cv. Camarosa stored for three days under refrigerated storage (2 °C) in a ozone-enriched atmosphere (0.35 μL/L) showed a 3-fold increase in vitamin C content when compared to berries stored at the same temperature under normal atmosphere as well as a 40% reduction in emissions of volatile esters in ozonized fruits (Perez, Sanz, Rios, Olias, & Olias, 1999). On the other hand, Kute, Zhou and Barth (1995) reported that strawberries stored in atmospheres with ozone ranging from 0.3 to 0.7 μL/L showed no effect on ascorbic acid levels after 7 days of storage under refrigerated conditions.

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. A transient increase in β-carotene, lutein and lycopene content was observed in ozone-treated fruit, though the effect was not consistent. 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) (Table 3).

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.

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