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Fruit water relations and osmoregulation on apples (*Malus domestica* Borkh.) with different sun exposures and sun-injury levels on the tree

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ABSTRACT

Sun-injury (=sunscald, sunburn) in fruit crops is caused by photodynamic reactions on heated fruit sections exposed to direct sunlight. There is evidence supporting the oxidative nature of this disorder. Nevertheless, there are other physiological events, typically observed in water-stressed plants, such as water relations and osmoregulation that greatly influence external and internal quality of sun-injured fruit and have poorly addressed in the literature. Apple tissues (skin and flesh) with different levels of sun exposure and sun-injury (mild, moderate (Mod), severe (Sev)) were sampled at different growing stages during 2011 and 2012, in Royal Gala and Fuji. Water, solutes, and turgor potentials, relative water content (RWC), carbohydrates concentration (sucrose, sorbitol, glucose, fructose), internal ethylene concentration (IEC), and textural curves were determined. Skin water potential decreased with fruit development and it was significantly more negative in sun-injured tissue compared to unexposed ones. Solutes potential also decreased in skin and flesh with increasing sun damage, but the opposite was found in turgor potential. Fruit RWC at harvest decreased with increasing sunburn severity. Sun exposure induced sorbitol and glucose accumulation in fruit peel and flesh. Tissue with Mod and Sev sunscald showed higher IEC early in the season. Fruit shape and firmness were also altered by sun exposure. The results might indicate that sun-exposed tissue via more negative water potentials activates an abiotic stress-response cascade, perhaps mediated by sugars and ethylene, to cope with the environmental stress caused by high irradiance and heat, whose consequences are peculiar fruit quality traits.

1. Introduction

Sun-injury or commonly called sunscald in many fruit crops, and sunburn in apples, is a major production problem in fruit crops grown under semi-arid regions in the world. These have high solar irradiance and elevated temperature during the growing season. These conditions are found in apple-producing countries, such as Chile (Yuri, 2010), South Africa (Gindaba and Wand, 2007), New Zealand (Wünsche et al., 2001); Argentina (Raffo and Iglesias, 2004), and Unites States of America (Andrews and Johnson, 1996; Schrader et al., 2003), among others.

In apples, sunburn symptoms may involve tissue discoloration, yellowing, browning, and necrosis on severe sun damaged (Racsko and Schrader, 2012).

Whether light or heat is more important for sunscald development, it probably depends on local climatic conditions. In vitro and in vivo experiments in different fruit crops have shown that both factors are required to induce sun-injury symptoms (Barber and Sharpe, 1971; Rabinowitch et al., 1974; Torres et al., 2006).

Some of the metabolic responses in sun-injured fruit that have been associated to defense mechanisms against photooxidative stress are: change in redox status and up-regulation of antioxidant metabolites (i.e. ascorbate, glutathione), higher antioxidant enzyme's activities (i.e. ascorbate peroxidase, ascorbate–glutathione cycle enzymes, superoxide dismutase; Ma and Cheng, 2003; Torres et al., 2006; Chen et al., 2008), and higher phenolic compounds accumulation (Felicetti and Schrader, 2008; Yuri et al., 2010). Chlorophylls and some carotenoids concentrations decrease while others, such as xanthophylls, increase (Wünsche et al., 2001; Ma and Cheng, 2003; Chen et al., 2008; Torres et al., 2006; Tartachnyk et al., 2012), which causes symptoms visualization.

In the field, direct sunlight (radiant heating) increases fleshy fruit surface temperature 10–15 °C above air temperature (Woolf

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and Ferguson, 2000). Therefore, peel of exposed fruit can reach 45 °C or more during the hottest periods of the day (Schroeder, 1965; Thorpe, 1974; Smart and Sinclair, 1976; Parchomchuk and Meheriuk, 1996; Schrader et al., 2003; Yuri, 2010). On apples, Schrader et al. (2003, 2009) suggested that sunburn symptoms appear when fruit surface temperature (FST) surpasses 46–49 °C depending on the cultivar. Yuri et al. (2000) reported that under Chilean conditions this FST would be 45 °C for at least 5 h during the day.

Elevated temperatures combined with high irradiance are inducing changes in external and internal fruit quality parameters, such as flesh firmness and soluble solids (Racskó et al., 2005; Schrader et al., 2009), which are not associated with the photooxidative nature of this disorder. Some of these fruit characteristics have been reported in water-stressed apple trees (Ebel and Proebsting, 1993), yet sun-injury is a tissue-specific event that occurs only on part of the fruit.

The objective of this work was to better understand acclimation events associated with fruit water relations and osmoregulation occurring in sun-exposed tissue. These events could be explaining those changes in fruit quality traits, such as firmness and soluble solids observed in sun-damaged tissue within a fruit.

2. Materials and methods

2.1. Plant material and fruit sampling

Experiments were conducted in two consecutive growing seasons, 2011 and 2012. Fruit were obtained from commercially grown apple (*Malus × domestica* Borkh.) trees, cvs. Royal Gala and Fuji planted in 1990 on seedling rootstock, and trained in 'Solaxe' system (San Clemente, Chile). Selected trees were homogeneous in size and vigor, as well as fully irrigated. Air temperature and vapor pressure deficit during both seasons are shown in Fig. 1.

Fruit with different levels of exposure to direct sunlight on the trees and sun-injury symptoms (Fig. 2) were randomly harvested (in the morning) during the growing season. These were separated into: 'Shaded', fruit from the interior of the tree; 'non-exposed' (Non-EXP), fruit section non-exposed to direct sunlight; 'Exposed' (EXP), fruit section exposed to direct sunlight; 'Mild', fruit section with slight discoloration on the skin or mild sun-injury symptoms; 'Mod' (Moderate), fruit section with yellowing, and browning on the skin or moderate sun-injury symptoms; and 'Severe' (Sev), fruit section with dark brown patches over light browning on the skin or severe sun-injury symptoms (Fig. 2). Sampling was carried out from different trees at different time intervals during both growing seasons (Table 1) until commercial harvest (130–145 days after full bloom (DAFB) in Royal Gala and 170–180 DAFB in Fuji, under Chilean conditions).

Table 1
Fruit sampling dates and development stage (days after full bloom) for cvs. Royal Gala and Fuji during 2011 and 2012 growing seasons.

Cultivar	2011	2012
Royal Gala	67, 80, 113, 123	111, 124, 139
Fuji	67, 80, 113, 123, 148	111, 124, 139, 152, 166, 180

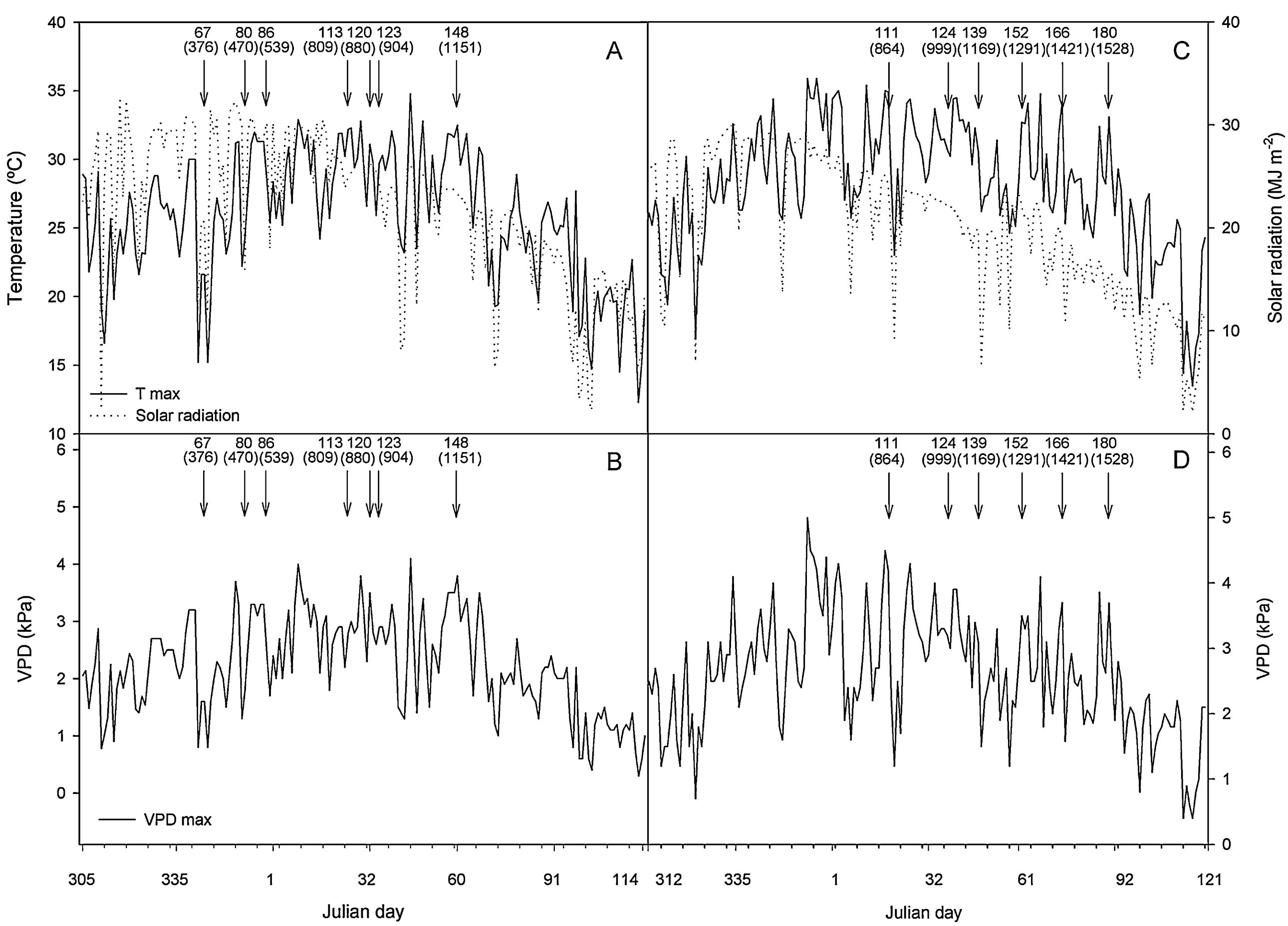

Fig. 1. Daily maximum temperature (°C) and solar radiation (MJ m^{-2}) (A and C), and vapor pressure deficit (kPa) (B and C) during 2011 (A and B) and 2012 (C and D) growing seasons. Days after full bloom and growing degree days (in parenthesis) are indicated by arrows within each season.