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How hail netting reduces apple fruit surface temperature: A microclimate and modelling study

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ABSTRACT

High fruit temperatures compromise fruit quality and cause production losses in the apple industry. In south-eastern Australia, orchardists have begun investing in netting because of empirical evidence that it reduces these losses, but the magnitude of its effect and mechanisms responsible have not yet been quantified. Models of fruit temperature based on meteorological conditions could inform the design of netting structures, and improve tactical management to reduce sun damage through treatments such as protective sprays and the use of overhead irrigation to cool fruit. The objectives of this study were firstly to measure the effect of netting on fruit surface temperature, and secondly to test the thermodynamic Smart-Sinclair model. The study was conducted near Shepparton, Victoria, in an orchard where there were adjacent netted and non-netted sections. During late afternoon when sun damage normally occurs, netting was able to reduce the median fruit surface temperature by 1.5–2.0 °C, but there was a greater reduction in maximum fruit surface temperature of 4.0 °C. The model required calibration to account for turbulence in the transfer of heat from fruit to the surrounding air. The optimised model was able to predict fruit surface temperature with a root mean square error of 2–4 °C. The mechanism for the reduction in fruit surface temperature was by reducing the intensity of the solar beam in the late afternoon by interception and scattering, which more than offset the potential fruit heating effect of netting that occurs through a reduction in internal orchard wind speed.

1. Introduction

Fruit exposed to high temperatures while growing on the tree suffers reduced quality, particularly in apples (*Malus domestica* (L.)). Reports from South Africa, USA, Australia and New Zealand suggest that pack-house culls of 10% could be expected in typical seasons (Bergh et al., 1980; Schrader et al., 2004; Wünsche et al., 2001) but losses can be much higher as these estimates do not include severely damaged fruit that is not picked. In Australia, apple growers estimate typical losses to vary from 6 to 30%, depending on season and fruit variety (Lolicato, 2011). Following some years of high losses, orchardists have begun investing in netting as a risk reduction strategy because of empirical evidence that it reduces these losses, but the magnitude of its effect and mechanisms responsible have not yet been quantified.

Schrader et al. (2003) identified fruit surface temperature thresholds at which two types of damage occurs. At a threshold of between 46 and 49 °C sunburn browning occurs, which consists of discolouration of the sun-exposed peel that reduces the saleability and storage life of the fruit. The threshold is cultivar-dependent, and requires a combination of both high temperatures and solar radiation. Protecting fruit from exposure to ultraviolet radiation greatly reduces the occurrence of sunburn browning (Schrader, 2011). At a threshold of 52 °C sunburn necrosis occurs, in which epidermal and subepidermal cells die leaving a necrotic spot on the sun-exposed side of the fruit. This type of damage can occur in the absence of solar radiation if the temperature threshold is reached. Fruit surface temperatures are dependent not only on the air temperature, but also solar radiation that heats the sun-exposed fruit surface, and wind that removes heat from the surface. Under conditions of high solar radiation and low wind speeds, the sun-exposed

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surface of fruit can be up to 15 °C warmer than air temperature (Schrader et al., 2003).

Several thermodynamic models have been developed to calculate temperatures in spherical fruit such as apples. Internally, these models use similar parameters and equations. Thorpe (1974) described a thermodynamic model of apple surface temperature, which included the effects of solar radiation, wind and the conduction of heat to the shaded side of the fruit. This model developed further by Smart and Sinclair (1976), who presented a series of equations that solve for the temperature of the most sun-exposed surface of spherical fruit, known as the "hot-spot". Since excessive hot-spot temperatures are sufficient to downgrade the entire apple, this is the most useful parameter to model. Later, Evans (2004) described a model that calculated the surface temperature of apples under evaporative cooling. Sauderau et al. (2007) presented a 3-dimensional model that calculated temperatures at all parts of ellipsoid fruit. Cola et al. (2009) described a model of grape temperature, which was validated at several sites in Italy, while Li et al. (2014) built on previous models and tested it on apples in Washington State, USA. Apart from Cola et al. (2009) and Li et al. (2014), these models have only had limited field validation, and none have been tested under netting. Potential uses of a validated model include both tactical and strategic management. Tactically, fruit surface temperature could be calculated from numerical weather forecasts so protective sprays can be applied prior to heat events, or evaporative cooling used when fruit surface temperature reaches a damage threshold. Strategically, the value of investment in infrastructure, such as netting or evaporative cooling systems, could be investigated with consideration of future climate change scenarios.

The objectives of this study were firstly to measure the effect of hail netting on fruit surface temperature and orchard microclimate, secondly to test the thermodynamic Smart-Sinclair model, and thirdly to quantify the mechanisms by which netting reduces sun damage.

2. Material and methods

Briefly, fruit surface temperatures were measured in adjacent netted and non-netted areas of a commercial orchard. Simulated fruit surface temperature was calculated using a modified version of the thermodynamic model developed by Smart and Sinclair (1976) using either microclimate measurements taken within the orchard, or surrogates derived from standard weather data measured external to the orchard. Table 1 summarises parameters used in the model and symbols used in this paper.

2.1. Field measurements

Fruit surface temperatures of Royal Gala apples were monitored at two sites ("netted" and "non-netted") within a commercial orchard located north of Shepparton Australia. The majority of the orchard was covered by permanent hail netting, except for five rows in the eastern side. The netting (Grey Quad 14, NetPro Pty Ltd, Stanthorpe, Qld, Australia) had a 10% shade rating and was installed 6 m above the ground with open sides. We refer to the product as "hail netting" because its primary purpose is to protect from hail, and to distinguish it from shade-cloth that has shade ratings of 16–80% (NetPro, 2010). Fruit surface temperatures were monitored from 8 January 2013 until the first fruit were harvested on 24 January 2013. At each site, 60 fruit were selected from 4 trees; 20 fruit were in the upper canopy, 20 in the middle and 20 in the lower canopy. Monitored fruit were selected from fruit on the western sides of trees that would be exposed to direct radiation in the afternoon, in the expectation that maximum daily fruit surface temperatures normally occur in the mid-afternoon between 1430 and 1645 h (Schrader et al., 2003). Copper-constantan thermocouples (Type T, Tranzflo NZ Ltd, Palmerston North, New Zealand) were inserted under the fruit skin on the sun-exposed face. Data were logged by four data loggers (CR1000, Campbell Scientific, Logan, Utah, USA), at each site at 1 min intervals. The target of 60 monitored fruit was sometimes not achieved because of datalogger difficulties, some sensors becoming dislodged from the fruit and because two loggers were not installed until 15 January. On the 2 hottest days (for which detailed data are reported later in the paper), 44 fruit were monitored under netting and 38 in the non-netted orchard on 11 January, while the equivalent numbers were 59 and 58 respectively on 17 January. The diameters of the monitored fruit were recorded on 11, 16 and 23 January 2013. Fruit were harvested, counted and weighted between 24 January and 4 February 2013 from 10 trees each in the netted and non-netted sites including the 4 trees logged for temperature. Fruit harvested from the 4 trees logged for temperature were visually assessed for sunburn damage. Damage was classified as (i) minor sunburn browning, (ii) major sunburn browning, (iii) necrosis, or (iv) photo-oxidative sunburn (Racsko and Schrader, 2012).

The microclimate was monitored at the netted and non-netted sites and data logged (DataTaker DT80M, Thermo Fisher Scientific Inc., Yokohama, Japan) at 1 min intervals. Air temperature (T_{air}, °C) and humidity (HMP155, Vaisala Oyj, Vantaa, Finland) were measured at 1.5 m height with the sensor mounted in a cylindrical white aluminium screen. Wind speed (v, m/s) was measured by cup anemometers (PA2 Wittich and Visser, Rijswijk, Netherlands) in the lower, middle and upper canopy at heights of 1, 2, and 3 m. Diffuse and total radiation (R_{df} and R_s, W/m^2) and ultraviolet-B (UV-B, W/m^2, 280–315 nm) were monitored above the canopy at 3 m height (SPN1, Delta T Devices, Cambridge, UK; SKU430, Skye Instruments, Llandrindod, Wales). Adjacent to the orchard the external environment was logged (6004C-21 STARLOG; Unidata, O'Connor, Australia) at 10 min intervals. Humidity and T_{air} (HMP 45A-T, Vaisala, Oyj, Vantaa, Finland) were measured at 1.5 m height with the sensor mounted in a cylindrical white aluminium screen. A cup anemometer (Wind sensor compact, Thies Clima, Gottingen, Germany) was used to measure v at 2 m height. Data from the external weather station were only available 8–29 January, whereas data from the orchard weather stations were available 1–31 January. Potential evapotranspiration (ET_o, mm) was calculated on a 10 min timestep from weather data measured in the netted and non-netted orchards by the FAO56 equations of Allen et al. (1998).

At both the netted and non-netted sites, trees were irrigated by microjet sprinklers spaced midway between trees and approximately 0.3 m above the soil surface. Trees were 1.5 m apart trained on a central leader system in rows 4.8 m apart, and rows were oriented NNW-SSE (345°). Tree age, variety, rootstock and management did not differ between the netted and non-netted sites, with the exception of increased irrigation flow rates in the non-netted area. All management activities (irrigation, fertilisation, and weed and pest control) were undertaken by staff of the commercial orchard.

2.2. Fruit temperature modelling

Smart and Sinclair (1976) proposed the following algebraic solution to calculate the instantaneous temperature increment above T_{air} on the sun-exposed surface of the fruit (ΔT_{max}, °C) as

$$\Delta T_{max} = \frac{I_0\,(1-\alpha)(k_s + 4h.r)}{(r.h + \mathrm{k_s})\,4h} \quad (1)$$

where I_0 is incident solar radiation received by a fruit surface perpendicular to the solar beam (W/m^2), α the reflectance of the fruit surface (albedo), k_s the thermal conductivity of the fruit (W/(m °C)), h the heat transfer coefficient from the fruit surface to the atmo-