horticulturae

Review

Reviewing the Tradeoffs between Sunburn Mitigation and Red Color Development in Apple under a Changing Climate

Noah Willsea [1,2], Victor Blanco [1,2], Kirti Rajagopalan [3,4], Thiago Campbell [1,2], Orlando Howe [1,2] and Lee Kalcsits [1,2,*]

[1] Tree Fruit Research and Extension Center, Washington State University, 1100 N Western Ave., Wenatchee, WA 98801, USA
[2] Department of Horticulture, Washington State University, Pullman, WA 99164, USA
[3] Center for Sustaining Agriculture and Natural Resources, Washington State University, Pullman, WA 99164, USA
[4] Department of Biological and Systems Engineering, Washington State University, Pullman, WA 99164, USA
* Correspondence: lee.kalcsits@wsu.edu

Abstract: Orchard systems have drastically changed over the last three decades to high-density plantings that prioritize light interception that is evenly distributed throughout the entire canopy. These conditions allow the production of fruit with a high red color that meets consumer demands for uniformly colored fruit without external disorders. However, these systems also expose a higher proportion of fruit to full-sunlight conditions. In many semi-arid apple production regions, summer temperatures often exceed thresholds for the development of fruit sunburn, which can lead to >10% fruit losses in some regions and some years. To combat this, growers and researchers use sunburn mitigation strategies such as shade netting and evaporative cooling, which bring a different set of potential fruit quality impacts. Often, there is a tradeoff between red color development and fruit sunburn, particularly for strategies that affect light intensity reaching the fruit surface. In this paper, we review agronomic and environmental factors leading to reductions in red color and increases in sunburn incidence, along with advancements in management practices that help mitigate these issues. Furthermore, we also identify gaps in knowledge on the influence climate change might have on the viability of some practices that either enhance red color or limit sunburn for apple orchards in semi-arid environments. There is a need for cost-effective management strategies that reduce losses to sunburn but do not inhibit red color development in bicolor apple cultivars.

Keywords: sunburn; fruit quality; climate change; heat stress; mitigation

Citation: Willsea, N.; Blanco, V.; Rajagopalan, K.; Campbell, T.; Howe, O.; Kalcsits, L. Reviewing the Tradeoffs between Sunburn Mitigation and Red Color Development in Apple under a Changing Climate. *Horticulturae* **2023**, *9*, 492. https://doi.org/10.3390/horticulturae9040492

Academic Editors: Alexandra Boini, Giulio Demetrio Perulli, Gregory Reighard and Darius Kviklys

Received: 20 February 2023
Revised: 31 March 2023
Accepted: 11 April 2023
Published: 14 April 2023

1. Introduction

Climate change will have negative consequences for many agricultural production regions around the world [1]. Climate change will increase temperatures throughout all seasons, affecting phenology, growth and productivity for perennial fruit crops, including apple (*Malus domestica* Borkh.). However, most of the research conducted on the impacts of climate change on apples has focused on phenological changes during the fall, winter, and spring, which are critical stages for apple production [2,3]. However, less is known about the impact of climate change on summer heat and its effects on fruit quality. Hot summer temperatures are challenging for apple production. The presence of high temperatures can cause fruit sunburn during the summer and poor red color at harvest, which cause significant economic losses for apple producers. Semi-arid production regions with hot summers regularly face the consequences of heat stress. For example, in a hot summer region such as Washington State in the United States, Brunner et al. [4] reported that sunburn and poor red color were among the factors responsible for most of the culls from commercial orchards.

Sunburn is a physiological disorder that occurs in many fruits and vegetables [5,6]. Sunburn damage occurs when elevated temperatures and excess light damage sensitive horticultural crops, causing blemishes and reducing the marketability of the fruit. It is an especially consequential disorder in apples [7]. Sunburn is responsible for significant fruit losses in many apple-growing regions around the world, such as parts of Europe [8], Chile [9], South Africa [10], and Australia [11]. There are three distinct types of sunburn with their own induction factors: sunburn browning, sunburn necrosis, and photooxidative sunburn [12,13]. Sunburn losses have been exacerbated by the shift to high-density plantings on dwarfing rootstocks that improve light interception and increase the number of fruit exposed to full sunlight [14,15]. Mitigation practices can reduce sunburn, but these practices must not also substantially limit red color development, which is stimulated by cool nights during autumn and is required for the highest-value bicolor cultivars. A red color is one of the primary quality standards valued by consumers when purchasing apples [5]. A red color is also an important selection trait for breeding programs, leading to many apples being developed, marketed, and sold based on their color [5]. Increased summer temperatures under climate change will increase the potential of sunburn risk and poor red color for many growing regions around the world. There is a need for new practices that decrease the impacts of heat on apple fruit quality for regions exposed to warmer summer temperatures in the future.

The objective of this review was to summarize current practices for heat mitigation and the promotion of color development for apple production and to identify knowledge gaps in our understanding of the impact of heat stress on fruit quality for regions that will face elevated sunburn pressure or slower color development under climate change. We used public journal databases to search for agricultural and biological literature using keywords identified above that were also focused on apples. The list of citations provides recent and classical literature on the impacts of summer temperatures on apples. This article provides insight into existing practices for reducing sunburn and improving red color, identifies gaps in our understanding of the tradeoffs between red color and sunburn, and provides some context into how to assess how these pressures will change in the future under climate change.

2. External Quality Standards

Fruit quality is normally determined by consumer preference and can change over time [5]. For many consumers, external quality remains the most important factor in the decision to purchase apples [5]. Government and producer organizations use marketing orders that impose standards and grades for agricultural products, known as minimum quality standards [16]. These minimum quality standards are used to increase the average quality of fresh market produce and thereby increase the average market price for these commodities [17]. There are various other ways that quality standards are imposed on fresh market produce, though many of these standards are market-driven and specific to packing houses, supermarkets, and other marketers of fruits and vegetables that control the quality of the food they are willing to sell. For modern apple production systems to remain profitable, producers need to maximize the amount of high-quality fruit produced every year.

For apples, there are many external quality standards used at various levels of the supply chain, from orchard to table. These metrics are often tightly regulated. For red and bicolor apples, which account for most fresh market apple sales [18], a large proportion of the peel color must be red to be classified as high quality. For example, in 'Red Delicious', more than 66% of the apple peel must be red for the apple to qualify as U.S Extra Fancy, while bicolor apples such as 'Honeycrisp' only need 33% of the peel to be red. Apples must also be free from all cosmetic defects such as sunburn and meet minimum size requirements to be classified as U.S. Extra Fancy [19]. Musacchi and Serra [5] have extensively reviewed the quality standards for specific production regions around the world. These losses are often the largest yet most poorly estimated source of food waste and often arise at the farm level and remain undocumented [20,21]. Food waste is defined as "wholesome edible material intended for human consumption, arising at any point in the food supply chain that is instead discarded, lost, degraded, or consumed by pests" [22]. Previous estimations indicate one-third of all food produced is lost or wasted before reaching the consumer [23]. Climate change will increase the summer temperatures in many apple-growing regions, making it more difficult to produce blemish-free fruit that meets specific color standards. There is a significant need to understand the risk of short-term heat events that can cause economic losses, such as sunburn and poor color, as well as to develop mitigation strategies that are cost-effective and feasible for commercial apple production systems.

3. Apple Sunburn

Apple sunburn occurs in several different ways. The most common type of sunburn is sunburn browning. This occurs when apples are exposed to a combination of solar radiation and heat for as little as 45–60 min [24]. The temperature threshold for sunburn browning ranges from 46–49 °C, depending on the cultivar [12]. However, various other studies have reported much wider ranges of threshold temperatures (Table 1). The various methods, cultivars, and names used to determine these thresholds and the resulting symptoms obfuscate the practical range of temperatures at which sunburn browning can be expected to occur. Apple growers have reported sunburn browning occurring at much lower temperatures in exposed fruit, while other studies report undamaged fruit that experienced conditions beyond those supposedly necessary to induce sunburn browning (Table 1). There is also a range in severity of sunburn browning that can occur within and across cultivars. Scales of severity have been developed for both green and bicolor apples, where a score of 0 indicates undamaged fruit, and scores of 1–4 range from slight browning to severe browning (Figure 1) [25,26]. Since small blemishes to the fruit surface can lead to discarding those fruit, even small portions of affected fruit surface can lead to higher grades of sunburn severity.

Figure 1. Sunburn grading classes modified from Schrader et al. [18] for bicolor apples. SB0 incidates no sunburn while SB1-3 have various degrees of sunburn and SB4 indicates the presence of tan browning on the peel surface.

Sunburn necrosis is more severe than sunburn browning and happens when cell death occurs, which can be solely induced by heat. The temperature threshold for sunburn necrosis has been estimated to be 52 °C for at least 10 min [12], producing black necrotic tissue on the fruit surface. Sunburn necrosis has been induced regardless of light exposure, indicating this is a result of thermal cell death [24]. This cell death may be relatively shallow or deep, damaging the cortex beneath the peel [27,28]. Cell death increases the production of ethylene and may contribute to early fruit drop [29]. Sunburn necrosis may develop from undamaged fruit or fruit that previously developed sunburn browning with sufficient heat [13].

Photooxidative sunburn can develop from sudden light exposure. The temperature threshold is likely lower than the other two types and is manifested as a visible bleached, white spot on the apple surface [30]. Photooxidative sunburn only develops on peel sections that were previously shaded and that receive sudden sunlight exposure. This can occur from fruit thinning, branches that droop as fruit growth occurs, or summer pruning [13,31]. This bleached area can turn yellow, brown, or black after continued exposure to sunlight [30].

Along with the immediate, within-orchard impacts sunburn has on fruit quality, apple sunburn can lead to additional disorders during storage, including lenticel blotch and sunscald, among others. Fruit sunburn has been associated with significantly greater levels of lenticel blotch in 'Honeycrisp' and begins to develop 7 to 14 days after harvest, reducing the storage, shelf-life, and longevity of apples throughout cold storage and the supply chain [32]. Sunscald typically begins to develop after about one month in storage and is characterized by an external darkening of the peel [33]. Both disorders increase fruit losses and the probability of pathogen infection [32].

3.1. Sunburn Physiology for Fruit

The physiological and biochemical pathways associated with the development of sunburn symptoms have been extensively studied [13,33]. Sunburn browning is caused by a combination of solar radiation and heat [24,34]. These two factors overwhelm internal protection mechanisms within the apple peel, causing irreversible damage to the Photosystem II (PSII) complex. Photosystems existing in the fruit peel are the same complexes of proteins and pigments found in all photosynthesizing organisms. These photosystems consist of an antenna system and a reaction center that converts incoming solar radiation to chemical energy [35]. While PSII is normally able to make efficient use of incoming radiation, it does have limitations. Excessive solar radiation or heat may damage this pathway. When excess photosynthetically active radiation is received by PSII, it can overexcite the chlorophyll molecules and produce reactive oxygen species that damage other parts of the cell, especially lipids [36]. Photoprotective pigments, including carotenoids and specialized carotenoid groups called xanthophylls, can be overcome by excess excitation, leading to photoinhibition or the destruction of PSII.

Optimal temperatures for the photosynthetic efficiency of different plants occur at different temperatures based on adaptation to the local climate, ranging from nearly 0 °C–nearly 50 °C [37]. These upper limits are also present for apple fruit. When the peel temperature reaches 45–49 °C in most apples, inhibition of photoprotective mechanisms of PSII occurs, and quenching of the excess excitation energy from incoming radiation cannot occur [37,38]. Subsequently, oxidation occurs in PSII on both the donor and acceptor sides, where damage is caused by free oxygen radicals [38]. Although the role of anthocyanins in leaf photoprotection has been extensively reported, these relationships for fruit have been less clear. Several studies have reported that anthocyanins do not play a photoprotective role in red-colored apples [39,40]. Cultivars with more red color development and highly increased anthocyanin concentrations near harvest, such as 'Cripps Pink', showed the same amount of severe sunburn compared to 'Gala', while minor sunburn was seemingly reduced. However, the maximum potential quantum efficiency of the Photosystem II (Fv/Fm) of the peel was similar among all cultivars independent of color. This suggests PSII can be similarly damaged even though visible symptoms of sunburn damage were lower in the blushed cultivars. Although green and yellow cultivars display a greater percentage of mild sunburn damage, all cultivars likely incur the same levels of damage and storage disorders when exposed to the same light and heat thresholds [41], implying red color development masks sunburn damage.

Fruits lack many of the physiological mechanisms present in leaves that provide cooling. Apples do not change position/orientation and have a fixed number of stomata regardless of sunlight exposure [39,41]. Thus, they are much more susceptible to rapid warming by solar radiation compared to leaves. As apple fruit matures, the thickness of the wax on the outside of the peel typically increases, while the stomatal (lenticel) density on the fruit surface decreases as the fruit expands [39,41]. The low stomatal density limits the physiological evaporative cooling of the fruit surface. High temperatures increase the pressure on PSII and increase the likelihood of sunburn damage [39]. Furthermore, the degradation of chlorophyll as fruit enters physiological maturity limits the quenching of excess energy, but carotenoids appear to provide additional protection during fruit ripening [42].

3.2. Sunburn Induction Factors

There are many indirect and direct factors to consider during sunburn induction. Solar radiation and temperature are the two most important direct factors, as they account for the damage to the fruit itself, although Yuri et al. [43] defined seven other indirect factors that contribute to sunburn damage, including the cultivar, developmental stage of fruit, training system, row orientation, vigor, water stress, and nutrient competition. All these factors determine how susceptible each fruit is to sunburn damage. Additionally, environmental factors play a role in fruit surface temperature. These conditions include relative humidity, wind speed, and solar radiation based on the presence of clouds [44].

Fruit surface temperature (FST) is the most widely used measurement for determining apple sunburn temperature thresholds. Weather-based FST measurements may be less accurate than sensing on the fruit, as noted by Ranjan et al. [45]. These approaches include direct measurement through contact/non-contact methods and indirect methods derived from biophysical models. A recent model developed by Li et al. [44] predicts the FST of completely exposed apples based on weather data (air temperature, relative humidity, solar radiation, and wind speed), accounting for 90% of the variation observed in infrared temperature measurements on the same fruit. This model is a useful tool for predicting FST. There is also great variation between the FST of fruits throughout the canopy. The fruits most exposed to direct sunlight are most likely to have higher FST and are at a greater risk for sunburn [46].

3.3. Sunburn Mitigation Strategies

In many growing regions, mitigation strategies need to be used to protect fruit from sunburn. The main strategies are netting, evaporative cooling (EC), particle film sprays, clay sprays, chemical protectants, and fruit bagging (Figure 2). Most of these strategies either reduce the solar radiation reaching the fruit surface or provide direct cooling of the fruit through the removal of heat. Netting, sprays, and fruit bagging reduce the solar radiation that reaches the fruit surface, keeping fruit closer to ambient temperature. Water-based cooling actively cools the fruit surface. Mitigation strategies are selected based on cultivar value, water availability, and overall risk of sunburn.

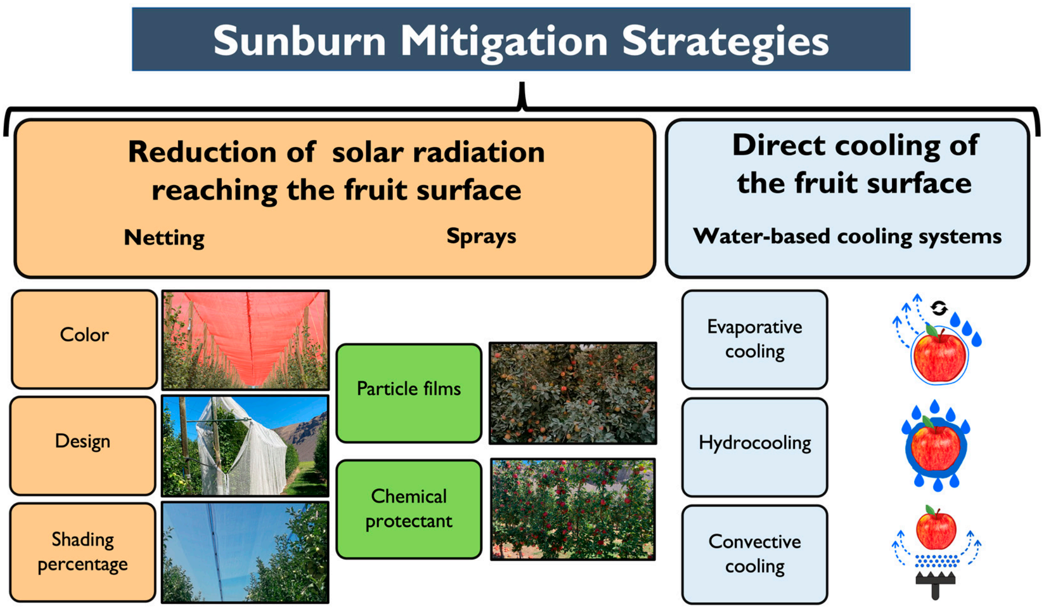

Figure 2. Sunburn mitigation strategies that reduce solar radiation reaching the fruit surface or reduce the temperature of the fruit through cooling.

Table 1. Sunburn incidence and sunburn temperature thresholds for several apple cultivars in different locations. * Values obtained according to the maximum temperature measured during the season.

	Sunburn Incidence	Cultivar	Location of Fruit Temperature Measurement	Temperature	Light Exposure	Location	Reference
Sunburn necrosis (SN)	Presence	'Gala'	Surface	52.2 °C (10 min)	No	Washington, UT, USA	[24]
Sunburn browning (SB)	Presence	'Gala'	Surface	47.8 °C (60 min)	Yes	Washington, UT, USA	[24]
Sunburn symptoms	Presence	'Braeburn'	Flesh	40 °C	Yes	Auckland, New Zealand	[47]
Sunburn symptoms	5%	'Mondial Gala'	Flesh	44 °C	Yes	Lleida, Spain	[8]
SN + SB	15%	'Cripps' Pink'	Surface	41 °C *	Yes	Stellenbosch, South Africa	[48]
SN + SB	9%	'Cripps' Pink'	Surface	33 °C *	Yes	Stellenbosch, South Africa	[49]
SN + SB	14%	'Fuji'	Surface	45 °C *	Yes	Sobo-myeon, Korea	[50]
SN + SB	23%	'Fuji'	Surface	48 °C *	Yes	Biobío, Chile	[9]
SN + SB	5%	'Fuji'	Surface	35 °C *	Yes	Ferrara, Italy	[51]
SN + SB	41%	'Fuji Raku Raku'	Surface	46 °C *	Yes	Ñuble, Chile	[52]
SN + SB	19%	'Gala'	Surface	52 °C *	Yes	Biobío, Chile	[9]
SN + SB	15%	'Gala'	Surface	47 °C *	Yes	Gansu, China	[53]
SN + SB	39%	'Gala Brookfield'	Surface	48 °C *	Yes	Ñuble, Chile	[52]
SN + SB	45%	'Granny Smith'	Surface	37 °C *	Yes	Grabouw, South Africa	[10]
SN + SB	39%	'Granny Smith'	Surface	40 °C *	Yes	Grabouw, South Africa	[10]
SN + SB	50%	'Granny Smith'	Surface	44 °C *	Yes	San José, Uruguay	[54]
SN + SB	30%	'Honeycrisp'	Surface	41 °C *	Yes	Washington, UT, USA	[55]
SN + SB	27%	'Honeycrisp'	Surface	42 °C *	Yes	New York, NY, USA	[56]
SN + SB	13%	'Honeycrisp'	Surface	44 °C *	Yes	New York, NY, USA	[56]
SN + SB	19%	'Royal Gala'	Surface	47 °C *	Yes	Stellenbosch, South Africa	[48]
SN + SB	16%	'Royal Gala'	Surface	48 °C *	Yes	Shepparton, Australia	[11]
SN + SB	17%	'Royal Gala'	Surface	53 °C *	Yes	Shepparton, Australia	[57]

There are three main ways water can be used to reduce crop temperatures [58]. In order of increasing effectiveness, they are: (1) evaporation of water in the air (undertree or overtree) and cooling the air, which reduces fruit temperatures through convective cooling, (2) hydrocooling by applying water to leaves and fruit, which uses the cool water to extract the sensible heat from the plant organs and carry it away via runoff, and (3) evaporative cooling through the application of water to leaves and fruit to directly extract heat by latent heat transfer (Figure 3). Evaporative cooling is commonly used in Washington State, where irrigation water is readily available. Other regions of the world often do not have adequate water to use evaporative or convective cooling techniques in orchards. Evaporative cooling systems often cycle on and off, limiting the amount of water applied. This reduces the amount of water reaching the orchard floor. Evaporative cooling can reduce fruit surface temperatures by up to 8.5 °C, which often brings fruit near ambient air temperatures [59–63]. When air temperatures and/or solar radiation are extremely high, evaporative cooling alone may not be enough to limit fruit sunburn.

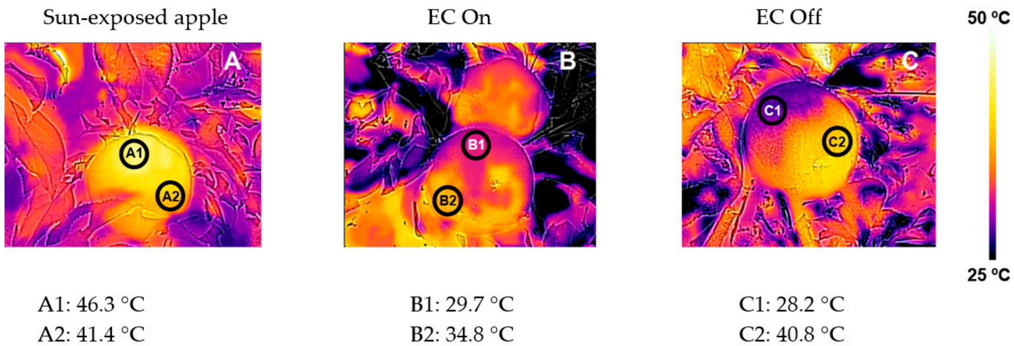

Figure 3. Fruit surface temperature (FST) of 'Honeycrisp' apples sun-exposed (**A**) and under evaporative cooling (EC) when the cycle is on (**B**) and 5 min after the cycle is off (**C**). FST was measured at 1630 h on 2 September 2022 in Rock Island (WA, USA). The air temperature was 36.6 °C, and the photosynthetically active radiation was 857 µmol m^{-2} s^{-1}. A1 is the most exposed part of the sun-exposed apple. A2 is the least exposed area of the sun-exposed apple. B1 and C1 are wet areas of the apples under evaporative cooling. B2 and C2 are dry areas of the apples under evaporative cooling.

Protective sprays and particle films are commonly used to protect fruit from sunburn. Kaolin clay, which was originally applied to apples to deter insect pests, reflects incoming solar radiation from the fruit surface and reduces sunburn [64]. There are other protective products composed of wax and other inorganic compounds that block incoming UV light and have been reported to reduce sunburn damage by greater than 50% [65].

Protective netting was originally developed for apple orchards to reduce hail damage to fruit and trees [66]. Growers in high light/temperature environments also use netting to reduce sunburn (Table 1). These regions include Australia [57], South Africa [48], Chile [67,68], and the USA [55,56,66]. Many different types of netting have been designed to provide sunburn protection. Different shading percentages, colors [68], and design systems are available to growers, although the commercial standard is approximately 20% shading, white, over-the-top nets [69]. This combination of features is typically cited as reducing the risk of limited growth and development of fruit and trees while providing maximum sunburn protection. These nets keep FST about 5–10 °C cooler than un-netted fruit under identical conditions [48,55,70]. Netting changes the quantity and quality of incoming solar radiation [71,72]. The magnitude of these changes depends on the color, mesh size, and type of net [73]. Light scattering can increase light penetration into the lower parts of the tree canopy [74]. The physical composition of netting can influence spectral transmissivity. It can also increase diffuse radiation by 17–170% depending on netting composition [75].

While netting is a reliable tool to decrease sunburn damage (Figures 4 and 5), it can also have costs. One of the most significant consequences of using netting is a reduction in red color development in some years and locations, which can lead to unmarketable fruit in red and bicolor cultivars [70]. Gindaba and Wand [70] reported shade netting significantly reduced red blush in 'Cripps' Pink' and 'Royal Gala'. This reduction in sunlight from netting (ranging from 10–50%) can be detrimental to red color development near harvest, especially when coupled with warm overnight temperatures and reduced sunlight from clouds. Red color was also reduced in an experiment in the USA, but the reductions were lower than those reported for previous studies [76].

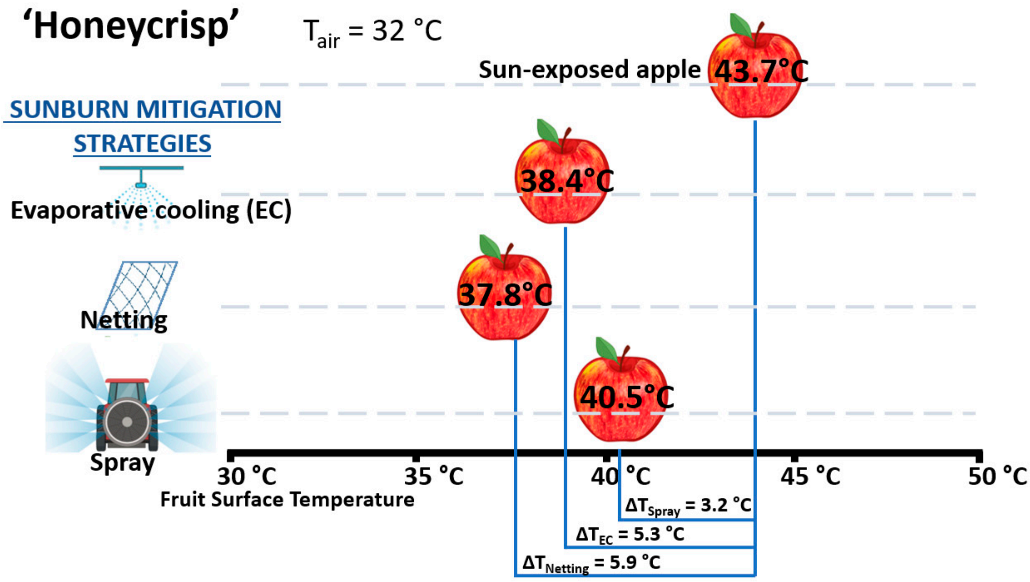

Figure 4. Comparisons of sunburn mitigation strategies on 'Honeycrisp' fruit surface temperatures. Adapted from Reig et al. [56].

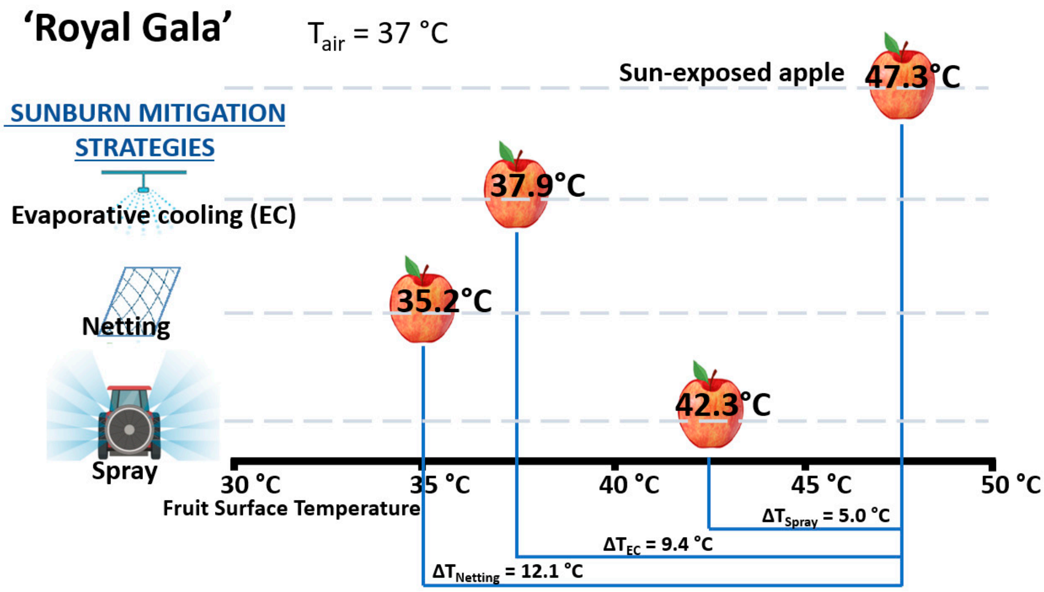

Figure 5. Comparisons of sunburn mitigation strategies on 'Royal Gala' fruit surface temperatures. Adapted from Gindaba and Wand [48].

4. Color Development in Apples

Red color varies strongly among cultivars and by the environment. While a red color is an important final quality parameter, it can be inconsistent and is often not a useful indicator of fruit maturity. Still though, many harvest timing decisions are based solely on red color development. Furthermore, there are many factors affecting the development of red color that can lead to high variation in red blush coverage within even a single tree [77] or an orchard. This variability can make it difficult to capture variation among treatments and locations.

Red color is produced by anthocyanin pigments formed prior to physiological and commercial maturity. This is controlled by the MYB transcription factor, and identification of this gene has been crucial for informed selective breeding [78]. Anthocyanins require cool nighttime temperatures and solar radiation for optimal development, often leading to red color development closer to harvest when temperatures begin to cool [79–82]. The range of optimal temperature varies by cultivar but has been estimated to be 16–25 °C [83]. Furthermore, the optimal temperature for anthocyanin development may also depend on overall temperatures throughout the growing season and acclimation to those temperatures. These factors are poorly understood due to the complexity of interactions. Crop load is also critical for sufficient red color development [84,85]. High crop loads limit the available carbohydrate pool for anthocyanin synthesis on the fruit surface [86].

4.1. Improving Red Color

Because red color development is such an important consideration, many practices have been developed for producers to improve it. One of the standard practices is the installation of reflective ground cover. There are many different materials and approaches to reflective ground covers. Typically, some type of mylar-type material is deployed in the drive rows a few weeks before harvest. This reflective material is effective at increasing the photosynthetically active radiation available to the lower part of the tree canopy [87]. Overall, the red color is also improved when compared to the control with no reflective ground cover [88]. One additional reason for the significant improvement in red color comes from the light-scattering effect created by some ground covers, distributing light to shaded and inner-canopy fruits [87]. There are other management practices that can increase light exposure for fruit, such as summer pruning, which increases light exposure and, consequently, results in more red color [89]. Manual or mechanical leaf removal is also increasingly being tested in many locations to increase light exposure for fruit near harvest. Other practices such as retracting netting prior to harvest or the use of cooling systems at different times of day can also either increase light exposure or cool fruit to stimulate anthocyanin synthesis. Grower practices to improve red color require further investigation, especially because the exact mechanisms and thresholds for red color development are not completely understood, and these practices may increase sunburn pressure.

4.2. Tradeoffs between Sunburn Susceptibility/Mitigation and Red Color

Sunlight and light interception are important for overall tree productivity and fruit quality [5]. Since direct sunlight is required for the development of red color, many of the fruit located in the inner canopies of larger, more vigorous trees often have poor red color due to the limited sunlight. However, fruit that is more exposed is more susceptible to sunburn conditions when temperatures are high (Table 2). The use of dwarfing rootstocks and new training systems has led to higher-density orchards with lower vigor, which increases light penetration into the canopy [10]. These orchards also face increased sunburn pressure because of the increase in light exposure for more fruit within the canopy. Netting limits incoming light conditions and reduces sunburn but can limit red color development [76]. In some years, high temperatures near harvest can limit red color development for earlier-developing cultivars and cultivars with poor coloring. In these situations, it is difficult to increase the red color of the fruit, and this can lead to issues with over-maturity since fruit might be left on the tree past optimum commercial maturity. It is an essential balance to protect the fruit from high summer temperatures but also provide sufficient light conditions that maintain optimum fruit color for most of the fruit within the orchard.

Table 2. Summary of the tradeoffs between red color and sunburn for a range of agronomic strategies to improve fruit quality in apples.

Agronomic Strategy	Agronomic Effect	Impact on Red Color	Impact on Sunburn	Reference(s)
Reflective material	Red color	Increase	Increase/no change	[88,90,91]
Deleafing	Red color	Increase	Decrease/no change	[92–94]
Phenylalanine spray	Red color	Increase	No change	[95]
Fruit thinning	Red color	Increase	Decrease/no change	[83,96,97]
Summer pruning	Red color	Increase	Increase/no change	[89,98–100]
Protective spray	Sunburn	Decrease/no change	Decrease	[101–104]
Evaporative cooling	Sunburn	Increase	Decrease	[25,48,58,63]
Netting	Sunburn	Decrease/no change	Decrease	[55,56,66–69,88,105]

5. The Impact of Changing Climate on Fruit Quality

The Earth's temperature has risen by about 0.74 °C during the 20th century [106]. In addition to the general average warming trend, there has been an increase in the duration, intensity, and frequency of extreme heat events across the globe [1]. In many apple-growing regions in the Pacific Northwest, annual average temperatures are projected to increase by 1.8–5.4 °C by 2070–2090 when compared to 1970–1999 [107]. Additionally, summer heat waves have become more frequent and intense and are expected to continue. The forecasted changes in summer temperatures are similar across many traditional apple-growing regions [108–110].

Increasing temperatures are expected to impact crop production through multiple factors related to the growing season length and phenology shifts [111]. With respect to perennial tree fruit, while the potential impact of warmer summers on sunburn risk has been recognized [13,33], there is limited work applying climate change projections to estimate this risk. To the best of our knowledge, Webb et al. [110] is the only work that has attempted to evaluate this risk for apple production in Australia. Their assessment is based on exposure to air temperatures above specific thresholds. However, sunburn is a function of fruit-surface temperatures rather than air temperatures, and these fruit-surface temperatures can be very different from air temperatures [44,45]. Climate change impact quantification using estimates of fruit-surface temperatures is lacking. Additionally, the sunburn reduction efficacy of different management practices can be altered in a changing climate, and these effects have also not been comprehensively evaluated. With respect to climate change impacts of warmer autumns on red color development, there is an even larger knowledge gap. To our knowledge, no study has quantified this utilizing climate change projections. This is in line with findings from Gallinet et al. [112] that autumn is an important but neglected season in climate change research.

Climate change is expected to exacerbate losses in fruit quality for apple producers [13]. Although the environmental factors causing sunburn are well understood, the dynamic susceptibility during fruit development is not. Increasing the probability of periodic extreme heat exposure may affect overall sunburn risk, but more research is needed to better model these changes and their impact on apple production. Advancing spring phenology will also likely advance maturity during warmer periods in the summer. Furthermore, elevated summer temperatures will also increase the risk of fruit damage once chlorophyll degradation begins during fruit ripening. In addition to increased pressure in regions where sunburn incidence was historically common, losses to sunburn may also become important in regions with traditionally low sunburn pressure. Shifting mitigation practices may be limited by access to capital or resources such as water for evaporative cooling.

The development of the red color of apples, a key factor affecting pricing and marketability, is also limited by high temperatures [113]. Under climate change, elevated temperatures near harvest will limit red color development [109]. There are significant cultivar differences in red color development, and although selection has occurred for new cultivars that develop color under warmer conditions, consumer choice will dictate popular cultivars, and producers will need information on risks for their regions and cultivars. Apple producers will need to balance the economics of enhancing red color through agronomic practices against potential risks of increased sunburn from elevated light exposure to ripening fruit. More research is needed to adequately study these tradeoffs under future conditions.

6. Conclusions

Sunburn incidence and poor color development are two of the largest causes of fruit losses. Tree fruit training systems that are highly productive and allow the best red color development are also the most susceptible to sunburn. These systems require substantial investments in sunburn mitigation in regions where summer temperatures exceed 35 °C. Our understanding of the physiological thresholds for sunburn browning is still poorly developed, and inconsistencies in the reported environmental conditions leading to these disorders need to be more closely examined. Increasing summer temperatures under climate change will elevate risks in regions where sunburn occurs and increase the probability of occurrence in regions where sunburn does not historically occur. Apple producers will need to adopt strategies that are either costly or come with tradeoffs for other measures of fruit quality. Almost all mitigation strategies influence light exposure to increase red color, which may increase sunburn during periods of fruit development when a red color is needed. It will be important to better understand these tradeoffs across multiple strategies to more effectively manage sunburn under future climates.

Author Contributions: Conceptualization, N.W. and L.K.; writing—original draft preparation, N.W., V.B., K.R., T.C., O.H. and L.K.; writing—review and editing, N.W., V.B., K.R., T.C., O.H. and L.K.; visualization, N.W. and V.B.; supervision, L.K.; funding acquisition, L.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Washington Tree Fruit Research Commission to L.K.

Data Availability Statement: Data are stored and available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IPCC. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; p. 3056.
2. Chmielewski, F.M.; Müller, A.; Bruns, E. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agric. For. Meteorol.* **2004**, *121*, 69–78. [CrossRef]
3. Wolfe, D.W.; Schwartz, M.D.; Lakso, A.N.; Otsuki, Y.; Pool, R.M.; Shaulis, N.J. Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *Int. J. Biometeorol.* **2005**, *49*, 303–309. [CrossRef] [PubMed]
4. Brunner, J.F.; Jones, W.; Kupferman, E.; Xiao, C.L.; Faubion, D.; Tangren, G. Information from the careful evaluation of packingline culls. In Proceedings of the Washington Tree Fruit Postharvest Conference, Wenatchee, WA, USA, 2–3 December 2003; pp. 1–6.
5. Musacchi, S.; Serra, S. Apple Fruit Quality: Overview on pre-harvest factors. *Sci. Hortic.* **2018**, *234*, 409–430. [CrossRef]
6. Barber, H.N.; Sharpe, P.J.H. Genetics and physiology of sunscald of fruits. *Agric. Meteorol.* **1971**, *8*, 175–191. [CrossRef]
7. Munné-Bosch, S.; Vincent, C. Physiological mechanisms underlying fruit sunburn. *Crit. Rev. Plant Sci.* **2019**, *38*, 140–157. [CrossRef]
8. Iglesias, I.; Alegre, S.A. The effect of anti-hail nets on fruit protection, radiation, temperature, quality and probability of 'mondial gala' apples. *J. Appl. Hortic.* **2006**, *8*, 91–100. [CrossRef]
9. Olivares-Soto, H.; Bastías, R.M. Photosynthetic efficiency of apples under protected shade nets. *Chil. J. Agric. Res.* **2018**, *78*, 126–138. [CrossRef]
10. Mupambi, G.; Schmeisser, M.; Dzikiti, S.; Reynolds, S.; Steyn, W.J. Ineffectiveness of foliar S-ABA application as an apple sunburn suppressant explained through effects on peel biochemistry and leaf ecophysiology. *Sci. Hortic.* **2018**, *232*, 256–263. [CrossRef]
11. Darbyshire, R.; McClymont, L.; Goodwin, I. Sun Damage Risk of royal gala apple in fruit-growing districts in Australia. *N. Z. J. Crop Hortic. Sci.* **2015**, *43*, 222–232. [CrossRef]
12. Schrader, L.; Sun, J.; Zhang, J.; Felicetti, D.; Tian, J. Heat and light-induced Apple Skin Disorders: Causes and prevention. *Acta Hortic.* **2008**, *772*, 51–58. [CrossRef]

13. Racsko, J.; Schrader, L.E. Sunburn of Apple Fruit: Historical Background, recent advances and future perspectives. *Crit. Rev. Plant Sci.* **2012**, *31*, 455–504. [CrossRef]
14. Wagenmakers, P.S.; Callesen, O. Light distribution in apple orchard systems in relation to production and fruit quality. *J. Hortic. Sci.* **1995**, *70*, 935–948. [CrossRef]
15. Racskó, J.; Nagy, J.; Szabó, Z.; Major, M.; Nyéki, J. The impact of location, row direction, plant density and rootstock on the sunburn damage of Apple cultivars. *Int. J. Hortic. Sci.* **2005**, *11*, 19–30. [CrossRef]
16. Saitone, T.L.; Sexton, R.J. Impacts of minimum quality standards imposed through marketing orders or related producer organizations. *Am. J. Agric. Econ.* **2010**, *92*, 164–180. [CrossRef]
17. Bockstael, N.E. The welfare implications of minimum quality standards. *Am. J. Agric. Econ.* **1984**, *66*, 466–471. [CrossRef]
18. Dar, J.A.; Wani, A.A.; Ahmed, M.; Nazir, R.; Zargar, S.M.; Javaid, K. Peel colour in Apple (*Malus* × *domestica* borkh.): An economic quality parameter in fruit market. *Sci. Hortic.* **2019**, *244*, 50–60. [CrossRef]
19. USDA; ARS. U.S. Standards for Grades of Apples. Available online: https://www.ams.usda.gov/grades-standards/apple-grades-standards (accessed on 15 February 2023).
20. Johnson, L.K.; Dunning, R.D.; Gunter, C.C.; Dara Bloom, J.; Boyette, M.D.; Creamer, N.G. Field measurement in vegetable crops indicates need for reevaluation of on-farm food loss estimates in North America. *Agric. Syst.* **2018**, *167*, 136–142. [CrossRef]
21. Baker, G.A.; Gray, L.C.; Harwood, M.J.; Osland, T.J.; Tooley, J.B. On-farm food loss in northern and Central California: Results of field survey measurements. *Resour. Conserv. Recycl.* **2019**, *149*, 541–549. [CrossRef]
22. FAO. *Food Loss Prevention in Perishable Crops*; FAO Agricultural Service Bulletin No. 43; FAO Statistics Division: Rome, Italy, 1981.
23. Gustavsson, J.; Cederberg, C.; Sonesson, U.; Emanuelsson, A. *The Methodology of the FAO Study: "Global Food Losses and Food Waste—Extent, Causes and Prevention"-FAO, 2011*; SIK Report No. 857; Swedish Institute for Food and Biotechnology: Goteborg, Sweden, 2013.
24. Schrader, L.E.; Zhang, J.; Duplaga, W.K. Two types of sunburn in apple caused by high fruit surface (peel) temperature. *Plant Health Prog.* **2001**, *2*, 3–8. [CrossRef]
25. Schrader, L.E.; Sun, J.; Felicetti, D.; Seo, J.-H.; Jedlow, L.; Zhang, J. Stress-induced disorders: Effects on apple fruit quality. In Proceedings of the Washington Tree Fruit Postharvest Conference, Wenatchee, WA, USA, 2–3 December 2003.
26. Schrader, L.E.; Sun, J.; Zhang, J.; Felicetti, D. Stress management in tree fruit production. In Proceedings of the 101st Annual Meeting, Washington State Association Horticultural, Wenatchee, WA, USA, 5–7 December 2005; p. 3.
27. Moore, M.H.; Rogers, W.S. *Sun Scald of Fruits*; Annual Report; East Malling Research Station: West Malling, UK, 1943; pp. 50–53.
28. Bergh, O.; Franken, J.; van Zyl, E.J.; Kloppers, F.; Dempers, A. Sunburn on apples—Preliminary results of an investigation conducted during the 1978/79 season. *Decid. Fruit Grow.* **1980**, *30*, 8–22.
29. Arseneault, M.H.; Cline, J.A. A review of Apple Preharvest Fruit Drop and practices for horticultural management. *Sci. Hortic.* **2016**, *211*, 40–52. [CrossRef]
30. Felicetti, D.A.; Schrader, L.E. Photooxidative sunburn of apples: Characterization of a third type of Apple Sunburn. *Int. J. Fruit Sci.* **2008**, *8*, 160–172. [CrossRef]
31. Naschitz, S.; Naor, A.; Sax, Y.; Shahak, Y.; Rabinowitch, H.D. Photo-oxidative sunscald of Apple: Effects of temperature and light on fruit peel photoinhibition, bleaching and short-term tolerance acquisition. *Sci. Hortic.* **2015**, *197*, 5–16. [CrossRef]
32. McTavish, C.K.; Poirier, B.C.; Torres, C.A.; Mattheis, J.P.; Rudell, D.R. A convergence of sunlight and cold chain: The influence of sun exposure on postharvest Apple Peel Metabolism. *Postharvest Biol. Technol.* **2020**, *164*, 111164. [CrossRef]
33. Morales-Quintana, L.; Waite, J.M.; Kalcsits, L.; Torres, C.A.; Ramos, P. Sun injury on apple fruit: Physiological, biochemical and molecular advances, and future challenges. *Sci. Hortic.* **2020**, *260*, 108866. [CrossRef]
34. Rabinowitch, H.D.; Kedar, N.; Budowski, P. Induction of sunscald damage in tomatoes under natural and controlled conditions. *Sci. Hortic.* **1974**, *2*, 265–272. [CrossRef]
35. Van Amerongen, H.; Wientjes, E. Harvesting light. In *Photosynthesis in Action*; Academic Press: Cambridge, MA, USA, 2022; pp. 3–16.
36. Su, X.; Fan, X.; Shao, R.; Guo, J.; Wang, Y.; Yang, J.; Yang, Q.; Guo, L. Physiological and itraq-based proteomic analyses reveal that melatonin alleviates oxidative damage in maize leaves exposed to drought stress. *Plant Physiol. Biochem.* **2019**, *142*, 263–274. [CrossRef]
37. Taiz, L.; Zeiger, E. *Plant Physiology*; W.H. Freeman: New York, NY, USA, 2002.
38. Chen, L.-S.; Li, P.; Cheng, L. Effects of high temperature coupled with high light on the balance between photooxidation and photoprotection in the sun-exposed peel of Apple. *Planta* **2008**, *228*, 745–756. [CrossRef]
39. Hengari, S.; Theron, K.I.; Midgley, S.J.E.; Steyn, W.J. Response of Apple (*Malus domestica* Borkh.) Fruit Peel photosystems to heat stress coupled with moderate photosynthetic active radiation at different fruit developmental stages. *Sci. Hortic.* **2014**, *178*, 154–162. [CrossRef]
40. Makeredza, B.; Marais, H.; Schmeisser, M.; Lötze, E.; Steyn, W.J. Ripening associated red color development masks sunburn browning in Apple Peel. *HortScience* **2015**, *50*, 814–818. [CrossRef]
41. Blanke, M.M.; Lenz, F. Fruit photosynthesis. *Plant Cell Environ.* **1989**, *12*, 31–46. [CrossRef]
42. Merzlyak, M.N.; Solovchenko, A.E. Photostability of pigments in ripening apple fruit: A possible photoprotective role of carotenoids during plant senescence. *Plant Sci.* **2002**, *163*, 881–888. [CrossRef]

43. Yuri, J.A.; Lepe, V.; Moggia, C.; Bastias, R.; Bertschinger, L. Sunburn on apple. *Schweiz. Z. Obst.-Weinbau.* **2004**, *8*, 7–10. (In German)
44. Li, L.; Peters, T.; Zhang, Q.; Zhang, J.; Huang, D. Modeling Apple Surface Temperature Dynamics based on weather data. *Sensors* **2014**, *14*, 20217–20234. [CrossRef] [PubMed]
45. Ranjan, R.; Khot, L.R.; Peters, R.T.; Salazar-Gutierrez, M.R.; Shi, G. In-field crop physiology sensing aided real-time apple fruit surface temperature monitoring for sunburn prediction. *Comput. Electron. Agric.* **2020**, *175*, 105558. [CrossRef]
46. Lal, N.; Sahu, N. Management strategies of sunburn in Fruit Crops-a review. *Int. J. Curr. Microbiol. Appl. Sci.* **2017**, *6*, 1126–1138. [CrossRef]
47. Ferguson, I.B.; Snelgar, W.; Lay-Yee, M.; Watkins, C.B.; Bowen, J.H. Expression of heat shock protein genes in apple fruit in the field. *Funct. Plant Biol.* **1998**, *25*, 155. [CrossRef]
48. Gindaba, J.; Wand, S.J.E. Comparative effects of evaporative cooling, kaolin particle film, and shade net on sunburn and fruit quality in apples. *HortScience* **2005**, *40*, 592–596. [CrossRef]
49. Makeredza, B.; Schmeisser, M.; Lötze, E.; Steyn, W.J. Water stress increases sunburn in 'Cripps' pink' Apple. *HortScience* **2013**, *48*, 444–447. [CrossRef]
50. Song, Y.Y.; Park, M.Y.; Yang, S.J.; SaGong, D.H. Influence of air temperature during midsummer on fruit sunburn occurrence in 'fuji'/m.9 apple tree. *Korean J. Agric. For. Meteorol.* **2009**, *11*, 127–134. [CrossRef]
51. Manfrini, L.; Gatti, G.; Morandi, B.; Corelli Grappadelli, L.; Bortolotti, G.; Rossi, F.; Facini, O.; Chieco, C.; Gerin, M.; Solimando, D.; et al. Microclimatic physiological and productive effect of the overcanopy irrigation in an Apple Orchard. *Acta Hortic.* **2020**, *1281*, 377–384. [CrossRef]
52. Olivares-Soto, H.; Bastías, R.M.; Calderón-Orellana, A.; López, M.D. Sunburn control by nets differentially affects the antioxidant properties of fruit peel in 'gala' and 'fuji' apples. *Hortic. Environ. Biotechnol.* **2020**, *61*, 241–254. [CrossRef]
53. Feng, Y.; Li, S.; Jia, R.; Yang, J.; Su, Q.; Zhao, Z. Physiological characteristics of sunburn peel after Apple Debagged. *Molecules* **2022**, *27*, 3775. [CrossRef] [PubMed]
54. Severino, V.; Arias-Sibillotte, M.; Dogliotti, S.; Frins, E.; Yuri, J.A.; González-Talice, J. Pre- and postharvest management of Sunburn in 'granny smith' apples (Malus × domestica Borkh) under Neotropical climate conditions. *Agronomy* **2021**, *11*, 1618. [CrossRef]
55. Kalcsits, L.; Musacchi, S.; Layne, D.R.; Schmidt, T.; Mupambi, G.; Serra, S.; Mendoza, M.; Asteggiano, L.; Jarolmasjed, S.; Sankaran, S.; et al. Above and below-ground environmental changes associated with the use of photoselective protective netting to reduce sunburn in apple. *Agric. For. Meteorol.* **2017**, *237*, 9–17. [CrossRef]
56. Reig, G.; Donahue, D.J.; Jentsch, P. The efficacy of four sunburn mitigation strategies and their effects on yield, fruit quality, and economic performance of Honeycrisp CV. Apples under Eastern New York (USA) climatic conditions. *Int. J. Fruit Sci.* **2019**, *20*, 541–561. [CrossRef]
57. McCaskill, M.R.; McClymont, L.; Goodwin, I.; Green, S.; Partington, D.L. How hail netting reduces apple fruit surface temperature: A microclimate and modelling study. *Agric. For. Meteorol.* **2016**, *226–227*, 148–160. [CrossRef]
58. Evans, R.G.; Kroeger, M.W.; Mahan, M.O. Evaporative cooling of apples by Overtree sprinkling. *Appl. Eng. Agric.* **1995**, *11*, 93–99. [CrossRef]
59. Unrath, C.R. The evaporative cooling effects of overtree sprinkler irrigation on 'red delicious' apples. *J. Am. Soc. Hortic. Sci.* **1972**, *97*, 55–58. [CrossRef]
60. Parchomchuk, P.; Meheriuk, M. Orchard cooling with pulsed overtree irrigation to prevent solar injury and improve fruit quality of 'jonagold' apples. *HortScience* **1996**, *31*, 802–804. [CrossRef]
61. Wünsche, J.N.; Greer, D.H.; Palmer, J.W.; Lang, A.; McGhie, T. Sunburn—The cost of a high light environment. *Acta Hortic.* **2001**, *557*, 349–356. [CrossRef]
62. Wünsche, J.N.; Bowen, J.; Ferguson, I.; Woolf, A.; McGhie, T. Sunburn on apples—Causes and control mechanisms. *Acta Hortic.* **2004**, *636*, 631–636. [CrossRef]
63. Van den Dool, K. Evaporative Cooling of Apple and Pear Orchards. Master Thesis, Stellenbosch University, Stellenbosch, South Africa, 2006.
64. Glenn, D.M.; Puterka, G.J. Particle films: A new technology for Agriculture. *Hortic. Rev.* **2010**, *31*, 1–44.
65. Schrader, L.E. Scientific basis of a unique formulation for reducing sunburn of fruits. *HortScience* **2011**, *46*, 6–11. [CrossRef]
66. Mupambi, G.; Anthony, B.M.; Layne, D.R.; Musacchi, S.; Serra, S.; Schmidt, T.; Kalcsits, L.A. The influence of protective netting on tree physiology and fruit quality of Apple: A Review. *Sci. Hortic.* **2018**, *236*, 60–72. [CrossRef]
67. Yuri, J.A.; Sepúlveda, Á.; Moya, M.; Simeone, D.; Fuentes, M. Shade Netting and Reflective Mulches Effect on Yield and Quality Variables of 'Gala Baigent' and 'Fuji Raku Raku' Apples. *N. Z. J. Crop Hortic. Sci.* **2022**, 1–20. [CrossRef]
68. Bastías, R.M.; Manfrini, L.; Grappadelli, L.C. Exploring the potential use of photo-selective nets for fruit growth regulation in apple. *Chil. J. Agric. Res.* **2012**, *72*, 224. [CrossRef]
69. Mupambi, G.; Layne, D.; Kalcsits, L.; Musacchi, S.; Serra, S.; Schmidt, T.; Hanrahan, I. Use of Protective Netting in Washington State Apple Production. 2019. Available online: https://tfrec.cahnrs.wsu.edu/kalcsits/wp-content/uploads/sites/7/2019/10/Mupambi-etal-2019-TB60E-Netting.pdf (accessed on 15 March 2023).
70. Gindaba, J.; Wand, S.J.E. Comparison of Climate Ameliorating Measures to Control Sunburn on 'Fuji' Apples. *Acta Hortic.* **2008**, *772*, 59–64. [CrossRef]

71. Basile, B.; Romano, R.; Giaccone, M.; Barlotti, E.; Colonna, V.; Cirillo, C.; Shahak, Y.; Forlani, M. Use of Photo-Selective Nets for Hail Protection of Kiwifruit Vines in Southern Italy. *Acta Hortic.* **2008**, *770*, 185–192. [CrossRef]
72. Castellano, S.; Russo, G.; Mugnozza, G.S. The Influence of Construction Parameters on Radiometric Performances of Agricultural Nets. *Acta Hortic.* **2006**, *718*, 283–290. [CrossRef]
73. Middleton, S.G.; Mcwaters, A.D. *Maximising Apple Orchard Productivity Under Hail Netting*; Final Report for Project AP96014; Department of Primary Industries and Fisheries: Brisbane, Australia, 2000.
74. Shahak, Y.; Gussakovsky, E.E.; Gal, E.; Ganelevin, R. Colornets: Crop Protection and Light-Quality Manipulation in One Technology. *Acta Hortic.* **2004**, *659*, 143–151. [CrossRef]
75. Abdel-Ghany, A.M.; Al-Helal, I.M. Characterization of Solar Radiation Transmission through Plastic Shading Nets. *Sol. Energy Mater Sol. Cells* **2010**, *94*, 1371–1378. [CrossRef]
76. Serra, S.; Borghi, S.; Mupambi, G.; Camargo-Alvarez, H.; Layne, D.; Schmidt, T.; Kalcsits, L.; Musacchi, S. Photoselective Protective Netting Improves "Honeycrisp" Fruit Quality. *Plants* **2020**, *9*, 1708. [CrossRef] [PubMed]
77. Kviklys, D.; Viškelis, J.; Liaudanskas, M.; Janulis, V.; Laužikė, K.; Samuolienė, G.; Uselis, N.; Lanauskas, J. Apple fruit growth and quality depend on the position in tree canopy. *Plants* **2022**, *11*, 196. [CrossRef]
78. Espley, R.V.; Hellens, R.P.; Putterill, J.; Stevenson, D.E.; Kutty-Amma, S.; Allan, A.C. Red Colouration in Apple Fruit Is Due to the Activity of the MYB Transcription Factor, MDMYB10. *Plant J.* **2007**, *49*, 414–427. [CrossRef] [PubMed]
79. Siegelman, H.W.; Hendricks, S.B. Photocontrol of Anthocyanin Synthesis in Apple Skin. *Plant Physiol.* **1958**, *33*, 185–190. [CrossRef] [PubMed]
80. Arakawa, O. Photoregulation of Anthocyanin Synthesis in Apple Fruit under UV-B and Red Light. *Plant Cell Physiol.* **1988**, *29*, 1385–1389.
81. Saure, M.C. External Control of Anthocyanin Formation in Apple. *Sci. Hortic.* **1990**, *42*, 181–218. [CrossRef]
82. Marais, E.; Jacobs, G.; Holcroft, D.M. Colour Response of 'Cripps' Pink' Apples to Postharvest Irradiation Is Influenced by Maturity and Temperature. *Sci. Hortic.* **2001**, *90*, 31–41. [CrossRef]
83. Gouws, A.; Steyn, W.J. The Effect of Temperature, Region and Season on Red Colour Development in Apple Peel under Constant Irradiance. *Sci. Hortic.* **2014**, *173*, 79–85. [CrossRef]
84. Gonzalez, L.; Torres, E.; Àvila, G.; Carbó, J.; Bonany, J.; Alegre, S.; Asin, L. Effect of Thinning with Metamitron, Naa, BA and Naphthenic Acids on Apple (Malus Domestica) Trees. *Plant Growth Regul.* **2023**. [CrossRef]
85. Serra, S.; Leisso, R.; Giordani, L.; Kalcsits, L.; Musacchi, S. Crop Load Influences Fruit Quality, Nutritional Balance, and Return Bloom in 'Honeycrisp' Apple. *HortScience* **2016**, *51*, 236–244. [CrossRef]
86. Ritenour, M.; Khemira, H. Red Color Development of Apple: A Literature Review. Washington State University—Tree Fruit Research and Extension Center. Postharvest Information Network. Printed 1997, Reprinted 2007. Available online: https://web.archive.org/web/20181221101058/http://postharvest.tfrec.wsu.edu:80/REP2007A.pdf (accessed on 13 April 2023).
87. Weber, S.; Damerow, L.; Kunz, A.; Blanke, M. Anthocyanin Synthesis and Light Utilisation Can Be Enhanced by Reflective Mulch—Visualisation of Light Penetration into a Tree Canopy. *J. Plant Physiol.* **2019**, *233*, 52–57. [CrossRef] [PubMed]
88. Mupambi, G.; Valverdi, N.A.; Camargo-Alvarez, H.; Reid, M.; Kalcsits, L.; Schmidt, T.; Castillo, F.; Toye, J. Reflective Groundcover Improves Fruit Skin Color in 'Honeycrisp' Apples Grown under Protective Netting. *Horttechnology* **2021**, *31*, 607–614. [CrossRef]
89. Lugaresi, A.; Steffens, C.A.; Souza, M.P.; Amarante, C.V.; Brighenti, A.F.; Pasa, M.D.; Martin, M.S. Late Summer Pruning Improves the Quality and Increases the Content of Functional Compounds in Fuji Apples. *Bragantia* **2022**, *81*, 3122–3132. [CrossRef]
90. Gonzalez, L.; Robinson, T.L. Effect of Different Reflective Ground Covers on the Coloring of Apples at Harvest. In *Fruit Quarterly*; NYS Horticultural Society: Geneva, NY, USA, 2021; pp. 15–18.
91. Meinhold, T.; Damerow, L.; Blanke, M. Reflective Materials under Hailnet Improve Orchard Light Utilisation, Fruit Quality and Particularly Fruit Colouration. *Sci. Hortic.* **2011**, *127*, 447–451. [CrossRef]
92. Andergassen, C.; Pichler, D. Pneumatic Defoliation of Apple Trees for Colour Improvement. *Acta Hortic.* **2022**, *1346*, 391–398. [CrossRef]
93. Matsumoto, K.; Fujita, T.; Sato, S.; Chun, J.P. Comparison of the Effects of Early and Conventional Defoliation on Fruit Growth, Quality and Skin Color Development in 'Fuji' Apples. *Hortic. Sci. Technol.* **2017**, *35*, 410–417.
94. Lee, C.H.; Seo, S.H.; Kwon, O.J.; Park, M.; Kim, W.C.; Kang, S.J. Functional Characterization of a Chemical Defoliant That Activates Fruit Cluster Leaf Defoliation in 'Fuji' Apple Trees. *Appl. Biol. Chem.* **2016**, *59*, 711–720. [CrossRef]
95. Fanyuk, M.; Kumar Patel, M.; Ovadia, R.; Maurer, D.; Feygenberg, O.; Oren-Shamir, M.; Alkan, N. Preharvest Application of Phenylalanine Induces Red Color in Mango and Apple Fruit's Skin. *Antioxidants* **2022**, *11*, 491. [CrossRef]
96. Gonzalez, L.; Torres, E.; Àvila, G.; Bonany, J.; Alegre, S.; Carbó, J.; Martín, B.; Recasens, I.; Asin, L. Evaluation of Chemical Fruit Thinning Efficiency Using Brevis® (Metamitron) on Apple Trees ('Gala') under Spanish Conditions. *Sci. Hortic.* **2020**, *261*, 109003. [CrossRef]
97. Hehnen, D.; Hanrahan, I.; Lewis, K.; McFerson, J.; Blanke, M. Mechanical Flower Thinning Improves Fruit Quality of Apples and Promotes Consistent Bearing. *Sci. Hortic.* **2012**, *134*, 241–244. [CrossRef]
98. Bhusal, N.; Han, S.G.; Yoon, T.M. Summer Pruning and Reflective Film Enhance Fruit Quality in Excessively Tall Spindle Apple Trees. *Hortic. Environ. Biotechnol.* **2017**, *58*, 560–567. [CrossRef]
99. Djordjeviä†, B.; Dejan, D.; Gordan, Z. Effects of Different Times of Summer Pruning to Productivity and Fruits Quality of Apple Cultivar Gala Brookfield. *Ann. Univ. Craiova* **2019**, *49*, 26–31.

100. Morgan, D.C.; Stanley, C.J.; Volz, R.; Warrington, I.J. Summer Pruning of 'Gala' Apple: The Relationships between Pruning Time, Radiation Penetration, and Fruit Quality. *J. Am. Soc. Hortic. Sci.* **1984**, *109*, 637–642. [CrossRef]
101. Aly, M.; El-Megeed, N.A.; Awad, R.M. Reflective Particle Films Affected on, Sunburn, Yield, Mineral Composition and Fruit Maturity of "Anna" Apple (Malus Domestica) Trees. *Res. J. Agric. Sci.* **2010**, *6*, 84–92.
102. Glenn, D.M.; Prado, E.; Erez, A.; McFerson, J.; Puterka, G.J.A. Reflective, Processed-Kaolin Particle Film Affects Fruit Temperature, Radiation Reflection, and Solar Injury in Apple. *J. Am. Soc. Hortic. Sci.* **2002**, *127*, 188–193. [CrossRef]
103. Sarooghinia, F.; Khadivi, A.; Abbasifar, A.; Khaleghi, A. Foliar Application of Kaolin to Reduce Sunburn in 'Red Delicious' Apple. *Erwerbs-Obstbau* **2019**, *62*, 83–87. [CrossRef]
104. Schupp, J.R.; Fallahi, E.; Chun, I.J. Effect of Particle Film on Fruit Sunburn, Maturity and Quality of 'Fuji' and 'Honeycrisp' Apples. *Horttechnology* **2002**, *12*, 87–90. [CrossRef]
105. Kalcsits, L.; Asteggiano, L.; Schmidt, T.; Musacchi, S.; Serra, S.; Layne, D.R.; Mupambi, G. Shade Netting Reduces Sunburn Damage and Soil Moisture Depletion in 'Granny Smith' Apples. *Acta Hortic.* **2018**, *1228*, 85–90. [CrossRef]
106. IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Eds.; Cambridge University Press: Cambridge, UK, 2007; 976p.
107. Mote, P.; Foster, J.G.; Daley-Laursen, S.B. Data mining to predict climate hotspots: An experiment in aligning federal climate enterprises in the Northwest. *AGU Fall Meet. Abstr.* **2014**, *2014*, PA41A-4024.
108. Fujisawa, M.; Kobayashi, K. Climate Change Adaptation Practices of Apple Growers in Nagano, Japan. *Mitig. Adapt. Strateg. Glob. Chang.* **2011**, *16*, 865–877. [CrossRef]
109. Lötze, E.; Daiber, S.H.; Midgley, S.J. Boron in combination with calcium reduces sunburn in apple fruit. *J. Boron.* **2017**, *2*, 123–127.
110. Webb, L.; Darbyshire, R.; Erwin, T.; Goodwin, I. A Robust Impact Assessment That Informs Actionable Climate Change Adaptation: Future Sunburn Browning Risk in Apple. *Int. J. Biometeorol.* **2016**, *61*, 891–901. [CrossRef] [PubMed]
111. Rajagopalan, K.; Chinnayakanahalli, K.J.; Stockle, C.O.; Nelson, R.L.; Kruger, C.E.; Brady, M.P.; Malek, K.; Dinesh, S.T.; Barber, M.E.; Hamlet, A.F.; et al. Impacts of near-Term Climate Change on Irrigation Demands and Crop Yields in the Columbia River Basin. *Water Resour. Res.* **2018**, *54*, 2152–2182. [CrossRef]
112. Gallinat, A.S.; Primack, R.B.; Wagner, D.L. Erratum: Autumn, the Neglected Season in Climate Change Research. *Trends Ecol. Evol.* **2015**, *30*, 364. [CrossRef]
113. Creasy, L.L. The role of low temperature in anthocyanin synthesis in 'McIntosh' apple. *Proc. Am. Soc. Hortic. Sci.* **1968**, *93*, 716–724.