Final report

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Albedo breakdown prediction

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Public summary

Citrus albedo breakdown (AB) is the development of cracks in the albedo layer of citrus fruit (the white layer of the rind) and the folding inwards of the flavedo (the orange-coloured, external part of the rind) into those fractures, causing the rind to develop creases, and diminishing fruit quality. Fruit with significant AB damage will often crack open in transit and then decay, resulting in lower prices and returns through fruit rejection, and a risk of a downgraded perception of Australian navel orange production quality.

This project investigated the possible association between the incidence of AB and historical weather observations. Albedo breakdown fruit damage data were sought from packing houses throughout the southern citrus-producing regions. Unfortunately, most packing houses did not have historical albedo breakdown data suitable for analysis, storing only grade pack-out data, which made it impossible to separate the contribution of AB from other issues, such as small fruit size and blemishes. One large packing house in Mildura, however, has been actively recording AB levels of delivered fruit for the past 10 years and was able to supply this data.

Two connections between AB incidence and weather conditions were found, one relating to the November before harvest and one relating to May (the usual timing for the start of harvesting).

The analysis identified a relationship between solar radiation in November (the growing season prior to harvest) and the incidence of AB at harvest (typically commencing in May). Specifically, seasons with lower average daily solar radiation in November were associated with higher levels of AB. In the 2021–2022 season, which had a very high AB incidence, November solar radiation was less than 22 MJ/m^2/day. In contrast, the following season (2022–2023), which had moderate AB incidence, recorded November values between 22 and 24 MJ/m^2/day, while seasons with consistently low AB incidence were generally associated with November solar radiation greater than 24 MJ/m^2/day.

These results indicate that reduced solar radiation, reflecting cloudier spring conditions, is associated with increased AB risk at harvest. However, this relationship should be interpreted cautiously, as the dataset included only one season with very high AB incidence. More broadly, solar radiation is likely acting as an indicator of wider environmental conditions, including higher humidity and lower evaporative demand, rather than being a direct cause in isolation.

Research suggests that a sufficient level of calcium in the citrus rind is needed to minimise the risk of AB. Most of the calcium in the rind is accumulated during the cell division stage, from early November to mid-December. The uptake of calcium by the plant's roots and its movement up the tree and into fruit is determined by the upward movement of water from the roots, which, in turn, is driven by evaporation and loss of water through the stomata, which are functional in fruitlets during the cell division stage. More water will be lost through leaves and fruitlets on a sunny, warm day than on a cloudy, mild day. Therefore, cloudy days in November could decrease water flow through the tree and the subsequent delivery and deposition of calcium into the rind, thereby increasing the risk of AB at harvest.

The analysis also showed a relationship between AB and late-season conditions in May, particularly rainfall, humidity and reduced evaporative demand. These combined conditions are likely to influence the expression of AB susceptibility close to harvest, rather than AB expression being caused by a single direct mechanism. A later start to harvest also increased AB expression, particularly in seasons where climatic conditions were already conducive to AB.

Statistical analysis was used to combine these seasonal factors in a single model. The final model included evapotranspiration in November, relative humidity (measured at the hottest part of the day) in May, and the day of the year on which harvest commenced, with terms for individual growers and years included as random effects. In practical terms, the model was based on plant–climate water relations during early fruit development and harvest, as well as the length of time that the fruit remains on the tree.

This supports the interpretation that AB risk is influenced by a sequence of interacting factors:

- early-season conditions that predispose the fruit to AB,
- late-season moisture conditions that contribute to symptom expression, and
- later harvesting that allows symptoms to worsen.

While these findings are based on a limited dataset that includes only one severe AB season, they provide a strong, biologically plausible explanation of how climate influences the disorder. The results establish a foundation for future work to validate and move towards predictive capability. Improved AB-related data capture by packing houses would strengthen future analyses and allow the model to be tested and refined. Field validation experiments should be carried out to test trees' responses to early-season solar radiation and evaporative demand conditions, including the application of temporary shading during November and, where feasible, complementary moisture and calcium-related treatments. These experiments would allow an assessment of whether the described conditions do predispose fruit to AB, and whether the risk can be managed.

Keywords

Albedo breakdown, citrus, calcium, solar radiation, harvest

Introduction

Citrus albedo breakdown (AB) is the development of cracks in the albedo layer (the white layer of the rind) and the folding inwards of the flavedo (the orange-coloured external part of the rind) into those fractures. It is a disorder that becomes obvious during the final weeks of navel orange fruit maturity, as the rind will have creases and sometimes cracks, diminishing fruit quality. Affected fruit are more prone to splitting during transport, causing fruit breakdown and reduced marketability. If the disorder is severe (that is, covering a large proportion of the rind), the fruit will be downgraded and split fruit will be discarded, resulting in reduced returns to producers.

The disorder usually occurs on the shaded side of the fruit and worsens the longer the fruit are left on the tree. It is generally a minor problem in most seasons, affecting approximately 5% of fruit. Occasionally, fruit in Australia's main citrus production regions can be severely affected. For instance, in the 2021–2022 season, up to 50% of fruit had AB. This substantially reduced grower returns and Australia's credibility as a supplier of quality fruit on the international markets. In that season, some orchard blocks were not harvested because the high level of AB created an unacceptable risk of rind rupture and breakdown during transit and marketing.

There has been extensive research worldwide into AB (see literature review by Golding et al. 2026), with mixed results and recommendations. Researchers have explored associations between varieties, rootstocks, and production practices and the incidence of AB. Early maturing varieties were found to be more susceptible than late maturing varieties, but linkages with production practices were far less clear. Australian researchers linked low calcium levels in the rind with the disorder (Storey et al. 2002), and subsequent research showed that a foliar application of calcium or gibberellic acid (GA; Jona 1989) reduced the incidence of AB but did not eliminate it (Treeby and Storey 2002). In the 2021–2022 and 2022–2023 seasons, some citrus producers who applied GA still had a high incidence of AB.

The apparent failure of foliar-applied calcium or GA to control AB suggests a climatic influence. Understanding the nature of that influence could form the basis of improved risk management strategies. One such strategy currently used is to harvest problem blocks earlier in high-risk seasons. However, this is not an industry-wide practical solution because not every block can be harvested early, as packing houses need a constant supply of fruit throughout the harvest season.

Identifying a relationship between weather conditions and AB would answer the question of whether specific conditions, or a combination of conditions, predispose fruit to developing the disorder. These conditions might occur at different stages of citrus fruit development. Furthermore, multiple factors might contribute to the occurrence of AB, increasing the complexity of identifying weather conditions and patterns that reliably indicate a high level of risk.

In this project, historical meteorological observations and the incidence of AB were analysed to determine if there was an association between weather and AB. Although there are no completely effective treatments during high-risk seasons, the insights gained could lead to future research into improved management options and the development of a predictive model for AB. Further, improved understanding of seasonal risk will assist marketers and industry stakeholder be aware of potential risks and can prepare for a challenging season.

Methodology

Study region

The orchard dataset used in this analysis represents commercial navel orange enterprises in the Sunraysia region of Victoria and NSW, the Riverina region of NSW and the Riverland region of South Australia (Figure 1). These regions constitute a major proportion of the inland irrigation-based citrus production area in south-eastern Australia and are among the primary citrus-producing regions nationally.

Orchards included in the packing house dataset are distributed throughout these production zones, which have generally dry climate with hot summers and cool winters. They rely on irrigation from the Murray–Darling river system and harvest is usually from May to August.

The spatial distribution of orchard locations included in the dataset in the Sunraysia, Riverina and Riverland production zones, is shown in Figure 1. A single orchard located near Wee Waa, NSW, is also included (north-east marker).

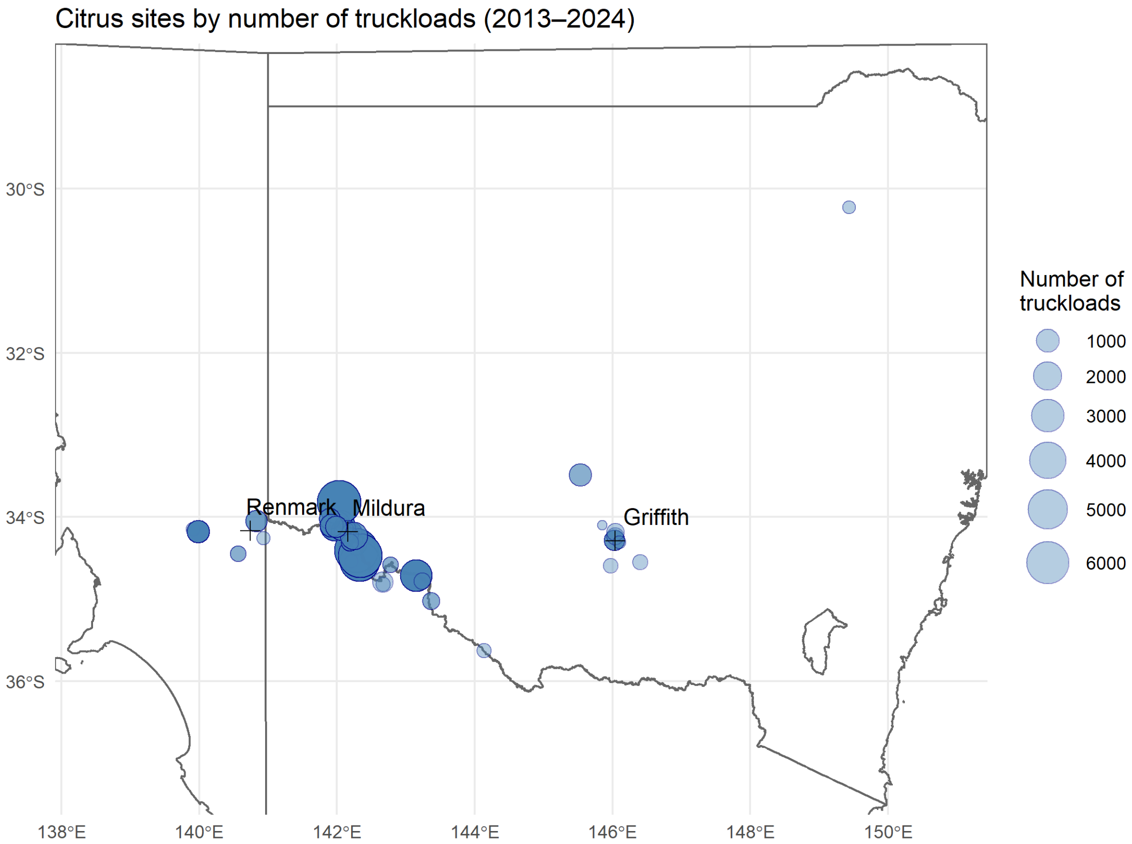

Figure 1. The number of truckloads of navel oranges received at the fruit packing company, and included in the analysed dataset, from each site during the study period (2013–2024) is represented by the size of the blue circles. The larger the circle, the more truckloads originated from that location.

Data sources and assessment of albedo breakdown incidence

Commercial fruit quality inspection records were obtained from a large packing house in Mildura. They contained details of incoming deliveries of navel oranges between the 2013 and 2024 harvest seasons, inclusive, based on routine intake inspections conducted at the packing facility as each load of fruit arrived.

For each delivery at the packing house, fruit quality inspectors sample fruit from a subset of bins on each truck and assess the prevalence of various quality defects in the load. The estimated percentage of fruit affected by the three most prevalent quality issues found in the sampled fruit is then recorded. Where AB was among these dominant defects, the estimated percentage of fruit affected in the truck sample was recorded as the AB incidence. If AB was not among the three most prevalent quality issues, no value for AB incidence was recorded.

The supplied dataset included records from 275 orchards and more than 50,000 truckloads of fruit delivered between 2013 and 2024. The analysis was restricted to the navel variety of oranges.

Records in the packing house dataset were allocated identifiers that distinguished individual orchards so that AB incidence could be analysed on a geographic and, thus, climatic basis.

Climate data and definition of analytical sites

Climate exposure was determined using daily gridded climate data (0.05° resolution, approximately 5-km grid cells) obtained from the SILO data service (https://www.longpaddock.qld.gov.au/silo/). Climate data (Table 1) were extracted for each orchard location for the period of analysis, and monthly climate variables were derived from the daily data. Orchards within the same climate grid cell were grouped into a common analytical site; in this analysis, a site represents a geographic locality corresponding to a single grid cell and can include multiple orchards.

Table 1. The climate variables used in the exploratory and modelling analyses.

Variable	*Units*	*Abbreviation*
Monthly rainfall	mm	Rainfall
Mean daily solar radiation	$MJ/m^2/day$	Solar radiation
Mean daily maximum temperature	°C	Tmax
Mean daily minimum temperature	°C	Tmin
Mean daily average temperature	°C	Tmean
Mean daily relative humidity at the time of maximum temperature	%	RH Tmax
Reference evapotranspiration (tall crop)	mm	Evapotranspiration

Daily rainfall values were summed to calculate monthly rainfall, while daily values of all other variables were averaged to produce mean monthly estimates. Evapotranspiration values for a tall reference crop were selected as they are more suited to the canopy characteristics of citrus orchards than short-crop reference values.

When more than one orchard was in the same SILO grid cell, the same climate data were used for all records in that grid cell.

To align climatic exposure with the developmental timing of navel oranges, two phenological stages were identified:

1. Flowering and fruit set: September to December of the year preceding harvest (the flowering year).
2. Harvest: May to August of the harvest year.

Truck-level estimates of AB were aggregated for each site-year combination by calculating the mean incidence rate for all deliveries received from all orchards within each SILO grid cell, for each harvest year.

The harvest date for each site-year was calculated as the mean day of the year of delivery to the packing facility from each site, averaging all deliveries in a year from all orchards within an individual SILO grid cell.

Exploratory analysis

An exploratory data analysis was undertaken to examine temporal trends in AB and to identify seasons with elevated or very high incidence of AB.

Annual distribution data revealed the incidence of AB was substantially higher (up to 50%) in the 2021–2022 season compared with other years in the 2013–24 study period. The 2021–2022 season was therefore classified as a 'severe' AB year (Figure 2, Results section), in alignment with citrus industry consensus that the 2021–2022 season was particularly severe for AB.

To investigate the specific climatic conditions associated with the study period, climate anomaly timelines for harvest between 2013 and 2024 were constructed. For each harvest year, the monthly climate anomaly at each site was calculated as the number of standard deviations away from the 2013–2024 mean for that calendar month (the 'z-score'). This was done for each month from September to August.

Visual inspection of these anomalies was used to identify weather conditions that were most unusual in the severe 2021–2022 season and to provide context for later statistical screening. November 2021 and May 2022 emerged as the most notable periods for anomalous conditions. Monthly Pearson correlations between site-year mean AB incidence and climate variables were then used as a screening step to identify candidate months and variables for formal model comparison. Finally, harvest timing was studied by comparing the distribution of harvest dates among seasons and by examining the relationship between site-year mean AB incidence and mean harvest date.

Statistical analyses

Potential relationships between AB incidence and climatic conditions were investigated using a two-stage approach combining exploratory analysis and generalised linear mixed-effects modelling (GLMM).

Exploratory Pearson correlation analyses were first used as a screening step to identify months and climate variables with strong and biologically plausible associations with AB. These analyses showed that the strongest relationships were concentrated in November of the flowering year and May of the harvest year. November was therefore used to represent early fruit development, and May to represent late-season conditions near harvest. Candidate variables for both months were rainfall, solar radiation, RH Tmax, and tall-crop evapotranspiration.

Based on this screening, a constrained set of candidate GLMMs was developed. Each model included one November predictor, one May predictor and harvest day-of-year. For each November × May predictor combination, both additive and fully interactive model forms were fitted. All candidate models included random effects for grower and harvest year to account for persistent grower-level differences and broader inter-annual variation not explained by the observed climate variables.

The modelling unit was a site × harvest-year observation, where AB incidence was defined as the mean of all deliveries for a given site and harvest year. As AB incidence is bounded between 0 and 100%, proportions were transformed using the Smithson–Verkuilen method (Smithson and Verkuilen 2006) to avoid boundary effects. Models were fitted with a beta-distributed error structure and a logit link function.

Candidate models were compared using the corrected Akaike Information Criterion (AICc), which balances goodness-of-fit against model complexity for modest sample sizes. Models within ΔAICc less than 2 were considered to have similar support, and the lowest-AICc model with acceptable diagnostics was selected as the primary explanatory model.

All spatial and statistical analyses, modelling and figure production were conducted in R (R Core Team 2026) using the sp, terra, ggplot2 and glmmTMB packages.

Results

Year-to-year variation in albedo breakdown

For most of the 2013–2024 period, orchard- and truck-level incidence remained low, with median rates at or close to zero and only a minor subset of deliveries had more than 5% AB (Figure 2). Although there were many truckloads with zero incidence recorded, these values are obscured in the graph because they are all clustered in one line at 0%. The best way to interpret the graph is to look at the median level of all truckloads each year, represented by the orange line. While focusing on the blue dots shows the spread of truckload with different incidence of AB, it can also be misleading because there could be a high concentration of blue dots at zero. The 2021–2022 harvest season was clearly anomalous, with a sharp increase in both the median and variance of AB in 2021–2022 relative to the rest of the time studied (Figure 2).

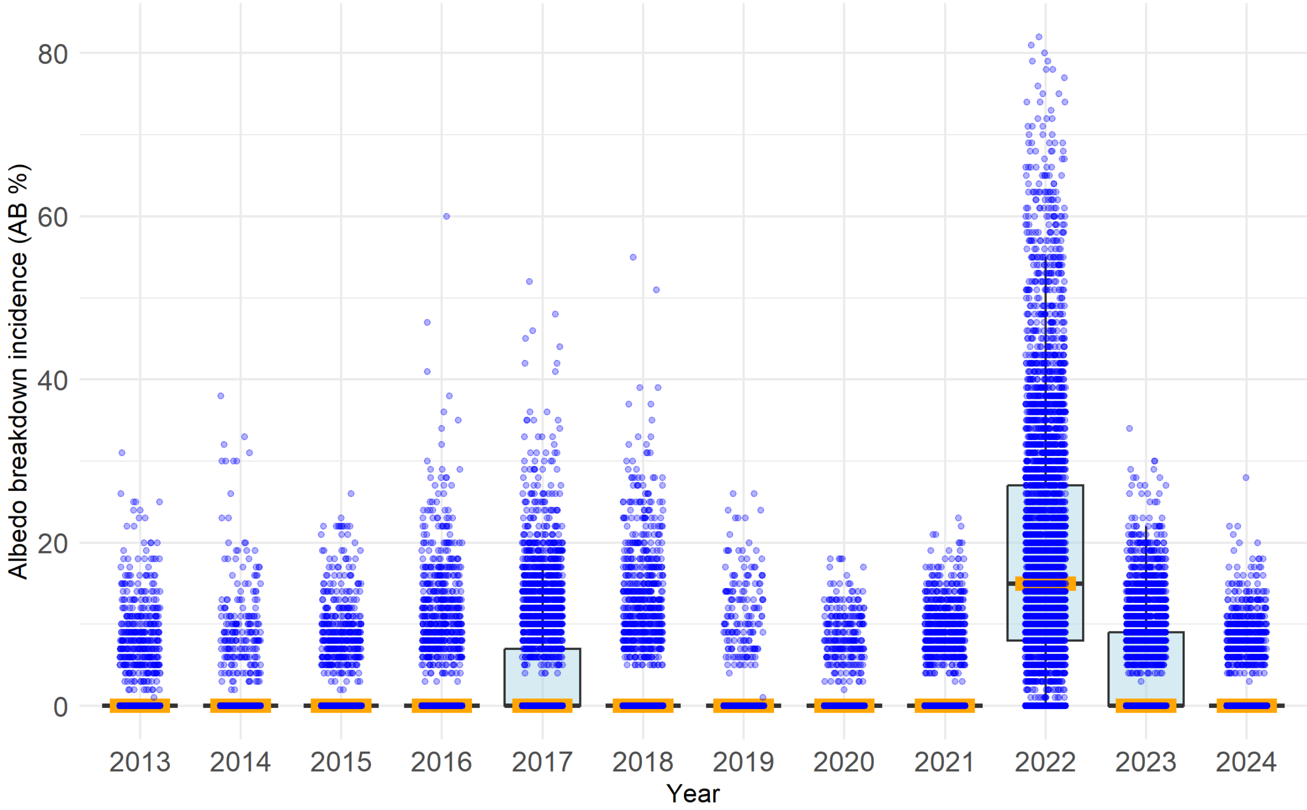

Figure 2. Albedo breakdown incidence in navel oranges by harvest year from 2013 to 2024. Blue points represent individual truckloads delivered to the packing company, orange horizontal lines show the annual median, and pale-green shaded boxes show the 25th and 75th percentiles of each annual distribution.

Spatial distribution of albedo breakdown in the 2021–2022 season

There were no discernible spatial patterns in the distribution of the severity of AB, despite the unusually high incidence in the 2021–2022 season. This means that AB was evident in all regions studied during this year (Figure 3).

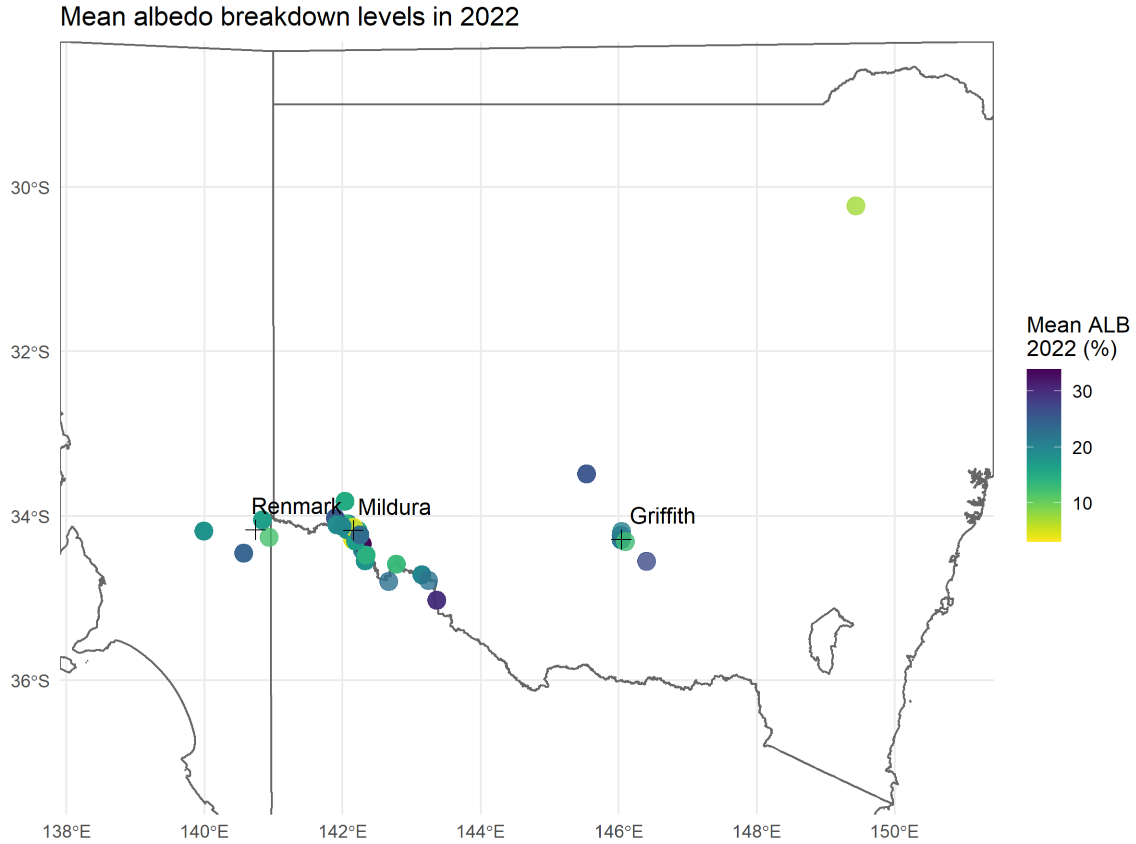

Figure 3. Average albedo breakdown incidence by site in the study region during the 2021–2022 season.

Climatic conditions preceding the 2021–2022 season

The climate anomaly timeline showed that the severe 2021–2022 harvest season was preceded by a distinctive sequence of conditions during both early fruit development and the lead-up to harvest. In November 2021, solar radiation and evapotranspiration were unusually low, while rainfall and humidity-related variables were elevated. In May 2022, rainfall and RH Tmax were high, and evapotranspiration was again low (Figure 4). Together, these anomalies indicate that the severe 2021–2022 season was associated with a broader pattern of low evaporative demand and high moisture at two biologically relevant stages, rather than with a single isolated climatic anomaly.

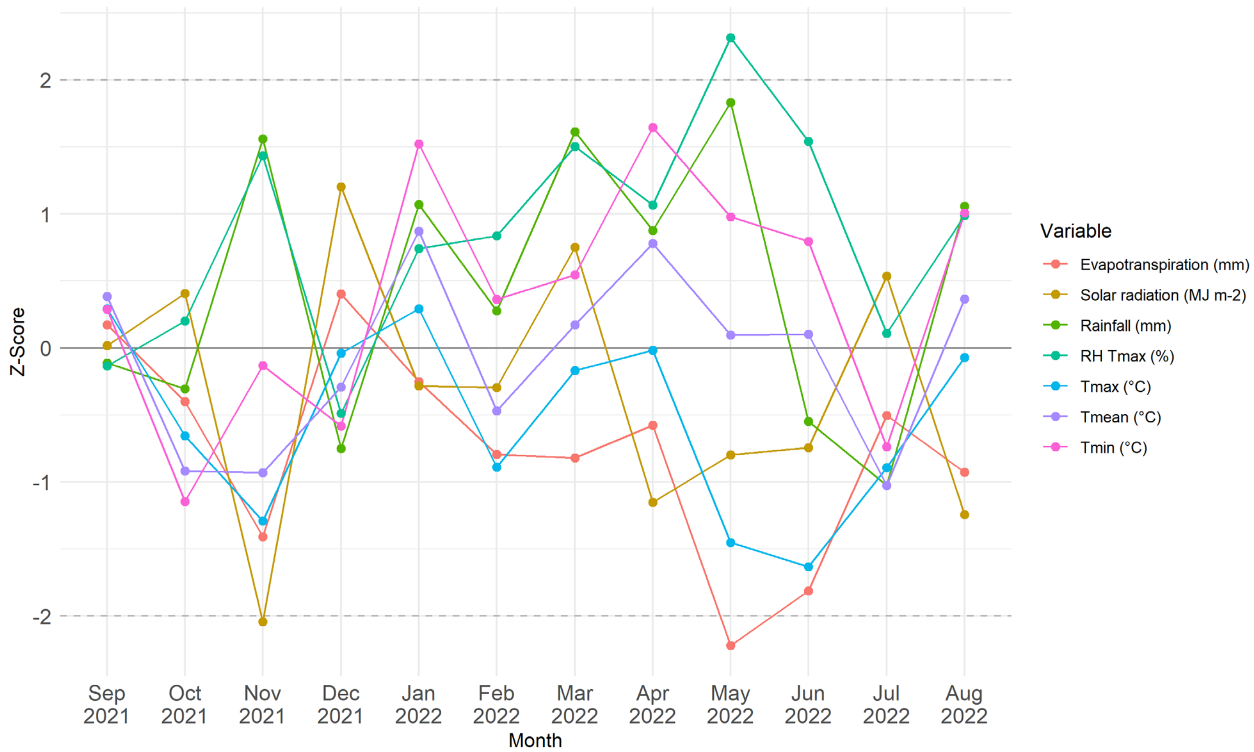

Figure 4. Standardised monthly climate anomalies from September 2021 to August 2022. The z-score on the y-axis shows the deviation from the 2013–2024 mean for each climate variable in each month. Negative values indicate below-average conditions, and positive values indicate above-average conditions. A z-score of 2 is equivalent to a p-value of 0.0455: values outside the 2 to −2 range (dashed lines) are significantly different from the mean for that month.

Relationships between albedo breakdown and monthly climate conditions

The broader month-by-month climate screening showed that the strongest associations between climate and AB were concentrated in November in the flowering year and May in the harvest year.

Mean AB incidence was positively associated with rainfall and RH Tmax, and negatively associated with solar radiation, evapotranspiration and Tmax during the November preceding harvest (Figure 5). November solar radiation was the strongest individual correlation, but the accompanying November rainfall, humidity and evapotranspiration signals indicate a broader low-radiation, high-moisture, low-evaporative-demand environment during early fruit development rather than proof of a radiation-only mechanism.

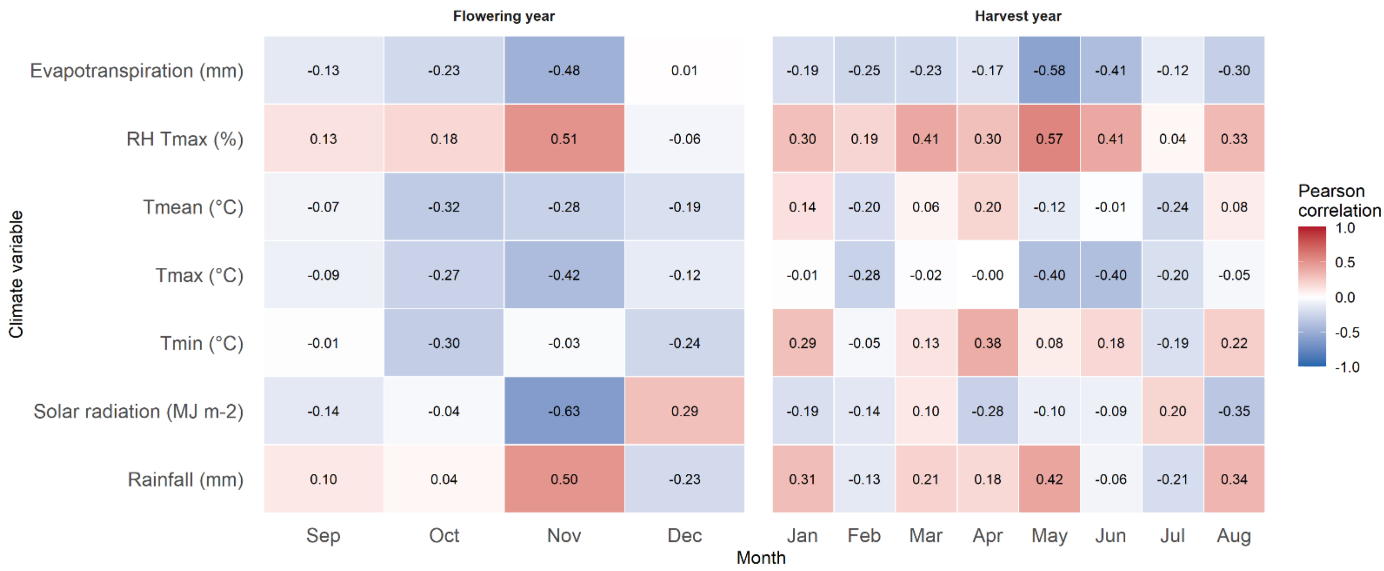

Figure 5. Correlation heatmap showing associations between monthly climate variables and mean albedo breakdown incidence. Numeric values show the Pearson correlation coefficient (r), where positive values indicate that higher values of the climate variable were associated with higher albedo breakdown incidence, and negative values indicate the opposite.

Scatterplots were used to explore the relationships between AB incidence at harvest and climate conditions in the preceding November, scatterplots were generated (Figure 6 and Figure 7). The 2021–2022 observations are clustered at the low-radiation, high-rainfall, high-humidity, and low-evapotranspiration ends of the climatic ranges, and they also occupy the highest AB range in the dataset.

The relationships between AB incidence and weather during the November preceding harvest are shown in Figure 6. AB incidence was negatively associated with mean solar radiation (Figure 7) and evapotranspiration in November and positively associated with rainfall, Tmax and mean RH Tmax (Figure 6).

Although November solar radiation had the highest correlation with AB, other November variables also showed moderate associations. These variables are not independent of each other; rather, they describe a broader weather pattern involving low radiation, higher rainfall, higher humidity and reduced evaporative demand. A similar pattern was evident for the May variables. For this reason, the relationships are best interpreted as evidence of linked seasonal weather conditions associated with AB incidence, rather than as separate effects of individual climate variables.

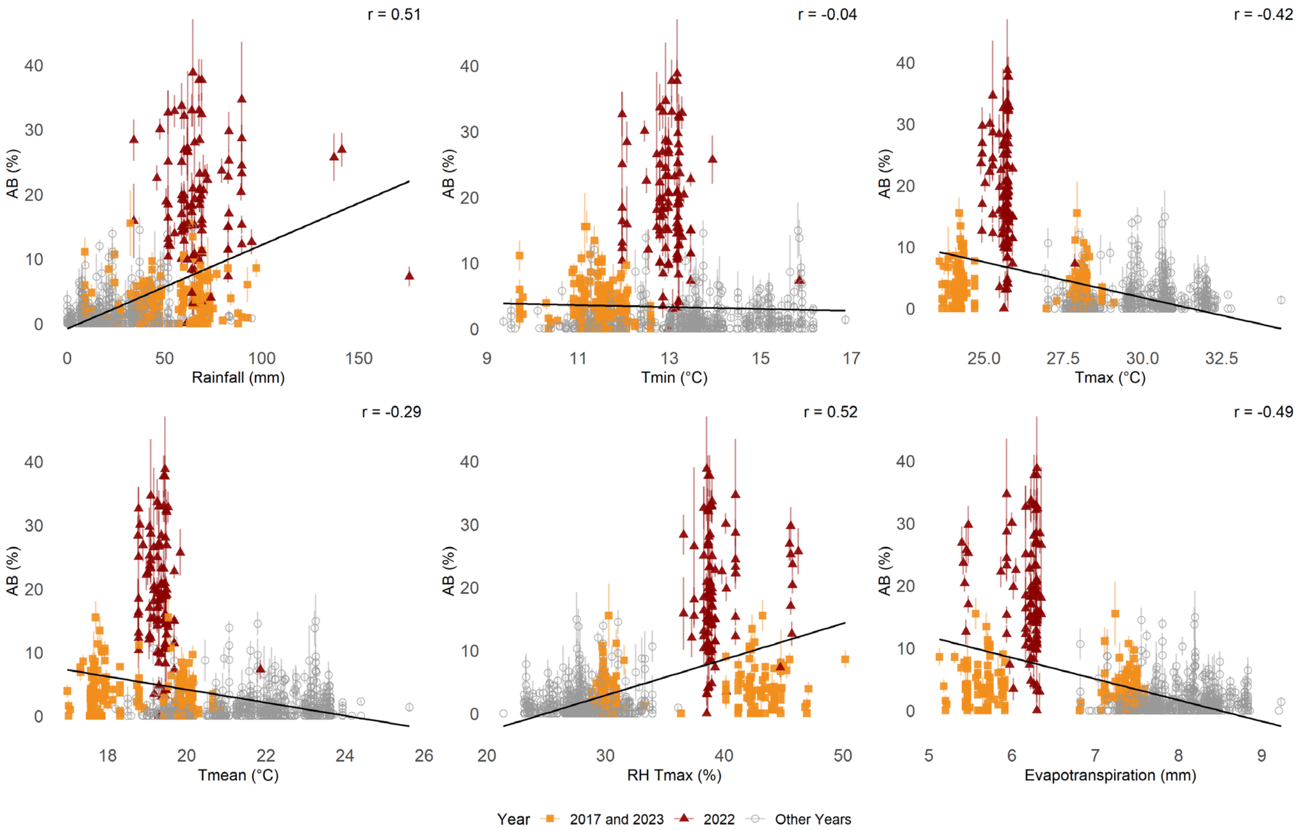

Figure 6. Exploratory relationships between mean climatic conditions during November and albedo breakdown incidence in navel oranges harvested the following year. Each point represents a site-year mean, aggregating deliveries from one or more orchards for a given year. The solid black line shows a simple linear regression fitted for visual screening only. The r values given are Pearson's correlation coefficients.

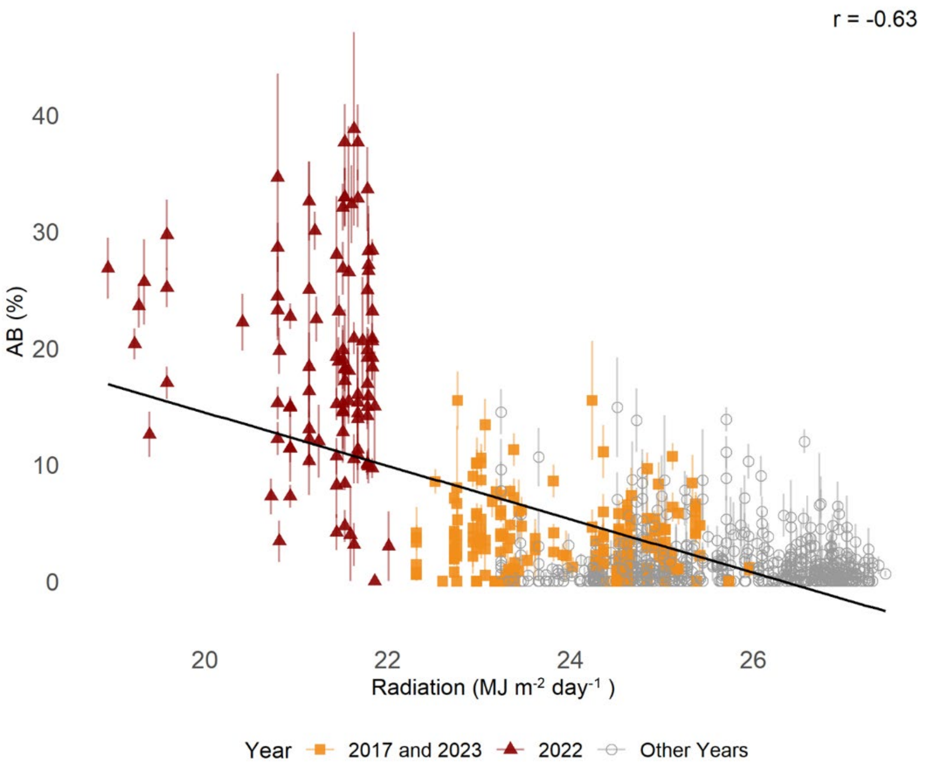

Figure 7. Relationships between mean solar radiation (MJ/m²/day) during November and albedo breakdown (AB) incidence in navel oranges harvested the following year. Each point represents a site-year mean, aggregating deliveries from one or more orchards for a given year. The solid black line shows a simple linear regression fitted for visual screening only. The r value given is the Pearson's correlation coefficient.

Solar radiation in November had the highest correlation (r=0.63; Figure 7). There are three distinct clusters of datapoints. The average daily solar radiation during November 2021 (representing the 2021–2022 season, in red) was less than 22 MJ/m²/day. There was a moderate incidence of AB in 2017 and 2023, and the average daily solar radiation in the preceding November was between 22 and 24 MJ/m²/day. In seasons with low AB, the average daily solar radiation in the preceding November was greater than 24 MJ/m²/day.

Similar relationships were seen between AB incidence and weather during May (Figure 8). AB incidence had positive relationships with rainfall and RH Tmax, and negative relationships with Tmax and evapotranspiration.

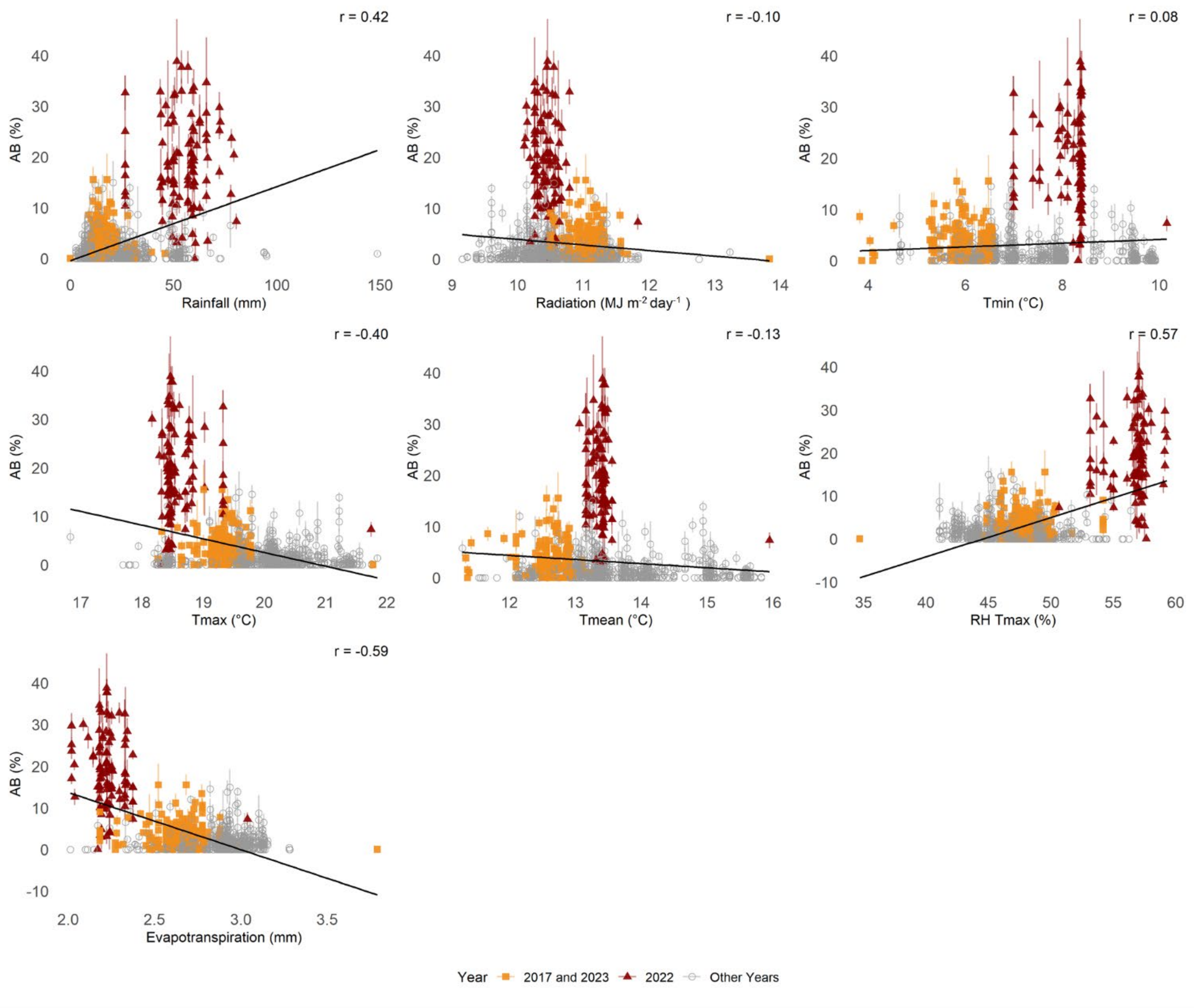

Figure 8. Exploratory relationships between mean climatic conditions during May and albedo breakdown incidence in navel oranges harvested that year. Each point represents a site-year mean, aggregating deliveries from one or more orchards for a given year. The solid black line shows a simple linear regression fitted for visual screening only. The r values given are Pearson's correlation coefficients.

Harvest timing and the incidence of albedo breakdown

Climate conditions were not the only factor associated with AB incidence. Harvest timing also showed a consistent relationship with the disorder. The 2021–2022 season had the second latest median harvest date after 2014–2015 and there were many truckloads delivered late in the harvest season compared with other years (Figure 9).

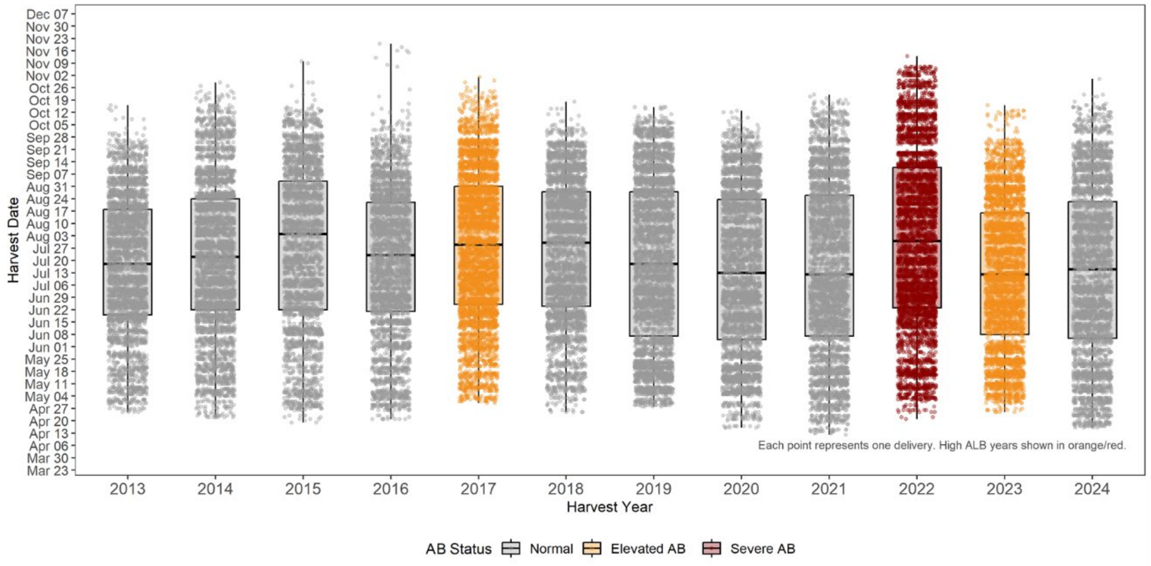

Figure 9. Annual distribution of harvest dates for deliveries arriving at a large packing house in Mildura from 2013 to 2024. Points represent individual truckloads. The black-bordered box shows the interquartile range, the centre line shows the median, and the whiskers show the range.

When site-year data were grouped by seasonal AB category, the relationship between harvest timing and AB differed between normal, elevated and severe seasons (Figure 10). In normal seasons, AB incidence remained low. In elevated and severe seasons, AB incidence was higher and increased more strongly with later harvest, indicating that the effect of harvest timing depends on the broader seasonal context.

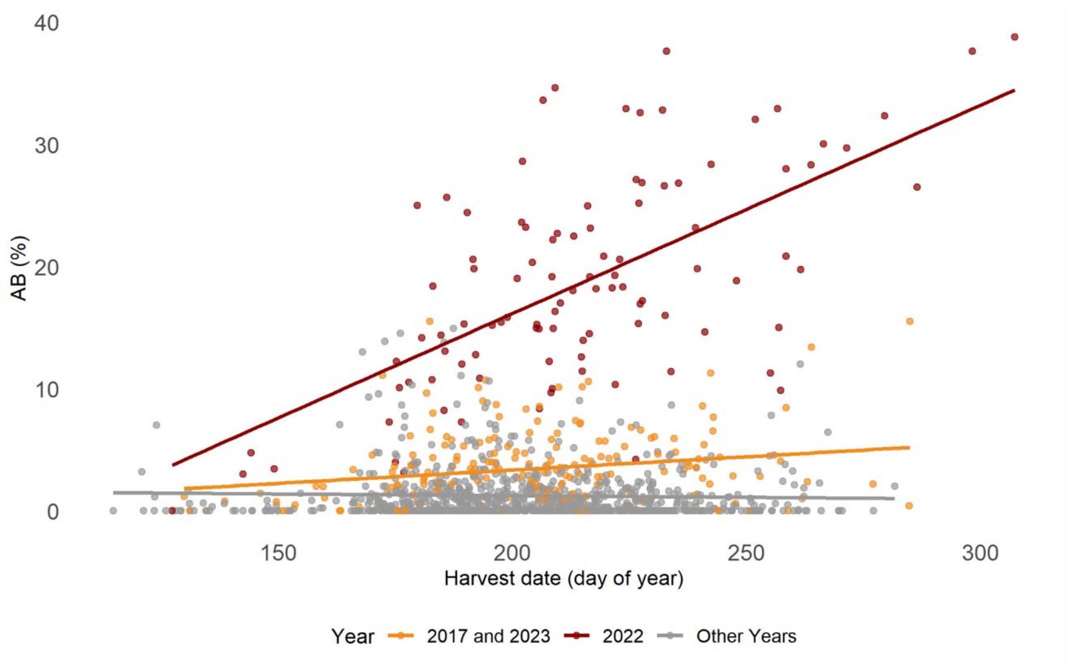

Figure 10. Site-year mean albedo breakdown (AB, %) plotted against mean harvest date (day of year), grouped by seasonal incidence category: normal (grey), elevated (orange) and severe (red). Lines show fitted linear trends for each category, illustrating that the relationship between later harvest and AB incidence was strongest in elevated and severe seasons.

Statistical modelling

As the strongest candidate climate variables were correlated, a constrained GLMM comparison was used rather than selecting a single variable from the correlation heatmap. Thirty-two models were fitted: 16 additive models and 16 fully interactive models. Each model included one November predictor, one May predictor, and harvest day-of-year, with grower and harvest year fitted as random effects.

The six highest-ranked models based on AICc are presented in Table 2. The top-ranked model was the fully interactive model incorporating November evapotranspiration, May RH Tmax, and harvest day-of-year. The next two models, which paired November evapotranspiration with either May rainfall or May evapotranspiration, also had ΔAICc values below 2.

The repeated inclusion of November evapotranspiration among the highest-ranked models suggests that this variable was consistently associated with AB risk, whereas the May predictor was less clearly defined and may reflect a broader late-season humidity, moisture, or water-balance effect. Although the top models differed in AICc support, their observed-predicted R^2 values were very similar, indicating that AICc was distinguishing likelihood support for alternative fixed-effect structures rather than producing large visual differences in observed-predicted agreement.

Table 2. Six top-ranked candidate generalised linear mixed model (GLMMs) for site-year albedo breakdown incidence from the additive and interaction model comparison. AICc is a measure of model fit that accounts for overfitting and sample size.

Rank	Structure	November variable	May variable	AICc	ΔAICc	Weight	Observed-predicted R^2
1	Interaction	Evapotranspiration	RH Tmax	-6978.02	0.00	0.40	0.847
2	Interaction	Evapotranspiration	Rainfall	-6976.97	1.05	0.24	0.848
3	Interaction	Evapotranspiration	Evapotranspiration	-6976.70	1.32	0.21	0.848
4	Interaction	Evapotranspiration	Solar radiation	-6974.21	3.81	0.06	0.849
5	Interaction	RH Tmax	Solar radiation	-6973.22	4.80	0.04	0.848
6	Interaction	RH Tmax	RH Tmax	-6972.54	5.48	0.03	0.847

Following the exploratory screening and candidate-model comparison, the selected GLMM was the fully interactive model containing November evapotranspiration, May RH Tmax and harvest day-of-year as fixed effects, together with grower and harvest-year random effects (RE). This selected model retained the key biological structure suggested by the exploratory analysis by combining an early-season evaporative-demand signal, a late-season moisture signal and harvest timing within a single explanatory framework.

The selected GLMM included November evapotranspiration (ET_Nov), May relative humidity at the time of maximum temperature (RH_May), and mean harvest day-of-year (H), together with all two-way and three-way interactions among these predictors:

$$\text{logit}(y^*) =$$
$$\beta_0 + \beta_1\, ET\_Nov + \beta_2\, RH\_May + \beta_3\, H + \beta_4\, (ET\_Nov \times RH\_May) +$$
$$\beta_5\, (ET\_Nov \times H) + \beta_6\, (RH\_May \times H) + \beta_7\, (ET\_Nov \times RH\_May \times H) + u\_grower + v\_year$$

Here, β_0–β_7 are fixed-effect regression coefficients. ET_Nov, RH_May and H are standardised predictors. The terms u_grower and v_year are random effects for grower and harvest year, respectively.

To show the contribution of different model components, four prediction settings were compared: fixed effects only (FX), fixed effects plus the grower random effect, fixed effects plus the harvest-year random effect, and the full model including both random effects (Figure 11).

The FX-only model captured the general range but under-predicted higher-incidence observations (panel R^2 = 0.57). Adding the grower RE substantially improved point-level agreement (R^2 = 0.73), indicating that persistent grower-level differences contributed to baseline variation in AB incidence. Adding the year RE produced a similar, slightly larger improvement (R^2 = 0.75), indicating that shared season-wide effects were also important. The full model combined both random effects and provided the best overall agreement (R^2 = 0.85), showing that both grower-level differences and broader year-to-year changes contributed to model performance. Residual spread around the 1:1 line remained largest in the 2021–2022 season, indicating that some variation associated with extreme AB expression remained unexplained.

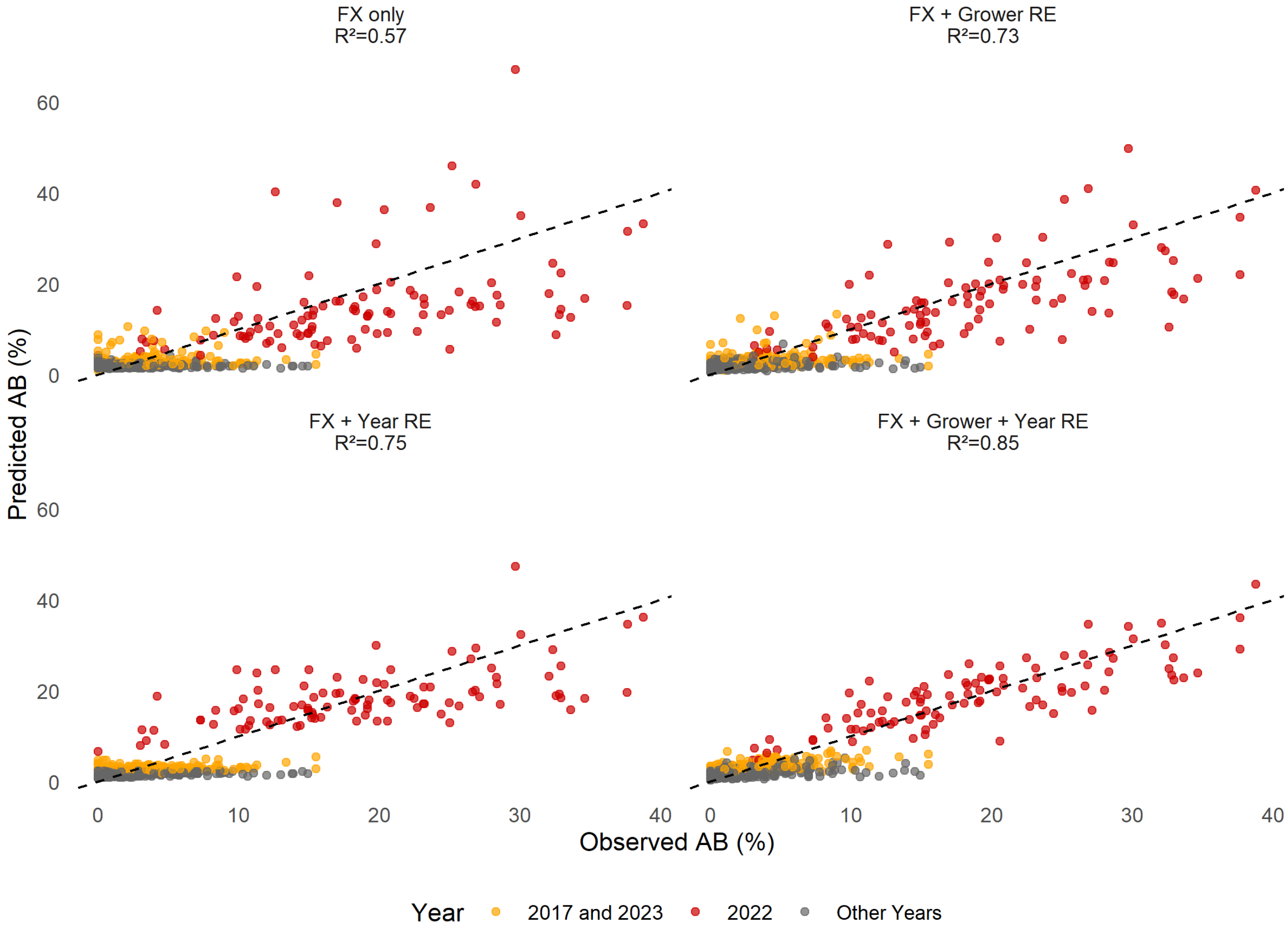

Figure 11. Observed versus predicted albedo breakdown (AB, %) under four model settings: fixed effects only (FX), FX plus grower random effect, FX plus harvest-year random effect, and the full model including both random effects. Each point represents a site in a single harvest year and is coloured according to the year from which that record was drawn. Points closer to the 1:1 line (dashed line) indicate better agreement between observed and predicted AB incidence.

The fixed-effects-only model captured the broad observed–predicted relationship but showed substantial scatter around the 1:1 line, with some observations markedly over- or under-predicted. Adding either the grower or year random effect reduced the most obvious over-predictions and improved overall agreement, indicating that both persistent grower-level differences and shared year-to-year effects contributed to prediction error. Combining both random effects in the full model further improved agreement with the 1:1 line and reduced both over-prediction and under-prediction in the observed AB range.

The annual mean observed AB incidence with predictions from the selected GLMM under different prediction settings are shown in Figure 12. The FX-only model captured the broad temporal pattern but showed both over- and under-prediction in specific years, including over-prediction in some low-incidence seasons and under-prediction of the severe 2021–2022 season peak. The grower random effect adjusted some site-level differences but did not fully resolve the annual discrepancies. The year random effect more closely followed the observed annual pattern, particularly the increase in 2021–2022 and subsequent decline. The full model, combining both random effects, provided the closest agreement with the observed annual means, indicating that the selected climate predictors captured part of the seasonal signal while additional year-wide influences remained important.

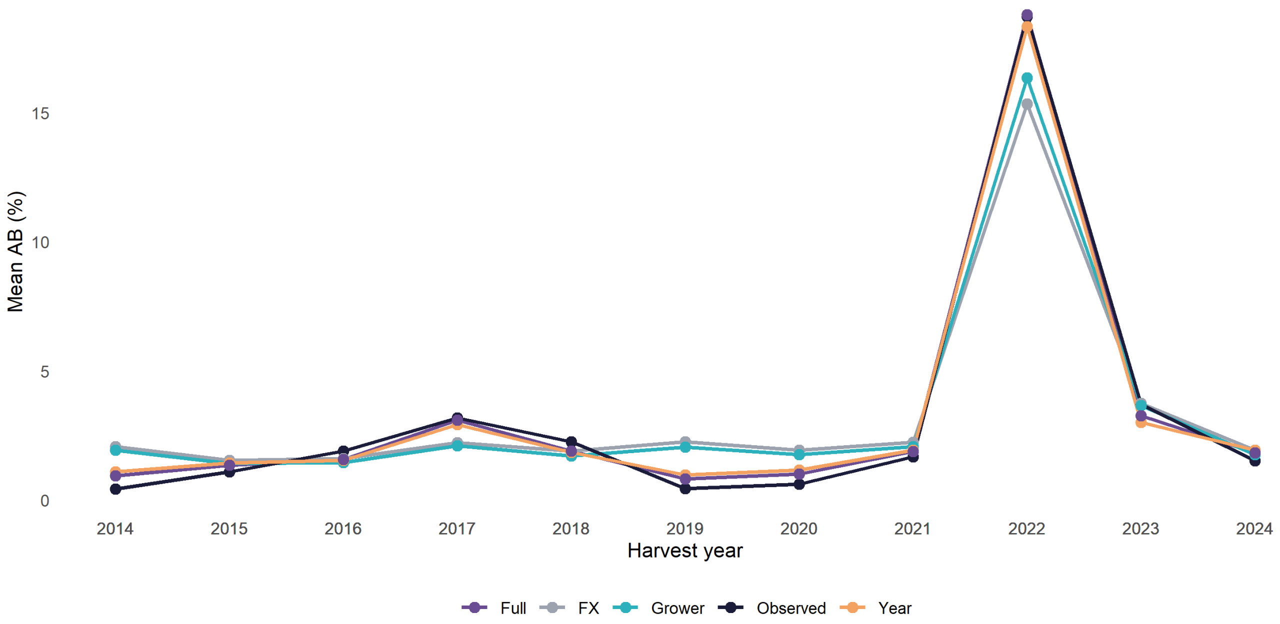

Figure 12. Mean observed annual albedo breakdown (AB) incidence (black) compared with mean predictions from GLMMs incorporating fixed effects only (FX, grey), grower random effects (grower, blue), year random effects (year, orange), and both fixed and random effects (full, purple).

Overall, the modelling results indicate that year-to-year changes in AB incidence were better explained by an interaction between early-season climate conditions in November, late-season climate conditions in May, and harvest timing than by any single climate variable in isolation. The harvest-year random effect improved performance in seasons with unusually high incidence, showing that some broader seasonal influences were not fully resolved by the measured fixed predictors.

Discussion

Albedo breakdown incidence varied from year to year in the study region, but the 2021–2022 season had a substantially greater incidence than the other years studied (2013–2024). Compared with the generally low incidence seen in most years, there was a higher median incidence and a broader spread of site-level incidence in the 2021–2022 season.

The strongest climatic associations were concentrated in November of the flowering year, May of the harvest year, and harvest timing, identified in the Results. Taken together, these findings indicate that AB expression is influenced by a sequence of interacting factors rather than a single climatic driver.

In November, the strongest positive associations were with rainfall and relative humidity, and the strongest negative associations were with solar radiation, evapotranspiration and maximum temperature. November solar radiation was the clearest single-variable correlate of AB (Figure 7), however, this should be interpreted as part of a broader low-radiation, high-moisture, low-evaporative-demand environment during early fruit development, rather than as a radiation-only effect. This supports the interpretation that early-season conditions (November) act to predispose fruit to AB, while later conditions influence the extent to which this susceptibility is expressed.

Evapotranspiration is an indicator that represents transpiration through the tree. Based on a hypothesis that AB is related to a lack of transpiration moving calcium into the rind of the fruit, it would be expected that evapotranspiration would have the highest correlation, especially as solar radiation strongly influences evapotranspiration (Allen et al. 1998). It is possible that the FAO56 equation might underestimate evapotranspiration in times of very low solar radiation (cloudy days), thereby reducing the evapotranspiration difference between cloudy and sunny days and weakening the observed relationship between evapotranspiration and AB. This would reduce the evapotranspiration estimate difference between cloudy and sunny days, introducing bias into any potential relationship between AB and evapotranspiration. Unpublished sap flow data measured by NSW DPIRD at Sunraysia, NSW, shows that sap flow often decreases more in relative terms than evapotranspiration predicted by the FAO56 equation. Field experiments could include sap flow measurements to explore this potential anomaly. It is also possible that the reason that solar radiation had a higher correlation than evapotranspiration is because of the effect of sunlight directly shining onto the fruit. The direct sunlight could affect the physiological growth of the rind, or the rind might transpire more than a leaf when in direct sunlight. These alternative or complementary mechanisms reinforce that solar radiation is likely to act as part of a broader environmental signal rather than as an isolated driver. All of these and other possible interrelationships can be further explored with field validation experimental work. As only one severe AB season was available in the dataset, these relationships should be interpreted as preliminary and hypothesis-generating rather than as a validated operational forecasting rule.

Late-season conditions in May, together with harvest day-of-year, also contributed to yearly variation in AB incidence. In the exploratory analysis, rainfall and RH Tmax were positively associated with AB, while evapotranspiration and Tmax were negatively associated. In the candidate-model comparison, these late-season variables were interpreted as alternative descriptions of a higher moisture and evaporative-demand environment close to harvest. This is consistent with the interpretation that late-season conditions influence the expression of AB, rather than the underlying susceptibility. This supports the view that AB is associated with a sequence of conditions during fruit development and maturation rather than with a single isolated circumstance at one stage.

The structural observations reported by Storey and Treeby (1994) suggest that in fruit affected by AB, fracture paths in the albedo developed predominantly from adjacent cells separating rather than the cleavage of individual cells. They suggested that changes in the cohesion of adjoining cells at the middle lamella predisposed fruit to AB. They also observed some degree of cell separation in unaffected fruit, but apparently not to the extent required to initiate fracture formation. This suggests the disorder might depend not simply on the presence or absence of cell separation, but on the degree to which tissue cohesion has been reduced.

As such, the structural integrity of the albedo could be affected during cell expansion, before visible symptoms of AB appear.

Storey and Treeby (1994) also examined the epicuticular wax layer and reported no apparent differences between affected and unaffected fruit in wax morphology on the shaded side of the rind. Their results, therefore, tended to discount a simple surface wax explanation for AB and instead placed greater emphasis on the rind's internal structure. This is important, as it supports the interpretation that the climatic variables identified in this study operate through internal physiological processes rather than direct surface effects only**.**

A physiological basis for linking such developmental conditions to rind structure is provided by Story and Treeby (2000). Calcium transport to developing navel orange fruitlets was found to be directly related to fruitlet transpiration and to the development of functional stomata. Calcium transport in the xylem, along with its timing and rate of delivery, is likely to be important in determining later rind properties (Story and Treeby 2000). The present study did not measure calcium directly, but the low radiation, high moisture and reduced evaporative demand during November are consistent with conditions that could reduce transpiration to the developing fruit. This provides a biologically plausible pathway linking early-season conditions to later AB susceptibility. These observations do not prove that altered calcium delivery occurred in the 2021–2022 season, but they do suggest the weather conditions in November are physiologically plausible as a predisposing influence.

A second, distinct period of climatic association was during May of the harvest year, immediately preceding harvest. AB incidence was positively associated with rainfall and relative humidity, and negatively associated with evapotranspiration and maximum temperature. Given that rind development is largely complete by May, conditions during this month are likely to influence the expression of susceptibility that developed earlier. Thus, a plausible mechanism underlying the observed correlations is that weather during November defines the conditions under which rind tissues become predisposed to later breakdown, while weather during May creates conditions under which that predisposition is more likely to become visible.

One hypothesis is that rainfall in May alters whole-tree and fruit water balance, resulting in faster or greater swelling and/or contraction of whole fruit or parts of the fruit. This could place mechanical stress on the albedo, increasing the likelihood that predisposed adjacent cell walls separate, giving rise to fractures and subsequent AB symptomology. The role of harvest timing can be interpreted in a similar way. Later harvest was associated with higher AB incidence, and the relationship between harvest day-of-year and AB was strong in the 2021–2022 and 2022–2023 seasons. These data suggest that later harvest extends the period during which symptoms might become apparent. In Treeby's (2001) report, the appearance of AB symptoms was thought to increase the longer the fruit stays on the tree.

The selected GLMM structure included all two-way and three-way interactions among November evapotranspiration, May relative humidity, and harvest day-of-year. This indicates that the effect of one variable depends on the state of the others. Thus, the influence of late-season moisture conditions is unlikely to be constant during all levels of developmental exposure in November, and a later harvest is unlikely to have the same implications in all seasons. The grouped harvest-date analysis (Results section, Figure 9) is consistent with this, because the slope relating harvest timing to AB was weak in most years but steeper in the 2021–2022 and 2022–2023 seasons. This supports the idea that harvest timing modifies the expression of AB within a broader seasonal climate context.

The random effects also accounted for a substantial portion of the variation in the full model. Both grower-level and harvest-year random effects improved observed–predicted agreement, indicating that AB expression was influenced by persistent differences among growers or orchards, as well as broader year-to-year seasonal effects. The harvest-year effect suggests that some shared seasonal influences remained unresolved by the measured monthly climate predictors, particularly in severe or elevated AB years. However, the grower-level effect indicates that orchards or growers differed in baseline susceptibility even after accounting for selected climate variables and harvest timing. Identifying specific management differences associated with reduced AB incidence would be a useful avenue for further research.

This result is important because it suggests that AB risk is not solely determined by region-wide seasonal anomalies. Earlier experimental work showed that factors such as rootstock, rind mineral composition and irrigation management can influence AB incidence under experimental conditions (Treeby 2001). The present model is consistent with that view: broader seasonal conditions might determine whether AB risk is widely expressed, while orchard-level factors might influence the baseline susceptibility and severity of expression. This leaves open the possibility that orchard-level management could reduce susceptibility or moderate AB expression, even in years with high regional weather-related risk.

There are several aspects of the dataset that limit our ability to identify and model statistical correlations between climate and AB incidence. AB was recorded only by the quality officer at one large fruit packing company when it was among the three main defects listed for a delivery, which creates a lower detection threshold during low-incidence seasons. This is visible in Figure 2 as a gap where few deliveries are recorded with AB incidence values below 5%. Additionally, there could be under-representation of extreme AB values above 70%, as entire truckloads of severely affected fruit were sent directly to the juicing factory and did not present at the packing house for grading first. Finally, the climatic analyses were based on site-year monthly values, which are appropriate for identifying seasonal biological signals over a broad region but do not resolve short-term weather sequences or within-orchard microclimatic effects.

Overall, the data suggest a developmental interpretation of AB incidence, in which the climatic environment during rind formation influences the structural integrity of the albedo and predisposition to AB, while conditions during late maturation influence the extent to which this susceptibility is expressed. These interpretations are consistent with the statistical modelling, which indicates that these factors act interactively rather than independently within a broader seasonal context.

Specifically:

- early-season conditions (November) influence rind structural integrity and the predisposition to AB, associated with low solar radiation, higher humidity, and reduced evaporative demand during early fruit development
- late-season conditions (May) influence the expression of this susceptibility, associated with higher moisture, rainfall, humidity, and reduced evaporative demand close to harvest
- harvest timing influences the extent of expression, with later harvest extending the period during which symptoms can develop

These factors act sequentially and interactively, providing a coherent explanation for the observed year-to-year variation in AB incidence in the study region. There are a number of opportunities to conduct research to validate and develop the model and explore new control options. This includes field fruit shade netting experiments, strategic application of calcium sprays to negate/minimise the predisposition associated with unfavourable November weather and improving industry data collection. These opportunities are discussed in more detail in the recommendations section.

Outputs

Table 3. Output summary

Output	Description	Detail
Project article *Australian Citrus News* (Figure 12)	An article to introduce the project to the industry.	The article described the aims of the project, inviting growers and packers to participate by submitting feedback. An online survey was prepared and promoted in the article for readers to respond, but only a few responses were received.
Updated albedo breakdown research summary	The albedo breakdown research summary, originally written by John Golding, has been updated.	The summary has been updated by revising sections and adding a summary table of the content.
Project poster and both at the 2026 CAL Citrus Congress	A booth was hired at the 2026 CAL Citrus Congress, and the albedo poster was featured at the booth.	The poster summarised the results of the albedo breakdown project.

SURVEY

Learning more about albedo breakdown

A new citrus research and development levy-funded project could eventually help growers predict the likelihood of a high albedo breakdown year.

Albedo breakdown has caused significant impact over recent seasons

Led by the New South Wales Department of Primary Industries and Regional Development (NSW DPIRD), the Albedo Breakdown Prediction (CT23003) project will initially focus on understanding more about the cause of albedo breakdown.

"We know that albedo breakdown caused significant marketing problems and eroded citrus producer returns in the 2022 harvest," said project leader and NSW DPIRD citrus development officer, Steven Falivene.

"We also know that reducing albedo breakdown would help everyone in the industry.

"What we don't know for certain is what causes it."

Mr Falivene said one theory on the cause of albedo breakdown is cloudy, cool weather during the cell division stage – November to early December for mandarins and navels – results in reduced tree-water uptake.

"Because calcium and other important nutrients move up the tree with water, the theory is less water movement means less calcium and nutrient movement into the tree and fruit, triggering albedo breakdown," Mr Falivene said.

"If an association between albedo breakdown and weather conditions is found, it might be possible to use this information to predict the risk of an upcoming high albedo breakdown year as part of future work."

The initial phase of the project will centre on data collection. The project team will visit citrus growers and packhouses to map incidences of albedo breakdown over the past 20 years.

"Obviously, we will not be able to visit every Australian producer or packhouse that has experienced albedo breakdown, but we've set up a system to capture as much data as possible," Mr Falivene said.

"If you can remember years and blocks where albedo breakdown was significantly above normal levels, or if you have seen any other interesting observations – like a block that always has low albedo breakdown, or a practice that seems to be associated with a lower incidence – we encourage you to complete our online survey (link and QR code provided at conclusion of this article)."

James Lawson, David Allingham and Jane Kelley from NSW DPIRD's Climate Vulnerability Assessment team will work alongside Mr Falivene on the project.

They will use historical climate data to see if there is a link between high amounts of albedo breakdown and the climate at that time.

The project team will be assisted by Michael Treeby, who has a long involvement in citrus research and development with the CSIRO and NSW DPIRD. Mr Treeby will provide technical guidance during the data analysis stage.

Mahmud Kare, a citrus research officer with NSW DPIRD, will work with Mr Falivene to strengthen the scientific rigour of the project.

"We're looking forward to working with industry members to learn more about albedo breakdown, then using this knowledge to develop better ways of managing it," Mr Falivene said.

For any further information or comments, contact Steven Mr Falivene on 0427 208 611 or email steven.falivene@dpi.nsw.gov.au

The Albedo Breakdown Prediction (CT23003) is delivered by the New South Wales Department of Primary Industries and Regional Development. It is funded by the national citrus research and development levy together with contributions from the Australian Government. Levies from Australian citrus growers are managed by Hort Innovation.

NSW Department of Primary Industries and Regional Development

Hort Innovation CITRUS FUND

TAKE THE SURVEY

We want to hear about your experiences and ideas with albedo breakdown. Scan the QR code to take this short online survey to share your experience or visit via the link;

https://tinyurl.com/albedoBreakdownSurveyWebpage

Figure 12. 2024 Issue 3 *Australian Citrus News* (ACN) article

Figure 13. Booth and albedo poster at the Citrus Australia Citrus Congress 2026.

Outcomes

Table 4. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
A preliminary understanding of how weather conditions are associated with albedo breakdown (AB).	This is aligned to the Citrus 2024–26 Strategic Plan OUTCOME 1: Protect the production base (Protect the production base to maintain local and	The project contributed to a pathway to reduce the incidence of AB that will help Australia's consistent supply of high-quality fruit to local and international	The project produced a preliminary explanatory model for AB risk and identified candidate climate-risk indicators concentrated in November, May and

	international competitiveness and viability of supply).	markets and improve Australia's international competitiveness.	harvest timing. These findings provide a defensible framework for future validation rather than a confirmed threshold-based prediction rule.
Improved knowledge and understanding of historical albedo breakdown incidence.		The project identified a relationship between AB and historical climate.	The relationship between AB and historical climate is described in the final report.
Improved knowledge of climatic factors contributing to albedo breakdown.		The report identified a relationship between November solar radiation and AB. With further experimental validation work this could be developed into a tool.	The climatic factors that can contribute to AB are described in the final report.
Industry is informed about the relationships and level of correlation between climate and albedo breakdown incidence.		Communication outputs were delivered to industry and growers about the project and its findings.	An article in the ACN, Australian Citrus Congress 2026 poster and another article in the ACN at the acceptance of the project report.

Monitoring and evaluation

Table 5. Key evaluation questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
The project description and results are communicated to the industry through *Australian Citrus News* (ACN) articles. The end of the project article will provide all results, an improved understanding and recommendations.	The outcomes were communicated at the CAL Citrus Congress 2026. When the report has been approved and accepted, the summary will be provided to ACN to co-write an article on the findings.	There is an opportunity to validate this work and provide the industry with a robust AB predictive model and tool.
To what extent has the project improved knowledge on the key climatic causes of albedo breakdown?	Since the project identified an association between albedo breakdown (AB) and November solar radiation ,and somewhat to evapotranspiration, this leads us to believe it is associated with the uptake of calcium related to transpiration. This hypothesis can be confirmed with further field experimentation as suggested in the recommendations of this report.	No continuous improvement ideas, other than confirming how this project was flexible enough to understand that there was a possibility of a nil response and was split into two sections with a stop/go milestone.
Has the project identified a relationship between climatic factors and albedo breakdown?	The project has identified a relationship between climatic factors and AB as explained in the report.	No continuous improvement ideas, other than confirming the great value of bringing together the two important skills of modelling and agronomy to make this project successful.
Has the project engaged with industry stakeholders through the project and provided updates?	The project engaged with packing houses during the project and updated them with the progress. An article was written in the Australian Citrus News (ACN), and a poster was delivered at the Australian citrus Congress 2026. A follow-up article (based on the project summary) will be submitted to the ACN once the report is accepted by Hort innovation.	It is good to communicate with industry and this project had an appropriate level of communication for the particular circumstances of the project. Sometimes too much communication can undermine the purpose of industry engagement by conducting repetitive meetings that have no meaningful purpose Communication should be informed through a communications/extension plan that is also adaptive, rather than milestone criteria, to meet the needs of end-users of the research.

Has the project recommended an appropriate adoption pathway for an albedo breakdown model should a relationship be found between climatic factors and AB incidence?	The project has provided recommendations on a pathway to validate the findings so that an industry tool can be developed.	It is important to take a stepwise approach in research rather than trying to predict too far in the future that commits ideas and research to a possible inappropriate pathway. A good project plan allows research to be fluid and allows evidence and new ideas to guide next steps.

Recommendations

Data limitations and knowledge gaps were identified in this project. Recommendations for further research include:

- Improving industry monitoring and recording of albedo breakdown.
- Field experiments to validate the associations found herein.
- Field experiments to identify control measures for AB.

Only a limited dataset with one incidence of severe AB was available from all the major citrus growing regions for this project. Regardless, promising associations between climatic conditions and the incidence of AB were found. There is confidence in these associations; however, the exact parameters are unknown because there were no other instances of similar weather conditions for sufficient periods to be included in the analysis, thus the associations need to be confirmed (for example, the window of high risk could be narrower or wider). Also, a method that could further explore other associations needs to be investigated.

The influential weather conditions could be tested directly through targeted field experiments. For example, temporary shade or bagging treatments during the November albedo cell expansion period could be used to test whether reduced light and evaporative demand increase AB incidence. Where feasible, complementary treatments that modify moisture conditions or calcium supply would help determine whether the broader plant–atmosphere water-relation signal identified in this study can be manipulated to reduce risk.

Advances in automated grading machinery offer an opportunity to improve the measurement of AB expression. With appropriate calibration, grading systems could potentially detect AB more sensitively and consistently than current intake records. They could quantify the severity of individual fruit rather than estimate the proportion of a load. This would enable more detailed analysis of the relationship between developmental conditions, severity of expression, and within-delivery variability.

Complementary laboratory-based approaches, such as scanning electron microscopy of albedo tissue from fruit exposed to a strongly contrasting developmental light environment, could also be used to assess whether structural differences consistent with altered cell cohesion are present before visible symptom expression. In parallel, continued intake data from the packing house would allow the GLMM to be updated and tested in new seasons, providing an opportunity to assess the reliability of the model. Finally, extending the analysis to other production regions, such as in Western Australia, would provide an important test of whether the same relationships apply outside the current study region, or whether region-specific parameters dominate AB expression.

If AB can be induced experimentally under controlled developmental conditions, this would create an opportunity to test products and management interventions more reliably. Such experiments could help determine whether calcium treatments, harvest-timing adjustments, or other management approaches reduce AB expression under high-risk climate contexts. Other fruit development stages could also be investigated to test whether additional periods of climatic sensitivity occur.

Modern packing house quality-assessment machines are not designed to store AB data. Once a piece of fruit is photographed and assessed for blemishes and defects, including AB, it is given a fruit quality grade. After the grade is allocated, all the blemish and defect data are deleted. To store these data would require databases that are perhaps beyond the capacity of the average packing house. To help industry improve AB prediction and management, there is an opportunity to work with packing line manufacturers to reconfigure machines so that AB data can be recorded consistently and without requiring significant infrastructure expense, such as isolating and summarising AB from other defects. These data can be easily used to improve AB research and management, but the work will require new firmware updates and reporting programming for each machine. This will require significant work by the manufacturer in coordination with the research team.

Finally, if a well-validated fully predictive model of AB can be developed by incorporating all of the research discussed above, such a model could enable the prediction of AB incidence for upcoming seasons based on weather predictions.

Refereed scientific publications

None to report.

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Intellectual property

No project IP or commercialisation to report

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