Is organic weed control beneficial for winegrape production in the Limestone Coast?

FINAL REPORT FOR INCUBATOR PROJECT

Project number: **UA1901**

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Abstract

This trial was conducted to better understand how non-standard weed management practices (such as mulching, compost with mulch and mechanical weeding) compare to undervine herbicide application in Padthaway, South Australia. Across the 2020, vintage soil physicochemical properties, leaf blade nutrient composition, plant available nitrogen and yields were quantified. Results showed that immediate changes in canopy size (leaf area) were detectable, berry juice pH was significantly lower, titratable acidity and yeast assimilable nitrogen significantly higher for the mulch and compost treatment than for other treatments. These effects might be explained by significant increases in soil and leaf nitrogen or phosphorous, or significant differences in soil moisture.

Executive Summary

Key Findings: In a single season, changes to berry chemistry and soil nutrient properties were achieved via the addition of mulch and compost. Mechanical weed control shows no significant advantages or disadvantages over traditional herbicide use based on this trial.

The use of herbicide in the undervine area of a vineyard to control the growth of competitive species is widespread. In recent years the use of mechanical weed control or mulching, with or without the addition of compost, has become increasingly popular. However, impacts on soil health and vine physiology associated with these new management practices are largely unknown and are dependent on many factors. This trial was designed to take in data from many facets of the vineyard to better understand how mulching and mechanical weed control (light surface tillage) might affect vine performance, and ultimately help determine whether these practices might be feasible for growers in the Padthaway region to adopt.

Two sites in Padthaway were chosen; one growing cabernet sauvignon (Site A), the other growing shiraz (Site B). Intensive data collection was carried out at Site A, while exclusively harvest and berry chemistry data were collected at Site B. The intensive data collection at Site A included soil physicochemical analysis, leaf blade analysis, soil moistures, plant available nitrogen, leaf area index as well as harvest and berry chemistry data. These data were collected at two time points; florescence (mid-November 2019) and pre-harvest (early March 2020).

Undervine weed cover was most effectively reduced by the mulch treatments, with mechanical weeding (light tillage) proving the least effective, but these differences were not significant by the end of the season. This means that if control of undervine competition is a viticulturalist’s high priority, any of the options trialled here are feasible solutions, though they may have differing effects on the vine’s nutrition and berry quality.

No significant differences in yield were detected at either Site A or Site B, however given the low yields across every South Australian region in 2020, effects may occur in future seasons.

Berry chemistry was influenced significantly by the treatments at Site B (though not at Site A). Titratable acidity (TA) and yeast assimilable nitrogen (YAN) were highest, and pH was lowest for the mulch and compost treatment. Low nutrient levels in the sandier soil at this site may help explain these differences, but soil data was not collected at Site B. In surface soils at Site A, moisture content was significantly higher for the mulch treatment, though this effect was not observable at the harvest timepoint.

Preliminary results from this trial were disseminated in early January 2020 at a field day. High levels of interest were shown by viticulturalists of the limestone coast wine region. To provide the complete data set and results to these groups, a presentation will be made during an upcoming meeting of the Limestone Coast Grape and Wine Council. Another field day may also be beneficial.

To summarise, the trialled undervine weed control measures are all effective at reducing weed coverage, however differing effects were observed in the vines over this season. Changes of note were the large differences present in berry juice quality for the shiraz cultivar when treated with mulch and compost. Further study is recommended to determine the persistence and long-term impacts of these treatments.

This research trial was carried out by staff from The University of Adelaide over the 2020 vintage, and gained substantial economic advantage through their other work for Wine Australia; exploring the effect of undervine cover crops on grape performance.

Background

To maximise the productivity of grapevines, undervine weed and soil management is of vital importance. With growers realising the detrimental effects of herbicide usage on soil quality over sustained periods of time, mulching is becoming increasingly popular. Excessive competition for water and nutrients is the primary reason for removal of weeds in the undervine surface of a vineyard. The most popular method for this is undoubtably herbicide application. Tillage of the soil is also a popular method, by which the surface soil is mechanically lifted and turned, however there is substantial evidence that this is detrimental to soil health. Increasingly tight regulation around herbicides and even the banning of their use in several wine regions globally has initiated the search for effective and economically viable weed control measures in viticulture. Simultaneously, wine markets have experienced growth in the organic and sustainable market, providing an economic incentive for growers to move away from herbicides.

It is widely accepted that herbicides (Zaller et al. 2014) and tillage (Congreves et al. 2015) are detrimental to soil health which is important on many levels. At a microscopic scale, soil bacteria and fungi provide ecosystem services that are beneficial to the grape vines and grape grower alike via the recruitment of beneficial soil microbes that may defend against pathogens (Berg et al. 2017, Berendsen et al. 2012). On a human level, grape and wine consumers are taking an increasing interest in the social benefits that might be provided by the wine producers; willing to spend more on wines they feel are environmentally friendly and less damaging to the soil (Alonso González & Parga-Dans 2020).

This project was initiated by growers in the limestone coast wine region, hoping to better understand how non-traditional viticultural practices might work in their area, given the local soil and climatic conditions.

In this project we tested three undervine weed control measures and compared them against each other as well as a traditional herbicide regime. These methods were:

- Straw mulch
- Straw mulch and compost (underneath)
- Mechanical weeder (light tillage of surface)

Mulch

Within a number of viticultural regions of South Australia, including the Barossa, the Riverland and Langhorne Creek, the use of undervine mulches has been shown to be cost neutral or negative over three growing seasons, while providing excellent suppression of weeds (Penfold 2003). Penfold also showed that undervine mulching had neutral or beneficial impact on yield, though this was site specific. The economic viability of mulch applications are dependent on herbicide price, mulch price and availability, labour costs, yield effects and market pricing of grapes (Nordblom et al. 2017). These factors change yearly and thus growers require confidence in the viticultural outcomes a new management approach before changing practices. While research has been previously carried out on the effectiveness of straw mulch in south Australian vineyards, no trials occurred in Padthaway, and little trial data is available on composts or mechanical weeding.

Compost

Compost is the biodegraded remnants of organic biomass and (for viticulture) is often sourced from municipal waste or wineries. The addition of compost to agricultural soils is beneficial in many ways; nutrients are added and continue to break down over time, carbon in the soil increases, it also provides nutrients and habitat for microbes (Tejada et al. 2009), as well as providing the social benefit of recycling waste.

Research conducted at the University of Adelaide by Nguyen et al. (2013) on merlot vines, found that application of compost, with mulch on top, lead to higher nitrogen and phosphorous in leaves, higher yields and berry size, and did not reduce berry quality.

Mechanical weed control

An alternative to herbicides or mulch application for weed control, mechanical methods have lagged technologically. Targeted weeding that works effectively under vine in the presence of drippers, wire and without high labour costs has been elusive until recent years. New weeders, such as the Fischers roller hoe and finger weeders (used in this trial) have been designed specifically for this purpose and provide an accessible alternative to standard weed control measures. Previous research in California has shown that undervine mowing and cultivation can produce varying results on soil moisture and weed composition (Steenwerth et al. 2016).

The overarching aim of the project is to determine the practical feasibility of the use of mechanical weeding, mulching or mulched compost as weed control measures, and quantify their effects on the physiological performance of the vines.

Project Aims

	Output	Target Date	Activities
a	Field sites identified	31/8/2019	Meet with grower and regional contact to finalise project design, responsibilities, and management requirements. Identify mulch and compost supplier. Determine exact field site location and design experimental layout.
b	Field site established. Infrastructure installed	31/8/2019	Spread mulch, compost and mix at each treatment plot. Spray herbicide control. Install soil moisture profile access tubes.
c	Primary data collected.	31/11/2019	Collect early season data on the following parameters; Weed coverage, leaf blade elemental composition, soil physicochemistry, plant available nitrogen, leaf area index, soil moisture profiles.
d	Late season data collected	1/4/2020	Collect and analyse late season data on the following parameters; Weed coverage, leaf blade elemental composition, soil physicochemistry, plant available nitrogen, leaf area index, soil moisture profiles.
e	Treatments harvested for end of season data collection.	1/4/2020	Hire pickers to pick treatments and collect data on; bunch number, vine yield. Count berries and carry out juice analysis.
f	Final Report	30/06/2020	Present written and verbal report of project findings and implications to Regional Partner Submit final report to Wine Australia

Methods

Site design

Using a randomised complete block design (Figure 3), each treatment was applied across nine vines per row will be replicated three times. This was carried out at two sites at Padthaway in the Limestone Coast region, in vineyards with shiraz or cabernet sauvignon grapevines. Treatments included;

- Herbicide (traditional method) – Two applications. Late September (Alliance ~4lt/ha & Goal 0.075ml/ha) and mid-December (Basta ~4lt/ha).
- Mechanical weed control (Fischers roller hoe and finger weeders) – Two uses. Late September and mid-December.
- Straw mulch (AKA “mulch”) – One application; 55 tonnes per hectare
- Straw mulch with compost layered beneath (AKA “mulch and compost”) – One application; 55 tonnes per hectare of straw with 10 tonnes per hectare layered underneath.

Figure 1: Undervine weeder implementing “Mechanical weed control” treatment.

Figure 2: A; straw mulch applied at 50 tonnes per hectare. B: Compost spread directly undervine before mulching.

Sites were selected based on access, consistency and variety. Approximate GPS coordinates of the sites were;

Site A: -36.661, 140.526

Site B: -36.628, 140.527

At Site "A", the primary site (cabernet sauvignon cultivar), data was collected at two time points throughout the season; florescence (19th November 2019) and pre-harvest (10th March 2020). Data was collected on the following parameters:

- Weed coverage
- Leaf blade composition
- Soil physicochemistry
- Plant available nitrogen
- Leaf area index
- Soil moisture profiles
- Juice chemistry analysis

At both sites, yield components were measured on a per metre basis. Data was then analysed using the statistical packages available in R.

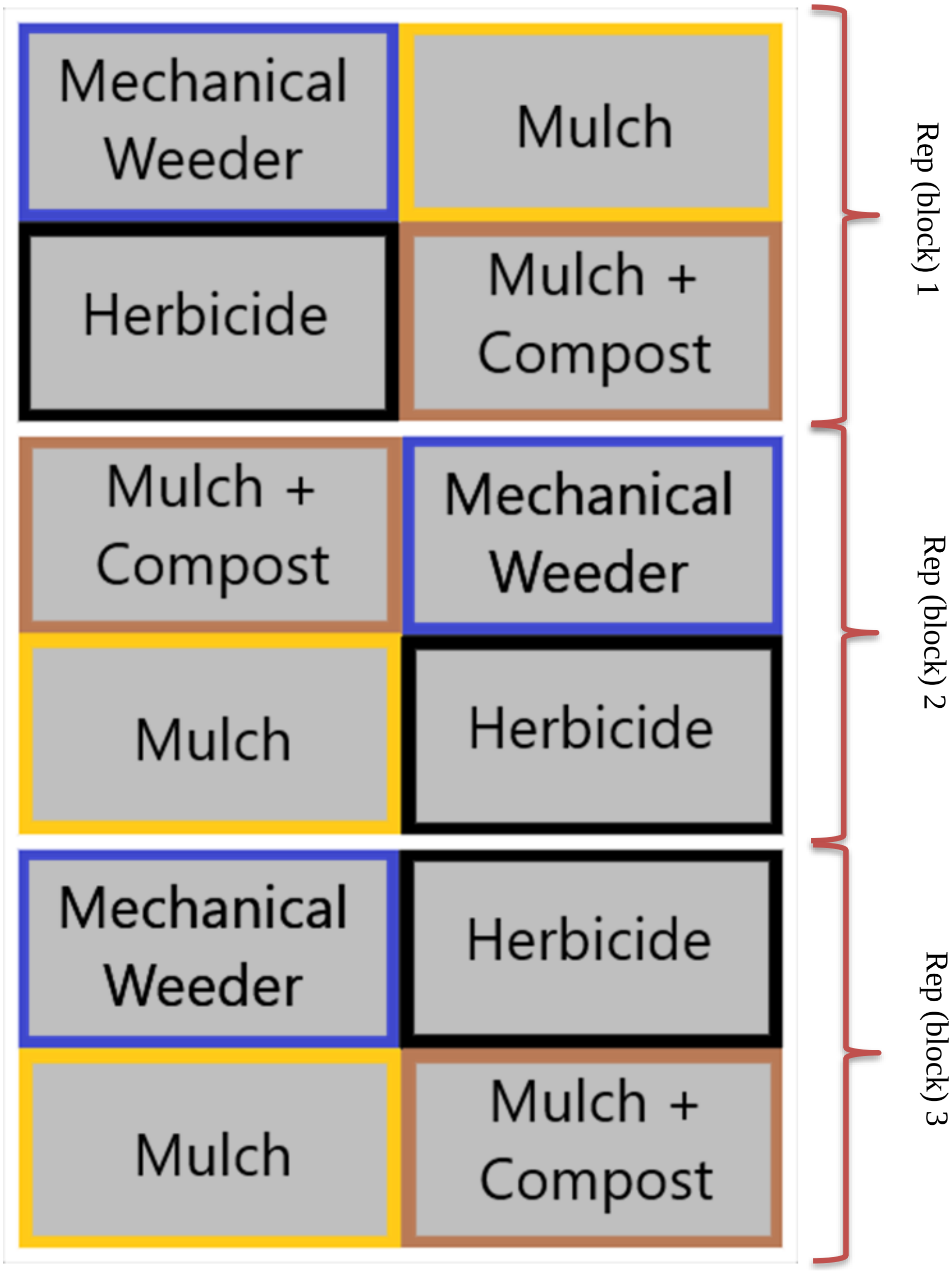

Figure 3: Randomised complete block design (RCBD) used at site A. Each rectangle represents at least nine vines along a row, to which the specified treatment was applied.

Weed coverage

Ground cover by weeds was estimated via the use of the smart phone application "Canopeo" (Patrignani & Ochsner 2015), which utilises the device's hardware to collect and analyse image data and provide a percentage cover value. The app was used in accordance with the instructions which can be found at canopeoapp.com. At three points throughout each plot, the Canopeo app was used to measure weed ground cover. This was averaged to provide a value of weed ground cover for that block (replicate).

Plant available nitrogen

Three cores to a depth of 10 cm were taken per plot and homogenised in a bag. Approximately five grams of this soil was weighed and mixed with 25 ml of 2 M potassium chloride (KCl) for extraction of plant available nitrogen (nitrate and ammonium). Extractions were shaken at 150 rpm for 60 minutes before being centrifuged at 3000 g for five minutes and samples of the supernatant removed for freezing. A larger sample of the same soil (approx. 20g) was weighed and dried at 105 deg C for 48 hrs to determine gravimetric water content of the soil. Concentrations of NO_3^- (nitrate) and NH_4^+ (ammonium) were quantified colorimetrically as described by Miranda et al. (2001) and Forster (1995) respectively.

Soil physicochemistry

At each plot three cores to 10 cm were taken and homogenised. These samples were air dried, sub sampled and delivered to Australian Precision Agriculture Laboratory (APAL) for analysis (https://www.apal.com.au/SoilTesting.aspx).

The following soil analytes were quantified;

Table 1: Soil physicochemical properties quantified by APAL using samples from Site A (Cabernet Sauvignon).

pH 1:5 water (pH units)	pH $CaCl_2$ (pH units)	Colwell Phosphorus (mg/kg)	Ca:Mg Ratio
K:Mg Ratio	ECR	CEC (cmol/kg)	Calcium (%)
Magnesium (%)	Potassium (%)	Sodium (%)	Salinity EC 1:5 (dS/m)
Iron (Fe) (mg/kg)	Manganese (Mn) (mg/kg)	Copper (Cu) (mg/kg)	Zinc (Zn) (mg/kg)
Dumas Total Nitrogen (%)	Dumas Total Carbon (%)		

Leaf blade composition

Two leaf blades were taken from three vines per plot. Petioles were removed and the leaves dried in an over at 40 degrees for at least 24 hours. Samples were then cooled in sealed bags containing hydroscopic silica gel before being transported to Australian Precision Ag Laboratory (APAL) for analysis (https://www.apal.com.au/PlantTesting.aspx)

Concentrations of the following elements were quantified;

Table 2: Leaf blade elemental nutrients quantified by APAL using samples from Site A (Cabernet Sauvignon)

Aluminium (mg/kg)	Boron (mg/kg)	Calcium (%)
Chloride (%)	Copper (mg/kg)	Cobalt (mg/kg)
Iron (mg/kg)	Magnesium (%)	Manganese (mg/kg)
Molybdenum (mg/kg)	Nitrogen (%)	Phosphorous (%)
Potassium (%)	Sodium (%)	Sulphur (%)
Zinc (mg/kg)		

Leaf area index

Leaf area index and T (ratio of transmitted to incident photoactive radiation [PAR]) were measured at the start of the season to quantify differences in canopy size. The AccuPar ceptometer was used at the November time point, and the viti-canopy app (De Bei et al. 2016) was used at the March time point (due to lack of access to the ceptometer).

Pruning weights

At the end of the season, after all leaves had dropped, pruning weights were taken from Site A. Two metres per plot were pruned to simulate barrel pruning (which is what will be and has been applied to all other vines in the past) and thus avoid pruning effects in later years of the trial, should they continue. Canes were counted and weighed.

Soil moisture profiles

Soil moisture profiles were taken using the odyssey capacitance probe (see Figure 4) at 200 mm intervals down to 1000 mm. Capacitance probes work by measuring the di-electric constant of the soil, which changes with water content. To enable this, one access tube was installed within 300 mm of a vine and dripper in each plot, however due to underlying limestone, most probes were unable to be installed at that depth. Measurements were taken successfully at the November time point, however at the March time point, it was found that machinery had removed the caps of the access tubes. Recent rain had then wetted the tubes making data collection impossible. To address this issue, soil surface moisture contents were measured as part of the plant available nitrogen analysis and will be presented in the absence of this data.

Figure 4: Example of a capacitance probe inserted into access tube to a depth of one metre.

Harvest data collection

When decided by the vineyard managers, grapes were harvested from both sites A and B. Three vines were picked per plot and the number of bunches were counted. Total yield of the three vines was weighed. Two bags of at least 1.5 kgs were randomly assembled from each plot; one for berry chemistry analysis, and the other for bunch weights and berry counts. Four bunches were weighed, and a total of 100 berries (25 per bunch) were also counted and weighed.

Berry chemistry analysis

Berry samples were submitted to the Australian Wine Research Institute (AWRI) for red wine analysis. The following metrics were quantified;

Table 3: Red wine metrics quantified by the AWRI using grapes from both sites A and B

Alpha Amino Nitrogen (mg/L)	Titratable acid pH 7.0 (g/L)
Ammonia (mg/L)	Titratable acid pH 8.2 (g/L)
Brix (°Brix)	Total phenolics (a.u./g)
Free Anthocyanins (mg/g)	Total tannin (mg/g)
pH	Yeast assimilable nitrogen (mg/L)

Departure from original application

No changes were made to the original application, however, as mentioned in the methods section, due to the operation of vineyard machinery in the area, the caps of some of the soil moisture access tubes had been detached, and the tubes had filled with water. This has never occurred in our other trials at other sites and was not anticipated. To overcome this issue, soil surface gravimetric water content was measured for the second “pre-harvest” timepoint. In future the fitted caps will be further reinforced.

Results and Discussion

Data are presented below in a number of formats. Box plots, such as that in Figure 6 below represent a visual summary of the data. The average (mean) of the data is represented by the central horizontal line, while the boxes either side represent the upper and lower quartiles. The whiskers either side of the boxes represent the maximum and minimum values of the data.

A second type of plot is also presented, such as that in Figure 5. These plots are the result of running a statistical analysis of the data. The central dot represents the mean, while the 'whiskers' either side represent 95 % confidence intervals (a measure of the variation of the data). These figures contain letters that define whether differences between the treatments were statistically significant. Box plots were also created for this data and can be accessed online via request.

Weed coverage

One of the primary aims of this project was to determine how different undervine management practices influence weed cover in the vineyard. As can be seen in Figure 5, the mechanical weed control treatment resulted in the highest level of weed cover, with a mean of close to 10%. This was significantly higher than the herbicide and mulch treatments.

The mulch treatments proved extremely effective at reducing weed presence, bringing the weed cover close to zero.

As the season progressed and water became more limiting, weed coverage decreased for the herbicide treatment, became increasingly variable for the mechanical weeder and did not change from close to zero for the mulch treatments (Figure 6). No differences were apparent when comparing the mulch and the mulch and compost treatments, despite the increased nutrient load being supplied by the compost. This suggests that mulch is an effective weed suppressant which will not be compromised by the presence of compost if applied directly below the mulch. It should also be noted that the operation of the mechanical weeder required some level of experience in its operation, and it is likely that later in the season the weeder was more effective.

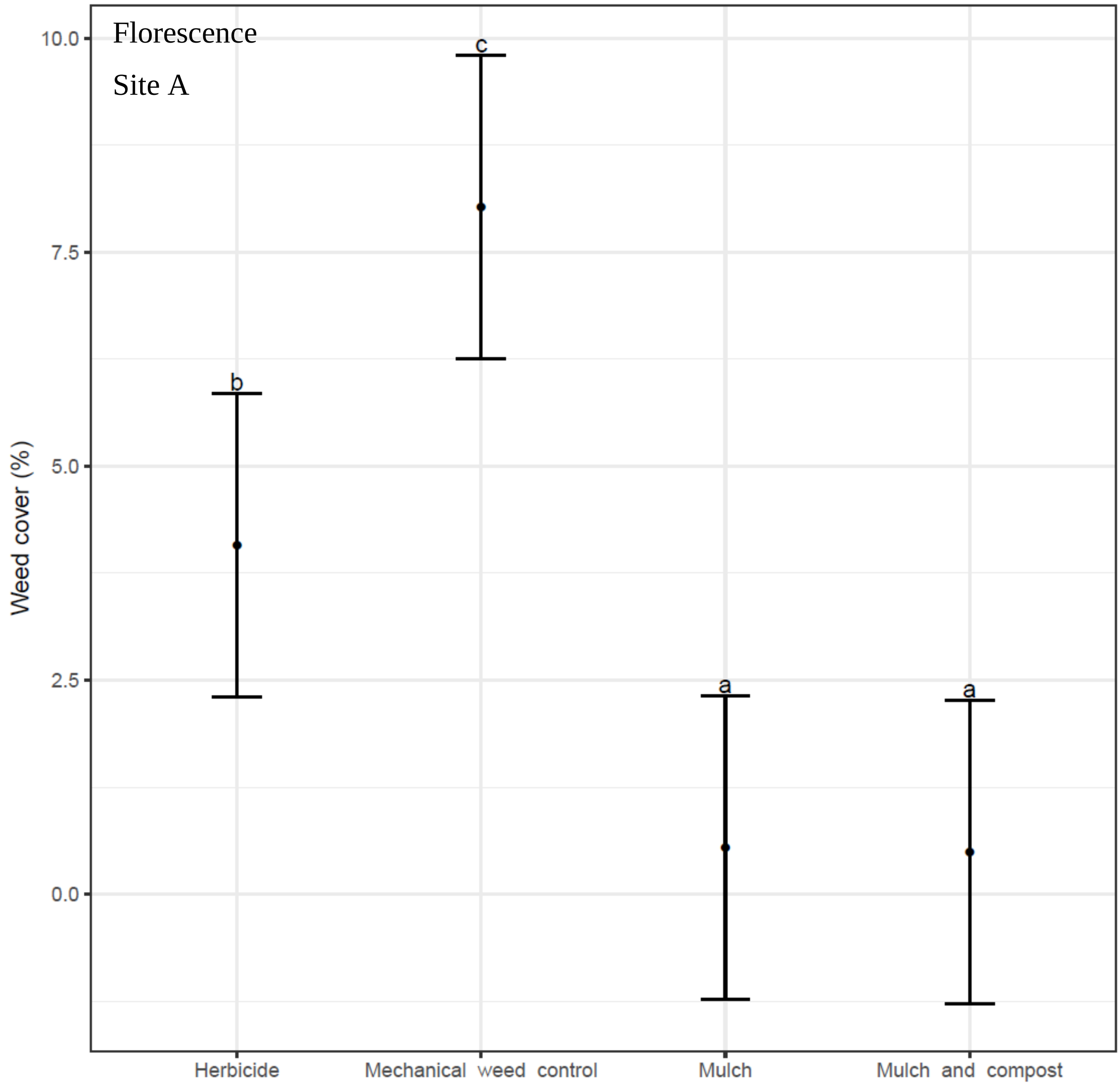

Figure 5: Weed cover statistical output from florescence measurements using the Canopeo app. Letters define significance based on two-way anova (p<0.05). Error bars are 95 % confidence intervals.

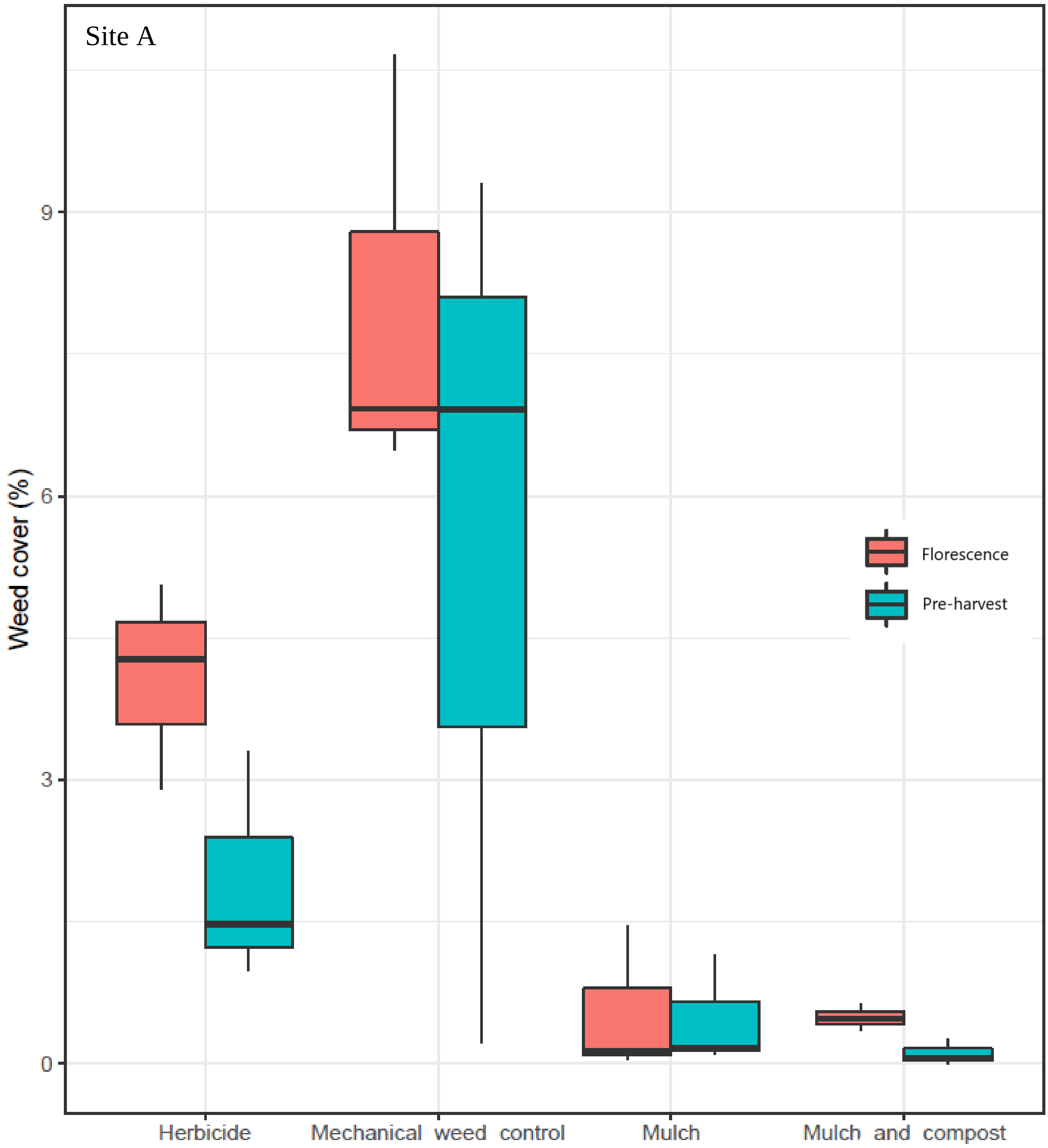

Figure 6: Weed coverage (%) boxplots at florescence (November 2019) and pre-harvest (March 2020) timepoints.

Harvest

The secondary aim of the project was to determine the influence of the undervine treatments on yield. Statistical analysis of the data revealed no significant effects of any treatment at either Site A (Figure 7) or B (Figure 8). Yield per metre was slightly higher on average at Site B than Site A.

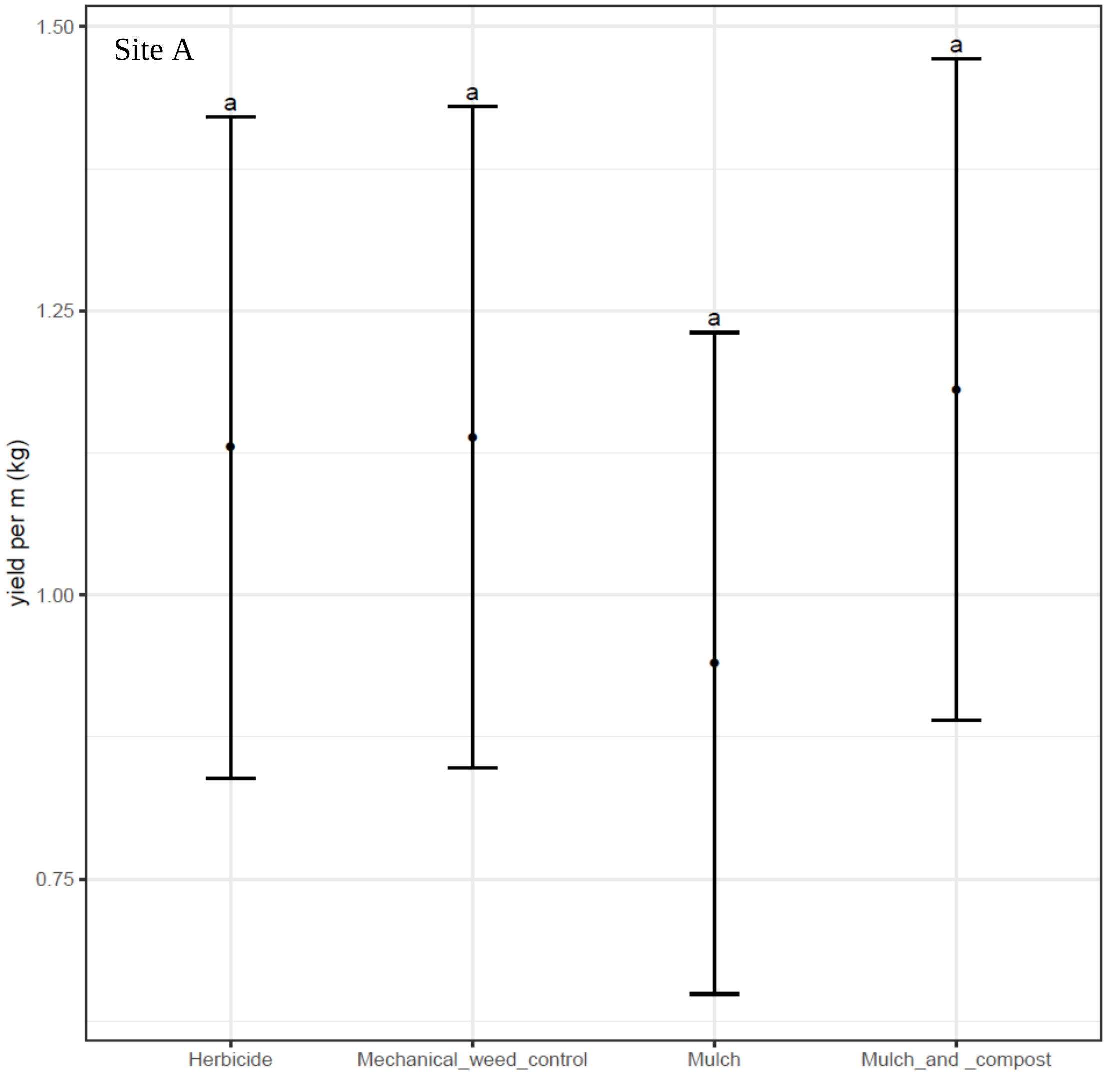

Figure 7: Yield calculated on a per metre basis from Site A (Cabernet Sauvignon). Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

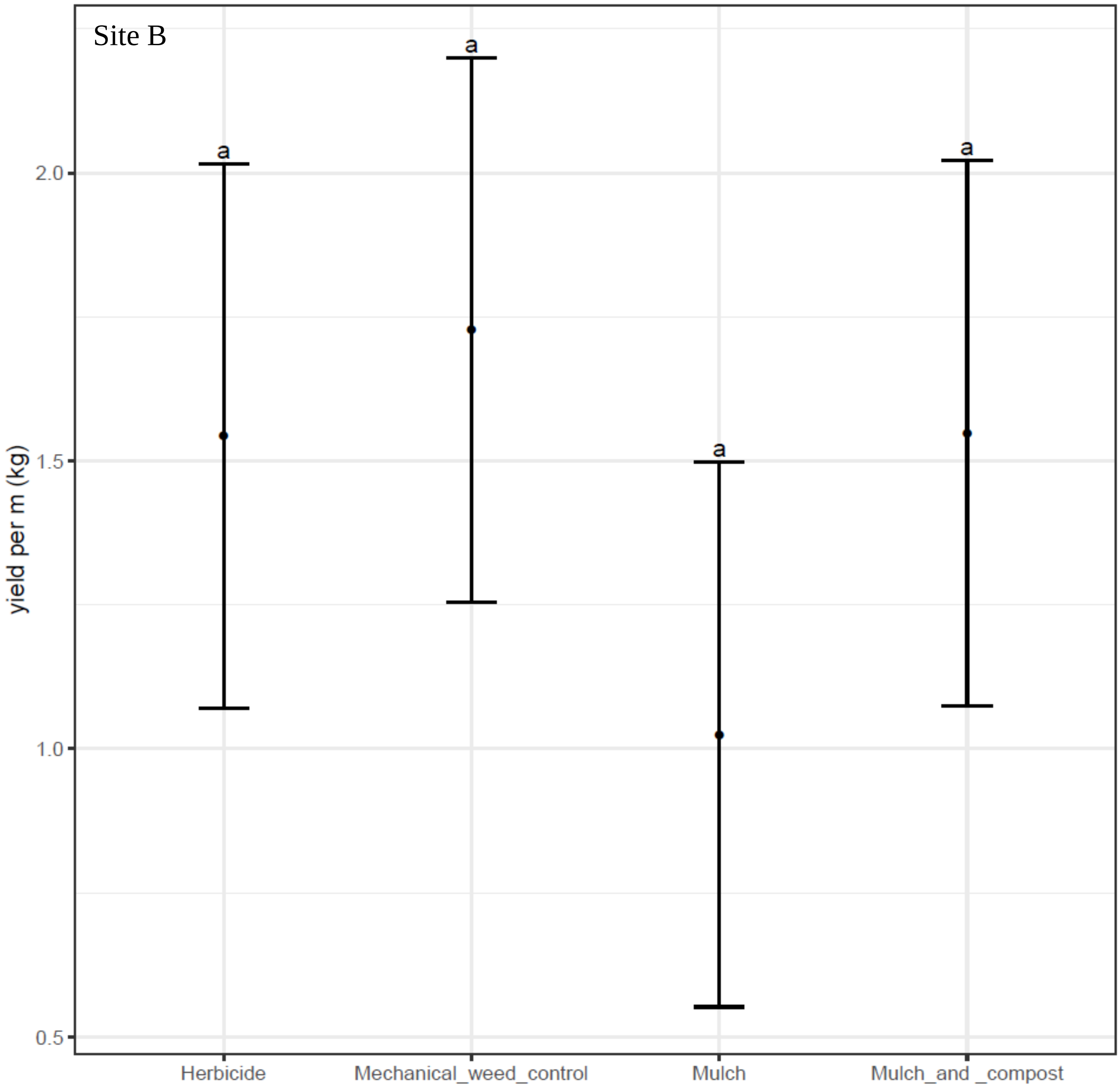

Figure 8: Yield calculated on a per metre basis from Site B (Shiraz). Significance defined by letters as tested by two-way anova ($p<0.05$). Bars represent 95% confidence intervals.

As no statistically significant differences were observed in total yield per plot within each site, only minor differences between treatments were apparent when measuring other harvest metrics. Figure 9 shows bunch weights from site A. Bunch weights for the mechanical weed control treatment were significantly higher than those for the mulch treatment.

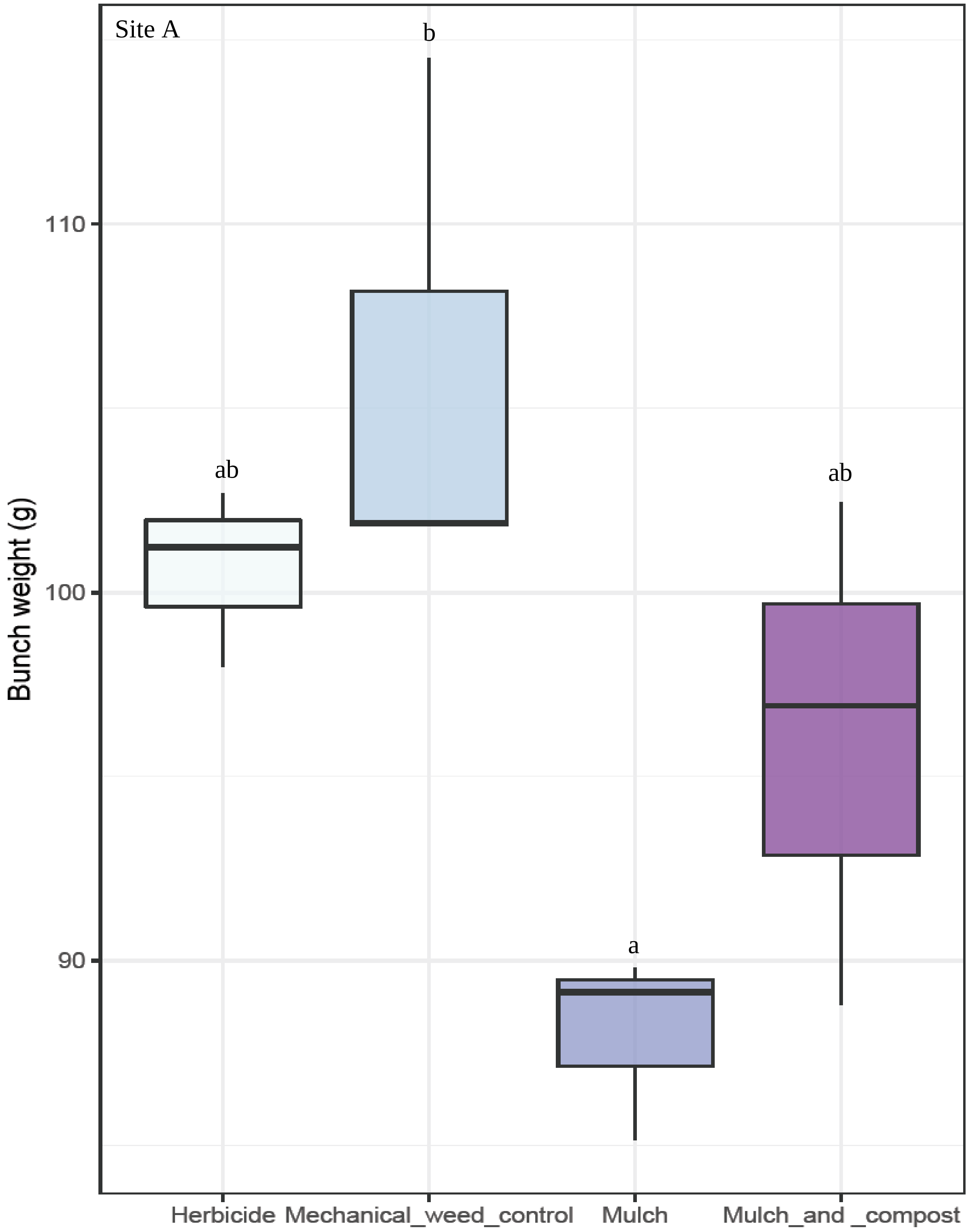

Figure 9: Bunch weight from Site A (Cabernet Sauvignon). Significance defined by letters as tested by two-way anova (p<0.05).

Berry Chemistry

Any changes in berry quality are of critical importance to wine makers and growers alike, as this effects wine quality and economic feasibility of the weeding treatments. No significant effects were discovered at Site A, though trends similar to the significant effects at Site B were observed suggesting that a study with higher repetitions or an older trial may yield difference.

At site B significant treatment effects were present in berry juice pH (Figure 10), where the mulch treatment mean pH was slightly above 3.7, significantly higher than both the mechanical weed control and mulch and compost treatments. The lowest berry juice pH was ~3.46 for the mulch and compost treatment, significantly lower than the mulch and herbicide treatments. As annual temperatures increase, lower pHs can be more desirable from a winemaking perspective as they increase the stability of the must, and reduce the number of inputs required in the winemaking process. Overall the pHs of the juices were close to an acceptable level.

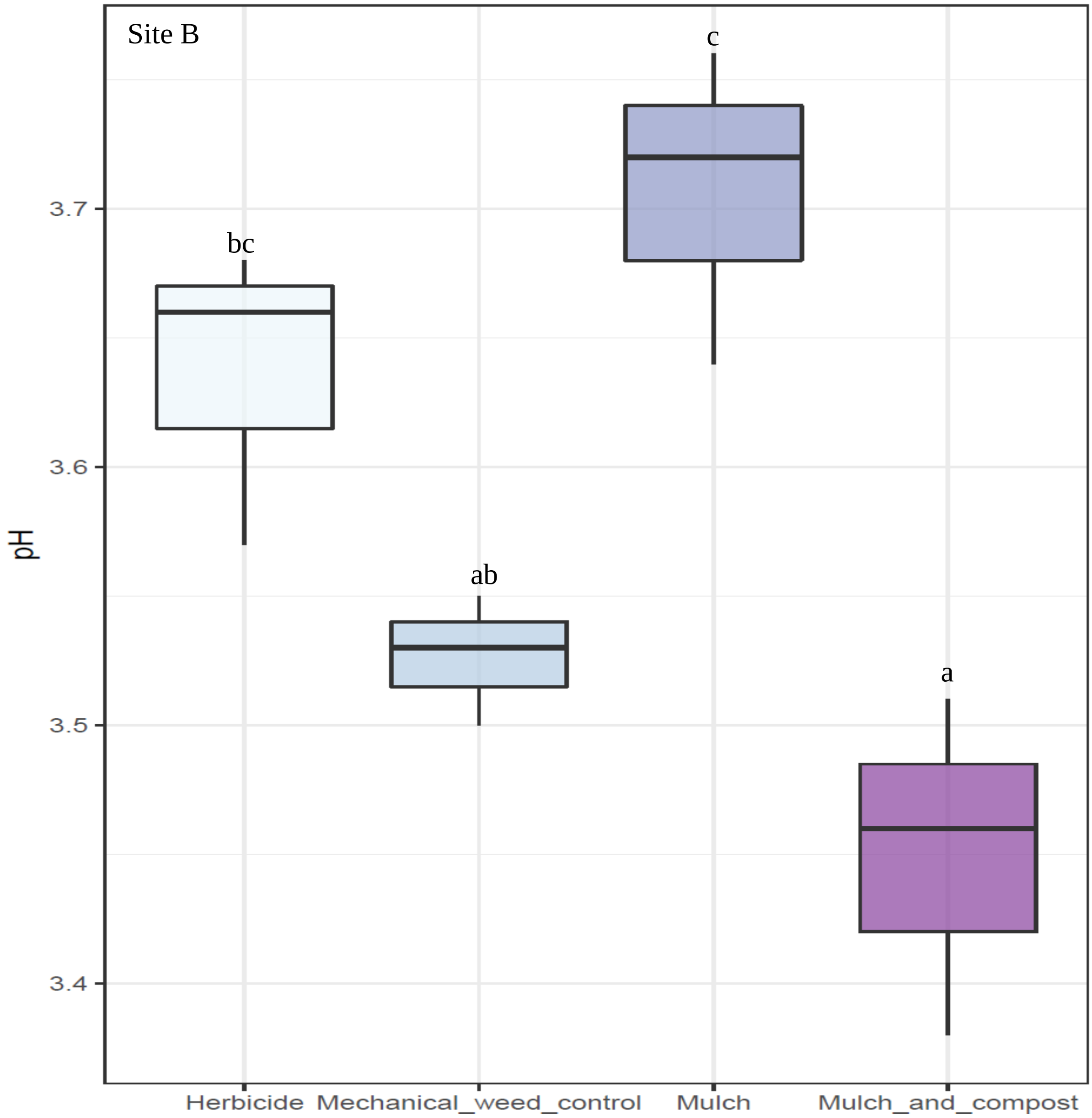

Figure 10: Berry juice pH from grapes harvested at Site B (shiraz). Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

Titratable acid (TA, Figure 11), was significantly higher for mulch and compost, relative to herbicide and mulch treatments. TA is a measure of the total amount of available hydrogen ions, while pH is influenced by the capacity for the acids to dissociate. It may be of note that for both mulch and mulch and compost treatments, pH and TA seem to be inversely proportionate, while the herbicide treatment does not follow the same pattern. From a winemaking perspective this may be desirable. TAs from 5-7 g/L are typical (AWRI 2020a).

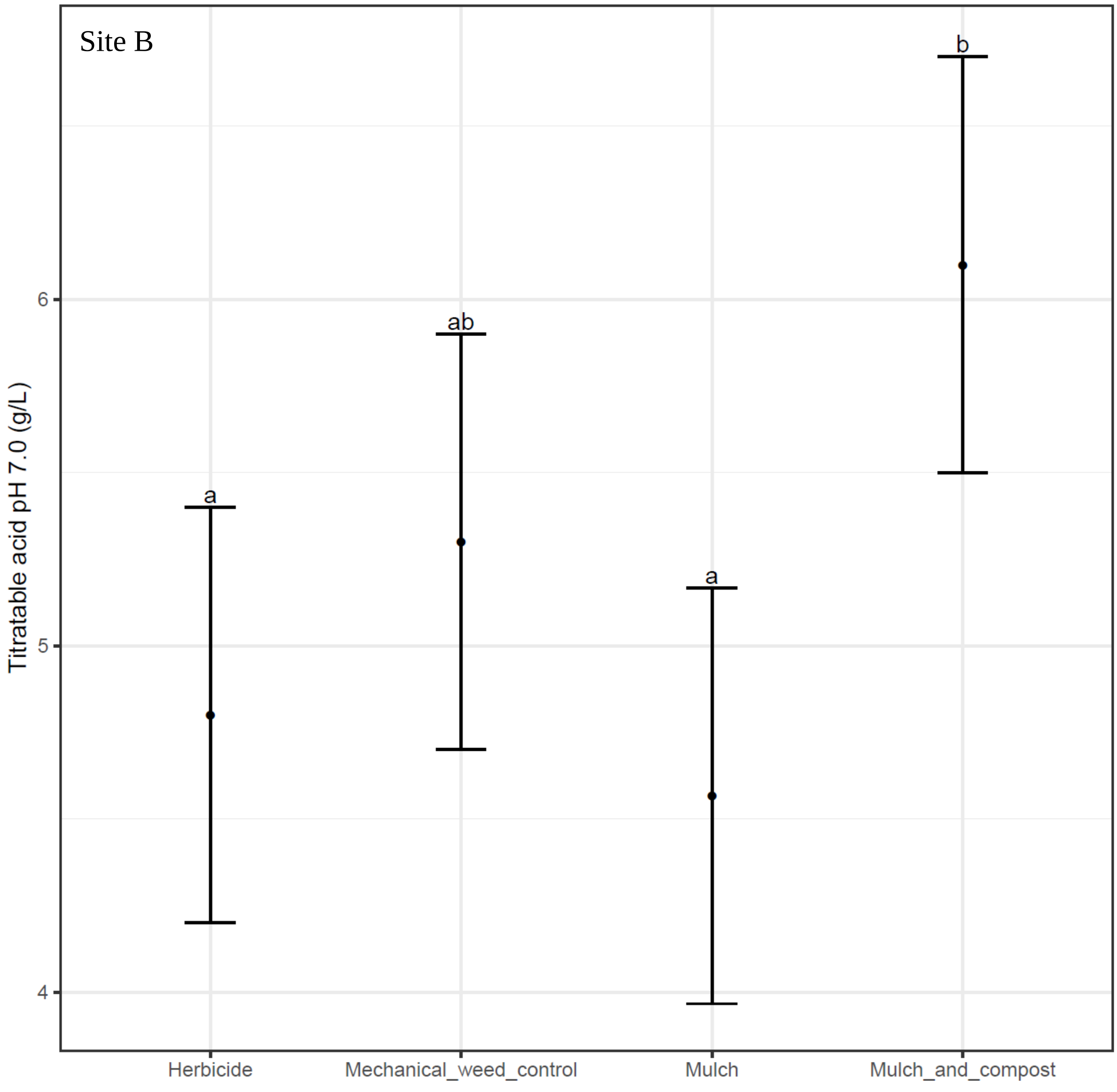

Figure 11: Titratable acid of berry juice from grapes harvested at Site B (shiraz). Significance defined by letters as tested by two-way anova ($p<0.05$). Bars represent 95% confidence intervals.

Yeast assimilable nitrogen (YAN; Figure 12), an important must characteristic for winemakers, was also significantly higher for the mulch and compost treatment than the other mulch treatment and mechanical weed control, with herbicide somewhere in between. Both the mulch and compost and herbicide treatments have YANs higher than the minimum level recommended by the AWRI (AWRI 2020b) for red grapes of 100 mg/L. Optimum YAN concentrations add value to the grapes as supplementation of a nitrogen source for fermentation is not needed.

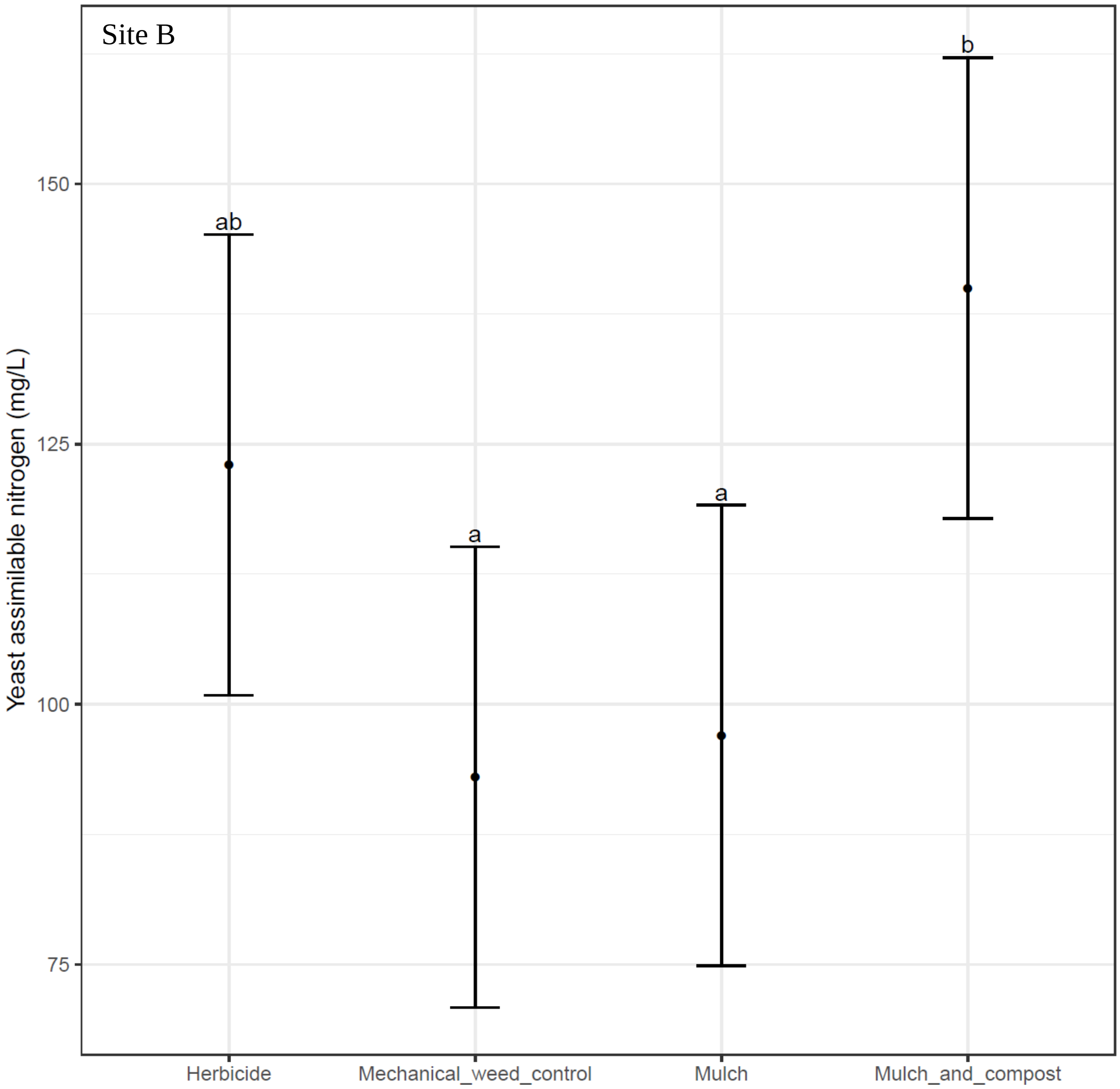

Figure 12: Berry juice yeast assimilable nitrogen from grapes harvested at Site B (shiraz). Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

Like pH, sugar content was also lower in the mulch and compost treatment, though this was not statistically significant. The combination of higher TA, lower pH and lower brix may have increased the value of these grapes, however the subsequent performance of the vines in a higher yielding year is yet to be seen.

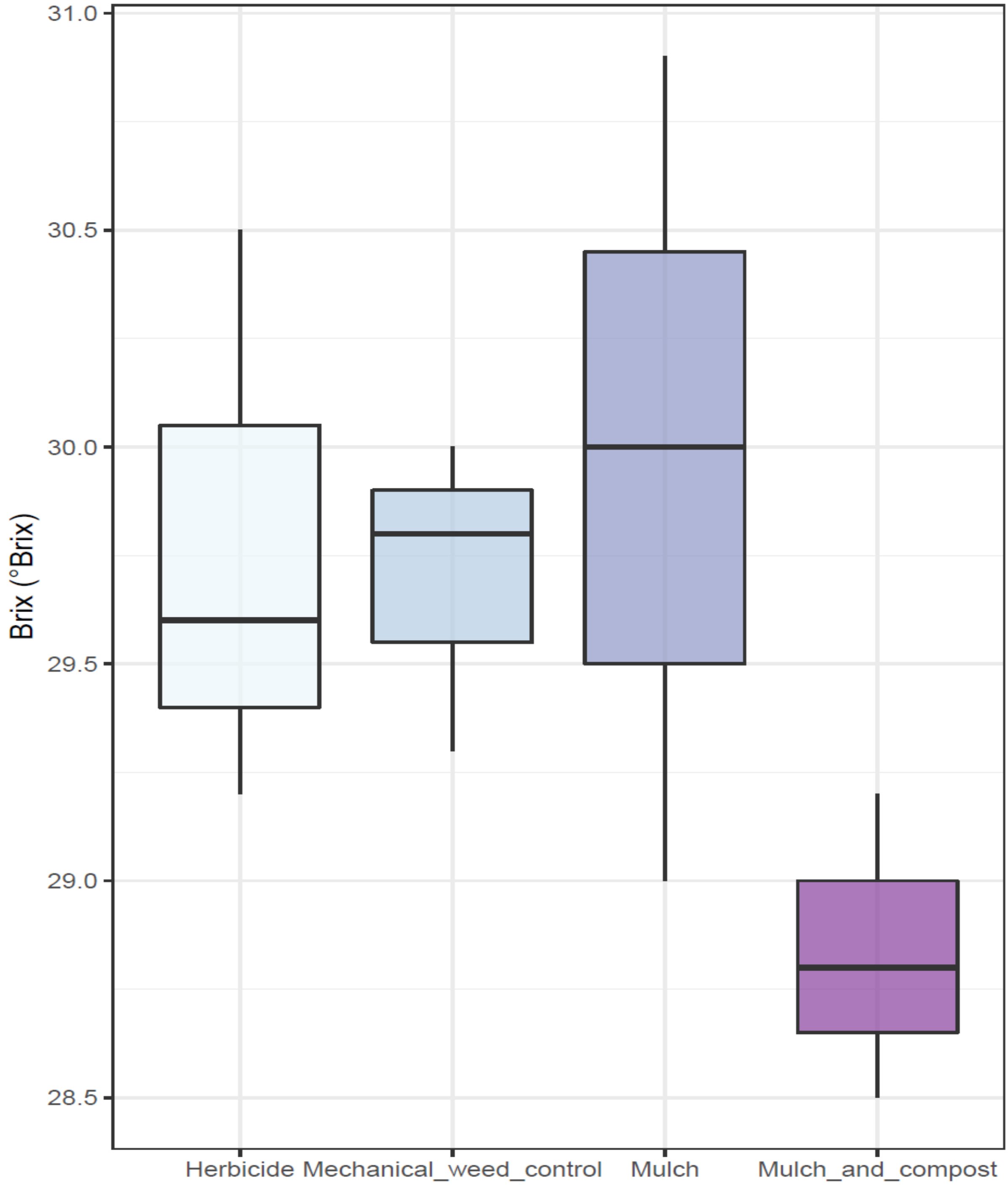

Figure 13: Boxplot of sugar content (Brix) of berry samples from Site B. No statistical significance was detected by two-way anova ($p<0.05$).

Ammonia levels (Figure 14) in the berry juice from Site B ranged from 20 mg/L in the mulch treatment to 50 mg/L in the mulch and compost treatment which was significantly higher than all other treatments. Ammonia contributes to yeast assimilable nitrogen, and at moderate levels is not detrimental to the fermentation process or downstream wine flavour (AWRI 2020b).

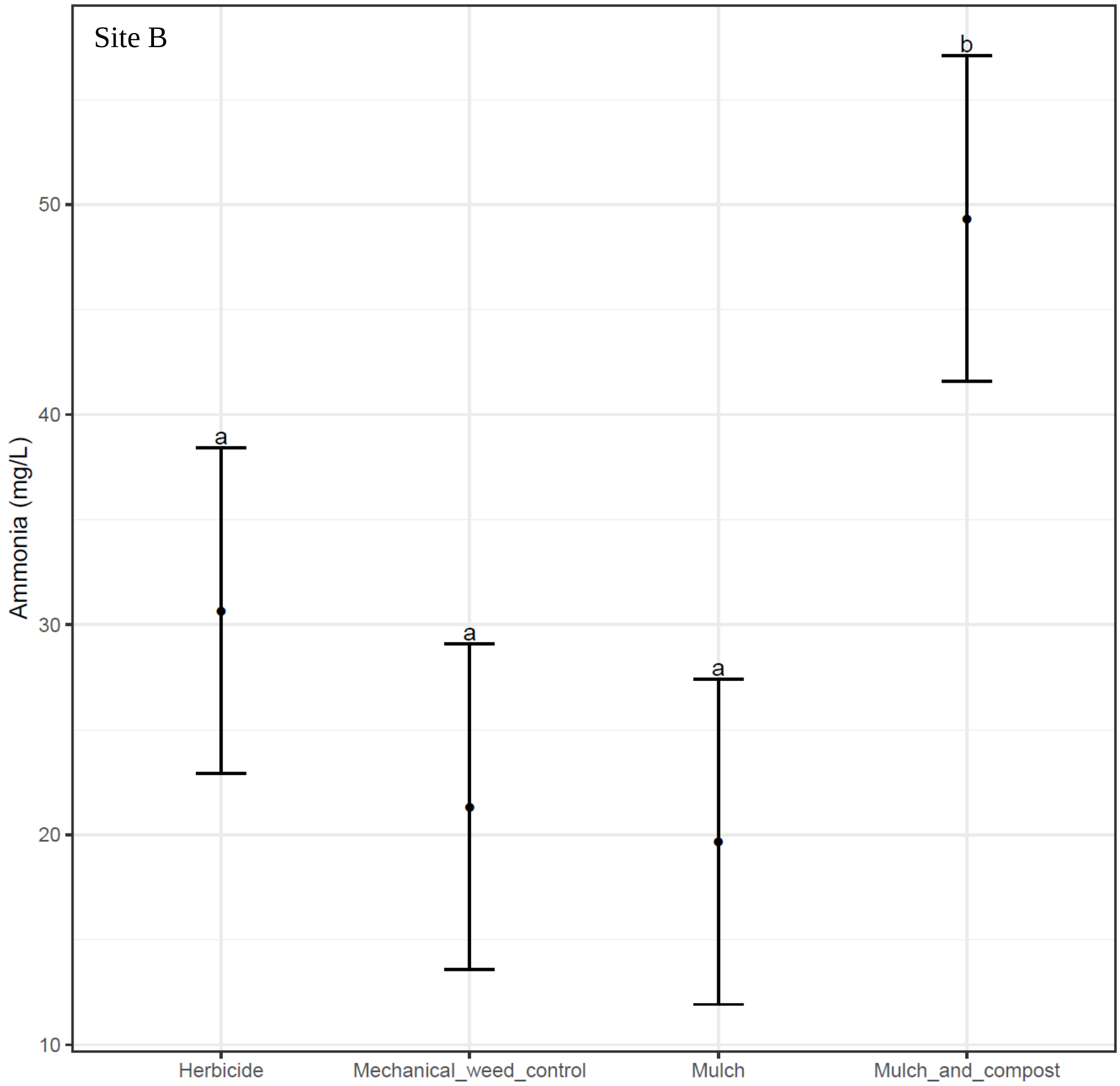

Figure 14: Ammonia in berry juice from grapes harvested at Site B (shiraz). Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

Soil Physicochemistry

Concentrations of key soil nutrients were quantified in order to determine the impacts of the undervine management treatments during the season. There were many significant differences between treatments at both florescence and pre-harvest timepoints; all of which can be found in Appendix 5. Here we will present the most viticulturally relevant data.

Plant available (Colwell) P (Figure 15) was significantly higher for compost treated vines than for all others. Many samples had levels of P less than the detectable limit. Recommended soil phosphorous concentrations range from 25 mg/kg to 80 mg/kg and vines are limited below 25 mg/kg (Oliver et al. 2013). This indicates that all treatments in the trial are phosphorous limited, except for the compost treatment, which is close to the ideal concentration.

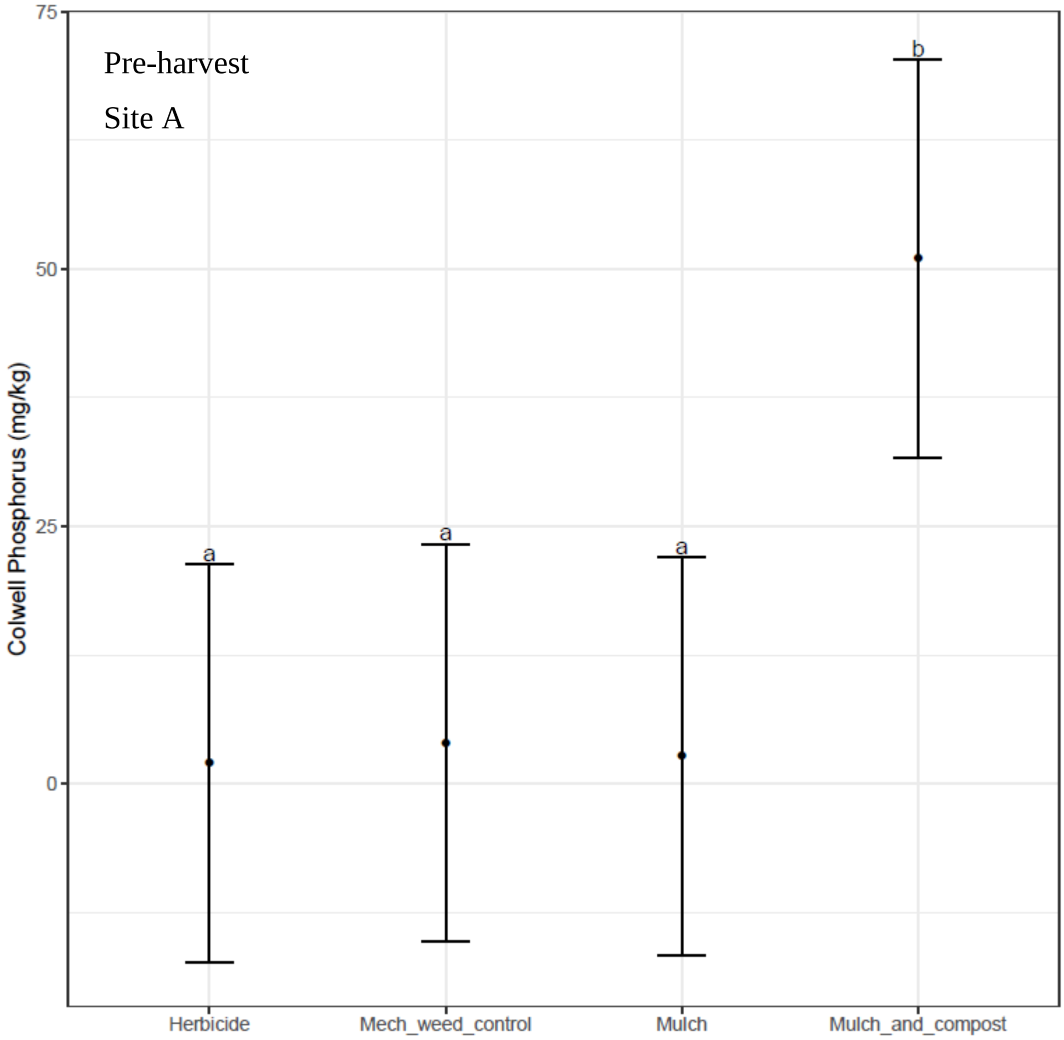

Figure 15: Colwell phosphorous (P) content (mg/kg AKA ppm) at pre-harvest time point at Site A. Samples taken from top 10 cm. Significance defined by letters as tested by two-way anova ($p<0.05$). Bars represent 95% confidence intervals.

As the organics in the compost continue to break down, plant available phosphorous will continue to be released, potentially leading to significant differences in the performance of the vines.

The application of mulch to vineyard soils has the capacity to increase soil potassium (K). Oversupply of which can lead to high berry pH and potassium, reducing berry quality (Chan & Fahey 2011). Soil potassium is significantly higher for the two mulch treatments than the herbicide and mechanical weed control treatments (Figure 16). This difference is close to a doubling of available K in the soil. Desirable limits for potassium are no higher than 100 ppm, meaning that all vines are supplied potentially excessive quantities of K. This has the potential to lead to elevated grape juice pH, dependent on its availability and uptake. These values did not change across the season (see Figure 17). Despite high soil K, berry juice pH was not excessively high, however these values suggest measuring berry K content may be worthwhile.

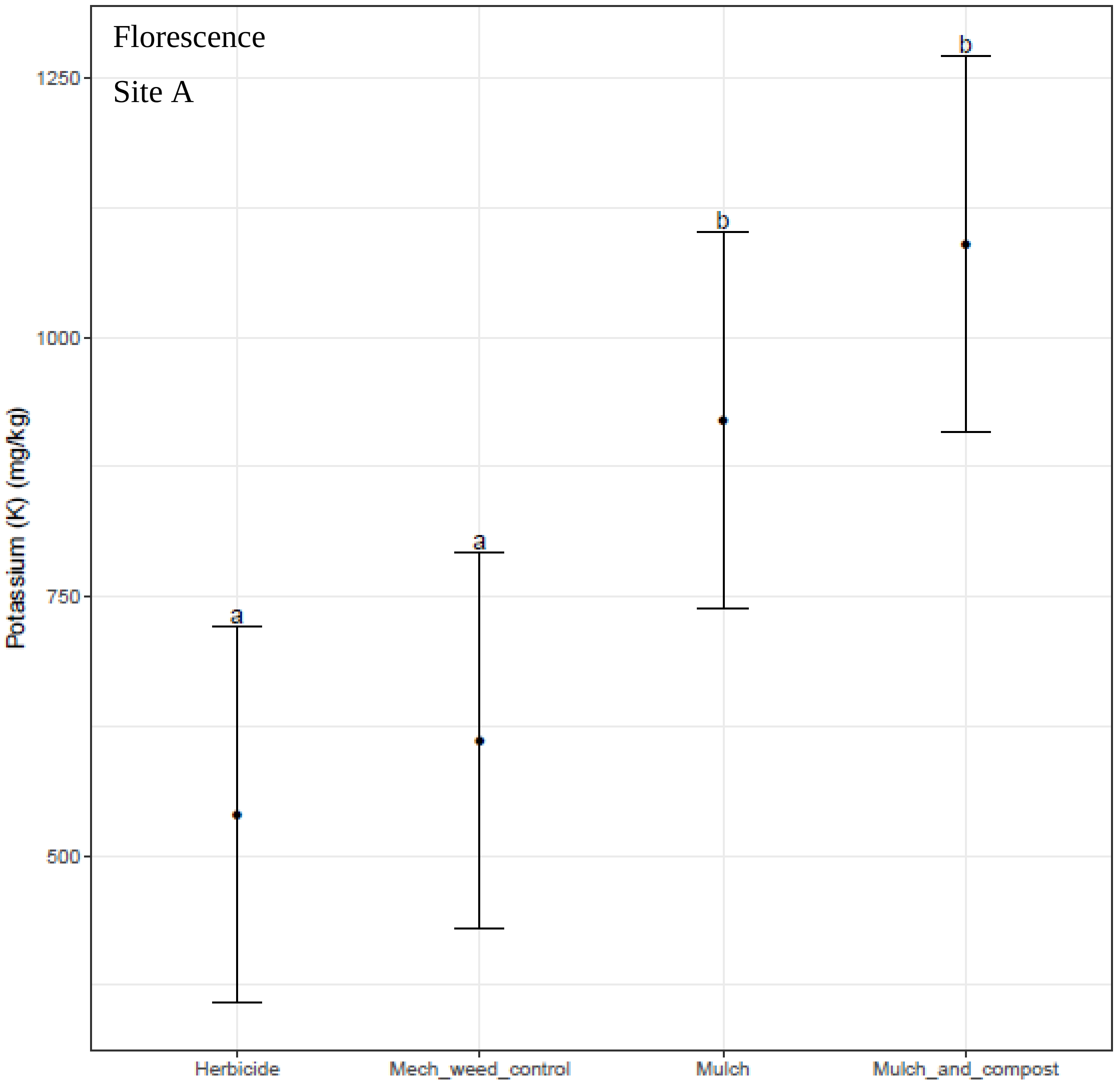

Figure 16: Soil potassium (K) content (mg/kg AKA ppm) at florescence time point at Site A. Samples taken from top 10 cm. Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

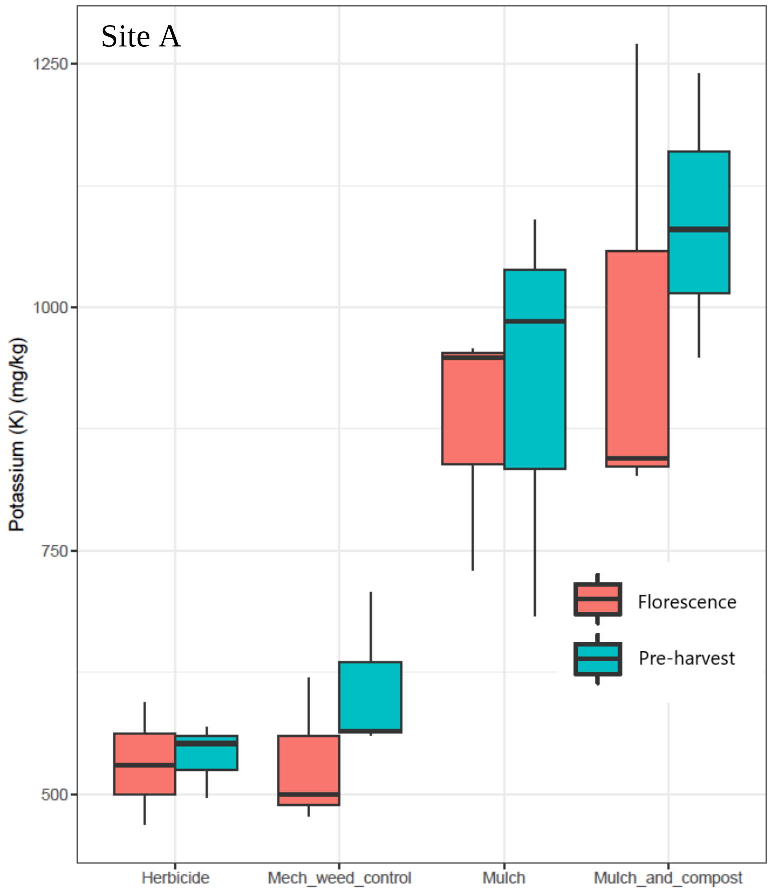

Figure 17: Boxplots of soil potassium (K) content (mg/kg AKA ppm) at florescence (November 2019) and pre-harvest (March 2020) timepoints. Samples taken at Site A from top 10 cm.

Salinity (EC aka electrical conductivity) was significantly higher for the mulch and compost treatment at the florescence time point, and also significantly higher than the herbicide treatment at the pre-harvest time point (see Figure 18). This is consistent with the addition of compost resulting in an increase in solute in the soil surface. This combines with increased salt retention caused by the protective effects of the mulch to further increase salinity in the soil surface. Overall however, these salinity levels are not a concern and will not effect the vines (AWRI 2010).

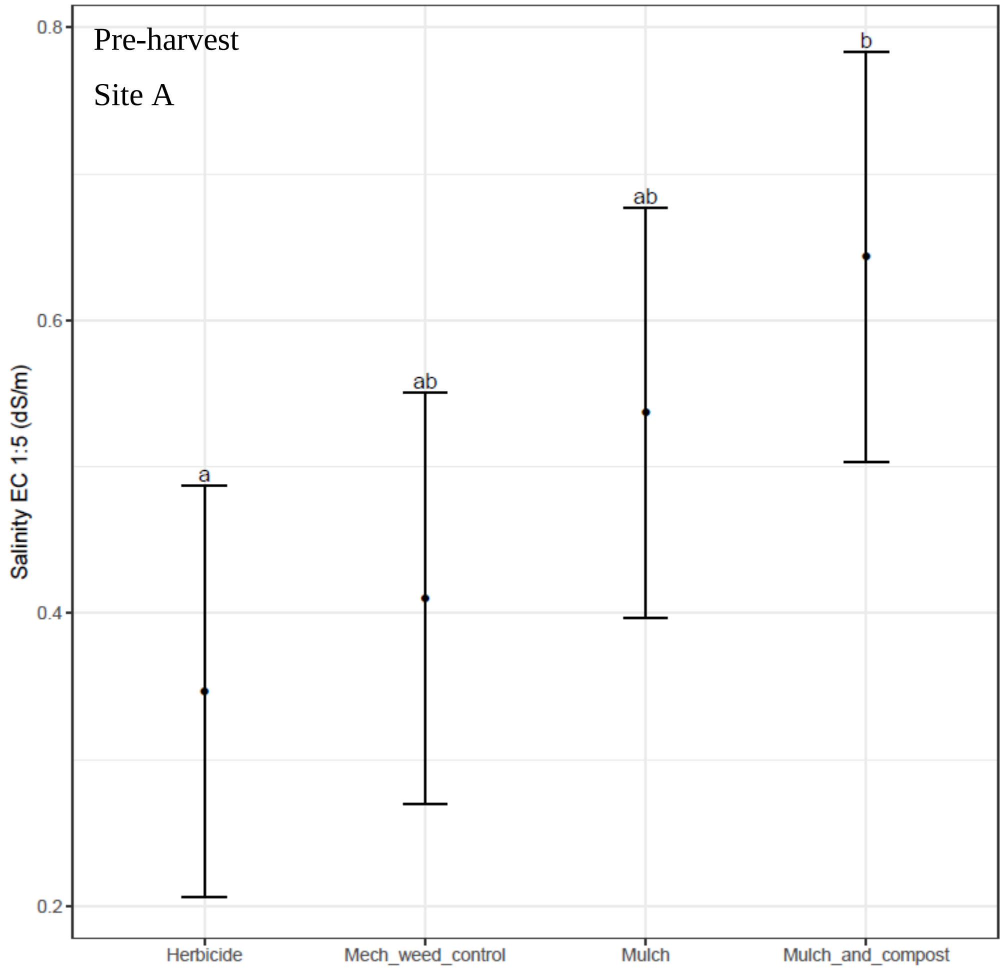

Figure 18: Soil salinity electrical conductivity (EC) from pre-harvest time point at Site A. Samples taken from top 10 cm. Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

Exchangeable cation ratio (ECR) was significantly higher for the mulch and compost than both herbicide and mechanical weed control treatments. Compost often contains high levels of salts and nutrients, which would explain the significant trend in Figure 19. Results were also significant at the pre-harvest sampling point (see appendices).

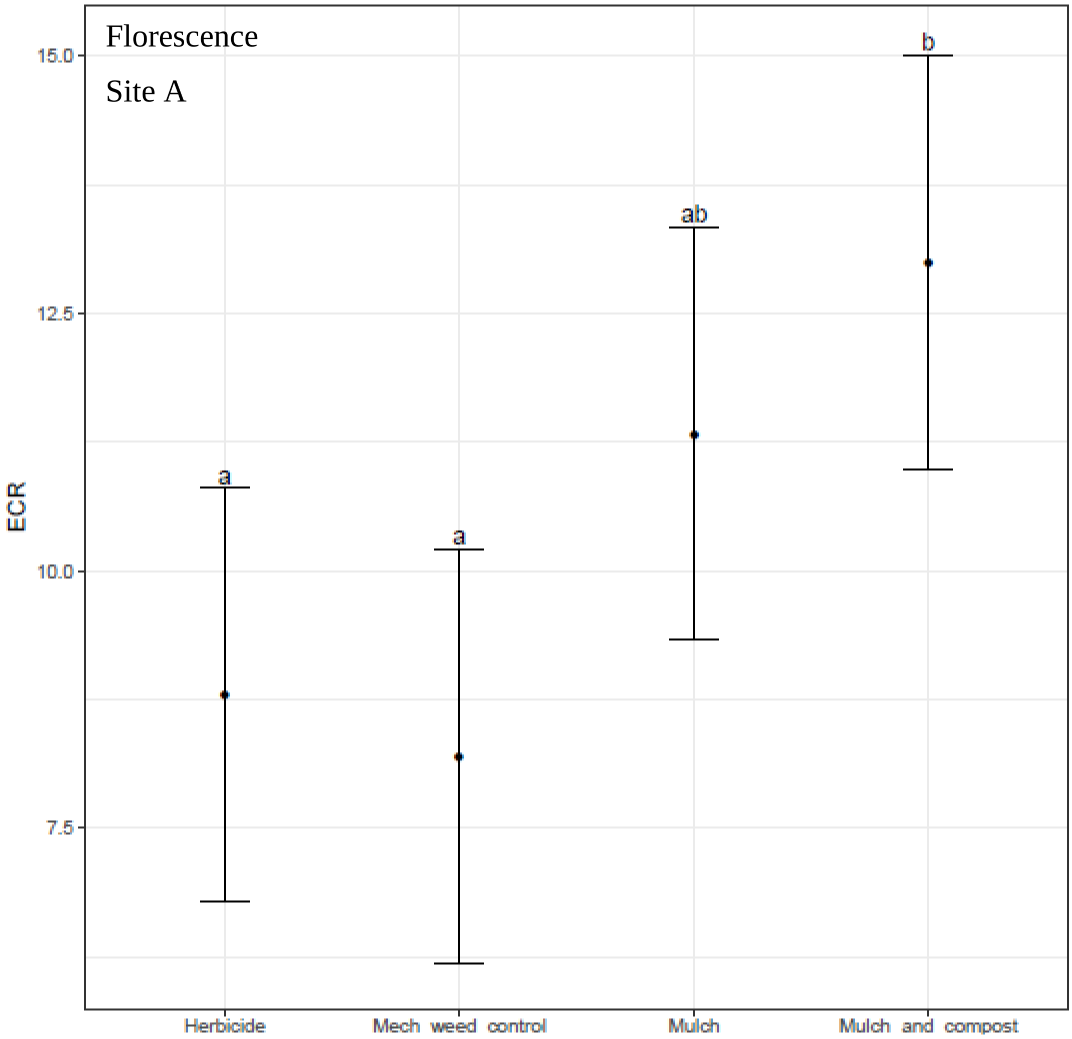

Figure 19: Soil exchangeable cation ratio (ECR) at florescence time point at Site A. Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

Plant Available Nitrogen

Nitrogen, when deposited in the form of compost is largely in organic form, inaccessible by plants. As the organic material breaks down, mineral nitrogen is released and can be taken up by the vine roots. Thus, it is important to measure mineral N (nitrate [NO_3^-] and ammonium [NH_4^+]), as well as total N to best understand where nitrogen pools are present. As a measure of available nitrogen in the soil, plant available nitrogen (mineral N) was measured across all treatments at both florescence and pre-harvest (Figure 20) time points.

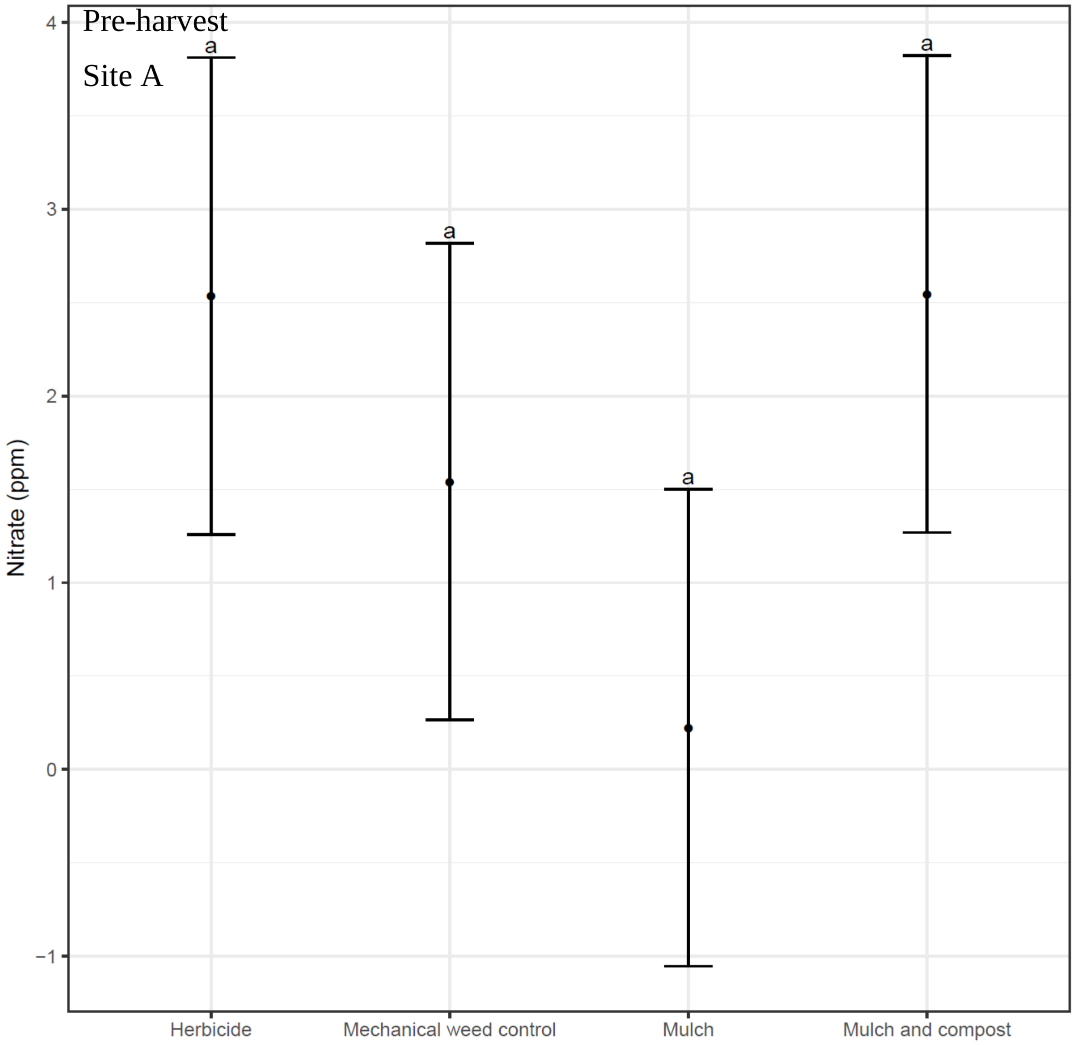

Figure 20: Plant available nitrate (ppm or mg/kg) from Site A at the pre-harvest timepoint. Six 0-10cm cores were taken across each plot and homogenised before subsampling for plant available nitrogen and soil physicochemical analysis. Significance defined by letters as tested by two-way anova ($p<0.05$). Bars represent 95% confidence intervals.

No significant differences were observed; however, trends are apparent that may become more detectable over time as organic N breaks down to from mineral N. Nitrogen drawdown (Butler et al. 2001) is explained as the usage of available N in the soil by microbes to generate biomass and metabolise carbon. This often occurs in soil treated with mulch, as the C (carbon): N (nitrogen) ratio is extremely high. Nitrogen draw down is thus likely to be occurring in both the mulch treatments, however the mulch and compost treatment is supplied with excess N in the form of compost. This higher availability of N in the soil, though not statistically significant, could be the explanation behind higher ammonium levels in the must, higher YANs, as well as differences in the canopy size (below).

Leaf blade composition

To better understand the cumulative effects of the treatments applied to the Site A, leaf blades were sent for analysis by APAL, instead of petioles which provide a 'snapshot' of the nutrient status in time. At florescence, nitrogen content in the leaf was significantly higher for both mulch treatments (Figure 21). This is somewhat surprising given that mulch treatments tend to cause nitrogen draw down, however it may be explained by the higher gravimetric water content of the surface soils at that time.

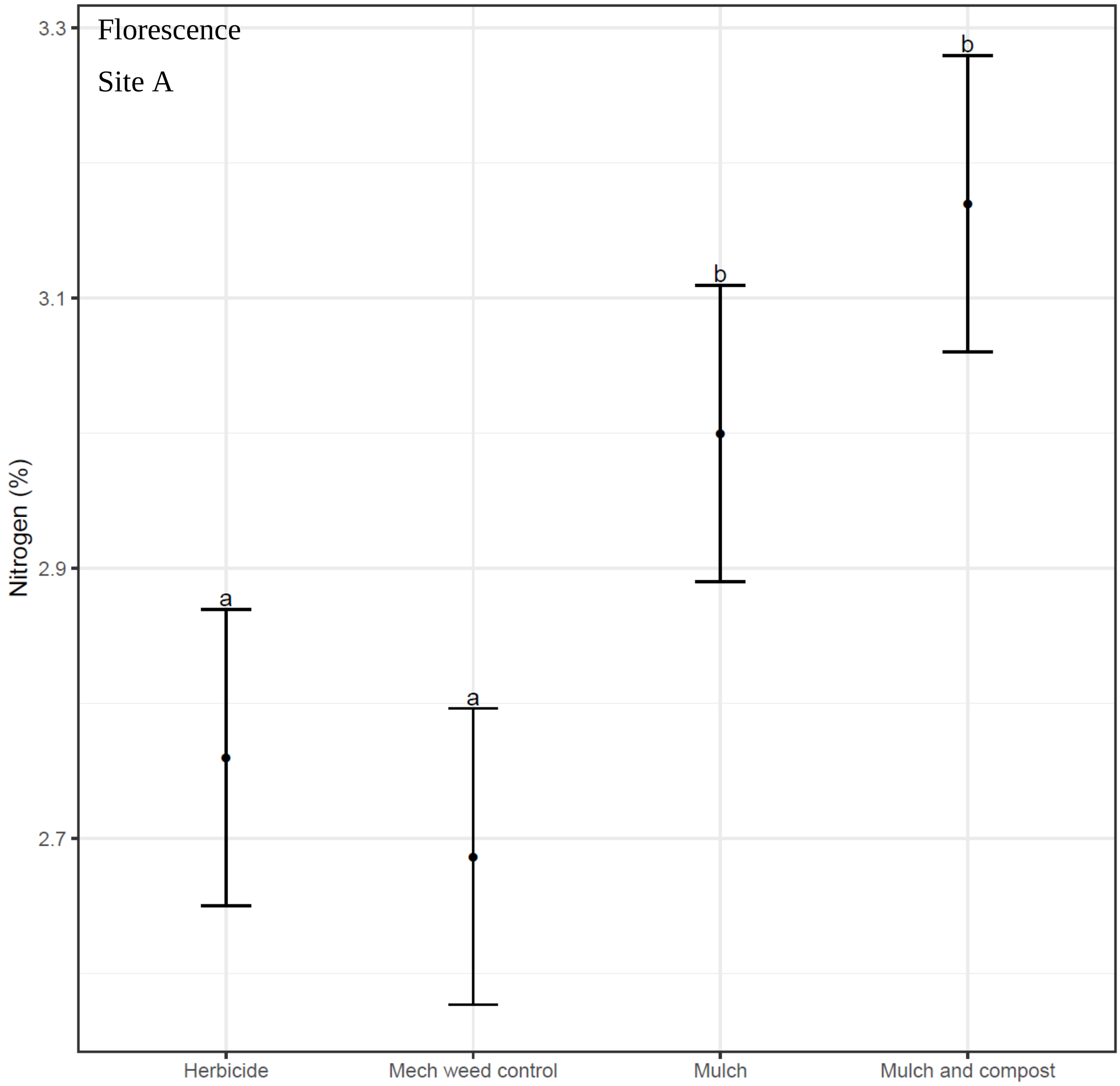

Figure 21: Leaf blade nitrogen content (%) at florescence, Site A. Significance defined by letters as tested by two-way anova ($p<0.05$). Bars represent 95% confidence intervals.

At the later, pre-harvest timepoint (see Figure 22), with all soils drier (see Figure 30 for water content), no statistical significance in leaf nitrogen content was present, however the mulch treatment's nitrogen content was lower than for all other treatments. As time progresses and the mulch continues to break down, soil nitrogen, at least on the surface may continue to be depleted for the mulch treatment and may lead to nitrogen limitation in future seasons.

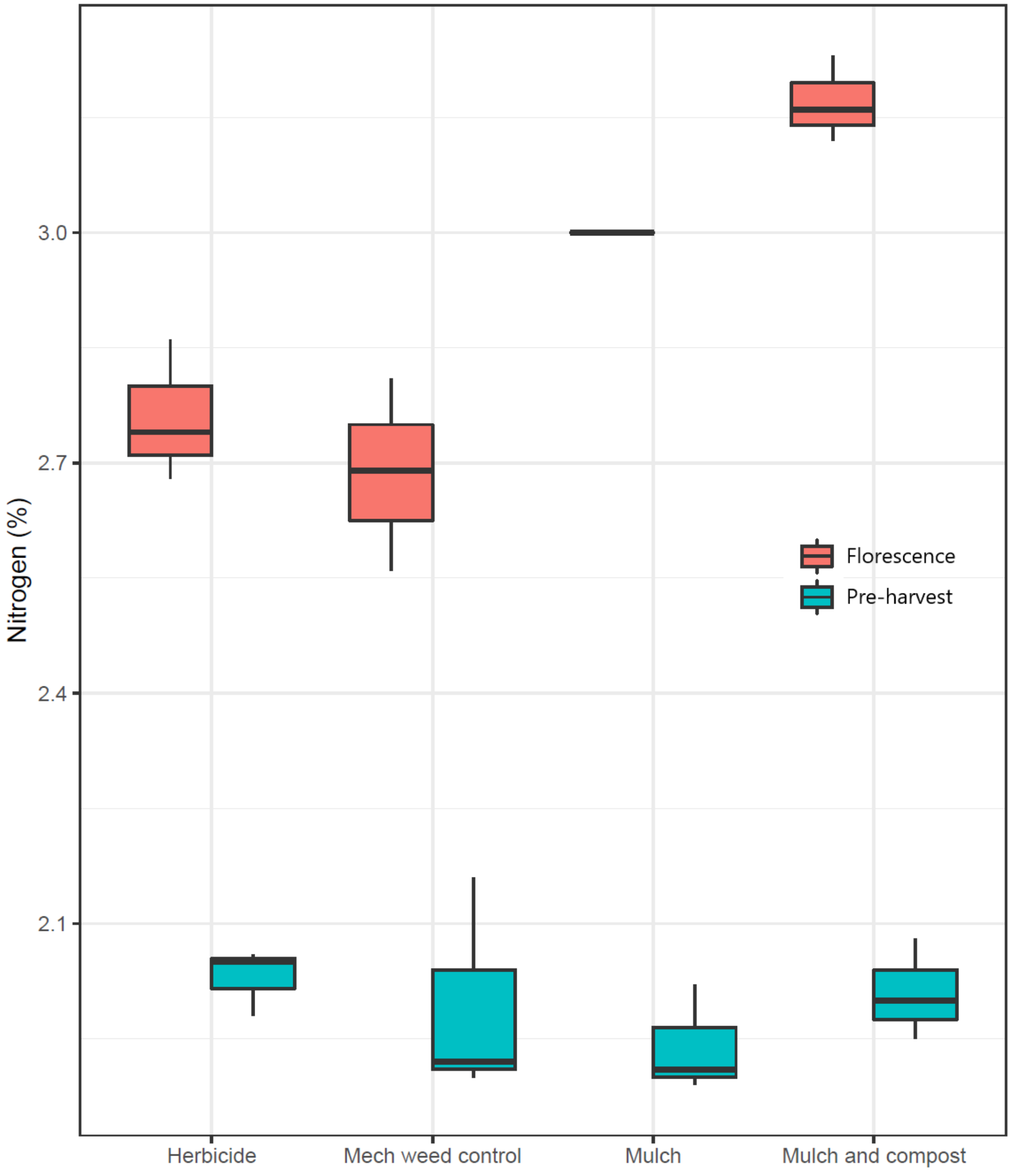

Figure 22: Across season leaf blade nitrogen content (%) boxplots. Data from florescence (orange) and pre-harvest (green) timepoints, Site A.

The mulch and compost treatment had significantly higher phosphorous than both the herbicide and mechanical weed control treatments. Some sources (Schreiner, Paul 2020) show these levels of P in leaf blades as deficient, at both florescence and pre-harvest time points. Given the levels of P in the soil which are also deficient, except for the mulch and compost treatment, this is not surprising and may explain some of the differences that have been observed.

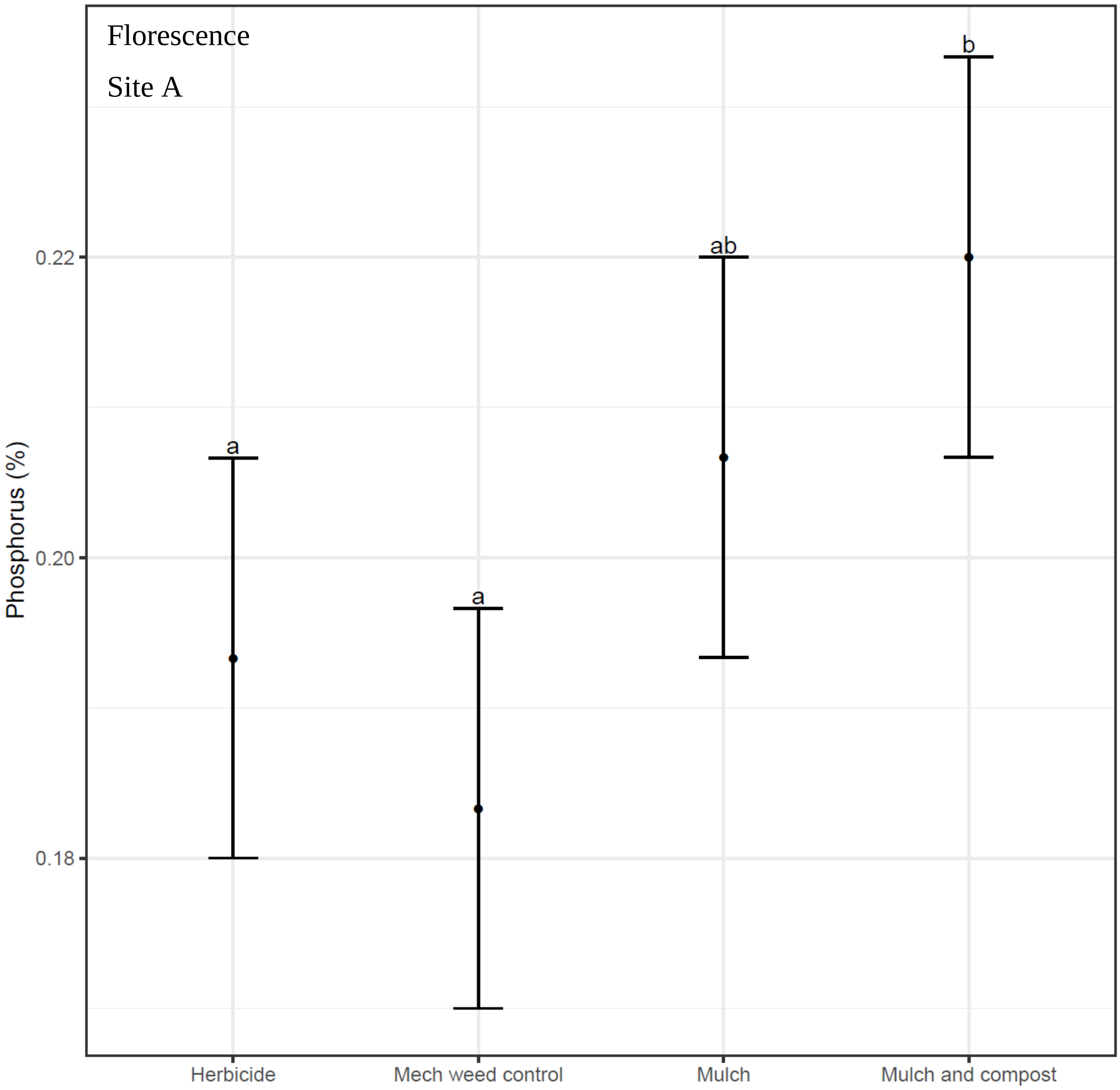

Figure 23: Leaf blade phosphorous content (%) at florescence, Site A. Significance defined by letters as tested by two-way anova ($p<0.05$). Bars represent 95% confidence intervals.

A significantly higher copper content in leaves from the mechanical weed control treatment is unexpected and is likely explained by residual copper from application of a fungicidal spray were residual on the surface of a coincidentally high number of leaves for this treatment. The levels detected here suggest a recent fungicide application, as the recommended levels of copper in leaf blades is between three and five parts per million (Cambrollé et al. 2015, Juang et al. 2012). The absence of unusually high copper levels in the soil at this time point also suggests the latter (see appendices).

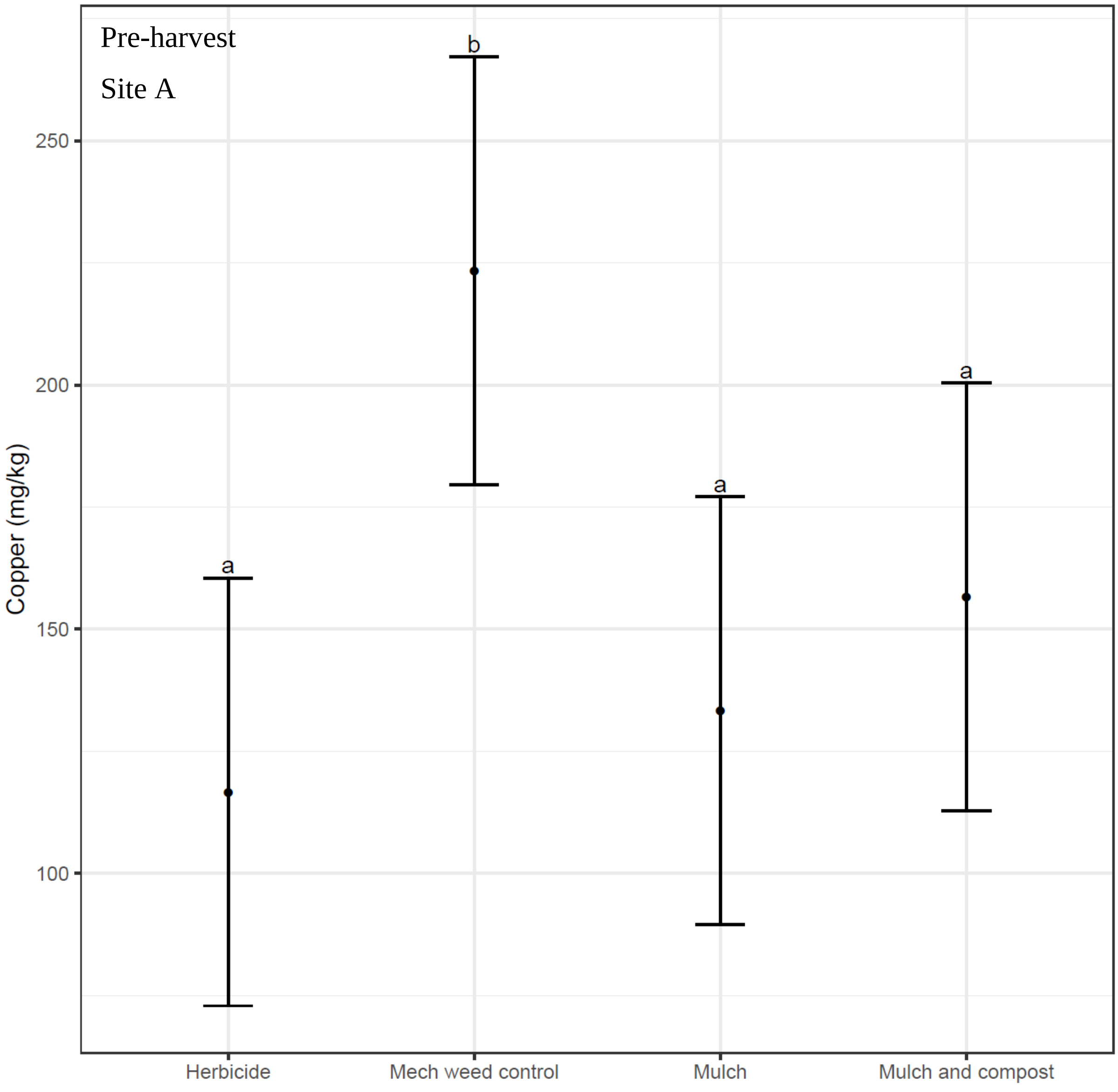

Figure 24: Leaf blade copper (mg/kg) from leaves sampled pre-harvest at Site A. Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

Leaf area and pruning weights

The leaf area index was significantly lower for the mechanical weed control treatment at the florescence time point (Figure 25, Figure 26). This suggests that a treatment effect is responsible for reducing the canopy size at this stage of the vine's development. No significant difference was detectable at the pre-harvest stage; however, this may be due to the less accurate "Viti-canopy" app that was used instead of the ceptometer. Higher weed coverage (Figure 5) and lower soil moisture (Figure 28) may be responsible for the smaller canopies in the mechanical weed control treatment.

Figure 25: Subtle differences in canopy size, subtly in this image taken at Site A at the florescence time point. Mulch (left) and mechanical weed control (right)

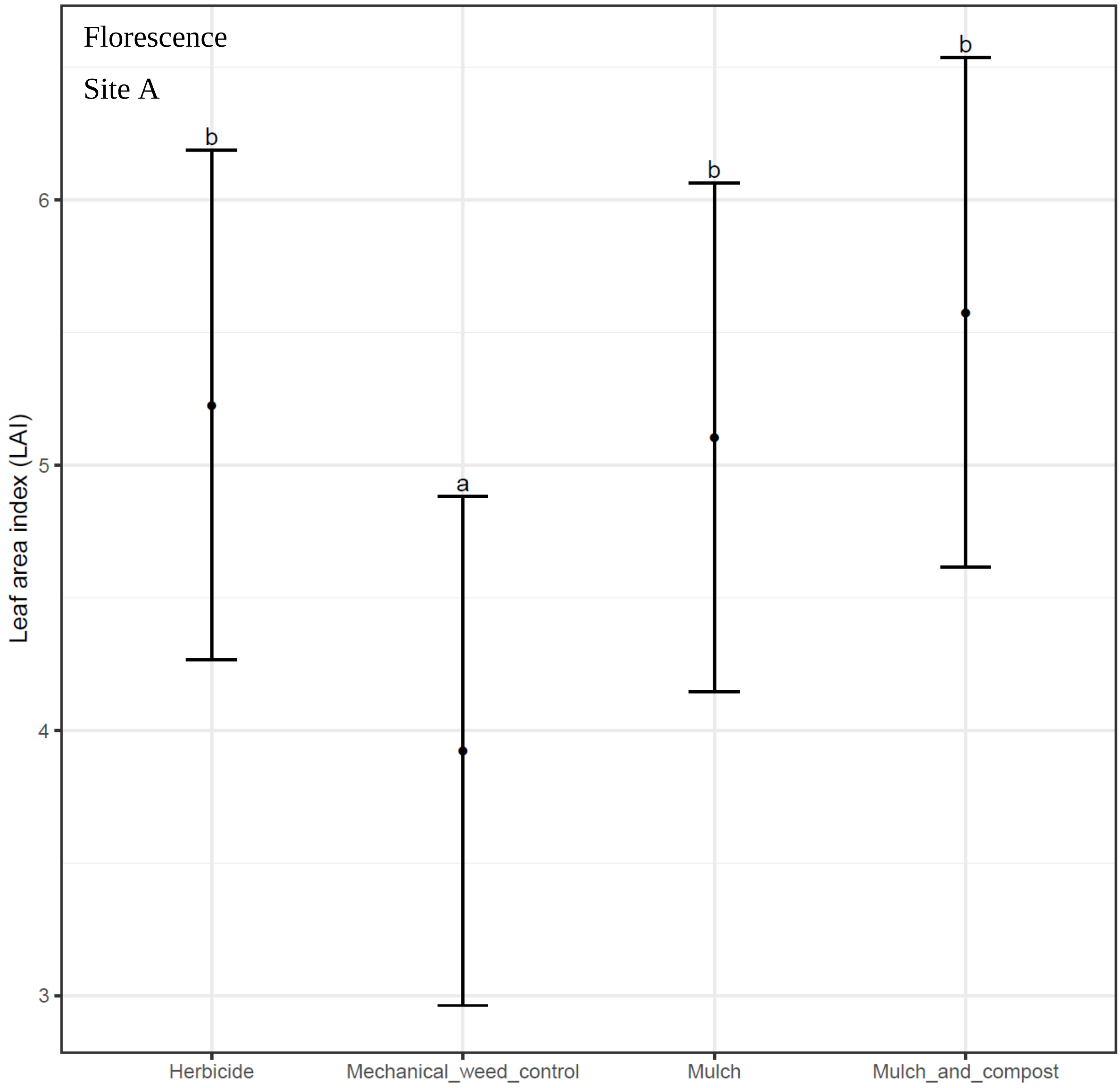

Figure 26: Leaf area index (LAI) collected via ceptometer at site A at the florescence time point. Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

To better understand the long-term effects of the treatments on canopy size, and whether the delay in canopy development experienced by the mechanical weed control treatment, pruning weights were taken post-harvest (Figure 27). No significant differences were identified. See appendices for cane counts. Ravaz index, a measure of the balance of pruning weight to fruit yield, was calculated and also showed no significant difference between treatments.

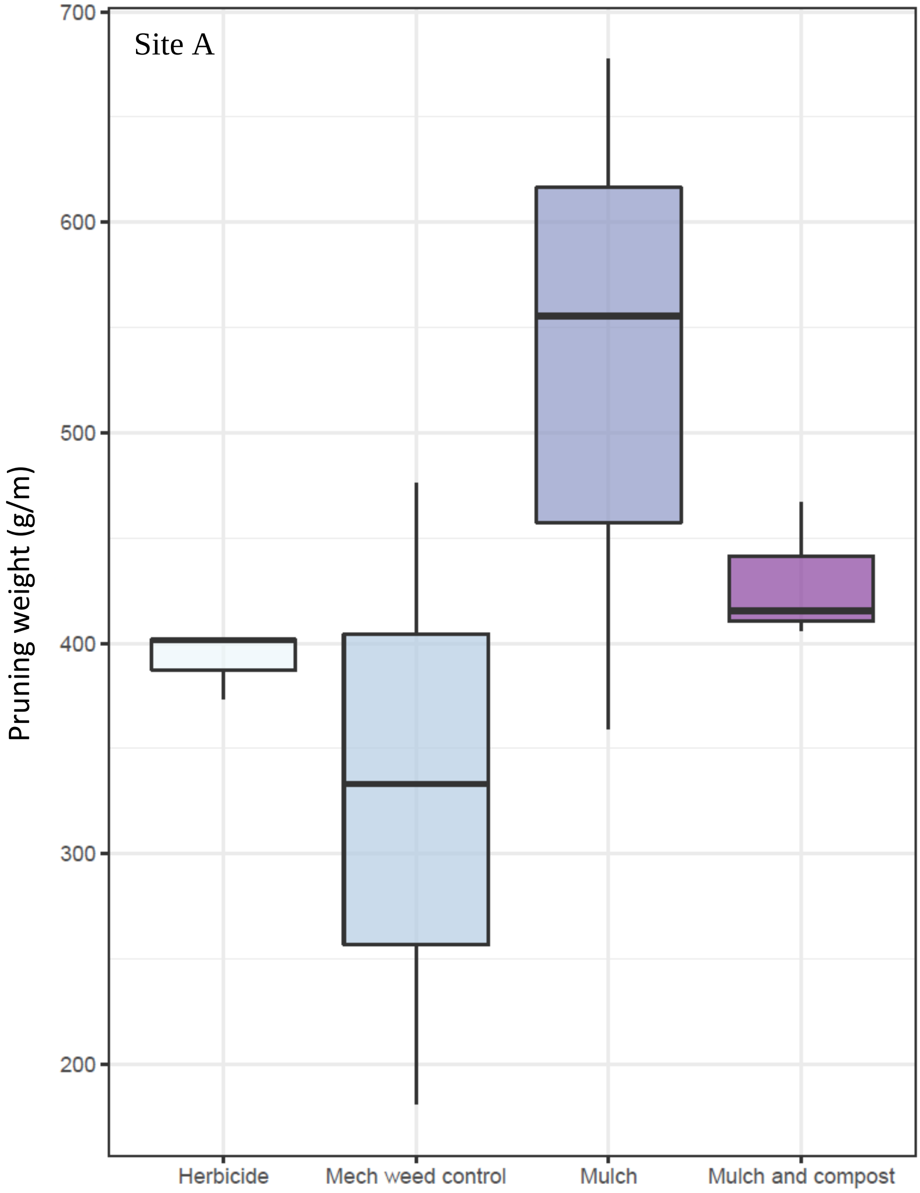

Figure 27: Pruning weight (grams per metre) from Site A after leaf drop. No significant differences were found as tested by two-way anova ($p<0.05$).

Soil moisture

By reducing evaporation from the soil's surface, it was expected that the mulch treatments would have higher levels of water. This is most apparent in Figure 28, where both mulch treatments show approximately 30 % higher water content. At the end of the season (Figure 29), no significant differences were present, most likely due to high rates of drying and little rainfall or irrigation, though the same trend is apparent.

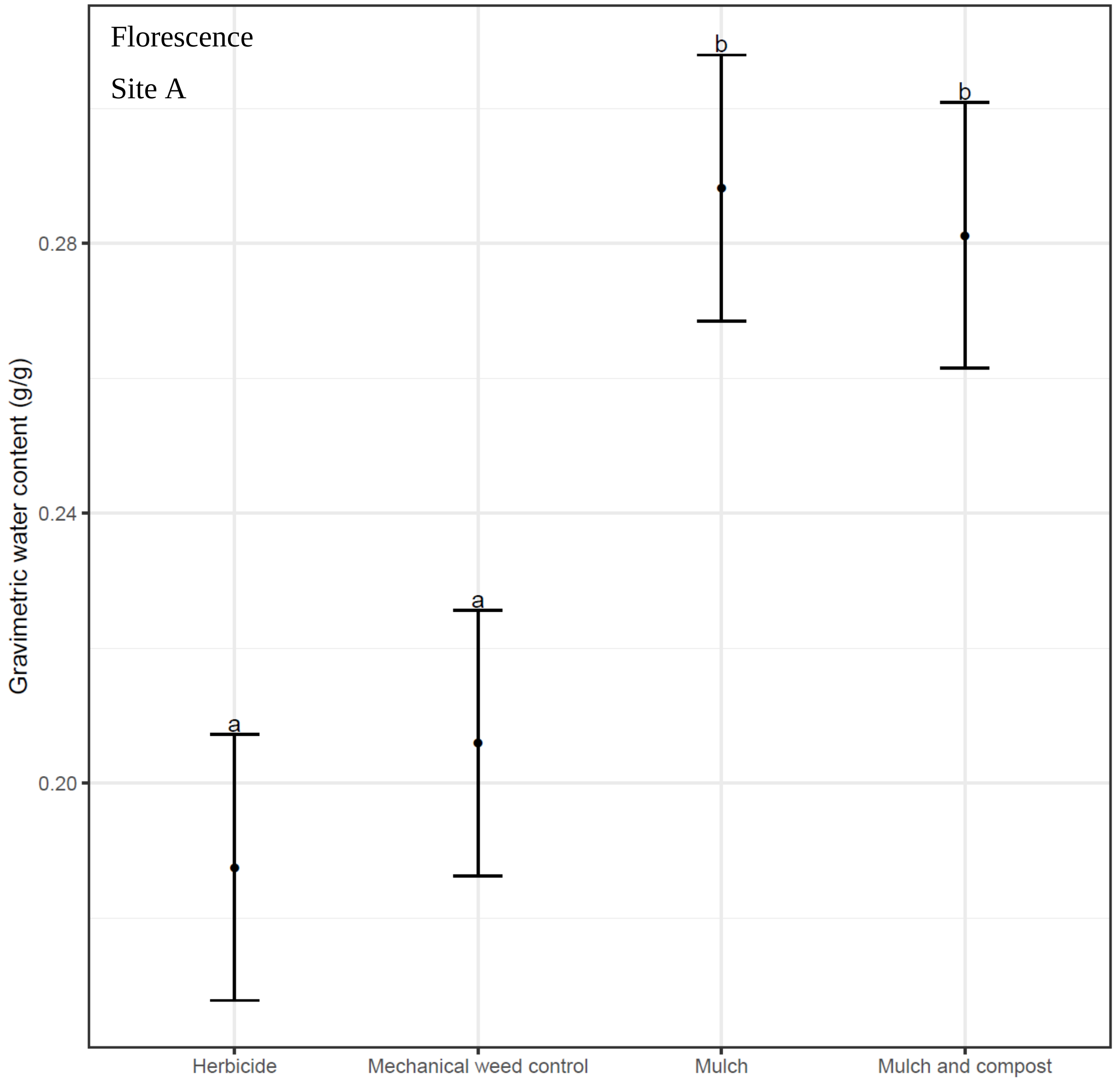

Figure 28: Gravimetric water content of surface soil at Site A, florescence. Significance defined by letters as tested by two-way anova (p<0.05). Bars represent 95% confidence intervals.

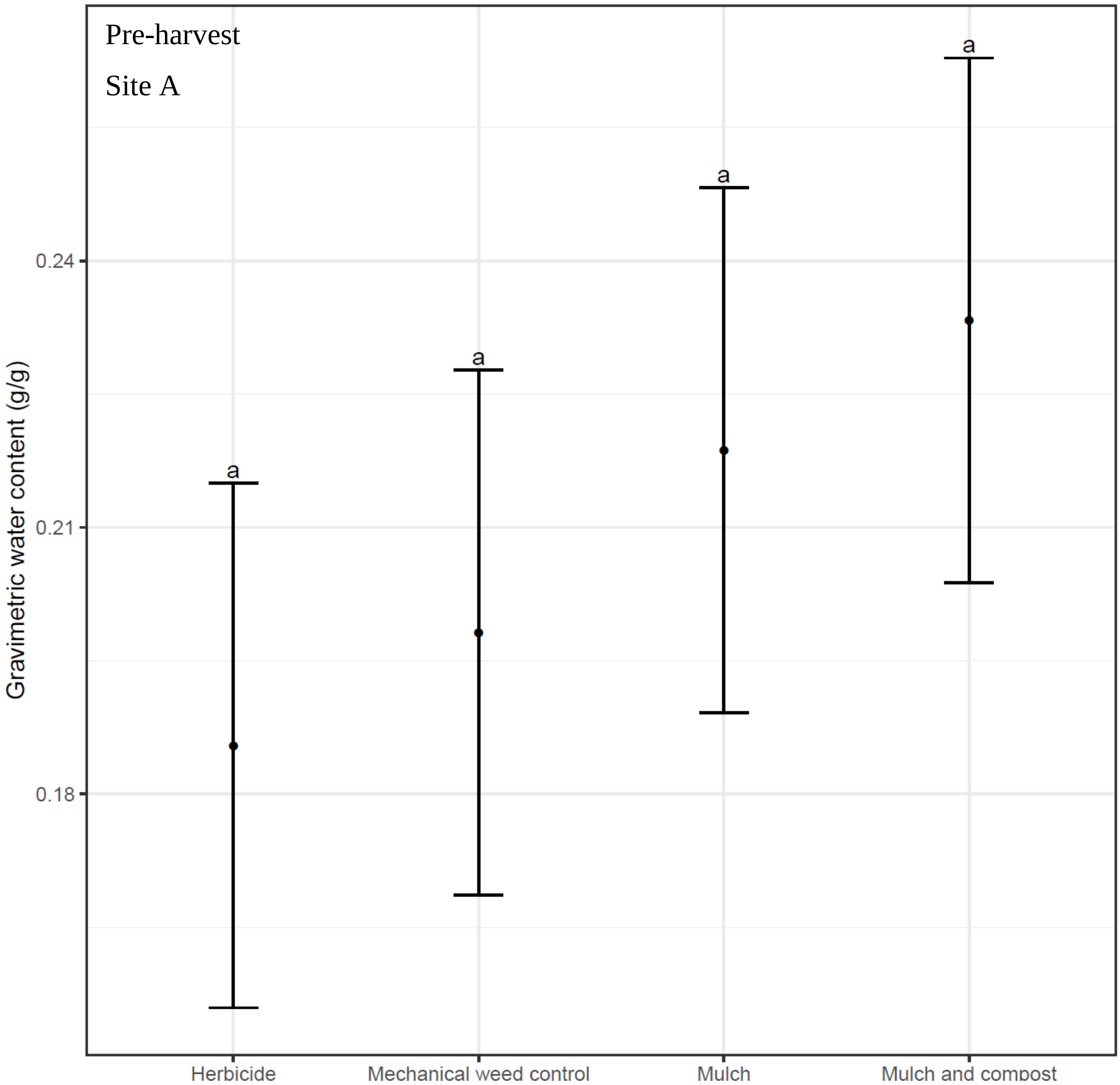

Figure 29: Gravimetric water content of surface soils from Site A at pre-harvest timepoint. Significance defined by letters as tested by two-way anova ($p<0.05$). Bars represent 95% confidence intervals. No significant differences were observed.

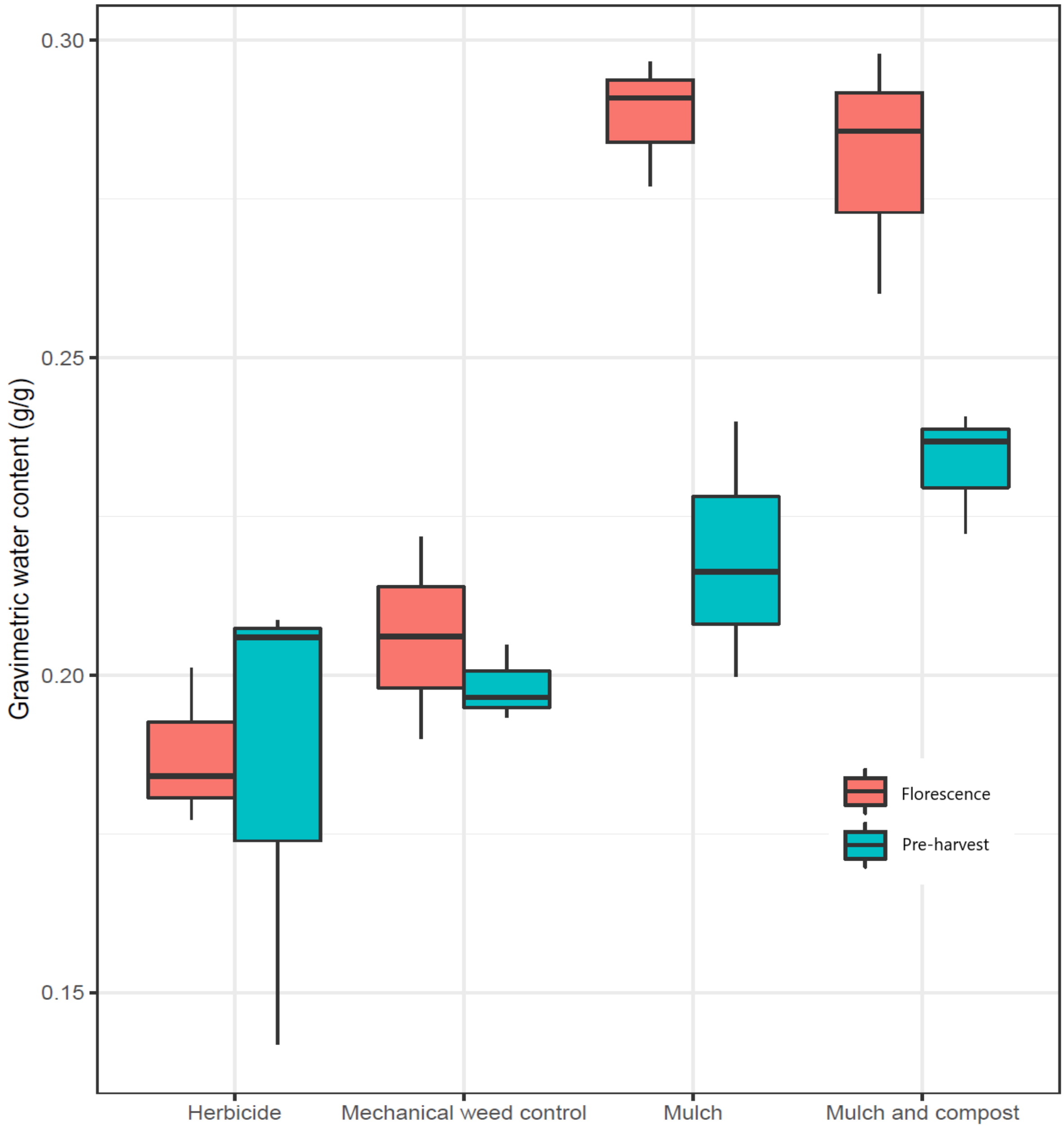

Figure 30: Gravimetric water content (g/g) of surface soil directly underneath treatment. Orange represents florescence timepoint, while green represents pre-harvest timepoint.

Moisture at the soil surface is only able to provide a superficial piece of information about what is occurring with respect to water usage at greater depths. Soil moisture probes were used collect information about the water profile and whether any trends were apparent down to one metre. Figure 31 presents gravimetric water content of soil down to a depth of 800 mm. A capacitance probe was used, and calibrated against excavated soil from which gravimetric water content was measured. Due to limestone in the soil, none of the access tubes were able to be inserted to one metre depth, however offsets were measured and the resulting figure was generated.

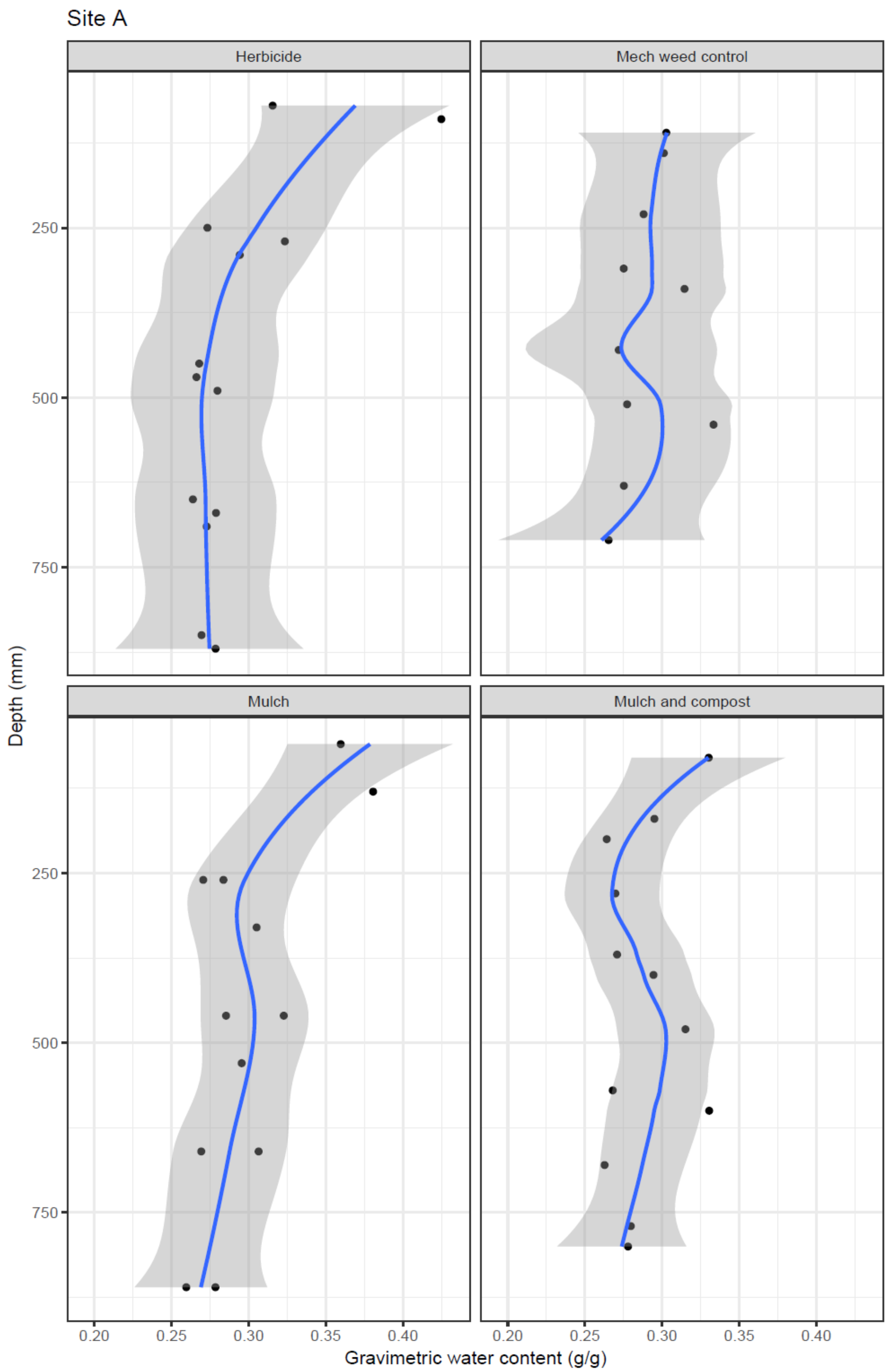

Figure 31: Soil moisture profiles of each treatment at site A from the florescence timepoint. Due to subterranean rocks, tubes were offset above the desired depth. To allow for this, the 'true' depth was calculated by subtracting the depth of the tube from the tube offset. Grey areas are 95% confidence intervals.

At the soil surface the mechanical weed control treatment is drier than all three other treatments, consistent with the gravimetric water content measured separately. Both mulch treatments appear to have a rapid decrease in soil moisture before a similar increase, leading the an ‘S’ shaped curve, with higher moisture contents than other treatments around the 500 mm depth.

Conclusions & Limitations

The overarching aim of the project is to determine the practical feasibility of the use of mechanical weeding, mulching or mulched compost as weed control measures, and quantify their effects on the physiological performance of the vines. Important conclusions can be drawn from each of the treatments trialled as part of this project. They answer the primary aims of the project and provide valuable information for growers in the region. These results are promising; however, they should be caveated with the low yields experienced in Padthaway and across the state in the 2020 vintage. Benefits of the mulch and compost treatment are clear (see below) and provide benefits to grape growers and winemakers, though a thorough economic rationalisation would be needed before this treatment is recommended. The costs of straw mulch and compost, as well as their relative longevity in the field needs to be established to make this possible.

Mechanical weed control

The mechanical weeder was capable of maintaining weed coverage below 10 % of the undervine surface throughout the season. Relative to the traditional herbicide and mulch treatments, the mechanical weeder allowed more weeds to persist, which may have caused a delay in canopy development as can be seen by the lower leaf area index. As mentioned above, operation of the weeder was a work in progress, which proved more effective across the season.

Mulch

The mulch treatment effectively covered all undervine weeds throughout the season. This ground cover also lead to significantly higher soil moisture content in the early part of the season and likely reduced evaporation throughout.

Nitrogen draw down is a risk when applying a high carbon mulch in the absence of any organic N. Though this was not observed, it may be due to the already low levels of nitrogen in the soil at Site A.

At site B the fruit of the mulch treatment had the highest pH and lowest TA relative to all other treatments. This may not be a desirable effect. At Site A these patterns were not significant but the trends were similar. Differences between sites may be due to the cultivar grown at each site, however it is more likely due to differences in soils. At Site B, high levels of sand possibly lead to heavier or more rapid influence of the treatments.

Mulch and compost

The mulch and compost treatment lead to the most profound effects of the trial. High suppression of weeds, high levels of phosphorous and nitrogen in the soil, in concert with higher soil moisture lead, in some way, to higher LAI, lower berry pH, and higher TA and YANs. For soil generally lacking macronutrients (N and P) the addition of organic sources of these elements had large influences on the vines. To justify the most expensive of the treatments, mulch and compost needs to provide value, not only for one year but for a number of years; thus following the effects of this trial for coming seasons would be valuable.

Limitations

The main limitations of the data collected during the project are as follows:

- Poor yielding vintage – Yields were down across the state, up to (and over) 90%, thus it is difficult to make confident predictions about the yields and commercial viability of the trialled treatments.
- Single season's data – While the results are promising, they are for only one season.
- Soil moisture profile problems – A better understanding of how soil moisture is impacted by these treatments at greater depths would be valuable. This was inhibited by rocky soils and the caps of the access tubes being inadvertently dislodged during routine vineyard operation. The installation method for the tubes could be improved for next season, as could the fixing of the caps.
- While the use of three replicates was practical and effective, more replicates with larger plots would increase statistical power and the confidence in the conclusions drawn.
- Only two varieties of grapes were trialled.
- Does not include other Undervine options.

Recommendations

Future work should include continued monitoring and maintenance of this trial to understand the long-term effects of these treatments relative to traditional herbicide undervine weed management in Padthaway. Examining, in detail, how these treatments affect the following parameters would also be of value;

- Water relations,
- Wine composition,
- Economics,
- Soil health
- Carbon stocks.

Increasing the number of varieties in the trial would increase the applicability of this research to other cultivars. Specifically, white grapes should be included in any trial expansion. All treatments tested proved they were viable alternatives to herbicide use for weed control, which may be important as regulations around the use of herbicides change.

Appendix 1: Communication

During the project -an open day was held and the trial site was visited by approximately thirty viticulturalists for a field day. Visitors were shown through Site A, before a short presentation was made by Dr Thomas Lines.

Dr Thomas Lines and Professor Timothy Cavagnaro also spoke with a national news service on the effects of alternatives to undervine herbicide application (McCarthy 2019).

We would welcome the opportunity to work with Wine Australia to produce further outreach. Future communication activities would be highly beneficial, as more valuable data has been collected since the field day. Data on yields and berry quality will be of interest to the local grape growing community. A second field day, online presentation or distribution of the key findings in pamphlet/flier form would enhance the value of this project and help answer the lingering questions in the mind of the interested parties.

Appendix 2: Intellectual Property

No intellectual property, nor specific valuable information has arisen from this research.

Appendix 3: References

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Appendix 4: Staff

Staff, providing in-kind support to this project at the university of Adelaide are;

Joseph Marks –The University of Adelaide - Assisted in trial setup.

Professor Timothy Cavagnaro – The University of Adelaide –Assistance in trial design, analytics and report writing.

Dr Vinay Pagay – The University of Adelaide – Assistance in trial design, analytics and report writing.

Appendix 5: Raw data, statistics and further figures

Full data sets and code for statistical analysis is available upon request.

Weed coverage

Plant available N and gravimetric water content

Table 4: Gravimetric water content and mineral N (Nitrate and Ammonium) from soil sampled at Site A at florescence. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova ($p<0.05$).

	Herbicide		*Mech weed control*		*Mulch*		*Mulch and compost*	
Florescence	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Gravimetric water content (g/g)	0.19 [a]	0.01	0.21 [a]	0.02	0.29 [b]	0.01	0.28 [b]	0.02
Ammonium (ppm)	0.44 [a]	0.12	0.84 [a]	0.54	0.68 [a]	0.14	0.79 [a]	0.34
Nitrate (ppm)	3.33 [a]	1.22	4.00 [a]	5.38	1.32 [a]	0.93	9.92 [a]	6.52

Table 5: Gravimetric water content and mineral N (Nitrate and Ammonium) from soil sampled at Site A at pre-harvest. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova ($p<0.05$).

	Herbicide		*Mech weed control*		*Mulch*		*Mulch and compost*	
Pre-harvest	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Gravimetric water content (g/g)	0.19 [a]	0.04	0.20 [a]	0.01	0.22 [a]	0.02	0.23 [a]	0.01
Ammonium (ppm)	0.43 [a]	0.19	0.47 [a]	0.10	0.56 [a]	0.05	0.60 [a]	0.20
Nitrate (ppm)	2.54 [a]	1.53	1.54 [a]	0.72	0.22 [a]	0.73	2.55 [a]	0.52

Harvest

Table 6: Harvest metrics - Yield per metre, bunches per metre, bunch weight and berry weight, across both site A and B. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova (p<0.05).

		Yield per m (kg)		Bunches per m		Bunch weight (g)		Berry weight (g)	
Site	**Treatment**	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Site A	Herbicide	1.13 [a]	0.38	11.17 [a]	3.49	100.63 [ab]	2.41	0.62 [a]	0.07
Site A	Mechanical weed control	1.14 [a]	0.04	10.78 [a]	1.01	106.06 [b]	7.31	0.60 [a]	0.02
Site A	Mulch	0.94 [a]	0.18	10.66 [a]	1.82	88.03 [a]	2.54	0.67 [a]	0.01
Site A	Mulch and compost	1.18 [a]	0.13	12.30 [a]	1.23	96.06 [ab]	6.86	0.60 [a]	0.03
Site B	Herbicide	1.54 [a]	0.36	8.05 [a]	0.72	192.26 [a]	42.23	0.96 [a]	0.15
Site B	Mechanical weed control	1.73 [a]	0.28	7.74 [a]	1.26	223.56 [a]	10.98	0.91 [a]	0.01
Site B	Mulch	1.02 [a]	0.35	5.31 [a]	1.05	189.06 [a]	30.13	0.99 [a]	0.07
Site B	Mulch and compost	1.55 [a]	0.42	7.61 [a]	1.48	202.43 [a]	32.34	1.00 [a]	0.02

Soil Physicochemistry

Table 7: Soil physicochemical data from samples sent to APAL at the florescence time point at Site A. Data are means of four replicates with standard deviation in the next column. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova ($p<0.05$).

	Herbicide		**Mechanical weed control**		**Mulch**		**Mulch and compost**	
Florescence - Soil Analyte	Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH 1:5 water (pH units)	8.39^{a}	0.04	8.29^{a}	0.05	8.23^{a}	0.09	8.20^{a}	0.08
pH CaCl2 (pH units)	7.78^{a}	0.04	7.72^{a}	0.03	7.71^{a}	0.09	7.70^{a}	0.06
Colwell Phosphorus (mg/kg)	6.33^{a}	0.47	0.00^{a}	0.00	7.00^{a}	0.82	38.00^{a}	28.71
Calcium (Ca) (mg/kg)	4646.67^{a}	146.59	4620.00^{a}	21.60	4693.33^{a}	293.18	4570.00^{a}	380.53
Magnesium (Mg) (mg/kg)	613.00^{a}	58.76	608.00^{a}	32.66	601.00^{a}	17.91	600.33^{a}	30.73
Potassium (K) (mg/kg)	531.00^{a}	51.04	532.33^{a}	61.94	878.33^{ab}	104.95	980.67^{b}	204.72
Sodium (Na) (mg/kg)	317.33^{a}	66.16	262.67^{a}	87.61	283.00^{a}	39.61	373.00^{a}	84.75
Calcium (Ca) (cmol/kg)	23.20^{a}	0.73	23.07^{a}	0.09	23.43^{a}	1.50	22.80^{a}	1.90
Magnesium (Mg) (cmol/kg)	5.04^{a}	0.48	5.00^{a}	0.27	4.95^{a}	0.15	4.94^{a}	0.25
Potassium (K) (cmol/kg)	1.36^{a}	0.13	1.36^{a}	0.16	2.25^{ab}	0.27	2.51^{b}	0.52
Sodium (Na) (cmol/kg)	1.38^{a}	0.29	1.14^{a}	0.38	1.23^{a}	0.17	1.62^{a}	0.37
Ca:Mg Ratio	4.67^{a}	0.39	4.60^{a}	0.24	4.77^{a}	0.45	4.60^{a}	0.14
K:Mg Ratio	0.27^{a}	0.04	0.27^{a}	0.03	0.46^{ab}	0.06	0.51^{b}	0.11
ECR	8.80^{a}	0.79	8.20^{a}	0.75	11.33^{ab}	0.47	13.00^{b}	2.16
CEC (cmol/kg)	31.00^{a}	1.63	30.33^{a}	0.47	32.00^{a}	1.41	32.00^{a}	2.83
Calcium (%)	74.93^{a}	1.48	75.43^{a}	1.23	73.50^{a}	1.47	71.57^{a}	1.64
Magnesium (%)	16.27^{a}	1.03	16.33^{a}	0.65	15.60^{a}	1.06	15.57^{a}	0.69
Potassium (%)	4.37^{a}	0.33	4.47^{a}	0.52	7.07^{ab}	0.82	7.87^{b}	1.35
Sodium (%)	4.43^{a}	0.74	3.73^{a}	1.19	3.87^{a}	0.60	5.03^{a}	0.85
Salinity EC 1:5 (dS/m)	0.25^{ab}	0.02	0.23^{a}	0.04	0.34^{ab}	0.01	0.43^{n}	0.11
Iron (Fe) (mg/kg)	13.00^{a}	0.82	14.33^{a}	0.94	13.33^{a}	1.25	16.33^{a}	1.25
Manganese (Mn) (mg/kg)	8.30^{a}	1.28	7.50^{a}	0.73	7.93^{a}	1.19	7.77^{a}	1.36
Copper (Cu) (mg/kg)	16.00^{a}	1.41	16.00^{a}	2.16	18.00^{a}	0.82	14.67^{a}	1.70
Zinc (Zn) (mg/kg)	3.40^{a}	0.78	4.03^{a}	1.36	4.80^{a}	1.14	4.77^{a}	1.51
Dumas Total Nitrogen (%)	0.28^{a}	0.02	0.29^{a}	0.03	0.30^{a}	0.00	0.30^{a}	0.02
Dumas Total Carbon (%)	2.09^{a}	0.31	1.99^{a}	0.17	2.00^{a}	0.15	2.14^{a}	0.31

Table 8: Soil physicochemical data from samples sent to APAL at the pre-harvest time point at Site A. Data are means of four replicates with standard deviation in the next column. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova (p<0.05).

	Herbicide		Mechanical weed control		Mulch		Mulch and compost	
Pre-harvest - Soil Analyte	Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH 1:5 water (pH units)	8.21 [a]	0.03	8.24 [a]	0.16	8.02 [a]	0.09	8.12 [a]	0.02
pH CaCl2 (pH units)	7.68 [a]	0.04	7.70 [a]	0.08	7.58 [a]	0.06	7.65 [a]	0.01
Colwell Phosphorus (mg/kg)	0.00 [a]	0.00	0.00 [a]	0.00	0.00 [a]	0.00	51.00 [b]	22.99
Calcium (Ca) (mg/kg)	4803.33 [bc]	521.30	5140.00 [c]	100.33	5163.33 [b]	185.71	4633.33 [a]	445.30
Magnesium (Mg) (mg/kg)	715.33 [a]	119.91	705.33 [a]	54.53	739.67 [a]	30.27	663.33 [a]	73.52
Potassium (K) (mg/kg)	539.33 [a]	30.73	611.00 [a]	67.90	919.67 [b]	172.65	1089.67 [b]	119.00
Sodium (Na) (mg/kg)	434.67 [a]	76.08	447.33 [a]	33.83	482.33 [ab]	35.65	644.33 [b]	59.96
Calcium (Ca) (cmol/kg)	23.97 [a]	2.62	25.63 [a]	0.48	25.77 [a]	0.93	23.13 [a]	2.21
Magnesium (Mg) (cmol/kg)	5.88 [a]	0.99	5.81 [a]	0.45	6.08 [a]	0.25	5.46 [a]	0.60
Potassium (K) (cmol/kg)	1.38 [a]	0.08	1.56 [a]	0.17	2.35 [a]	0.44	2.79 [a]	0.30
Sodium (Na) (cmol/kg)	1.89 [a]	0.33	1.95 [a]	0.14	2.10 [ab]	0.16	2.80 [b]	0.26
Ca:Mg Ratio	4.13 [a]	0.37	4.43 [a]	0.33	4.27 [a]	0.29	4.23 [a]	0.05
K:Mg Ratio	0.24 [a]	0.05	0.27 [a]	0.02	0.39 [ab]	0.08	0.51 [b]	0.05
ECR	9.87 [a]	0.90	10.17 [a]	0.62	12.33 [a]	1.70	16.33 [b]	1.25
CEC (cmol/kg)	33.00 [a]	3.74	35.00 [a]	0.82	36.67 [a]	0.47	34.00 [a]	2.94
Calcium (%)	72.37 [a]	0.54	73.37 [a]	0.66	70.97 [a]	1.60	67.63 [a]	1.15
Magnesium (%)	17.70 [a]	1.51	16.60 [a]	1.00	16.77 [a]	0.79	15.97 [a]	0.40
Potassium (%)	4.23 [a]	0.69	4.47 [a]	0.38	6.50 [ab]	1.22	8.17 [b]	0.69
Sodium (%)	5.70 [a]	0.78	5.57 [a]	0.52	5.77 [a]	0.49	8.23 [b]	0.79
Salinity EC 1:5 (dS/m)	0.35 [a]	0.07	0.41 [ab]	0.07	0.54 [ab]	0.11	0.64 [b]	0.09
Iron (Fe) (mg/kg)	12.33 [a]	0.47	12.33 [a]	0.47	12.33 [a]	0.47	17.33 [b]	2.05
Manganese (Mn) (mg/kg)	4.67 [a]	0.26	5.73 [a]	1.11	6.57 [a]	1.22	5.33 [a]	0.33
Copper (Cu) (mg/kg)	13.33 [a]	1.25	16.00 [a]	3.56	16.33 [a]	2.36	12.33 [a]	1.25
Zinc (Zn) (mg/kg)	3.53 [a]	0.48	4.70 [a]	1.56	5.07 [a]	1.62	5.97 [a]	0.87
Dumas Total Nitrogen (%)	0.21 [a]	0.00	0.23 [a]	0.02	0.21 [a]	0.01	0.23 [a]	0.01
Dumas Total Carbon (%)	1.68 [a]	0.12	2.22 [a]	0.40	2.01 [a]	0.17	2.13 [a]	0.25

Leaf blade composition

Table 9: Leaf blade nutrient analysis from florescence time point at Site A. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova (p<0.05).

Florescence - Leaf blade analyte	Herbicide		Mech weed control		Mulch		Mulch and compost	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Nitrogen (%)	2.76 [a]	0.09	2.69 [a]	0.13	3.00 [a]	0.00	3.17 [a]	0.06
Phosphorus (%)	0.19 [a]	0.01	0.18 [a]	0.01	0.21 [ab]	0.01	0.22 [b]	0.02
Potassium (%)	1.05 [a]	0.04	0.94 [a]	0.06	1.04 [a]	0.06	1.10 [a]	0.10
Calcium (%)	1.14 [a]	0.03	1.03 [a]	0.14	1.07 [a]	0.03	1.16 [a]	0.04
Magnesium (%)	0.19 [a]	0.02	0.18 [a]	0.02	0.17 [a]	0.01	0.18 [a]	0.01
Sodium (%)	0.06 [a]	0.00	0.06 [a]	0.01	0.06 [a]	0.01	0.06 [a]	0.01
Sulfur (%)	0.41 [a]	0.04	0.35 [a]	0.02	0.36 [a]	0.02	0.37 [a]	0.03
Boron (mg/kg)	23.00 [a]	1.00	25.67 [a]	1.53	23.33 [a]	0.58	24.00 [a]	1.00
Copper (mg/kg)	23.33 [a]	4.16	23.67 [a]	7.51	17.00 [a]	2.65	17.00 [a]	1.00
Zinc (mg/kg)	39.33 [a]	10.69	40.33 [a]	9.29	30.67 [a]	1.53	34.00 [a]	3.46
Manganese (mg/kg)	61.00 [a]	15.62	63.33 [a]	15.31	50.00 [a]	6.24	51.67 [a]	8.62
Iron (mg/kg)	59.67 [a]	5.51	58.00 [a]	4.36	57.00 [a]	2.00	58.67 [a]	3.06
Aluminium (mg/kg)	44.00 [a]	4.58	39.67 [a]	1.53	37.67 [a]	4.16	40.00 [a]	8.54
Cobalt (mg/kg)	0.17	NA	0.20	NA	<0.16	NA	0.17	NA
Molybdenum (mg/kg)	0.46	0.03	<0.4	NA	0.45	0.06	0.49	0.01
Chloride (%)	0.15 [a]	0.01	0.15 [a]	0.01	0.17 [a]	0.03	0.19 [a]	0.01

Table 10:Leaf blade nutrient analysis from pre-harvest time point at Site A. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova (p<0.05).

Pre-harvest - Leaf blade analyte	Herbicide		Mech weed control		Mulch		Mulch and compost	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Nitrogen (%)	2.03 [a]	0.04	1.99 [a]	0.14	1.94 [a]	0.07	2.01 [a]	0.07
Phosphorus (%)	0.12 [a]	0.00	0.13 [a]	0.04	0.12 [a]	0.01	0.13 [a]	0.01
Potassium (%)	0.97 [a]	0.10	0.94 [a]	0.41	0.95 [a]	0.04	1.02 [a]	0.13
Calcium (%)	2.49 [a]	0.29	2.88 [a]	0.93	2.68 [a]	0.25	2.63 [a]	0.10
Magnesium (%)	0.38 [a]	0.04	0.43 [a]	0.13	0.40 [a]	0.03	0.38 [a]	0.01
Sodium (%)	0.05 [a]	0.01	0.07 [a]	0.02	0.06 [a]	0.00	0.05 [a]	0.00
Sulfur (%)	0.26 [a]	0.01	0.30 [a]	0.11	0.28 [a]	0.00	0.27 [a]	0.01
Boron (mg/kg)	45.67 [a]	6.66	47.33 [a]	17.39	44.00 [a]	4.58	39.00 [a]	1.00
Copper (mg/kg)	116.67 [a]	15.28	223.33 [b]	47.26	133.33 [a]	15.28	156.67 [a]	40.41
Zinc (mg/kg)	30.67 [a]	4.93	48.00 [a]	28.16	32.67 [a]	8.39	23.67 [a]	3.21
Manganese (mg/kg)	57.00 [a]	17.58	91.67 [a]	51.81	61.00 [a]	13.00	52.00 [a]	7.00
Iron (mg/kg)	140.00 [a]	26.46	150.00 [a]	36.06	120.00 [a]	10.00	123.33 [a]	11.55
Aluminium (mg/kg)	126.67 [a]	15.28	153.33 [a]	40.41	113.33 [a]	11.55	120.00 [a]	0.00
Cobalt (mg/kg)	<0.16	NA	0.21	0.06	0.17	0.01	<0.16	NA
Molybdenum (mg/kg)	<0.4	NA	<0.4	NA	<0.4	NA	<0.4	NA
Chloride (%)	0.68 [a]	0.03	0.65 [a]	0.05	0.62 [a]	0.04	0.71 [a]	0.05

Weed cover, leaf area index and pruning weights

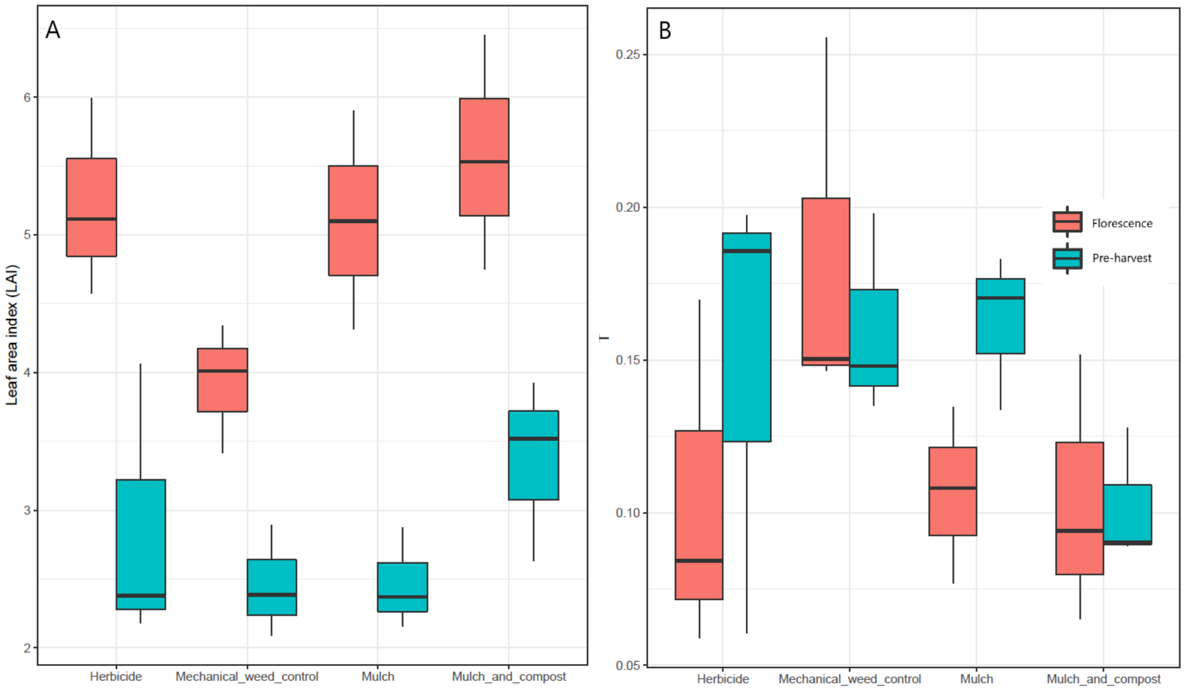

Figure 32: Canopy measurements from Site A; LAI (A) and T (B) across the season.

Table 11: Weed coverage, leaf area index and light transmission ratio from Site A at florescence. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova (p<0.05).

	Herbicide		***Mech weed control***		***Mulch***		***Mulch and compost***	
Florescence	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Weed cover (%)	4.08 ^{b}	1.09	8.02 ^{c}	2.29	0.54 ^{a}	0.79	0.49 ^{a}	0.14
Leaf area index (LAI)	5.23 ^{b}	0.71	3.92 ^{a}	0.47	5.11 ^{b}	0.79	5.58 ^{b}	0.85
T	0.10 ^{a}	0.06	0.18 ^{b}	0.06	0.11 ^{a}	0.03	0.10 ^{a}	0.04

Table 12: Weed coverage, leaf area index and light transmission ratio from Site A at pre-harvest. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova (p<0.05).

	Herbicide		***Mech weed control***		***Mulch***		***Mulch and compost***	
Pre-harvest	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Weed cover (%)	1.92 ^{a}	1.23	5.48 ^{a}	4.71	0.47 ^{a}	0.59	0.11 ^{a}	0.14
Leaf area index (LAI)	2.87 ^{a}	1.03	2.46 ^{a}	0.41	2.47 ^{a}	0.37	3.36 ^{a}	0.66
T	0.15 ^{a}	0.08	0.16 ^{a}	0.03	0.16 ^{a}	0.03	0.10 ^{a}	0.02

Table 13: Pruning metrics and Ravaz index from Site A, post-harvest. Significance (comparing treatments from same treatment and same timepoint) defined by letters as tested by two-way anova (p<0.05).

	Herbicide		***Mech weed control***		***Mulch***		***Mulch and compost***	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Canes per metre	27.67 [a]	2.02	24.50 [a]	3.12	29.33 [a]	3.06	30.33 [a]	1.15
Cane weight per metre	392.33 [a]	16.31	330.00 [a]	147.52	530.83 [a]	160.43	429.50 [a]	32.82
Ravaz index	2.91 [a]	1.09	4.07 [a]	2.16	1.98 [a]	1.04	2.75 [a]	0.15