Paper for submission to journal; Advances in Applied Energy. A report describing a multi-disciplinary study of applied research that investigated pasture production for sheep grazing within commercial scale solar farms in Victoria, Australia.

Microclimate observations and pasture trials within commercial solar farms and their implications for sheep grazing agrivoltaic developments.

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Abstract

Complementary solar electricity and agricultural production enterprises (agrivotaics or agrisolar) are becoming widespread across Australia, although there is little data on the specific growing conditions within these sites. In northern Victoria, Australia, a study was conducted on two commercial solar energy farms to gather evidence on this. Automatic weather stations and sensors were installed outside, between, under, and along the drip lines of solar panels to record temperature, relative humidity, wind speed, wind direction, solar radiation and soil moisture. The objectives were to gather operating conditions data within the solar panels to consider how they may influence pasture growth and animal shelter conditions. Soil moisture measurements showed variations consistent with some interception and diversion of rainfall by the panels, as did soil temperature variability due to the shade cast by the panels. Measurements from trial plots of several forage pasture species (low-growing grasses and legumes) sown within the solar panels provided some practical understanding of their production performance. This gave guidance to system scale modelling of pasture productivity and economic indicators for sheep farming within solar farms. Lamb survival biophysical modelling based on the wind, rainfall and temperature data suggested significant improvement in lamb survival would be possible due to the shelter provided within panel fields. Overall, results from this study provide evidence for how renewable energy infrastructure can co-exist with economically viable sheep production in agricultural landscapes to achieve both power generation and food /fibre production from the same area of land.

Keywords:

Agrivoltaics; Grazing systems; Large Scale photovoltaics; Pasture modelling; dual-use farmland

1. Introduction

Large scale solar farms are being built throughout the world to harvest solar energy for national electricity grids. In Victoria, Australia, there is an increasing interest in the development of solar farms, with over 1 GW of capacity operational and a further 6.6GW approved or under construction in September 2023. [1]

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Goetzberger and Zastrow (1982) [2] first explored agrivoltaic (AV) systems over 40 years ago by proposing a configuration of a solar plant that allowed for additional agricultural use. These authors calculated the fraction of light that was still available for agricultural use and concluded that solar energy collectors/arrays/panels and agriculture were very compatible. Despite this early research, further study on the environment under agrivoltaic systems did not progress until the recent decade. In particular, there have been few studies integrating the variables of climate, soil, energy and agricultural production as they apply to agrivoltaics under Australian conditions.

Agrivoltaics has been defined as "mixed systems associating solar panels and crops at the same time on the same land area" [3] and has been observed to decrease the conflict between agricultural and energy sectors and efficiently and effectively promote sustainable land use [4]. Thus, it is believed that "Agrivoltaic systems are a strategic and innovative approach to combine renewable energy with agricultural production" [5]. Other research is finding that there are multiple additive and synergistic benefits from co-locating photovoltaic and food harvesting on the same areas of land [6,7].

There are potential benefits and trade-offs involved in integrating power generation and agriculture. Benefits to agriculture may include; provision of livestock shade and shelter; enhanced animal reproduction performance; improved plant productivity; protection of plants from frosts and sunburn, better rainfall utilization; additional water resource use. Benefits to the solar farm may include; reduced panel temperatures; reduced on-site dust generation, reduction in fire hazard management costs, additional income generated from the asset [4, 5].

Fire hazard reduction is a particularly important consideration in Victoria and more broadly across much of Australia. Solar farm sites may have a regulatory requirement included in the development application from local fire authorities to minimise grass fuel loads during the fire danger period, such as keeping vegetation to less than 100mm height. Under these regulations, managing the vegetation through grazing may be more efficient and economical than slashing and mowing [8].

Some trade-offs, or potential negative impacts, of combining solar electricity production and agriculture may include; shading effects on crops reducing yield [9]; rain interception leading to uneven soil moisture distribution; air and soil temperature anomalies [10], a build-up of weeds, animal or machinery damage to electrical equipment and the additional compliance costs of both electrical and farm safety.

Several researchers [3, 11-13] conclude that combining solar electricity production with plant production leads to an increase in land productivity ranging from 30% [10] to 70% [3, 8] depending on the plant species that are grown (e.g., whether they are shade tolerant). Similarly, it is important to optimise the system according to latitude by identifying the optimum slope and shading to ensure that sunlight below the panels is sufficient to ensure profitable crop production. A trade-off between panel density, slope angle or tracking system of the panels may be required [3, 9].

Research nearly a decade ago by Marrou et al (2013) [14] to determine if the microclimate under AV systems varied from land not under photovoltaic panels (PVP) panels found that wind speeds were similar and there were no significant effects of shading on air vapour pressure deficit (VPD) or humidity. These researchers included the crops of lettuce, cucumber (short cycle crops) and wheat (a longer cycle crop) in their study. Mean daily soil temperature decreased under panels but there was little difference observed in mean daily air temperatures between the shade and full sun treatment.

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Amaducci et al (2018) [15] found that soil temperatures and evapotranspiration levels were lower under PVPs than in full light conditions. These researchers found that on average, PVP provided more favourable growing conditions for plant growth than in full light and indicated that agrivoltaic systems could increase crop resilience to climate change.

Other research on the measured benefits of grazing pastures under solar panels is reasonably scarce. In a study in Oregon USA, Andrew (2020) [12] concluded that grazing under solar panels can maintain a higher carrying capacity of pastures toward summer, and that land productivity could be increased up to 200% through combining sheep grazing and solar electricity production on the same land. Likewise, a land-use efficiency of 183% was reported in Fraunhofer (2020) [16] due to the combination of energy and agricultural outputs.

Selecting suitable plant species for solar panel arrays can benefit from accurate information on the environmental growth conditions such as soil moisture, temperatures and light/irradiance (shading) around under the solar panels as well as knowledge of individual species tolerances to these growth conditions [17-19].

Information on shade tolerance of many agricultural plants indicates that shading can have a range of impacts, both beneficial and detrimental, depending upon the plant species [13]. In most plants, full sun (or open sky) growing conditions can provide more light than plants can use, known as light saturation point [20], beyond which the increased light intensity does not increase the rate of photosynthesis. Temperature extremes and less than optimal water availability can also curtail photosynthesis, especially in dryland farming systems. Shade tolerant plants are also optimised for light harvesting, adapting their photosynthesis to function optimally under low light conditions [21] and often obtaining a high proportion of light energy as back-scatter and diffuse light [22].

The range of suitable crops that have been reported to grow well under the type of shading provided by low density solar panels include: aloe vera, lettuce [14], tomatoes, pastures, maize [22,23], blueberries, celery, rye, oats, sugar beet [2], as well as shade tolerant grasses such as orchard grass (cocksfoot)[24]. Annual clover pastures (sub clover, balansa clover and gland clover) have also been identified as being appropriate for agrivoltaic systems in south-eastern Australia because of their low growth habit and because these species dry or hay off in late spring which reduces the fire risk [25]. Further testing of swards with mixed species, including some suitable legumes (clovers) would boost natural nitrogen capture as well as enable the plant species to find their more favoured niche within the open sky, dripline and shaded soil locations beneath the solar panels.

Given the limited research related to livestock production in AV systems for local conditions, the study reported here was funded by the Victorian Government Agriculture Policy branch to fill some of these local knowledge gaps. In Australia, commercial solar farm developments are most likely to be developed on farmland, often dryland grazing farms, where rainfall is mostly less than 700mm per year. Increased state and national requirements for renewable electricity to meet emissions reduction targets and replace retiring coal fired power stations is placing pressure on governments to approve developments, yet community sentiment often opposes solar developments on the grounds that it will erode food production or alter local climatic conditions.

This study was conducted on two commercial solar energy farms where climatic sensors were installed within and outside of the panels to record climatic variables, soil moisture and soil temperature. Pasture trials within panels in combination with climatic information informed modelling of solar farm scale pasture production potential, sheep stocking rates and economic aspects of grazing agrivoltaic systems. Models used were existing proprietary models of Victorian

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farming systems. Climatic data was used to test what the influence solar arrays might be on animal welfare and lamb survival and generally improve understanding of the interaction of solar energy harvesting on agricultural production.

2.0 Methodology

2.1 Study sites

The measurements and pasture trials were undertaken at two commercial solar farms in northern Victoria, Australia, with climatic data collection commenced in Spring 2021. Notably, establishing and running this study was a significant achievement despite complications arising from COVID related travel restrictions, construction site access regulations, financial limitations and commercial in-confidence arrangements. Figure 1 shows the location of the two study sites in relation to Australia and the state of Victoria.

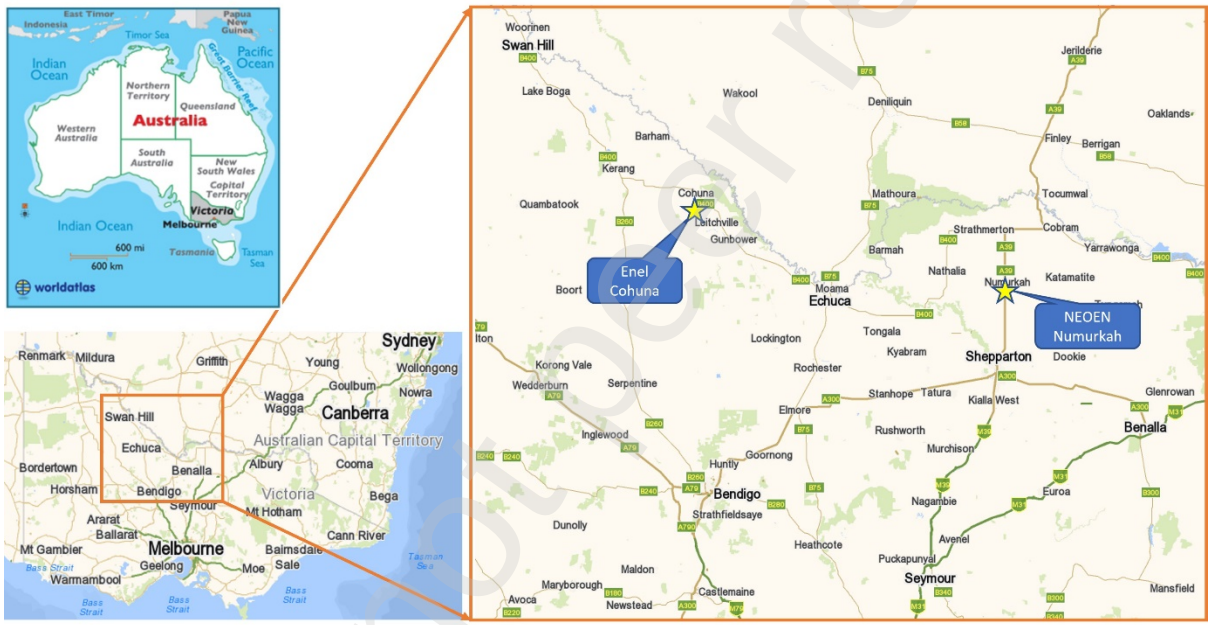


Figure 1. Locations of the two commercial solar facilities on which this study took place; Enel Cohuna (35°52’50.01”S, 144°13’12.30”E) and Neoen Numurkah (36°9’34.46”S, 145°28’26.78”E).

The solar arrays and tracking systems at both sites comprised north south aligned panel rows on single axis (east-west) tracker tables. At the Numurkah site, single solar panel rows were spaced about 7 metres apart, while at Cohuna, each row consisted of two bi-facial solar panels mounted end to end on tracker tables spaced about 13 metres apart. Both configurations result in a panel coverage of about 33% of the land area when horizontal. Importantly, the solar panel tracking of the sun prevents fixed areas of shadow falling on the land under the panels, but a strip of land also receives less rainfall under the panels.

The predominant soils of northern Victoria’s riverine plains region are described as red-brown to grey-brown earths, depending upon drainage and landscape position relating to the alluvial geomorphology of the Murray River floodplain. [26, 27]. On the Victorian soil map [28] the solar farms occurred within areas mapped as being dominated by sodosols, which due to recent (5 decades) history of high watertables and soil salinity problems, often have sodic subsoils, although the Numurkah area has lower salinity risk than the Cohuna site.

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2.2 Climate and soil monitoring

At each study site, two high-end ICT™ International brand automatic weather stations (AWS) were installed, one outside of the solar panel arrays on vegetated open ground and a second within a large solar panel array block at least 80 metres in from the edge. The external weather station was equipped with rain gauge, air temperature and humidity sensors, solar radiation (pyranometer), a single 80cm depth soil moisture and temperature probe, a barometric sensor and anemometer. The second AWS had temperature, humidity, anemometer and three temperature/soil moisture sensors to 40cm depth. Four additional Dragino™ temperature and humidity loggers were also placed about 40 metres to the north, east, south and west of the panel field AWS, while a further two loggers recorded solar panel temperatures.

The soil moisture probes at each study site are EnviroPro™ EP100GL probes, with an 80cm deep 10cm interval probe attached to the outside panel AWS and three 40cm deep by 10cm interval probes connected to the in-panel AWS. These soil probes were placed at centre row, on the drip line and one under the panel centre. They provide soil moisture readings as volumetric water content (VWC%). Accuracy is stated as ±2%@ 0%VWC to 50%VWC. Fifteen-minute readings from each 10cm depth sensor (including temperature) has been reliably received into an Amazon Web Services database.

Ultrasonic wind speed and direction sensors were part of each AWS, set at an observation height of 2 metres above ground. Analysis of the whole of year monitoring data from the out-of-panel AWS compared to the in-panel AWS was carried out using the WindRosePRO™ version 3.01 software to generate wind rose plots and statistical outputs.

Data was recorded in real time using LoRaWAN (Long Range Wide Area Network) and IoT (Internet of Things) technology. Each of the solar farm field sensors transmitted data through a LAIRD™ gateway via a 4G mobile data router powered from the solar farm operations buildings. A remote video camera running on a separate online platform allowed viewing of the solar panels and capture of shadow movement across the ground as the panels tracked the sun during the day. Data received by the IoT was quality checked, processed into sensor type and passed into a secure, Amazon Web Services 'S3' cloud storage database, containing over twelve months of 15-minute interval data from the two study sites.

2.3 Pasture Trials

Experimental plots of five pasture species were established at the two solar farms within the solar arrays. Herbicide was applied several weeks before the plots were rotary hoed, raked and divided into 20 x 1.5m strips 7m long under the single panel system and 9 metres long under the double panel system. This allowed four replicates of each of the five test forage species.

The plots were established in May (Cohuna site) and September (Numurkah site) 2021. They were sub-divided for measurement purposes into three zones relating to the overhead solar panel positions: (i) between the solar panel rows, (ii) under the solar panels and (iii) under the panel driplines. Figures 2a and 2b show the trial plots.

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Figure 2a and b. Pasture species trial plot under the double panel system at the Cohuna site (left) and the seven metre plots under the single panel system at the Numurkah site.

Plot management consisted of single superphosphate and urea application at a rate of 5 g/m2 prior to hand sowing the seeds which were then watered to aid establishment. Thereafter, the plots then relied on rainfall . Broadleaf weeds were controlled by spraying with a selective herbicide and grassweeds were controlled by hand weeding.

The frequency of measurement of the pasture trials was dependant on how the seasonal rainfall conditions unfolded, but in general were as follows:

- Plant establishment – an estimate of the number of germinated seedlings at each position in each plot. This measurement was made in June at Cohuna and November at Numurkah.
- Plant cover – an estimate of the number of plants at each position in each plot. Four measurements were taken at the Cohuna site and three at the Numurkah site.
- Dry matter production was measured by harvesting each species sub-plot using a rotary hand-mower on seven occasions on the Cohuna site, but due to late sowing and dry summer, only one cut was made from the Numurkah trial site. Each cut (from each position in relation to the overhead solar panel) was weighed separately. Samples were then dried at 100 C for 48 hours to measure dry matter production.

2.4 Estimating solar panel impact on lamb survival.

The potential of the solar farm to provide a more favourable environment for the survival of new-born lambs was estimated using previous work on the mortality of Merino based on chill index equations of Nixon-Smith (1974), Donnelly (1984) and Young (2014) [29 - 31].

The study used hourly data for wind speed, temperature and rainfall recorded by the AWS outside the panels and wind speed and temperature measurements within the panels for the Nurmurkah site from May to August 2022. Three scenarios were simulated:

(a) The open area, calculated from the AWS outside the panels.
(b) Within the panels assuming the panels offered no protection from rain, using rainfall data measured at the site, and
(c) Within the panels assuming the lambs could find sufficient protection from rain that their skin remained dry, using rainfall of zero.

2.5. Pasture production simulation

Three established and industry used daily pasture growth models were used to simulate pasture production for sheep grazing under panels. The pasture growth models were selected based on

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their validated ability to simulate specific pasture species production for different climatic zones in Victorian farming. The models were: (1) Grassgro [32,33] (to simulate lucerne, cocksfoot and kikuyu; (2) DairyMod [34] to simulate perennial ryegrass, annual ryegrass, phalaris and tall fescue; and CAT (Catchment Assessment Tool) [35,36] to simulate a generic native. Each model was run to evaluate six scenarios chosen to explore mild to extreme solar panel interactions with rainfall and light availability to see how it might influence pasture production. Averaged daily climatic data for the two study sites for the period 1 Jan 2000 to 31 Dec 2021 were sourced from the Australian National meteorological records for the locations [37] and informed by the data recorded at the two sites. The simulation scenarios are as follows:

- Control condition: This scenario represents the environment outside the solar panel zone of impact.
- Scenario 1: Any rainfall less than 5 mm/day were discarded on the basis of redirection by the panel and a 30% reduction in solar radiation.
- Scenario 2: Assume 25% reduction in rainfall due to shelter from the panel and a 30% reduction in solar radiation.
- Scenario 3: Assume 50% reduction in rainfall due to shelter from the panel and a 30% reduction in solar radiation.
- Scenario 4: Assume a 30% reduction in solar radiation (no adjustment to rainfall)
- Scenario 5: Assume a 50% reduction in solar radiation (no adjustment to rainfall)
- Scenario 6: Assume a 75% reduction in solar radiation (no adjustment to rainfall)

The scenarios were not intended to represent the specific conditions of the two trial sites; rather, the models were used to satisfy more general testing of enterprise scale questions about pasture production and management and the thresholds at which sheep production is economical for pasture species suitable under different densities of panels. The modelling was a practical addition to the study because is utilised in-house modelling capability to economically expand study findings and may help subsequent work address new questions and uncertainties.

2.6 Sheep grazing economic modelling

The GrassGro^{TM}, decision support tool developed by Australia's CSIRO [32] was also used to model plant production and economic returns to see how the industry based sheep production models might inform the potential of large scale Agrivoltaic sites for sheep production. This model was selected because it is an Australian sheep industry accredited model and simulates a whole grazing enterprise including soil-water-plant interactions, management and financial details. The enterprise selected for GrassGro modelling was based on typical Victorian wool production enterprises, being a medium-fine wool self-replacing flock (Merino ewe X Merino ram) representative of the current sheep system on the Neoen site.

Main parameters used for the GrassGro simulations were based on published research with GrassGro [38-39] and the standard GrassGro3 settings (e.g., for sheep, lamb and wool prices).

The following rules were developed based on previous GrassGro studies in Victoria:

- Pasture mass rule: Maintain more than 800 kg dry matter/ha (dead and total) on the paddock from 1st January through to 30th April for at least 8 out of 10 years.

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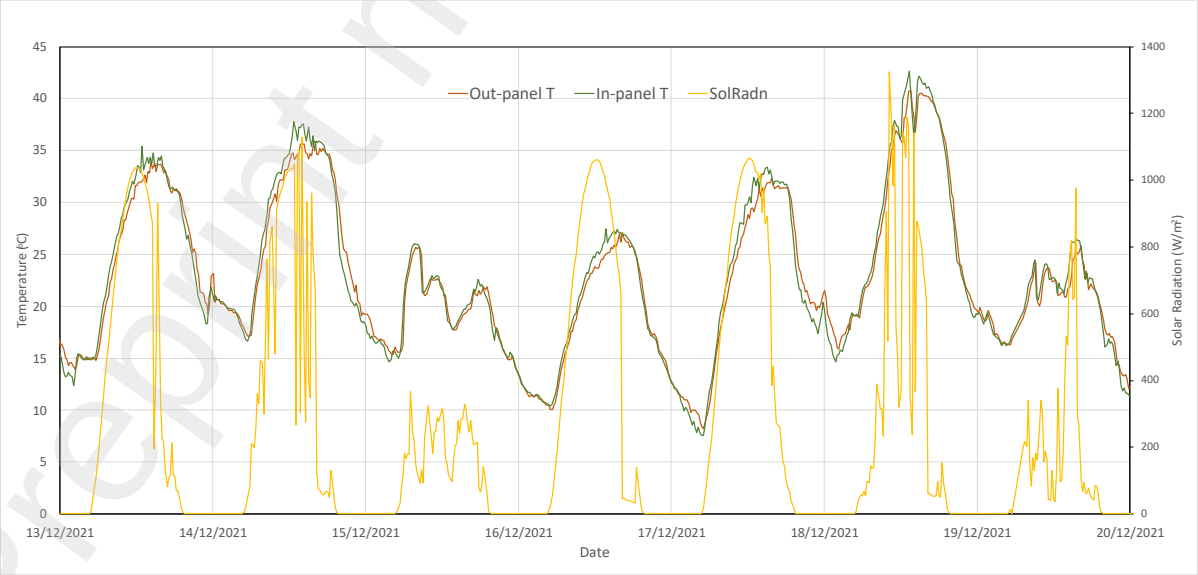
- Supplementary feeding rule: Feed ewes>30 g grain/head per year in only four out of ten years. (Thus, the upper limit for stocking rate for each enterprise was defined as the highest that could meet these two rules).
- A fertility scalar of 0.9 was used in all simulations.
- Soil type was not a variable.

Simulations were run over 12 years using rainfall records from 1 January 2010 until 10 August 2022 using BOM/SILO data with FAO 56 (evapotranspiration). This period includes a range of climate situations (drought and wet years) and produced a range of farm production scenarios (as per Tocker et al, 2020 [40). The SILO data was used because of the need for multi-year input to the models. Adjustments to the rainfall and ET data to reflect micro-meteorological difference within the panel fields was not considered necessary because there was no statistically significant difference in the majority of temperature readings measured within the panels.

3.0 Results

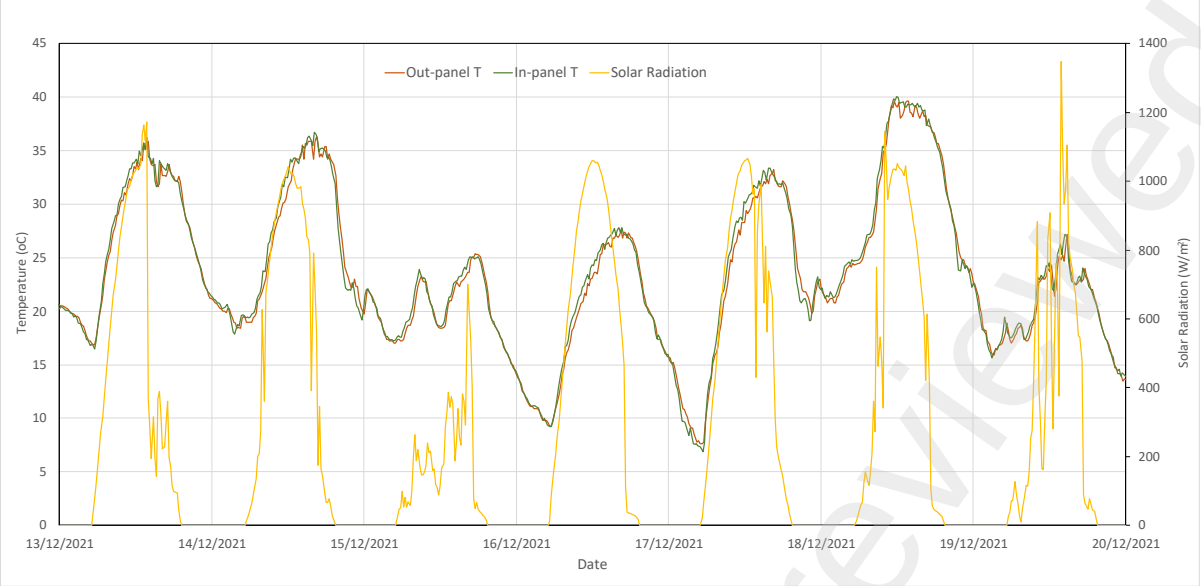
3.1 Climate Monitoring

Plots of time-series temperature data comparing the outside and in-panel array data showed that there was very little separation of the temperature readings. A slight separation of readings at certain times of the day indicated that slight warming of the air at sensor height occurred as the sun warmed the nearby panels and metal support structures. Figure 3a and 3b show air temperature for an example week in December 2021 for outside air temperature and within-panel air temperature, together with solar radiation from the two study sites. This is most clearly illustrated on the clear days of 14, 16 and 17 December, when the air temperature within the arrays was up to 2 degrees warmer than at the AWS outside the arrays for a few hours when peak sunlight energy was warming the panels. Note also that on some clear sky, low wind speed nights, the night-time air temperature appears to cool slightly faster, becoming 1 – 2 degrees cooler compared to outside the panels before dawn. Hundreds of days of data for each site showed similar results.



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Figures 3a and b. Example plots of air temperature (°C) from the two solar farms for one week in December 2021. Note there is slight separation of air temperature readings within the solar panels compared to the out of panel field readings on sunny days and clear nights (green = in panel field, brown = outside; yellow trace = solar radiation (or irradiance) on right axis, w/m^2).

3.2 In-field temperature variation

Comparison of the mid-row AWS temperature data with the stand-alone thermometers placed at the four main compass points on the metal support structures (see figure 4) showed that on sunny days, the daytime peak air temperature achieved was several degrees higher than the out-of-panel AWS air temperature. Sensors attached to panels showed a similar temperature pattern, but with slightly higher peak temperatures. Statistical analyses indicate that average temperature in the panel structure was one degree warmer at the Numurkah site and two degrees warmer at Cohuna, likely due to air around the sensors being warmed by the solar panels and metal structure components.



Figure 4. One of the small Stevenson screen housed T&H Dragino LoRaWA sensors installed on a panel structure support.

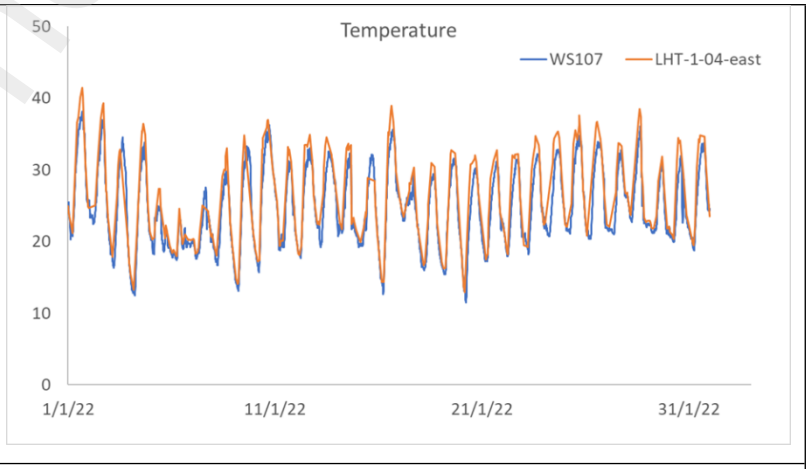


Figure 5. An example of one month's temperature data comparing the in-panel structure air temperature with the out of panel air temperature for January 2022.

3.3 Statistical analysis of SILO vs AWS temperature

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To enable use of long term BOM records for grazing production simulations, the measured sensor data was compared with the same period BOM data to determine if the key parameters of temperature and humidity on the solar farm sites were significantly different. Visual comparison indicated a strong concordance between the data, but analyses using EXCEL and GENSTAT were conducted to determine if some sensors was statistically different.

Analysis of temperatures for the solar farm against the daily minimum and maximum temperatures obtained from the BOM – SILO data-drill location nearby is shown in Figures 6 – 7. Each figure shows on the left daily readings of maximum and minimum temperatures recorded by the out and in-panel AWS and T_{max} from the SILO data. The right hand regression plots show correlation of the maximum and minimum temperatures accord quite closely, but the slightly higher air temperatures within the panel field on sunny days (illustrated in figure 3) translate into the slight separation of the lines Max T-109 and Max T-107.

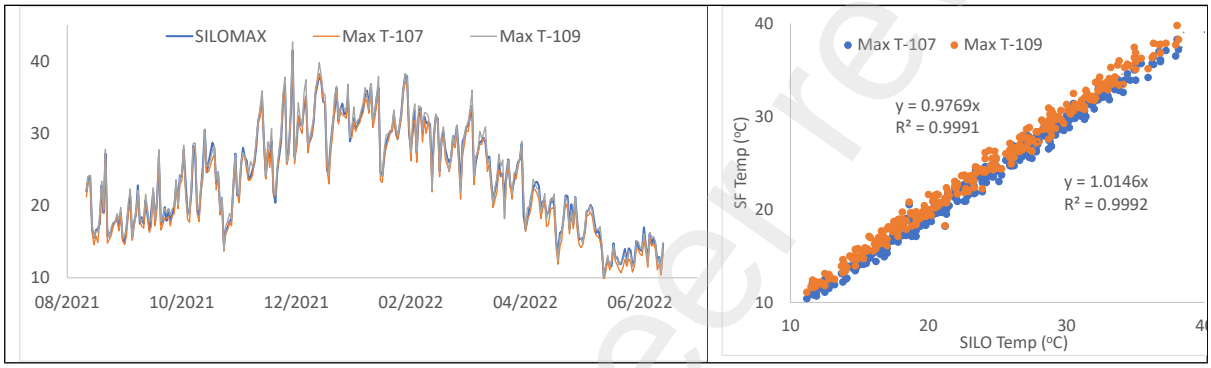


Figure 6. Numurkah Solar Farm AWS 107 (out of panel) & 109 (in-panel) against SILO Site 'Drumanure' (Latitude: -36.15, Longitude: 145.50) maximum day temperature; daily readings on the left, regression plot on right.

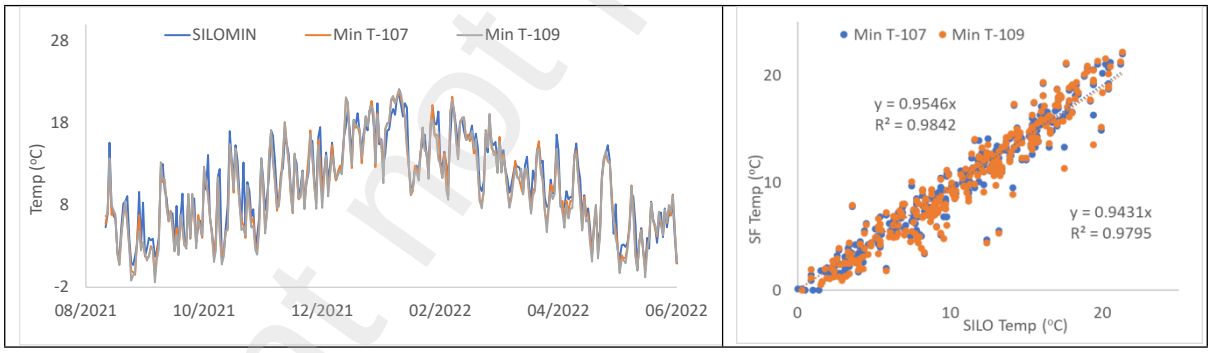


Figure 7. Numurkah Solar Farm AWS 107(out of panel) &109 (in-panel) daily minimums against SILO minimum day temperature; daily readings for the year on the left, regression plot on right.

Note that the daily maxima lines show the in-solar panel field air temperature orange points plotting slightly above the blue out-of-solar field points, which accords with the daily peak, sunny day temperature separations illustrated in Figure 3.

Daily maximum and minimum temperatures were compared to location derived SILO daily climate data, which were found to be closely correlated (Table 1). Lin's concordance correlation coefficient (LCCC) was used to measure how well the one set of observations reproduce an original. In this case, the four AWS daily T readings from each site and their corresponding SILO daily T_{min} and T_{max}. Over 300 days data were compared by linear regression in GENSTAT and the results for the in-panel and out-panel AWS are tabulated below.

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Table 1. Concordance figures for statistical comparison of the two site AWS with BOM SILO sources T_{max} and T_{min}.

AWS#	Concordance	Lower95%	Upper95%	Correlation	Cb
Min T-107 (o)	0.96	0.95	0.96	0.96	0.99
Min T-109 (i)	0.95	0.93	0.95	0.96	0.98
Max T-107 (o)	0.99	0.98	0.99	0.99	0.99
Max T-109 (i)	0.99	0.99	0.99	0.99	0.99
Min T-108 (o)	0.95	0.93	0.95	0.97	0.97
Min T-110 (i)	0.94	0.93	0.95	0.96	0.97
Max T-108 (o)	0.99	0.99	0.99	0.99	0.99
Max T-110 (i)	1.00	0.99	0.99	0.99	0.99

NOTES: (i) – indicates in-panel; (o) indicates outside panel field
Values of 1 show perfect concordance.

The results for T_{min} (shaded grey, above) show strong agreement with the SILO data, but as indicated by the slightly greater scatter compared to T_{max}, (compare Figures 34 & 35) the T_{min} concordance is not quite as close to unity as T_{max} is.

3.4 Humidity

Data recorded every fifteen minutes by the AWS humidity sensors showed that there was little separation in readings in-panel compared to outside the panel field. Figure 8 shows a month of data from December 2021 from the Numurkah site, showing only slight separation in values at the daily peaks and troughs. The same pattern was observed at the Cohuna site.

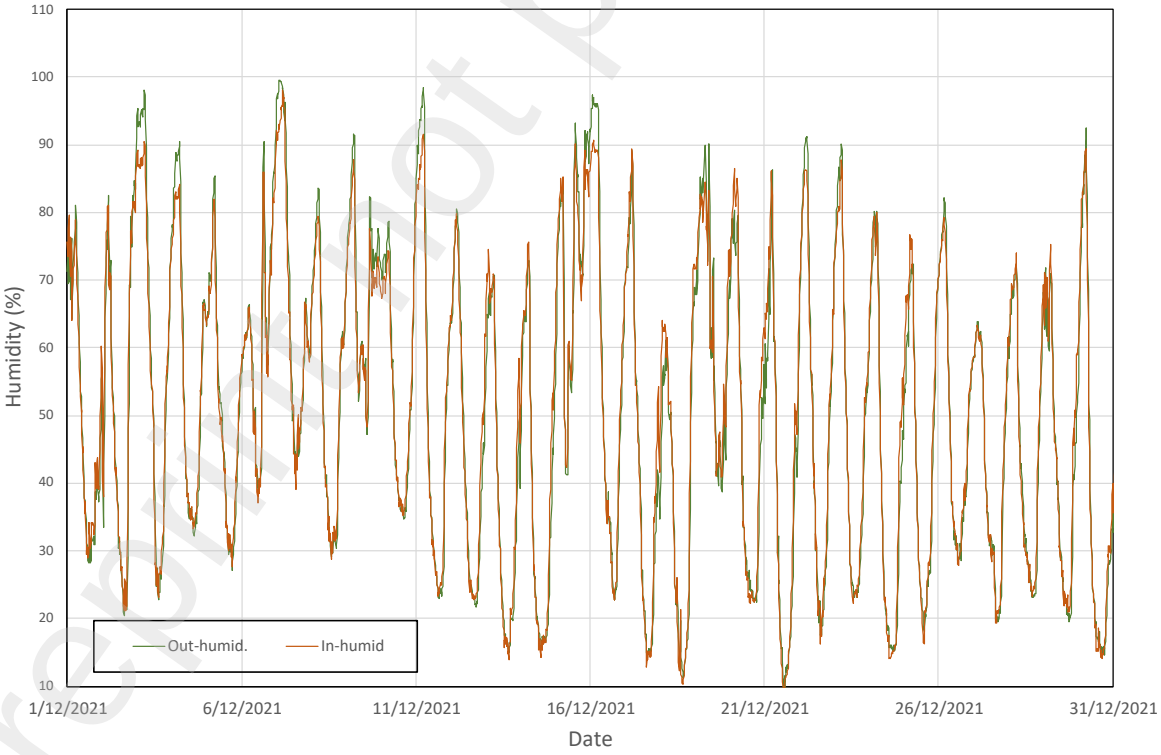


Figure 8. In-field and outside panel area humidity readings for December 2021 from the Numurkah study site.

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The complex interplay of sunlight, rainfall, condensation and wind on humidity readings is illustrated by plotting temperature with humidity (figure 9). For a week in June 2022, the humidity (left hand axis) behaved inversely to temperature (right hand axis) which rose and fells with the diurnal cycle. The slight daytime warming of the panels and structure and night-time cooling and condensation effects of the metal and glass also seemed to influence the in-panel humidity compared to the outside observations.

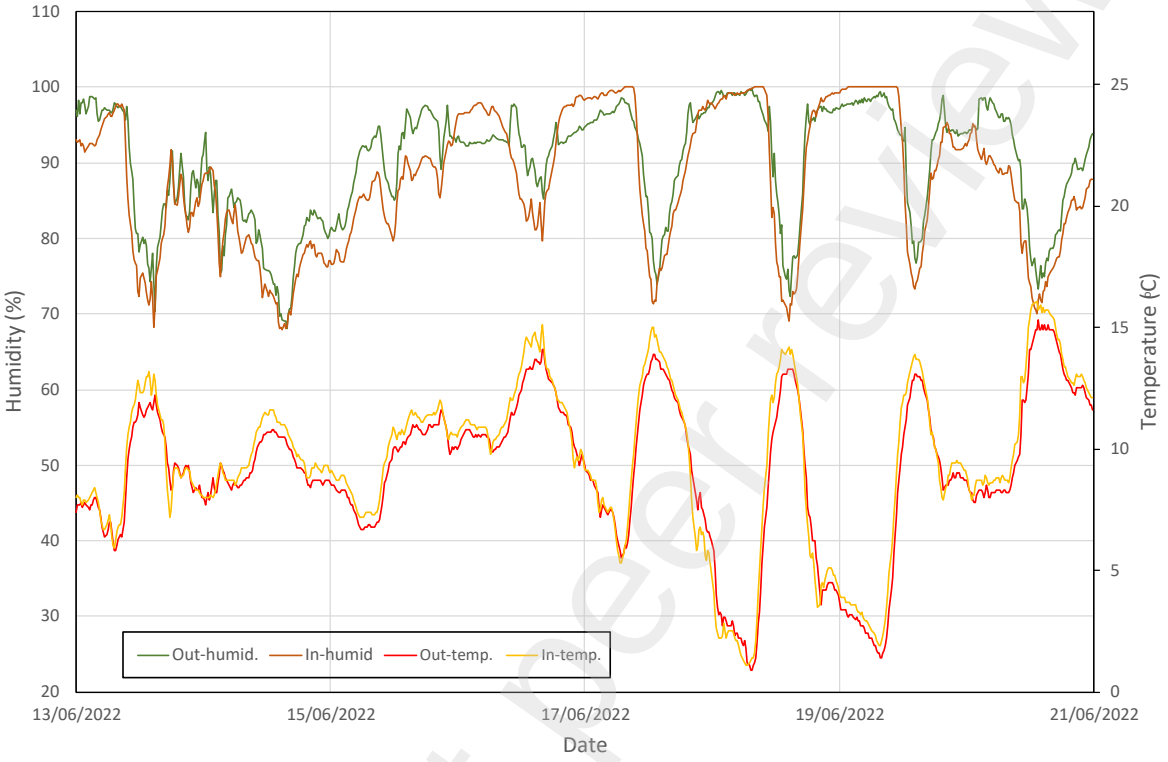


Figure 9. One week in June illustrating the temperature-humidity dynamic for the infield and out-of-field AWS data. As daily T rises (yellow and red, RH axis), H declines (green and brown, LH axis) illustrating little humidity difference for pasture conditions under the panels.

3.5 Soil Temperature

Soil temperature data from the soil probes connected to each AWS show separation in temperature during the summer months (Figure 10– Numurkah site). Half-hour photographs taken during the December 2021 solstice show the passage of the panel shadow over the ground which may explain the reduced soil temperature recorded directly under the panel centre line. (see powerpoint animation attached after reference)

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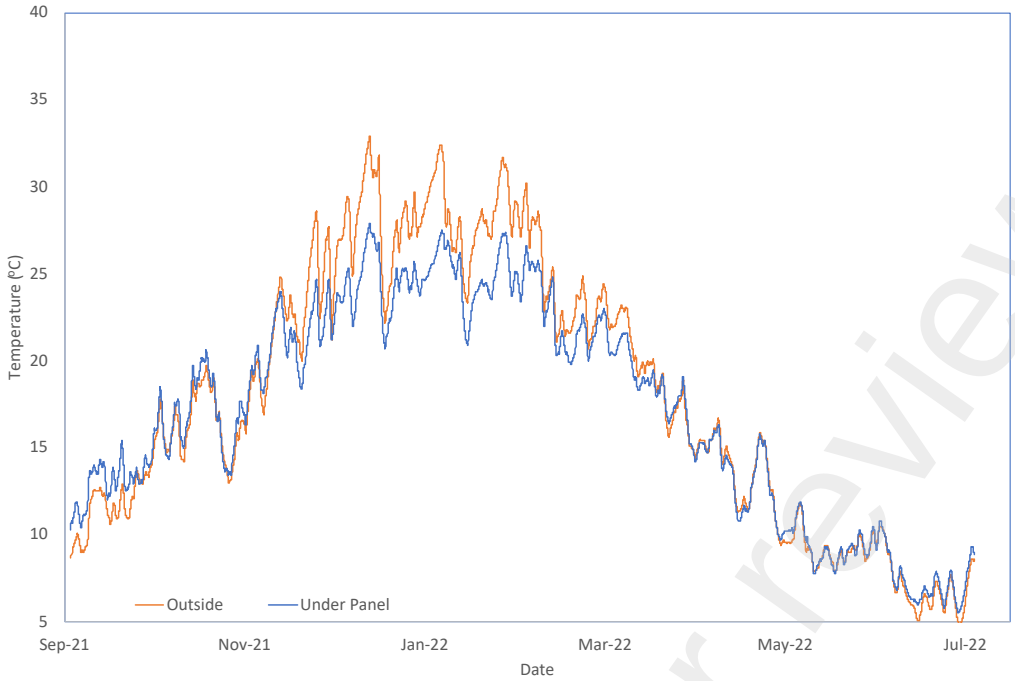


Figure 10. Soil T for 10cm depth, comparing outside panel field (orange trace) to under panel shadow zone centre (blue). Note the low points, where the temperature converges, are associated with rain events. The September 2021 separation may be due to dry conditions and winter frosts having greater cooling on the open field measurement soil.

The ground temperature beneath the panels was reduced over the hottest months by shading from direct sunlight. Note that soil temperature difference largely disappeared post March 2022, where good rainfall over Autumn also brought soil moisture levels close to each other across the site. When compared to the start of monitoring in September 2021, the under-panel soil was considerably drier, perhaps enabling the observed temperature separation.

Daily fluctuations in soil temperature (Figure 11) at the height of summer show all positions warming as the sun moves overhead, but soil directly below the solar panels was up to 9 degrees cooler than the mid row soil and up to 7 degrees cooler than the out-of-panel 10cm soil. Note also the soil temperatures returning to near parity overnight and during days with cloud cover (e.g. later in the week), where soil temperatures at the three sensor positions converged.

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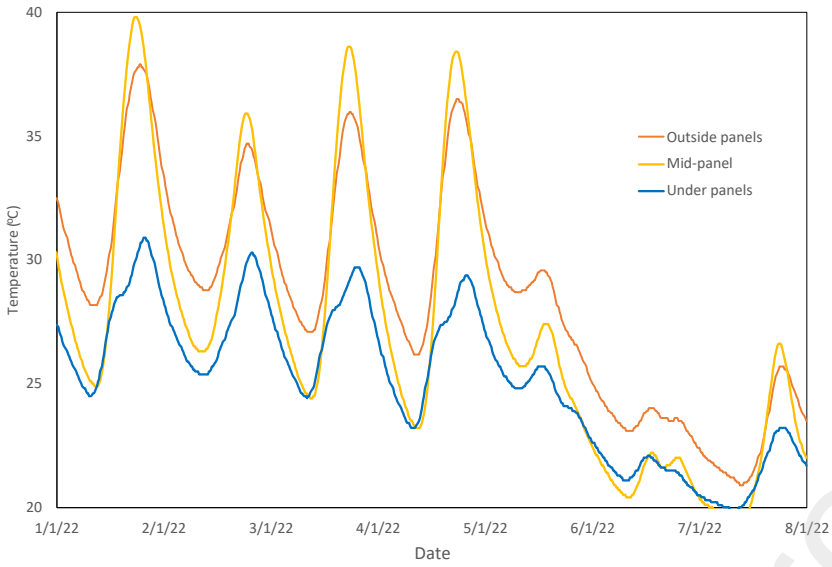


Figure 11. Detail of 10cm depth soil temperature behaviour for a week in early January 2022 comparing the out-panel, mid-row and under panel shadow, 4-hour moving average. Note that during this time, soil moisture levels were low.

3.6 Soil Moisture

Comparisons of the data from the out-of-panel sensor and the sensor midway between panel rows show comparable wetting and drying throughout the year. Substantial difference in soil moisture existed between the under-panel rain-shadow sensors and the dripline sensors (Figures 12 & 13). These illustrate rainfall redistribution by the solar panels, albeit less so at the Numurkah site during the wet autumn period than was seen at the Cohuna site.

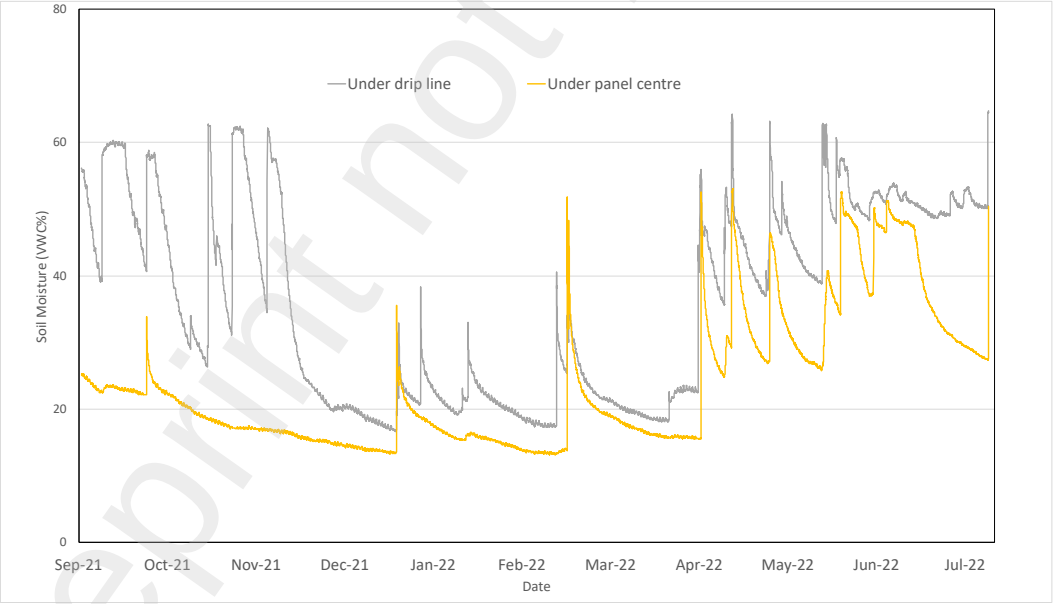


Figure 12. 10cm depth soil moisture plots (%VWC, y axis) comparing the dripline and shaded under-solar panel sensor data for the Numurkah study site for the year Sept. 2021 to July 2022.

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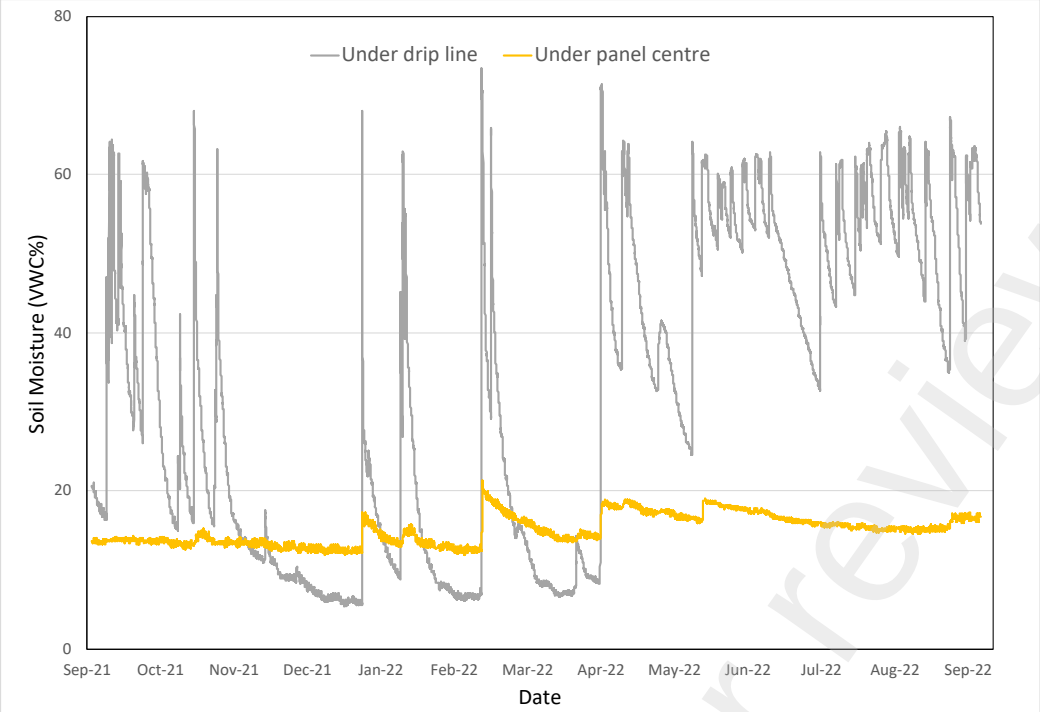
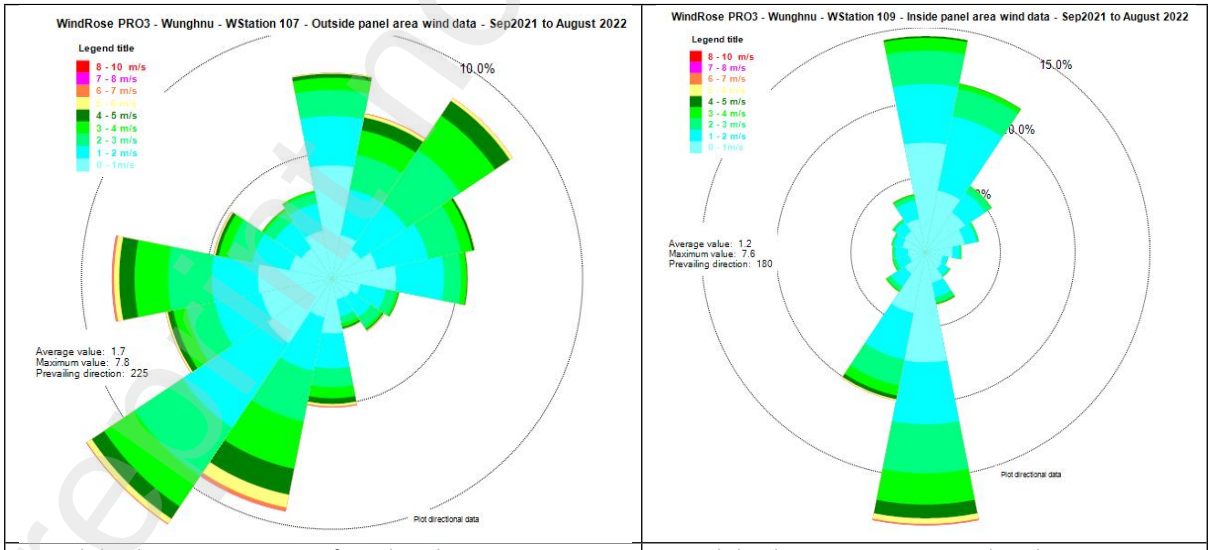


Figure 13. 10cm depth soil moisture plots (%VWC, y axis) comparing the dripline and shaded under-solar panel sensor data for the Cohuna study site for Sept. 2021 to Sept. 2022.

3.7 Wind speed and direction

The year of data was processed to monthly plots to compare seasonal variations reflective of the prevailing seasonal conditions in northern Victoria. Aggregation of the monthly data to yearly plots (Figure 14) show quite clearly the attenuation of wind speed and directional realignment between the outside panel AWS (left) and the in-panel AWS (right).



Numurkah Solar Farm, WS107 out-of-panel windrose. | Numurkah Solar Farm, WS109 In-panel windrose

Figure 14 – Windrose and compass direction plots for the whole year of recorded 15 minutes interval data from the two AWS at the Numurkah site. (Windspeed is indicated in colour segments)

Attenuation of wind direction was more strongly observed at the Numurkah site simply because the out-of-panel AWS at Cohuna could not be located as far from influence of the next panel block to

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the south. The height of the Cohuna panels was also greater, so wind direction was more north-south aligned. Average and peak windspeeds within the panels at both study sites were very similar.

3.8 Trial pasture plot results

The seasonal response of the trial plant species influences the interpretation of the data for the field plots. The trial plots at Cohuna were sown in autumn 2021 and evaluated for the year, but the Numurkah site was not able to be sown until September, so it missed early season rainfall and produced limited field data.

The autumn sowing at Cohuna favoured production for the temperate species – perennial ryegrass and tall fescue. While there was some rainfall in January, December and February were dry, so the summer active kikuyu and Chloris had limited growth opportunities. Images of the plots are shown in figure 15. Note though that kikuyu growth in Autumn 2022 did respond well to rainfall while soil temperatures remained warm.

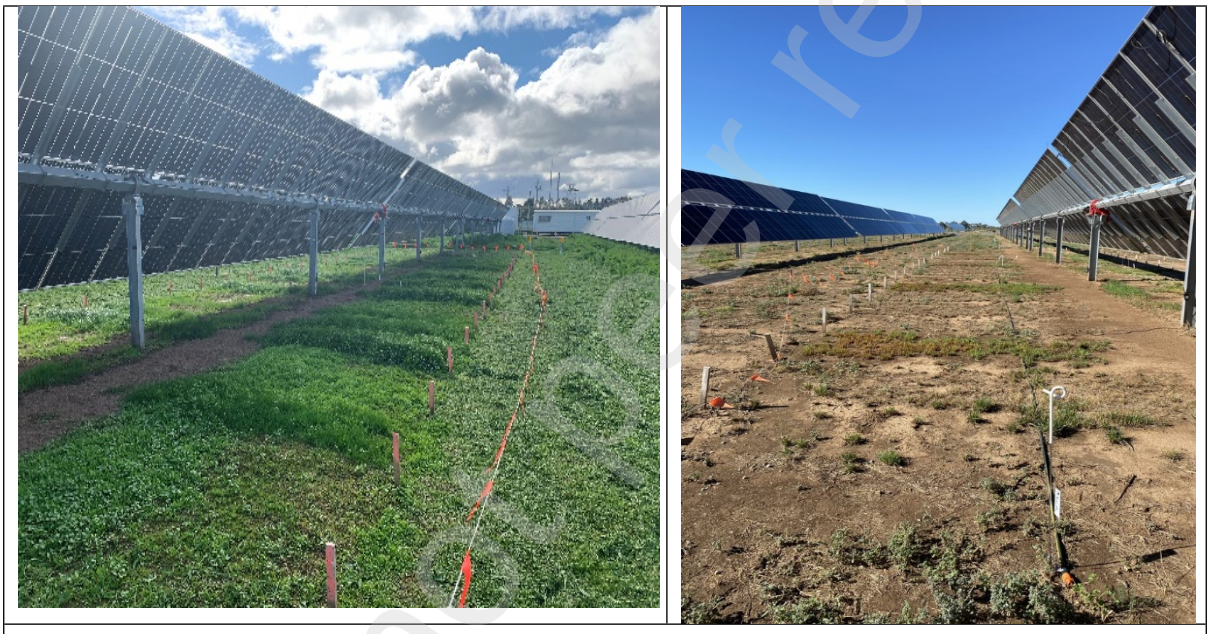


Figure 15. Experimental plots at the Cohuna site showing lush growth from September 2021 and dry conditions in March 2022 (right)

The temperate perennial species - perennial ryegrass and tall fescue achieved highest plant cover rates during winter and early spring, reaching up to 90%, but decreased over the warmer months to less than 30% (figs 16 a&e). In comparison, the summer growing species *Chloris truncata* and kikuyu (figs 16 c&d) were slower to establish, however, in these species, plant cover increased as the temperatures rose in late spring and summer, reaching a maximum of around 70% for kikuyu. For annual ryegrass, plant cover was greatest during winter and spring (up to 95%), after which the plants produced seed and senesced (figure 16b)

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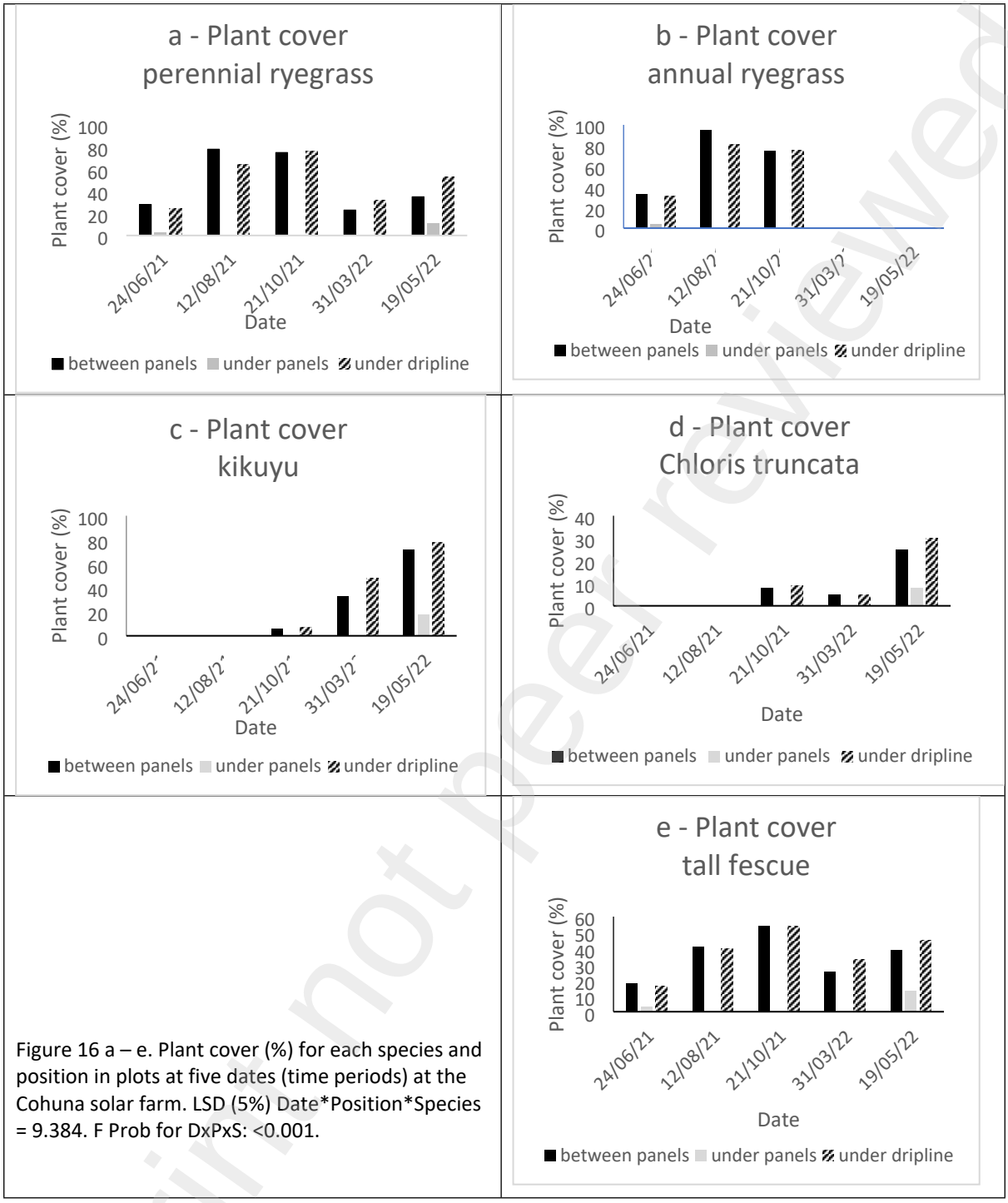


Figure 16 a – e. Plant cover (%) for each species and position in plots at five dates (time periods) at the Cohuna solar farm. LSD (5%) Date*Position*Species = 9.384. F Prob for DxPxS: <0.001.

Figure 17 illustrates that plant cover tended to be greatest between the panels during the cooler months, however, as the plots dried out over the warmer months, plant cover was greater under the dripline. Plant cover directly under the panels was very low due to lack of water but rose when soil moisture became available following more substantial rainfall events. Another observation was that plant cover under the panels for the kikuyu plots did show signs of increasing over time, possibly due to its prostrate growth habit and its ability to spread laterally. Light intensity under the panels was not measured as it was not considered that the moving panel shadow was likely to have a detrimental impact on plant production.

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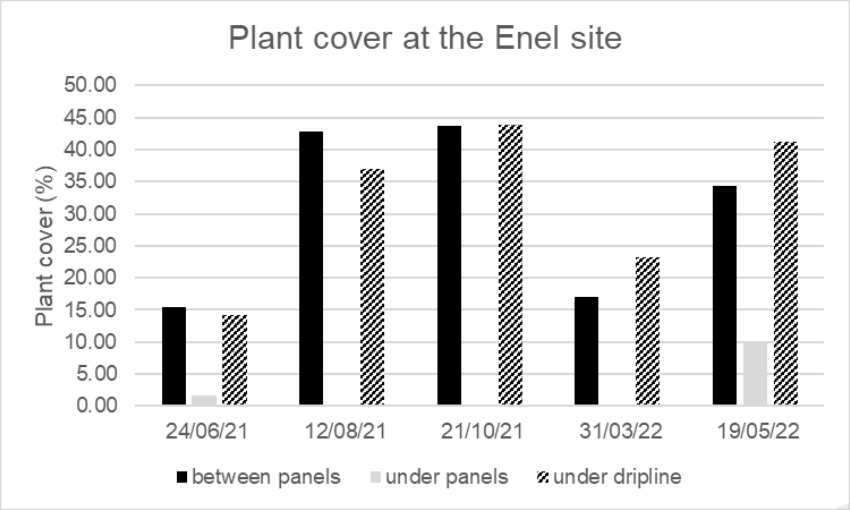


Figure 17. Mean plant cover (%) for five species in each of the positions in the plot over time for the Cohuna study site.

Total dry matter production for the five species for the period July 2021 to June 2022 is shown in Figure 18. The trend in dry matter production was closely related to the measurements of plant cover – with dry matter production being greatest in the plots showing the highest plant cover. Dry matter production was greatest in the perennial ryegrass plots and least in the plots of *Chloris truncata.* Production was highest in the "between panel" position of the plots and least in the plots under the solar panel. Dry matter production under the solar panel drip line of the plot was similar to that between the panels.

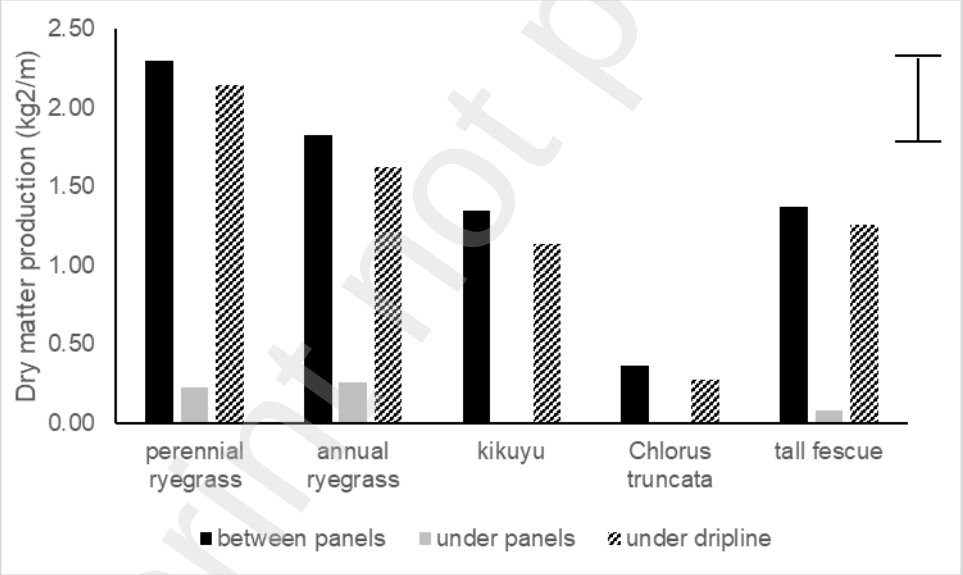


Figure 18. Total dry matter production (July 2021-June 2022, Cohuna site) for each species and position in plot.

4.0 Pasture and sheep production modelling results

The modelling was used to explore the assumption that plant production under the panels could be impacted by a reduction in available sunlight during growing times when water is not limited. For suitable low growing pasture species, the following graphs (Figure 19) simulate the six hypothetical

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scenarios of the shade and moisture re-distribution on the production of perennial and annual ryegrass, kikuyu, tall fescue, cocksfoot, lucerne and an Australian native C4 grass analogue for the Numurkah site.

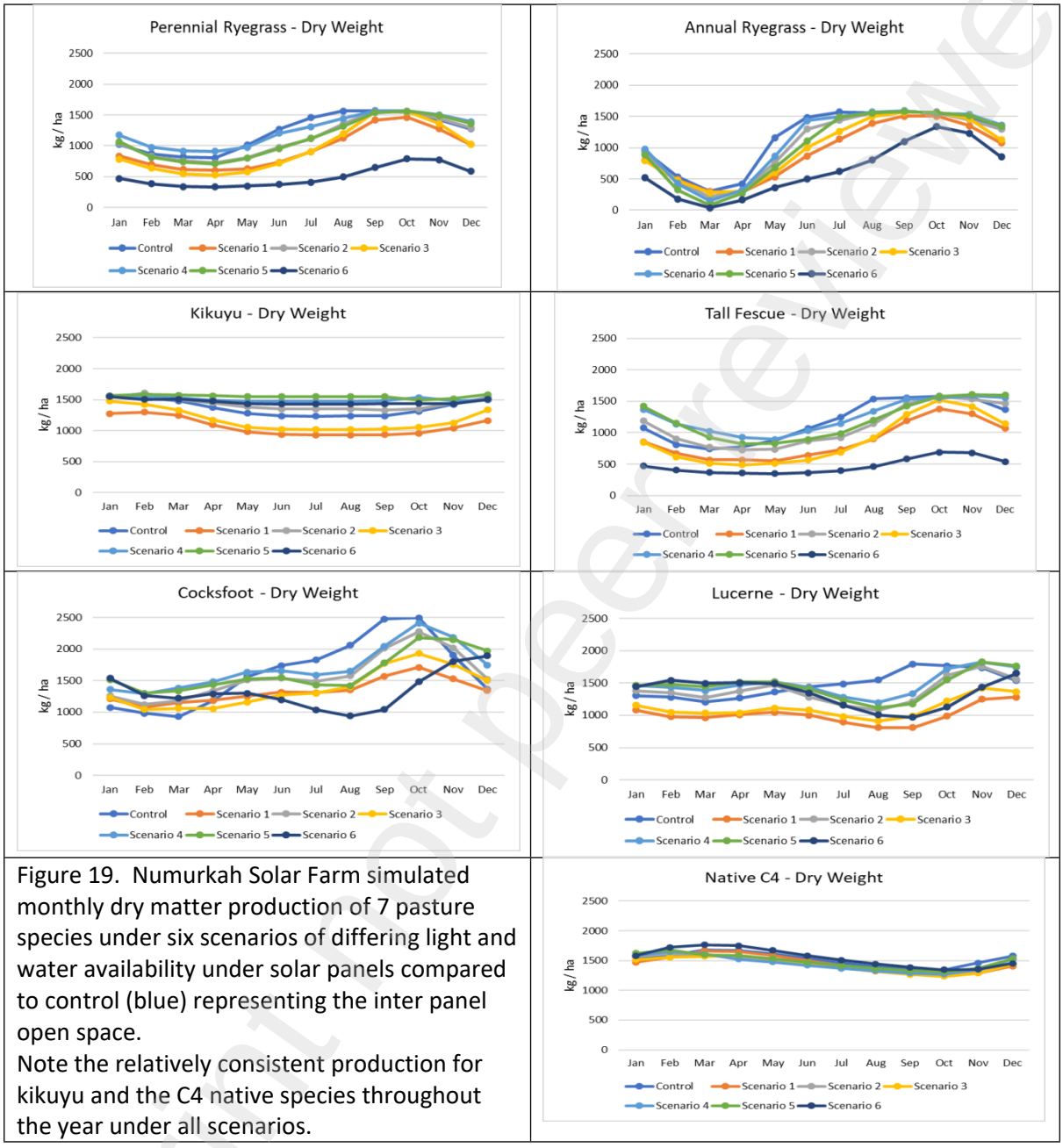


Figure 19. Numurkah Solar Farm simulated monthly dry matter production of 7 pasture species under six scenarios of differing light and water availability under solar panels compared to control (blue) representing the inter panel open space.
Note the relatively consistent production for kikuyu and the C4 native species throughout the year under all scenarios.

The simulations suggest that pasture growth rates and pasture seasonal growth patterns show the potential availability of stock feed throughout the year. This information can then inform sheep production systems and can assist in decisions regarding flock numbers, grazing and lambing schedules during the year as well as selection of pasture types to match feed demand. Figure 20 shows model outputs of monthly growth rates for the different pasture species.

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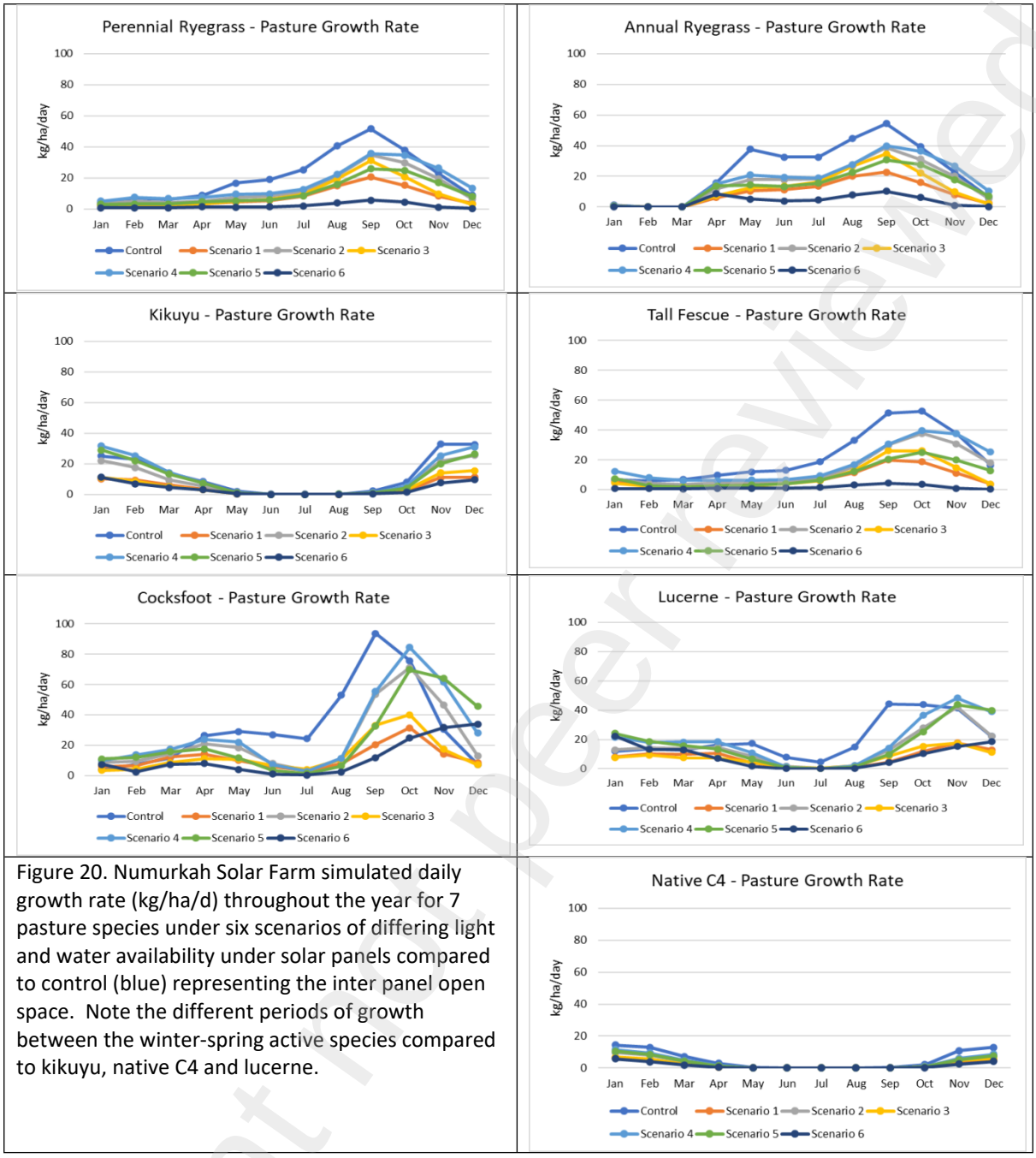


Figure 20. Numurkah Solar Farm simulated daily growth rate (kg/ha/d) throughout the year for 7 pasture species under six scenarios of differing light and water availability under solar panels compared to control (blue) representing the inter panel open space. Note the different periods of growth between the winter-spring active species compared to kikuyu, native C4 and lucerne.

Two other outputs derived from the pasture simulation models were: 'percent of pasture that is green', and 'number of cuts required'. Percent of pasture that is green illustrates the availability of green stock feed during the seasons and can help inform grazing timing, while the number of cuts required could provide information to the solar farm operator, for example, on how to manage pasture biomass to prevent a build-up of fuel loads leading to fire hazards. If pastures are not grazed, then the grass will need to be mowed or slashed during the fire danger period, typically requiring that it be kept under 100mm. Simulations of the pasture species growth were undertaken where a "cut" is triggered when the pasture biomass exceeded 1.5 tonnes/ha. The greatest number of cuts were required for the control scenario, which required (on average) 11 cuts per year for cocksfoot, down to two cuts per year for native C4.

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Simulated annual average pasture growth varied greatly across the six scenarios, with the species requiring the least number of cuts found in the reduced rainfall (50% or non-rain < 5mm/day) or very low solar radiation (i.e., 25%). In these scenarios, the average number of cuts per year ranged from zero for three of the winter active species (perennial ryegrass, annual ryegrass, tall fescue for Scenario 6: 25% solar radiation) to at least 9 cuts per year for the other winter active species (cocksfoot) under Scenario 4: 70% solar radiation.

4.2 Sheep production potential

Simulation results for pasture production beneath the panels under a conservative scenario of rain and light shadowing by panels for March lambing (figure 21) shows decreased gross margins at all stocking rates for all species compared to July lambing, with negative gross margins for higher stocking rates on lucerne and no return on kikuyu and *Bothriochloa* (the analogue species representative of native grass – *Chlorus truncata*). Note that this scenario covers only a small proportion of the solar farm, with approximately 80% of the area occurring between and outside of the panels. While production is significantly lowered by the dry strip shadowed by panels, any feed consumption from under the panels could be considered a bonus.

The simulations show there was high year-to-year variability in financial returns. The most profitable pasture species (annual ryegrass/subclover and perennial ryegrass/subclover) in the control scenario show mean gross margin for each Dry Sheep Equivalent (DSE) number as positive across all years, however, at the very high DSEs there was a financial loss for some of the years due to extremely low rainfall. This would be expected regardless of whether the farm was a solar farm. The high year-to-year variability and poor match between feed supply and demand for some pasture types are the main limitations on carrying capacity in any northern Victorian non-irrigated farm environment.

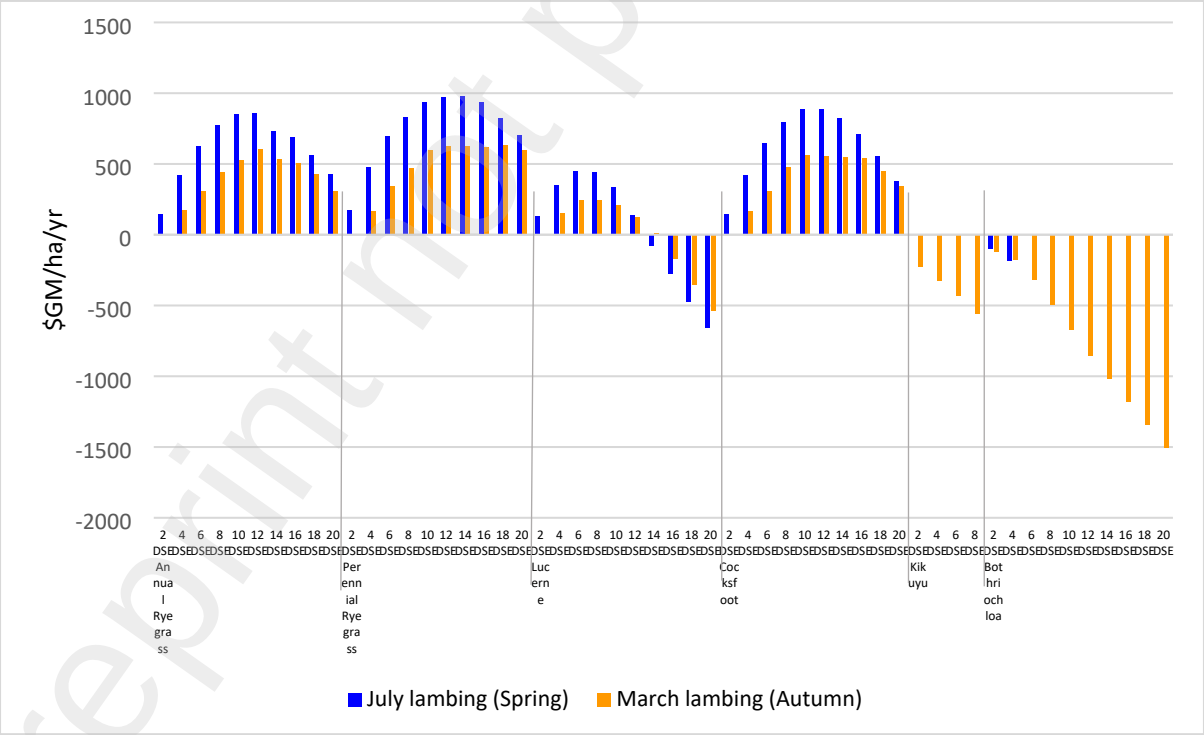


Figure 21. Median Gross Margin across pastures species for the control treatment across a range of DSEs for July (Spring) and March (Autumn) lambing from GrassGro modelling of the Numurkah site.

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4.3 Lamb survival

The highest values of the lamb chill index were in the open area, followed by the within panel area assuming no protection for lambs from rain (Figure 22a). The lowest chill indices were for the within panel area with the assumption that the lambs could find protection from rain. The chill index was rarely above the threshold of 1000kJ.m-2.h-1 at which mortality rates increase sharply. The highest chill values occurred following rainfall on 26 May and 5 June. The estimated mortality of twin Merino lambs was substantially reduced to near baseline levels by the shelter from wind and rain (Figure 22b).

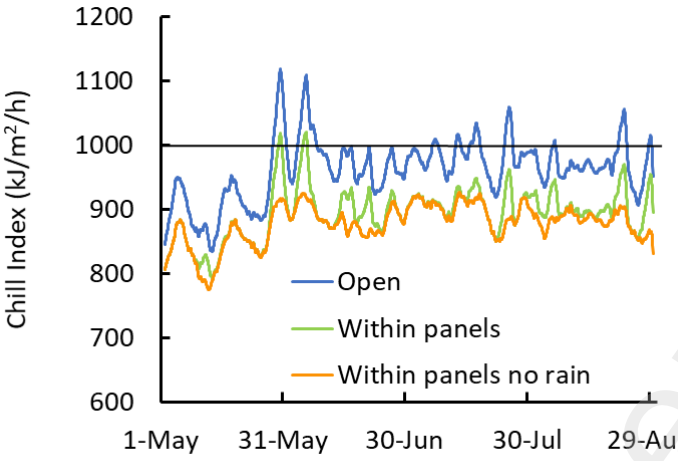


Figure 22a. Chill index plot for Numurkah and the threshold of 1000kJ.m^2.h^{-1} wind chill above which mortality increases rapidly.

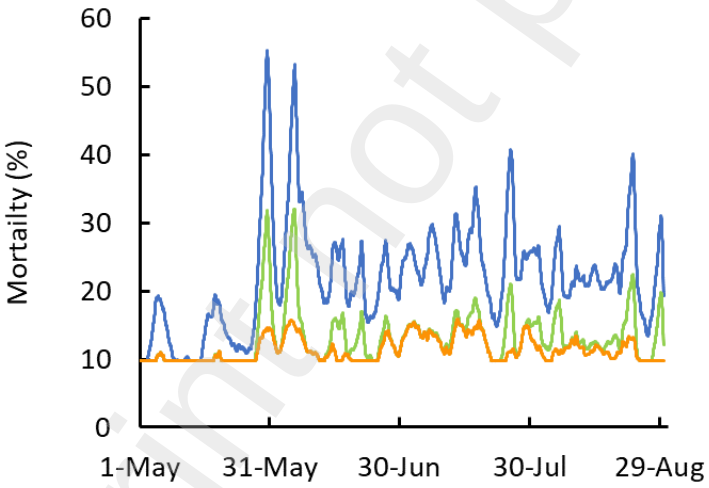


Figure 22b. Mortality rate for twin lambs May to August 2022 for the Numurkah site predicted from the hourly chill index using the equations of Donnelly (1984) [31].

In northern Victoria, the coldest weather systems arrive from a south – westerly direction, so the north-south orientation of the panels provides some wind mitigation benefit. Note that the 'open paddock' (blue line) is the situation if sheep are unable to find any shelter due to the absence of trees, shrubs or topographic wind shelters. A further reduction in wind chill is possible during rain events where the ewes and lambs seek shelter under the panels so that the fleece of newborn lambs can remain dry (orange trace).

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While the environment has a relatively low risk of lamb mortality much of the time, the main mortality risk occurs when lambing coincides with significant rainfall. Increased lamb survival would not be expected in every year, because in many years, the peak of lambing may not coincide with significant rainfall events. Instead, the shelter available with a panel field could be a risk mitigation strategy that may work well with lambing in winter, which is also the optimal time to utilise the spring peak of growth from the winter-active pasture species.

5.0 Discussion

Recent studies have provided some insights into conditions under grazing agrivoltaics [e.g. 6, 10, 40] but none of these studies have focussed specifically on measuring the pasture production environment under solar panels as it pertains to sheep grazing. The approach taken in this study (measuring the micro-climate, trialling some forage species to measure production within the panels and modelling sheep production based upon the observations made) was designed to give some objective assessment of the grazing environment under agrivoltaics. The aim was to improve the knowledge base upon which the large-scale PV utility sector and Government can progress development of dual purpose facilities. In part, the aim was also to allay community opposition to Large Scale Photovoltaics (LSPV) on the grounds that it alienates agricultural production. The following discussion section considers the study findings and develops the thinking around how to successfully integrate sheep grazing into LSPV.

5.1 Microclimate findings

Initial interest in this study was partly based on a desire to find out whether LSPV would have any off-site climate impacts as well as to measure in-panel conditions of soil and micro-climate relevant to pasture production. Findings suggest that the LSPV sites have no significant off-site climate impact, but within the panel arrays, there was slight increase in air temperature at panel height. This warming of a couple of degrees was only observed at times when the sun intensity was sufficient to warm the panels and hence warm the surrounding air. This generally only occurred on sunny days for about 5 hours under light breeze situations. During times when there was no wind, the warmed air likely moved upwards by convection, whereas under stronger wind flow, the warming effect was swamped by the larger mass of air moving through the panels.

At a much smaller scale (directly under the panels) cooler soil temperature was observed under the panel centre due to the shadow cast by the panel as it tracked the sun. This contrast only occurred during the summer months. Time-lapse photographs of the panel tracking during the summer solstice (21/12/21) showed that the centre line of the panels was shaded from about 10:45AM until 4:00PM. Sunlight fell on the centre line from 7:45-10:45AM and 4:00 till 6:45PM at low sun angles. Shading of the most intense sunlight during the day enabled the ground to stay cooler during the summer months.

At the micro scale, soil moisture was significantly impacted by the panels due to rain re-direction, causing desiccation of soil under the centre line of the panel and higher moisture levels under the drip lines, depending upon rain intensity and duration. Soil moisture data showed that the soil under the panels could be re-wetted by overland flow and pooling after heavy rainfall events, or after periods of repeated rainfall during cooler months.

5.2 Pasture trials findings

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The forage plots planted within the solar panel array provided some useful data on plant establishment success and forage production performance under solar panels. The results indicated that a range of forage species can be grown productively in conjunction with solar panels, however more long-term research is required to determine which species and species mix should be recommended, as well as the management systems such as grazing intensity, rotations and seasonality suitable for these forage species.

The temperate grass species: perennial ryegrass, tall fescue and annual ryegrass established quickly whereas the summer growing species – kikuyu and *Chloris truncata* did not properly establish until Spring of 2021. The forage production and grazing management systems of the temperate forage species, particularly perennial ryegrass, are well known and could be easily applied to agrivoltaic systems. However, the growth of perennial ryegrass can be severely impacted by hot and dry summers, so in northern Victoria, other species such as kikuyu may be more suited to grow under the solar panels [41]. Kikuyu has a low, prostrate growth habit, which allows it to spread into the dryer areas under panels and it is able to tolerate hot, dry conditions and partial shade. These features would also reduce fire risk over summer, especially is sufficient summer rainfall maintained green cover for longer periods. While kikuyu may have limitations in terms of its nutritive characteristics, under a potentially warming climate, this could be offset somewhat by its higher yield compared with perennial ryegrass [42] (Bell et al 2013).

The plant cover and herbage production across the field plots varied depending on position in the plot (i.e. under the panels, under the drip line, or between the panels). Measured herbage production indicated the drip line was similar to production between the panels. Anecdotally, the "drip line" has been recognised as being important to farmers who graze under solar panels during drought periods since it can sustain some green feed due to the concentration of small rainfall events onto a small area (T. Warren pers. Com. in CEC 2021) [43]. However, this may apply more to fixed panel systems (not tracking systems) where the dripline concentrates small rainfall events and condensation consistently onto the one location, potentially causing winter soil waterlogging, compared to tracking panels that divert rainfall onto a variable dripline, depending upon time of day and rainfall timing.

It may be useful to continue research over a drought period to measure the impact of the drip line in providing additional moisture to plants under seasonally dry conditions. A further area of study would be to look at opportunistic irrigation to ensure continued pasture production during dry periods, maintain perennial groundcover species, minimise fire risk and provide cooler panel temperatures.

5.3 Implications for sheep production

The pasture trials, production simulations and initial sheep enterprise modelling enabled a range of parameters to be tested in a sheep farm system. Pasture species selection, their management, animal husbandry and management (such as mating, shearing and lambing times) were simulated using industry standard models. The micro-climate monitoring results did indicate that there were subtle differences within the panel field, particularly lower wind speeds and cooler soil under the panels. Reduced plant production under the narrow strips throughout the array areas was mostly attributed to soil moisture deficit due to the rain shadowing, but light measurements should be made to confirm what practical significance shadowing might have on plant production.

Simulation results provided information on the estimated forage supply throughout the year as well as the profitability, or gross margins, for the tested forage systems. The information on forage

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supply, used in conjunction with the measured data obtained from other experimental field plots grown elsewhere in the region, provided useful guidance on the projected forage yield available throughout the year. This information can inform the development of suitable grazing management schedules (e.g. stocking rates and times of the year) for agrivoltaic sites.

The use of Gross Margins as an indicator of profitability of an enterprise is recognised as being simplistic because many other inputs such as labour costs are not considered. Nevertheless, GrassGro predicted an average annual gross margin of nearly $1000/ha.yr for the most optimised system of perennial ryegrass with July lambing at a stocking rate of 12-14 eyes/ha. The interpretation of these simulation results should focus more on the shape of response relationship rather than the actual values. Stocking rate has a large bearing on the enterprise gross margin and can be a more important driver of profit than other management decisions - such as time of lambing. Simulations for the Cohuna site (not shown) showed lower gross margins and higher variability, primarily due to the lower average rainfall received at that location.

Further economic research could include other management options, outputs and management limitations specific to running sheep in agrivoltaic systems, which would provide a more complete set of information on the economics of agrivoltaic systems. This study results indicate that pasture production in solar fields can support sheep grazing with acceptable economic returns.

In the simulations presented here, the models do not take into account the income from solar energy, which would have a major influence of the overall profitability of the agricultural system. A theoretical estimate, based upon 15% solar energy capture by solar panels covering 33% of a hectare earning $50/MWh using a typical (sunny) November day of solar radiation data, suggests electricity revenues of around $180/ha/day are possible. These revenues are much larger than the gross margins returned from sheep grazing alone. Clearly there are many variables and assumptions involved, however sheep grazing and LSPV are generally viable enterprises on their own. If they are developed as an agrivoltaic co-development, the solar facility can save on vegetation management costs, reducing electricity plant operating costs, and the sheep grazier has reduced land costs. Animal welfare benefits arising from the shelter provided within the panels may also outweigh reduction in stocking rate needed to match a lower pasture production from solar farm suitable pasture species (i.e. low growth habit, summer active low fire risk species).

5.4 Animal welfare considerations

Prior to the research study reported here, Neoen conducted two trials which involved grazing sheep on a section of the farm under panels [6]. Neoen wished to ensure that the fire risk was limited and that they could comply fire management regulations by ensuring grass was less than 100 mm during the fire season. The sheep and the site were carefully monitored during these trials to check on sheep welfare, feed availability and damage to the solar equipment. The results showed that the sheep controlled the vegetation to ground level and were able to pass under panels easily without posing risk of contact with panels even when arrays were fully tilted. The results of these trials have already allowed Neoen to successfully implement sheep grazing in partnership with the neighbouring sheep grazier knowing that sheep welfare and integrity of the electrical equipment would not be compromised.

Lamb chill index assessment using the in-panel and out-panel wind and temperature data indicated that the significant reduction in wind speed afforded by the panels provided a higher lamb survival opportunity compared to the open. The twin lamb survival rate may be further improved if lambs are able to make use of the umbrella effect provided by the panels and reduce their chance of

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getting wet during winter rain events. Anecdotally, sheep seek shade under the panels during hot weather [8] accords with where cooler soil temperatures were observed. Water demand is therefore reduced and small rainfall events and condensation from the panel drip lines can provide opportunistic green feed in dry periods. Another benefit to animal welfare noted in [43] is reduced predation due to secure LSPV perimeter fencing.

5.5 Weed management

Weeds are a major problem, particularly on LSPV sites where the weed seed load is often substantial. Especially during the planning, design, approval and construction time period, weeds have often a substantial chance to thrive. Soil disturbance and loss of favourable vegetation cover also promotes weed propagation so that once the solar farm starts operating, weeds may then be the dominant plants found.

Site preparation is key to the successful establishment of agricultural plant species. CEC (2021)[43] advocates for the establishment of a healthy ground cover prior to the introduction of sheep. Based upon observations from this study, it is suggested that establishment of a healthy groundcover should be commenced well before construction begins, while it is cost effective to run large scale spraying, cultivation, sowing and mowing equipment (readily available in rural areas) across the development site. Having sufficient time helps with being able to sow when rainfall and growing season is more favourable, especially for perennial spreading grasses such as kikuyu and couch, allowing time for the thatch to spread and crowd out the weed seeds. Soil disturbance due to construction is unavoidable, so weed control before construction commences will reduce subsequent control need.

Once sheep grazing begins, weeds still need to be managed. Having a strong and productive ground cover established prior to grazing, coupled with a grazing schedule that maintains the resilience of the palatable plants will set up a more stable and lower maintenance system. Grazing management needs to be in tune with actual rainfall availability and timing each season and the growth response and life-cycle of the chosen pasture species to reduce the potential for bare ground developing during dry spells and fostering the spread of summer active weeds such as Spiny Emex (*Rumex hypogaeus*).

The emerging development of autonomous machines such as spot weed sprayers and robotic mowers may also have a role to play in future LSPV farms, especially where machines can easily pass under panels. For weeds that grow much taller than the favourable pasture species, regular mowing and spot spraying by low machines could be an effective weed control adjuvant to grazing by exerting regular pressure on weeds that sheep do not eat.

6.0 Conclusions

Collection of climate and soil sensor data over the course of a year has provided valuable data on the growing conditions within a solar panel array. Analysis of the data revealed that only subtle differences in temperature and humidity were found within the panel array compared to outside, and that these differences only occurred at certain times and weather conditions. A notable difference was that the wind speed was attenuated by about 30% and direction became aligned with the panels compared to wind outside.

Soil moisture effects were found directly under the solar panels where rainfall was diverted to the drip-line, resulting in a consistently dryer profile compared to the inter-panel soil, and especially

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compared to the drip-line soil. A substantial reduction in soil temperature of up to 10°C was observed at 10cm depth as a result of shading directly under the panels during hot sunny summer days.

The field trials of pasture species suitable for low growth height within solar panels were able to generate some results for establishment and groundcover, showing that perennial ryegrass, tall fescue and annual ryegrass were quick to establish and produced promising growth rates from reasonable rainfall in September to November 2021. Establishment for the summer active kikuyu was also very good. Dry matter yield for all species were significantly reduced in the dry strip directly beneath the panels, but the drip-line and between panel yields generally matched each other in spring and it was slightly higher under the dripline in autumn.

Windspeed, temperature and rainfall data were used to calculate lamb-chill index for within a solar panel array and compared to the open paddock index. This showed a significant improvement in lamb survival potential due to the reduced wind speed, which was further enhanced if lambs took advantage of the rain shelter afforded by the panels.

Biophysical modelling to assess pasture options and sheep grazing production within a hypothetical large scale agrivoltaic farming system found that microclimatic differences are insufficient to produce significant positive or negative impacts on pasture production. The necessity to choose low growing pasture species to minimise vegetation growth rates and height to minimise any interaction with electrical equipment and for fire management can impose limits on feed availability (based on single species) which in turn impacts on sheep production.

Grazing modelled for self-contained pasture systems indicated Gross Margins vary depending on annual climate, pasture species and stocking rate, with the modelled median Gross Margin mostly positive for 3 of the pasture species at a range of stocking rates, generally peaking around 14 DSEs. Overall land unit production ($/ha) would be higher due to the combination of electricity and sheep production. Solar farm management can further benefit from lower vegetation management costs and animal welfare can benefit from the shade and shelter provided by the solar panels, especially for lamb survival due to the reduced wind speed and rain shelter afforded by the panels.

Further development of advice and guidelines for the advancement of grazing agrivoltaics can utilise data and findings from this study, especially in making use of the conclusion that the pasture growing climatic conditions within panel array blocks can be slightly more favourable for some forage species. The more complex issues seem to be related to matters of pasture establishment and weed management within the physical constraints of solar panel arrays. It is also apparent that determining a suitable livestock management system that can balance the objectives of both the sheep enterprise and the solar power station is equally as important as the pasture grown within the panels.

A key conclusion is that if sheep grazing is to be included in the solar power station, then planning toward that objective should start as early as possible. Establishing the preferred pasture and reducing weed loads should proceed before construction. Grazing management needs such as fencing, watering points, mustering needs should be considered at the design stage. Equipment specifications should include sheep proof wiring and maximising machinery access for future pasture and weed management needs.

Further work could include gathering longer term pasture production data once perennial species are well established, measure light intensity under the panels, trial mixed pasture species swards, test suitable over-sowing methods and even test the proposition of sub-surface drip irrigation.

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Additional study and testing of the models used would help to improve confidence in how solar arrays are factored in to simulations of the Agrivoltaics system. This would benefit industry, community and government by having more confidence in knowing how agricultural production can be maintained within LSPV developments.

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Summer Solstice photographs from the Numurkah study site showing the passage of the panel shadow over the ground. To view, open PowerPoint, start slide show, click on first slide, it will then auto-play.

<<INSERT LINK TO SUMMER SOLSTICE POWERPOINT SLIDE SHOW HERE FOR SUBMITTED VERSION >>>

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