

Lamb growth and pasture production in agrivoltaic production system

by
Alyssa Andrew

A THESIS

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Serkan Ates

Grasslands and croplands located in temperate agro-ecologies are ranked to be the best places to install solar panels for maximum energy production. Therefore, agrivoltaic systems (agricultural production under solar panels) are designed to mutually benefit solar energy and agricultural production in the same location for dual-use of land. However, both livestock farmers and energy companies require information for the application of efficient livestock management practices under solar panels. Therefore, this study was conducted to compare lamb growth and pasture production under solar panels and in open pastures in Corvallis, Oregon in spring 2019 and 2020. Averaged across the grazing periods, weaned Polypay lambs grew at 120 and 119 g/head/d under solar panels and open pastures, respectively in spring 2019 ($P=0.90$). Although a higher stocking density (36.6 lambs/ha) at the pastures under solar panels was maintained than open pastures (30 lambs/ha) in the late spring period, the liveweight production between grazing under solar panels (1.5 kg ha/d) and open pastures (1.3 kg ha/d) were comparable ($P=0.67$). Similarly, lambs liveweight gains and liveweight productions were comparable in both pasture types (all $P>0.05$). The daily water consumption of the lambs in spring 2019 were similar during early spring, but lambs in open pastures consumed 0.72 l/head/d more water than those grazed under solar panels in

the late spring period ($P<0.01$). However, no difference was observed in water intake of the lambs in spring 2020 ($P=0.42$) The preliminary results from our grazing study indicated that grazing under solar panels can maintain higher carrying capacity of pasture toward summer, and land productivity could be increased up to 200% through combining sheep grazing and solar energy production on the same land. More importantly, solar panels may provide a more animal welfare friendly environment for the grazing livestock as they provide shelter from sun and wind.

Key Words: agrivoltaics; lamb growth; solar farming; pasture production

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Alyssa C. Andrew, Author

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Introduction

The U.S. Energy Information Administration (EIA) predicts energy use to increase by more than 28% by the year 2040 (DeMartis, 2018). With this increase in demand for energy comes a need to find more efficient production systems. One such solution is to introduce a more widespread use of solar energy using photovoltaic panels (PVP). Solar energy is incredibly beneficial as its carbon emission is 43 times less than that of natural gas (DeMartis, 2018). However, this requires using a lot of land, leading to competition between agricultural uses, including to feed the planet, and energy use (Marrou et al., 2013a). In an attempt to overcome this competition, Goetzberger and Zastrow (1982) became the first to suggest that perhaps the two could be combined. In the early 1980's they proposed a potential solution involving the pairing of photovoltaics (PV) with open field crop conditions (Amaducci et al., 2018). This discovery initiated the study of agrivoltaics (AV) which is defined as “mixed systems associating solar panels and crop at the time on the same land area (Marrou et al., 2013b).” While this dual use of the land initially seems like an ideal option, there are still a variety of factors that need to be considered. For example, crops should be able to grow under panels and efficient enough to justify the added cost of installing the PVPs and adapting farming practices. Goetzberger and Zastrow (1982) completed a theoretical study that determined enough radiation is underneath PVP to permit the cultivation of many different crops (Beck et al., 2012).

Currently, countries such as Germany and Italy have passed legislation preventing the use of agriculture lands for solar energy to attempt to avoid the competition between food production and PV (Beck et al., 2012). However, this decision is worth revisiting as the benefits of agrivoltaics come to light. AV not only decreases the conflict between agricultural and energy sectors, but it efficiently and effectively promotes sustainable land use (Obergeil et al., 2013). These AV systems

have the potential to increase global land productivity by an impressive 35-73% (Dupraz et al., 2016a). Additionally, AV helps to improve the productivity of farms, as there is a 30% increase in economic value for those that combine shade-tolerant crop production and solar generated electricity as compared to more traditional practices (Dinesh and Pearce, 2016). This added income from the solar panels is especially beneficial, as the panels themselves can partially displace grain, vegetable, and fruit crops, which has the potential to decrease yields by 5-20% in locations such as Germany (Apostoleris and Chiesa, 2019). However, not all crops face a decreased yield with the introduction of the PVPs. For example, a study done in Massachusetts reported that crop growth and yield was actually improved with the use of solar panels (Apostoleris and Chiesa, 2019). Crops that tend to do well in these conditions are those that benefit from the added protection from scorching or excessive evaporation (Apostoleris and Chiesa, 2019). In addition to improving some crop yields and increasing economic and land productivity, AV may also benefit the PV industry further by supporting bringing more ground mounted PV systems back into the mainstream market, thereby increasing the economy further (Obergeil et al., 2013).

Benefits of Solar Power

As the world population continues to grow, the global energy demand is expected to double by the mid-century (Adeh et al., 2018). This calls for including more renewable forms of energy. There has been a lot of push to use bioenergy as one of the main sources to alleviate this problem; however, bioenergy is not sufficient to meet increasing demands (Santra et al., 2017). Not only is bioenergy incapable of fulfilling all of society's energy requirements, but its demand for land to replace fossil fuels greatly exceeds the available cropland area (Santra et al., 2017). While PV also requires a large amount of land, it shows the largest potential as these systems generate the greatest amount of power per area in terms of land-use efficiency when compared to other sources of

renewable energy (Santra et al., 2017, Hernandez et al., 2014). A further benefit of solar energy is that it can be obtained in a few different ways. The majority of the global demand for PV can be achieved by adding panels to existing rooftops or by integrating it directly into buildings (Dinesh and Pearce, 2016). This can help decrease the competition for land use between energy and agricultural sectors.

As the use of PV panels becomes increasingly more common, the cost to purchase the panels have decreased by 10% per year over a 30-year period and solar energy production has increased by 30% per year (Adeh et al., 2018). This decrease in cost and increase in production aids in making PV a more realistic option as the benefits of solar energy are better studied. Additional positives of solar energy include reduced carbon dioxide gas emissions, helping the country in the international energy market, a strengthened economy, added job opportunities, stabilization of degraded land, and an overall improved quality of life (Adeh et al., 2019, Hernandez et al., 2014). Solar energy not only improves human quality of life, but it can also help improve crop and animal lives. For example, the panels can serve as shelter for grazing animals, but also for birds who can build their nests there (Hernandez et al., 2014). Additionally, a higher soil moisture achieved by the installation of PVPs can be a more water efficient means of farming, leading to a significant increase in late season biomass of forages (Santra et al., 2017). Because of findings like these, the study of agrivoltaics is becoming more common.

An Introduction to Agrivoltaics

The practice of agrivoltaics uses the same land to combine growing crops with the use of photovoltaic panels to produce both food and energy (Dupraz et al., 2011b). The precursor for this system was agroforestry, which involves planting trees in or around fields used for agricultural purposes (Dinesh and Pearce, 2016). A study published by Beck et al. (2012) describes four main

findings about plant growth under established PVPs (Beck et al., 2012). The first finding is that food crops have the capability to grow under solar panels based on the abundant growth of natural vegetation under and around the preexisting PV system. The second finding is that shade tolerant plants are the most successful. Third, there is higher humidity directly underneath the panels. Finally, the fourth finding is higher modules resulted in more uniform light and humidity. This initial study helped demonstrate that AV systems could be a reality, leading to more studies, including the first detailed experiments in France in 2013 (Dinesh and Pearce, 2016).

Agrivoltaics was introduced into the Phoenix Metropolitan Statistical Area (MSA), with the findings published in 2017 by Majumdar and Pasqualetti. This study showed that using solar PV has the ability to preserve agricultural land and reduce the land commitment. Additionally, they discovered that farmlands produce more than enough energy than is necessary for crop production when this system is used. When half density panel distribution was instituted in the Phoenix MSA, private agricultural lands produced roughly eight times the current residential electrical energy and 3.4 times the total electrical energy requirements of the residential, commercial, and industrial sectors of that area. These findings revealed real promise for the AV system.

Benefits of Agrivoltaics

Agrivoltaics production system has several benefits, including improving crop production, the environment, energy production, land productivity, and livelihoods of farmers. As AV is considered a complex system, it is more resilient to climate change than monocultures are (Dupraz et al., 2011b). While it is more complex than monocultures, it does provide a more stable environment. The solar panels allow for the shading pattern to remain consistent yearly, which prevents competition for below-ground resources (Dupraz et al., 2011b). The excess shading helps to save 14-29% water, which is especially beneficial for dry season, severe drought, and water

limited areas (Dinesh and Pearce, 2016, Adeh et al., 2018). Agroforestry systems are a precursor for the practice of agrivoltaics, so both see similar benefits from the extra shade provided. For example, both experience heterogeneous availability of rainwater into soil and reduction of available radiation, while the shade help protect crops from excess heat (Dupraz et al., 2011b).¹⁴

With improved crop protection and production comes a 60-70% increase in land productivity (Adeh et al., 2018). This is a direct result of combining agriculture with solar energy. If approximately 11% of US cropped land started incorporating PVPs, the electricity production for the country would be met (Hernandez et al., 2014). This connects with AV increasing electrical energy production by 30% (Dupraz et al., 2011b). The excess energy is beneficial for the health of the planet. By utilizing the land in such a way that multiple outputs are being produced, farmers are ensured that they will receive at least some income, even in cases of extreme drought (Santra et al., 2017). In addition to improving the quality of the planet, the additional production from AV systems improve the economic value by 30% (DeMartis, 2018). This extra income benefits farmers and increases property value, which helps promote local farming (Majumdar and Pasqualetti, 2018).

Challenges of Agrivoltaics

Like all forms of energy production, agrivoltaics is not without its faults. Not all crops can thrive under the panels, installation is expensive and requires a lot of land, and there could be potential hazards to the public or environment. However, the majority of these complications can be overcome with better planning and research on the subject.

While the intermittent shading from PVPs is beneficial to crops such as lettuce (*Lactuca sativa*), it can significantly reduce average available light, which is not realistic for the cultivation of all plants (Marrou et al., 2013b). The excessive shading can also lead to an increase of fungal

diseases, further causing problems for various crops (Marrou et al., 2013b). As a result, it is not realistic to incorporate AV into every type of farm, but instead requires careful planning and research into which crops would benefit from this system.

There also needs to be special consideration about the environment when choosing where to introduce AV systems. By combining solar with agriculture, AV helps to minimize farmland loss that can be associated with large-scale installation of solar panels; however, it could affect the ecology (DeMartis, 2018). Incorporating such a large amount of PVPs increases soil loss as a result of vegetation removal, construction of access roads, and soil compaction (Hernandez et al., 2014). The excess soil loss can increase the concentration of dust, which could pose hazards to air and water quality or the health of plant employees and the public as there is increased concentration in the air of particulate matter and soil-borne pathogens (Hernandez et al., 2014). However, AV could help decrease some of these complications when compared to large-scale installations not on farmlands. For example, agrivoltaics can employ the use of sheep or goats to graze the vegetation around the panels or efficiently recycle the water used to dust the panels to water the crops, both of which also help decrease the cost of installation (Majumdar and Pasqualetti, 2018).

The cost to transfer solar energy to transmission or local distribution substations is rather high, especially when considering the added cost of installing the panels (DeMartis, 2018). Furthermore, it is expensive to make changes to existing panels. However, if the installation with AV is well planned, some of these challenges can be overcome. For example, PVPs can be set up high enough for tractors or livestock to get under (Marrou et al., 2013b). Another important financial aspect to consider is that, because agrivoltaics is more efficient and productive than vegetable or fruit cultivation alone, it can lead to an increase in the cost of land leasing (DeMartis, 2018). This challenge can be difficult to overcome; however, as previously stated, agrivoltaics increases economic value by 30%, which could significantly help farmers to employ this strategy

(DeMartis, 2018).

Microclimate

Solar panel efficiency is a function of its microclimate, with the greatest production involving those with light winds, moderate temperatures, low humidity, and plentiful insolation (Adeh et al., 2019). These conditions are also desirable for agricultural crops, further demonstrating the benefits of agrivoltaics. Marrou et al. (2013b) performed a study to determine if the microclimate under agrivoltaic systems varied significantly than that of the same type of land not under the PV panels (Marrou et al., 2013b). They found that, as a result of sufficient air circulation, wind speeds were similar and there was no significant effect of shading found on air vapor pressure deficit (VPD) or air humidity. Soil temperature and day-time crop temperature decreased under panels, while crop temperatures increased during the night in the shade. This was mainly due to a decrease in incoming shortwave radiations. The night-time crop temperature increase was only significant for durum wheat and was most likely due to heat conduction from the soil and reduced radiative losses. Overall, crop temperature was only marginally modified under PVPs, suggesting that cropping practices would only need slight adaptation when switching to AV systems. Marrou et al. (2013b) concluded that most of the attention should be paid to light reduction mitigation when implementing the use of solar panels.

Amaducci et al. (2018) also found a lower soil temperature under PVPs than full light conditions and determined that evapotranspiration was lower in the shade as well. Unlike Marrou et al. (2013b), Adeh et al. (2019) found statistically significant differences in mean relative humidity and wind speed. They also determined that there were subtle, but significant, differences in wind direction. PVPs that provided full cover were significantly more water efficient, which would benefit crops. Based on these studies, the microclimatic conditions of AV are not drastically

different than open conditions, suggesting that few adaptations would be made to create an efficient AV system.

Beneficial Plants and Techniques for Agrivoltaics

Most of the research done on AV attempts to conclude which will be the most profitable option. It is challenging to predict exactly how each forage behaves under the PVPs, but there seems to be a correlation between leaf structure and plant tolerance (Dinesh and Pearce, 2016). Additionally, plants should be selected that are shorter to not interfere with the functional efficiency of the panels, preferably perennial, and have rapid ground cover in shade (Santra et al., 2017, Hernandez et al., 2014). Crops with a high net photosynthesis rate and less root density are also ideal for AV systems (Adeh et al., 2018). Recent agrivoltaics experiments have successfully grown a variety of plants, including aloe vera (*Aloe vera*), lettuce, tomatoes (*Solanum lycopersicum*), pasture grass, and biogas maize (*Zea mays*), while potatoes (*Solanum tuberosum*), and spinach (*Spinacia oleracea*) show promise (Adeh et al., 2019. Beck et al., 2012).

Table 1. Example of various plants and their growth category. “+” Crops are expected to grow well under AV conditions, while “-“ would be inefficient (Beck et al., 2012).

Category		
-	0	+
Corn Maize	Rape	Potatoes
Wheat	Rye	Salad (all kinds)
Horticulture	Oats	Spinach

Lettuce seems to be one of the more promising crops utilized in AV systems. Marrou et al. (2013a) found that lettuce did not lose any productivity when planted between PV rows, and

generated roughly the same revenue in terms of prices of crop, electricity, and PVPs. Additionally, switching lettuce cultivation to AV systems would result in a 40-70 GW power increase in solar energy (Dinesh and Pearce, 2016). Other plants could be beneficial in less conventional places used for AV. For example, bananas (*Musa acuminata*), coffee (*Coffea arabica*), and tea (*Camellia sinensis*) have been cultivated in agroforestry systems and may be able to grow well in tropical or semitropical AV systems (Beck et al., 2012). Additionally, incorporating PVPs on rocky scrubs or degraded lands could be used to cultivate medicinal plants (Santra et al., 2017).

Since solar panels can be installed in a variety of places, it is important to consider which locations and orientations are most successful. Some of the best places for capturing solar energy using PVPs are cool places with high irradiance (Hernandez et al., 2014). This includes croplands, grasslands, and wetlands in locations such as western America, southern Africa, and the Middle East (Adeh et al., 2019). These locations are partially chosen because they are the same areas where typical crops would normally grow. However, since PVPs allow for more moisture and shade, they could also be used in arid or semiarid regions to cultivate certain crops that would not normally grow there (Beck et al., 2012).

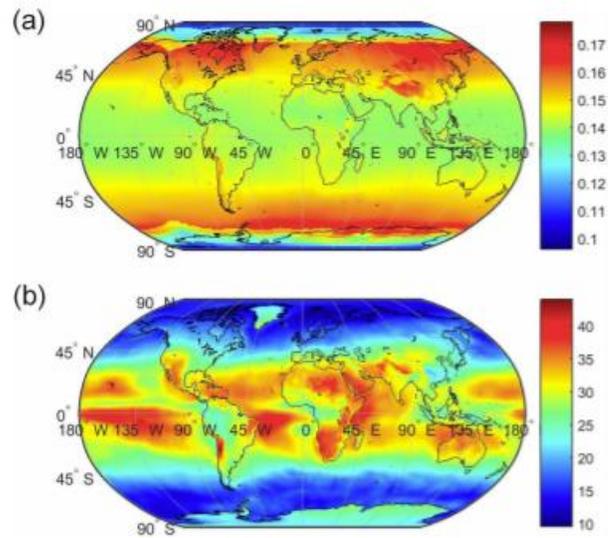


Figure 1. (a) Yearly average of monthly efficiencies with inputs of satellite derived solar radiation, humidity, air temperature, and wind speed; (b) annual mean of the potential of photovoltaic power in W/m^2 (Adeh et al., 2019)

Conventional installation of PVPs usually face towards the south; however, this leads to excessive shade which results in an uneven ripening of crops (Beck et al., 2012). If arrays were instead oriented either towards southeast or southwest, this would help provide more light for crops (Beck et al., 2012). AV would produce the most efficient plants if PVPs were arranged in a way that at least 70% of light is available (Marrou et al., 2013a). Electricity yield is expected to decrease by less than 5% due to this change in position (Beck et al., 2012). Despite this decrease, AV producers would be maximizing their profits by combining agriculture and solar energy, so it would not be too much of a trade-off.

Livestock Use in Agrivoltaics

The majority of research on AV systems has to do with crop cultivation. However, the use

of livestock in agrivoltaics should also be investigated. The typical installation of panels is usually high enough for grazing animals to fit underneath. By allowing animals to graze under panels, herbicide costs could be dramatically cut down (DeMartis, 2018). This could also limit erosion, which is one of the negatives involved with installing solar panels (Hernandez et al., 2014). Additionally, production would increase because the system allows for energy, food, and fiber production (Hernandez et al., 2014). Currently, sheep are the main livestock used in AV systems because arrays are too close to each other and the ground to allow for larger animals (Beck et al., 2012). However, goats may also be used (Hernandez et al., 2014). The panels also provide shade and shelter to the livestock, which could improve their quality of life. More research should be done to see what effect there is on animal production from grazing in this type of system.

Silvopastoral Systems

Silvopastoral systems (SPS) are similar to the agrivoltaic system; however, SPS uses trees as the source of shade, rather than solar panels. Like AV systems, it's important to consider the tolerance of forage species to shade; however, as long as proper forage species are implemented and shade percentages are within the 30-40% range, pasture growth shouldn't be significantly affected (Paciullo et al., 2011). Since the systems work in a similar way, some of the benefits of SPS may also be experienced in AV systems. Some of these potential benefits include increased soil fertility and conservation, increased forage and animal production, biodiversity conservation, and income diversification (Paciullo et al., 2011).

Along with an increase in livestock production, SPS—and potentially AVS—promote better animal welfare. This is a result of a higher animal thermal comfort being observed in silvopastoral systems due to the shading and change in microclimate that is present from the trees (Pezzopane et al., 2019). Additionally, sheep in a SPS have a reduced water consumption by 10%

and they have higher grazing times, while bovine reduce panting scores and respiratory frequencies (Pezzopane et al., 2019). Dairy heifers reared in a SPS have higher annual body weight gains and crude proteins levels are higher when compared to a monoculture system (Paciullo et al., 2011). Additionally, as climate temperature continues to rise, silvopastoral systems may help livestock to adapt, improving productive and reproductive efficiency (Pezzopane et al., 2019). Research should be done to see if these benefits also result from AV systems.

Steps to Implement and Further Studies

Creating efficient agrivoltaics systems requires more than just selecting the proper crops, livestock, and location. It is also necessary to educate producers. By providing information to farmers about the benefits and specific examples of AV, any potential negative impacts of installation can be minimized (Irie et al., 2019). Majumdar and Pasqualetti (2018) proposed a five-stage innovative decision process when introducing agrivoltaics into the Phoenix MSA. Stage one involves teaching potential adopters about the technique. This would include giving a brief summary of the system to get their attention. Stage two persuades producers of the benefits of agrivoltaics. One should also acknowledge the complications associated with AV, as well as how to overcome them. The third stage is when farmers decide to adopt this system. They would then need to go through the process of acquiring the panels for stage four, which is when farmers implement AV. After the system has successfully been installed and allowed to work for a while, stage five involves confirmation that these farmers made the correct decision. If all stages are successful, the information can then be relayed to other producers, repeating the cycle.

In addition to farmers, it is important to meet with researchers, solar developers, environmentalists, economists, and locals in order to review current policies and research site selection (DeMartis, 2018). This would help minimize potential harmful impacts and allow all

those involved to understand the various opportunities involved with AV. Further studies should also be performed to gain a fuller understanding of agrivoltaics systems. For example, shading from PVPs may affect summer vs winter or short vs long cycle crops (Marrou et al., 2013b). By looking into this, researchers can help determine which crops and production system would be most efficient in this system. Microclimatic effects of solar panels should also be further researched, including crop and soil temperature changes, rain redistribution under panels, and the validity of results for a variety of latitudes (Dupraz et al., 2011a). Finally, the effect on livestock and their production should be investigated as there are currently no scientific reports related to livestock production in AV systems. There is a paucity of information on the effect of AV on forage production, lamb growth rates, behavior and welfare.

Conclusions

Agrivoltaic systems were proposed to reduce land competition and conflict between agricultural production and renewable energy in the form of solar power (Adeh et al., 2018). Both solar energy and agriculture are efficient producers but require a large amount of land. By establishing dual-purpose systems, production greatly increases. While beneficial, agrivoltaics is not without complications. Negative impacts can be minimized in a variety of ways, including understanding the environmental impacts of creating these systems (Hernandez et al., 2014). Additionally, producers should emphasize choosing land, crops, and panel orientations that maximizes energy output and minimizes environmental and economic costs (Hernandez et al., 2014). This can be accomplished by performing further research into what crops, locations, microclimatic conditions, and livestock result in the most efficient systems. AV could be a promising solution for the competition for land to feed the planet and produce cleaner energy and these benefits should be shared with producers to implement these practices on a large scale.

Materials and Methods

Site, experimental design, and grazing management:

The grazing experiment was carried out at the Oregon State University in Corvallis, OR (44° 34' N, 123° 18' W 78 m a.s.l.) to test the effect of grazing pastures under solar panels vs. pastures in open fields on pasture production and lamb liveweight gains in spring. All procedures were approved by the Institutional Animal Care and Use Committee (ACUP# 5146) prior to the commencement of the experiment. A 0.6 ha pasture paddock under solar panels and in adjacent open areas was fenced and divided into three, 0.2-ha blocks to serve as replicates. Each block was divided into 2 subplots (0.1 ha), which were randomly assigned to the grazing under solar panels and grazing in open pasture fields (control). The experiment layout was a randomized complete block design with three replicates.

Grazing management

A core group of 36 Polypay weaned lambs were stratified by body weight (mean LW = 24.6 ± 4.1 kg) into 6 groups of 6 animals (2 groups per block). Each treatment had a core group of 6 lambs (testers) with spare lambs (regulators) in spring. A put-and-take grazing system to match feed demand with changing supply. Animals had a free access to fresh water in portable water troughs connected to a permanent water supply in open pastures and under solar fields. The groups of lambs were randomly assigned to one of six, 0.1 ha pastures where they continuously grazed from 20 April to 11 June at the stocking rate of 60 weaned lambs/ha in the first and 30 and 36.6 weaned lambs/ha stocking rate in open and solar panel pastures, respectively in late spring period.

Measurements

Lamb liveweight gains

Liveweight gain was determined by weighing individual tester animals prior to and following each grazing period. Lambs were held overnight without food and water and weighed “empty” the following morning. Liveweight gain per head of tester lambs was calculated from the change in weight between each liveweight measurement date. Liveweight gain (kg/ha/d) was calculated by multiplying liveweight gain per head of tester lambs by the number of testers plus regulator lambs per hectare.

Seasonal dry matter production:

Dry matter production (kg/ha) was measured during active growth in spring, summer, and autumn under fully shaded, partially shaded and open areas. Herbage growth was measured from a rectangular quadrat (0.25 m²), harvested using electric hand clippers to a stubble height of approximately 3 cm. After collecting the forage cuts, the plots were mowed to the same height approximately 3 cm using a rotary mower. All herbage from the quadrat cuts were oven dried at 65°C for 48 hours. Forage cuts were sub-sampled for sorting into botanical fractions (sown forage, weed, dead material) before drying. Herbage growth rates were calculated at each harvest by dividing total DM production by the number of elapsed days since the previous harvest.

Statistical Analysis

Liveweight gain per head (g/d) and per ha (kg/ha/d) were analyzed by one-way ANOVA with repeated measures for each liveweight gain measurement period. Pasture production and water consumption of lambs (L/d) was analyzed by one-way ANOVA with three replicates at each date.

Results and discussion

In 2019, total herbage yield in spring-summer period was 3609, 2893, and 3700 kg DM/ha for open pastures, partially shaded, and fully shaded solar pastures, respectively (Fig 1). While the DM yield from open and partially shaded areas was similar, pastures under fully shaded sites were substantially lower ($P<0.01$). Seasonal herbage DM production between open pastures and partially shaded areas did not differ in 2019 ($P>0.05$). However, the forage production in the fully shaded areas under solar panels was lower ($P<0.05$) than open pastures on 23 May and 23 October while it was greater ($P<0.05$) than open pastures on 11 July.

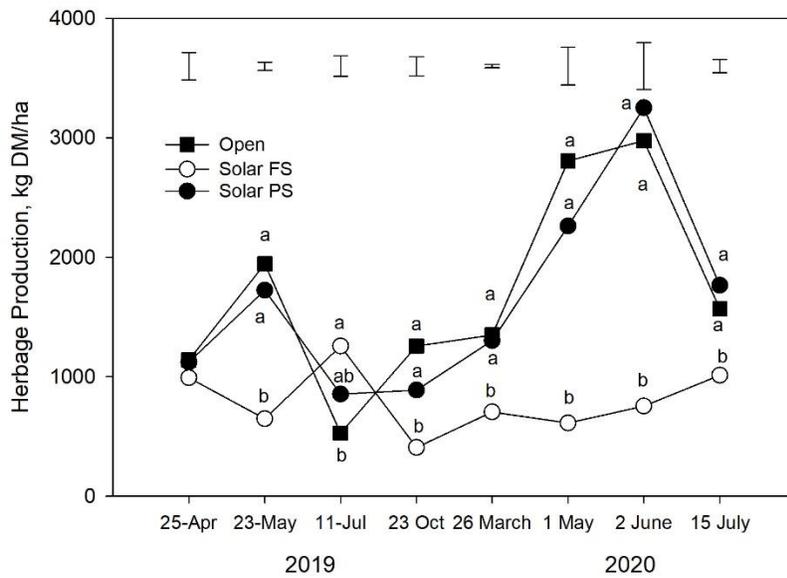


Figure 1. Herbage production (kg DM/ha) in fully (FS) and partially shaded (PS) areas under solar panels and open pastures in 2019 and 2020.

Earlier closing of the pastures in fall 2019 resulted in greater spring-summer 2020 production for both open and partially shaded pastures, while pasture production in fully shaded areas remained similar. In spring-summer 2020 total herbage yield in spring-summer period was 8700, 3079 and

8579 kg DM/ha for open pastures, partially shaded and fully shaded solar pastures, respectively (Fig 1). On average the pasture production was 9-33% less in agrivoltaics systems than open pastures.

Averaged across the grazing periods, weaned lambs grew at 120 and 119 g/head/d under solar panels and open pastures, respectively in spring 2019 ($P=0.90$; Fig 2a). Although a higher stocking density (36.6 lambs/ha) at the pastures under solar panels was maintained than open pastures (30 lambs/ha) in the late spring period, the liveweight production between grazing under solar panels (1.5 kg ha/d) and open pastures (1.3 kg ha/d) were comparable ($P=0.67$; Fig 2c). Similarly, in spring 2020, lambs in both solar and open pastures had similar liveweight gains ($P=0.64$; Fig 2b). In period 1, lambs grew at 129.7 g/ha/d. as the season progressed the average daily liveweight gains of the lambs dropped to 49.7 g/head/d ($P<0.01$). Liveweight production of the lambs were similar as both open and solar pastures were grazed at same stocking rates in both periods ($P=0.97$; Fig 2d).

In 2019, the daily water consumption of the lambs was similar during early spring, but lambs in open pastures consumed 0.72 L/head/d more water than those grazed under solar panels in the late spring period ($P < 0.01$; Fig 3a). In spring 2020, the daily water intake of the lambs was 1.48 and 1.32 L/head/d for the lambs in open and solar pastures, respectively but the difference was not significant at neither early nor late spring periods ($P=0.42$; Fig 3b). The water intake of the lambs increased from 0.59 L/head/d in early spring to 2.21 L/head/d in the late spring period ($P<0.01$). The inconsistency in the water intake of the lambs in 2019 and 2020 is possibly due to the variations in the climatic conditions. It is highly probable that the lambs in open pastures may require higher water consumption in arid and semiarid regions as compared to PNW with a mild temperate climate. Agrivoltaics systems where solar energy and livestock production are integrated

may help increasing the water use efficiency in meat production. Increasing the water productivity is of paramount importance as a means of reducing the effects of global warming.

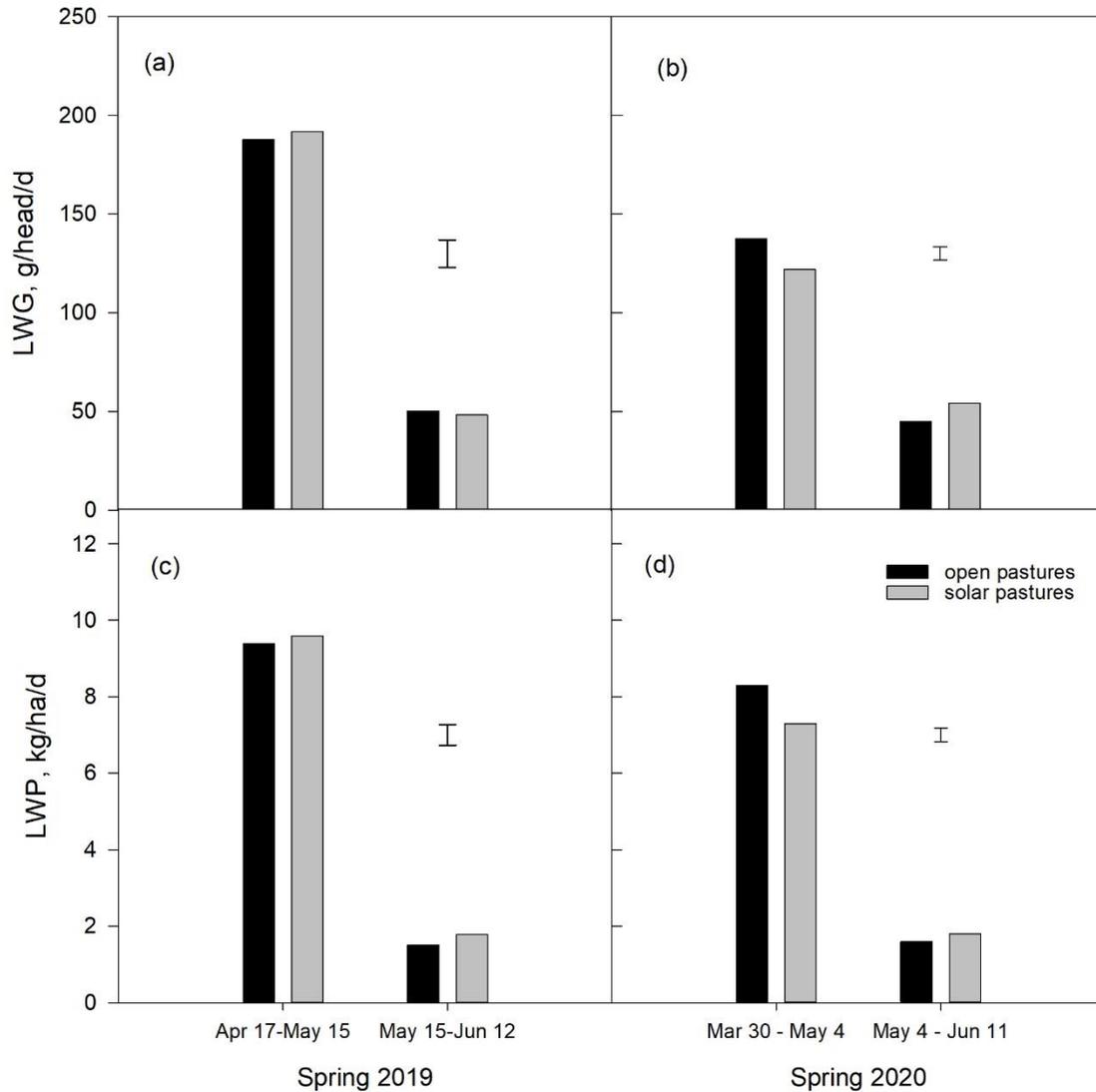


Figure 2. Liveweight gains (LWG, g/head/d; Fig. a, b) and liveweight production (LWP, kg/ha/d; Fig. c, d) of lambs grazing under solar panels and open pastures in spring 2019 and 2020.

The results from our grazing study indicated that grazing under solar panels can maintain higher stocking rate of pasture toward summer, and land productivity in spring could be increased up to 200% through combining sheep grazing and solar energy production in the same land, as neither

lamb production nor solar energy production is negatively impacted. More importantly, solar panels may provide a more animal welfare friendly environment for the grazing livestock as they provide shelter from sun and wind. Lower pasture yields under in fully shaded areas under the solar panels were the main cause of inferior pasture production in agrivoltaics site in the current study. It is probable that using shade tolerant pasture species such as orchard grass and more controlled winter grazing, the productivity of fully shaded areas can be increased substantially.

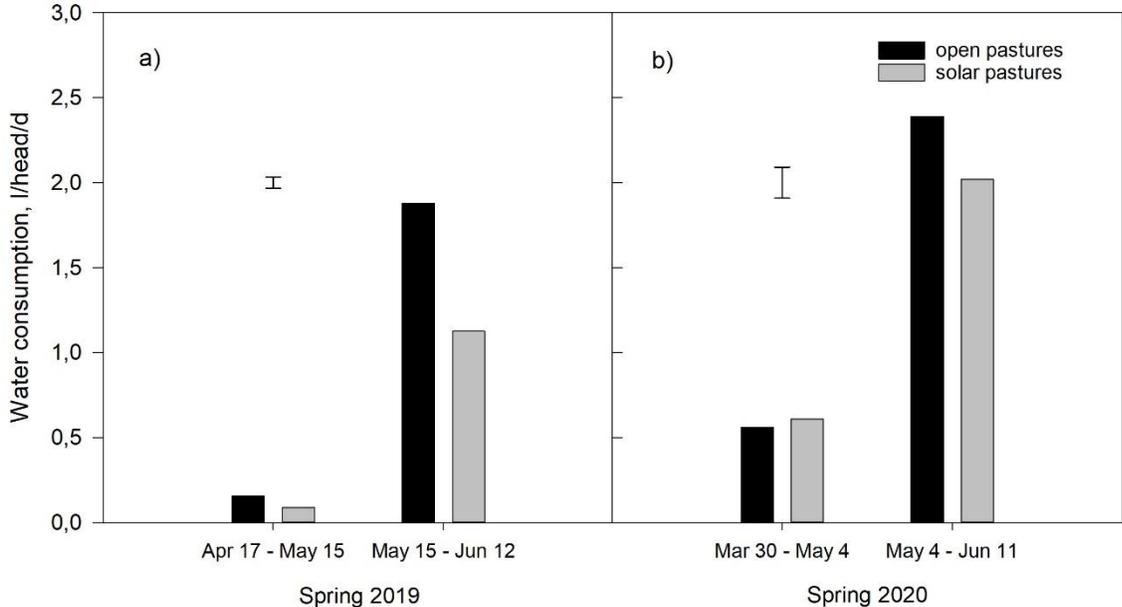


Figure 3. Daily water consumption (L/head/d) of lambs grazing under solar panels and open pastures in spring 2019 (Fig. a) and 2020 (Fig b).

Conclusions

This study reveals that agrivoltaics production systems can be used to improve lamb production and welfare. While factors such as liveweight gains and early spring water consumption were comparable in the open, partially shaded, and full shaded pastures, this demonstrates that producing lambs in AV systems would not decrease the production value.

Furthermore, some aspects were more favorable in the fully solar treatments, including water consumption in late spring 2019, the ability to maintain a higher stocking rate towards summer, and increased herbage yields in July of 2019. In addition to the increased land productivity and improved animal welfare, the results from this study support the benefits of agrivoltaics as a sustainable agricultural system.

More work should be done to properly establish pastures when creating an AV system. This can help accommodate for the lower herbage yields in full shade experienced throughout most of the experiment. Additionally, information about agrivoltaics should be made readily available to farmers, energy producers, researchers, and the general public as it becomes available. Further studies should be done to gain opinions of farmers to determine which factors either encourage or discourage from pursuing a change to an AV system. With better knowledge about animal welfare and production, pasture establishment, and public opinion, it is hoped that agrivoltaics will become a more commonly used practice.

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