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# A preliminary investigation of the effect of solar panels and rotation frequency on the grazing behavior of sheep (*Ovis aries*) grazing dormant pasture

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ABSTRACT

Vegetation management on solar farms can be accomplished through targeted grazing with sheep. To the authors' knowledge, no research has been conducted to date on sheep grazing behavior on solar farms, yet such research is crucial to inform grazing management practices for contract grazers on solar farms. The objectives of this study were to investigate both the effects of solar panels on sheep grazing behavior and the grazing management strategy (intensive rotational grazing (1-day rotations (1d))) or rotational grazing (4-day rotations (4d))) best suited for vegetation management on a solar farm. Data were collected on Gold Tree Solar Farm in San Luis Obispo, CA, USA. Sheep with predominantly Dorper genetics (over 99%; n = 80) were stratified by body weight (BW) and age in a crossover design across treatment grazing locations, solar farm (S) or native rangeland (NR), and grazing managements, intensive rotational (1d) or rotational (4d). Grazing location treatments (S or NR) were randomly assigned a grazing management, 4d (paddock size = 0.405 ha, 4 days/paddock), or 1d (paddock size = 0.101 ha, 1 day/paddock, 4 paddocks), resulting in a 2 × 2 factorial design. All sheep were equipped with a HOBO Pendant G data logger (Onset Computer Corporation, Bourne, MA, USA) in a medial-dorsal position on their necks using vet wrap (Dura-Tech), to record 'grazing' behavior, defined as standing or walking slowly with the head down. The sensitivity, accuracy, and precision were > 90% for 'grazing' behavior with 2-minute intervals. 'Grazing' behavior exhibited a treatment × management (< 0.01) interaction. Both solar (S-4d and S-1d) groups spent more time (< 0.01) 'grazing' than both NR (NR-4d and NR-1d) groups. The presence of solar panels may have provided sheep relief from heat, wind, and rain, which could increase grazing activity. During the study, forage was senescent and low-quality in terms of nutritive value. Both forage digestibility and protein content were higher in the S than in the NR paddocks. Sheep spent less time 'grazing' under intensive rotational management (1d) when compared with rotational management (4d) (< 0.001). The use of sheep for vegetation management on solar farms has great potential. Sheep are effective grazers, easily able to maneuver between solar panels and can graze on steep slopes utilizing the panels to provide shade and protection from climatic conditions. In conclusion, utilizing a mix of intensive rotational and rotational grazing according to forage conditions – rotational 4d grazing management types being most effective for grazing behavior with senescent forage conditions – may be the most effective grazing management strategy on solar farms.

*Abbreviations:* ADG, Average Daily Gain; AMP, Adaptive Multi-Paddock; BCS, Body Condition Score; BW, Body Weight; DM, Dry Matter; DMI, Dry Matter Intake; GLMM, Generalized Linear Mixed Model; IACUC, Institutional Animal Care and Use Committee; 1d, Intensive Rotational; M, Mean; MP, Multi-paddock; MW, Megawatt; $NR_P$ or $_M$, Native Rangeland$_{(\text{Pilot study or Main study})}$; 4d, Rotational; $S_P$ or $_M$, Solar$_{(\text{Pilot study or Main study})}$; SEM, Standard Error of the Mean.

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# 1. Introduction

## 1.1. Solar farms

In locations with many sun hours year-round, such as California (3201 solar hours yearly in San Luis Obispo, CA (Average monthly hours of sunshine in San Luis Obispo (California) [WWW Document], 2022)), solar energy shows great potential as a renewable energy source. Recent literature suggests the dual purpose use of land, in which solar photovoltaics (the conversion of light into electricity using solar panels (Kippelen and Brédas, 2009)) farms are combined with agriculture and/or grazing ruminants and vice versa (Willockx et al., 2020). This diversifies the outputs of the system (energy and agricultural products), keeps the land in agricultural use, reduces vegetation maintenance expenses and labor associated with managing plant growth, reduces wildfire risk potential and is compatible with pollinator projects such as the creation of habitats for wild pollinators or placement of beehives (Agrivoltaic Solutions, 2020; Kochendoerfer et al., 2019; Montag et al., 2016). The abundance of standing biomass on solar farms must be managed to mitigate wildfires as well as the obstruction of the panels and subsequent reduction in solar energy harvest (Starns et al., 2019). Furthermore, solar farms can provide shelter and protection for wildlife such as mammals and birds (Montag et al., 2016; Phillips and Cypher, 2019; Sinha et al., 2018; Wilbert et al., 2015). Panels provide for varying degrees of shade, leading to differences in soil moisture retention and different microclimates, which support botanical, invertebrate and bird diversity and abundance (Sinha et al., 2018). Grazing management is currently being viewed as a service that animal managers can provide. This service includes an ecological service that meets the nutritional needs of the sheep and the forage management needs of the solar farm owners.

## 1.2. Vegetation management

Targeted grazing is the use of ruminants for landscape management, including land health improvement, wildfire prevention, weed control, and ecosystem enhancement (Frost et al., 2012). As opposed to cattle and goats, sheep are the most appropriate ruminant species when it comes to vegetation management on solar farms because they are too small to damage the panels when rubbing against them, and they are not predisposed to chewing on wires or jumping on the panels, as goats would (Agrivoltaic Solutions, 2020). Additionally, sheep are effective grazers, easily able to maneuver between panels and able to graze on steep slopes that are harder to reach for mowers. Sheep eat a large variety of weeds and graze grasses and forbs that would otherwise end up shading the panels (Olson and Lacey, 1994). When using sheep instead of mowers for vegetation management, fewer fossil fuels are used and costs associated to labor are reduced (Kochendoerfer et al., 2019; Pickerel, 2016).

## 1.3. Heat stress

Annually, $3 billion on average are lost to heat stress in livestock in the United States due to reduced weight gains, reproductive success and death or illness (Maia et al., 2020). Sheep lose a large part of excessive heat through their legs and ears, but when the environmental temperature increases to 36 °C or higher, the physiological mechanisms to reduce excess heat fail, leading to an increase in rectal temperature (Marai et al., 2007). Simultaneously, heat stress causes large changes in biological functions, such as decreasing feed intake efficiency and utilization, as well as disturbances in balances of water, protein, energy and minerals and in blood metabolites, secretions of hormones and enzymatic reactions (Marai et al., 2007). Therefore, contract grazers and their sheep also benefit from solar farms by reducing heat stress and protection from other harsh weather conditions and solar radiation, subsequently improving feed efficiency and water use, as well as reduced predation due to stronger and taller fencing (Bhattacharya and Hussain, 1974; Kochendoerfer and Thonney, 2021).

## 1.4. Grazing management

Sheep grazing behavior is dependent on the structure of the pasture, which is a combination of many factors, such as forage density and length, forage species, nutritional quality of the forage, plant vegetative stages, the presence of barriers to defoliation (e.g. stems and sheaths), and leaf blade fibrousness (Animut et al., 2005; Dias-Silva and Filho, 2020). The sheep try to optimize their forage intake, which affects their behavioral activities, such as selectivity (Dias-Silva and Filho, 2020). Sheep will eat forages of lower or higher nutritive quality, depending on the degree of selectivity (Dias-Silva and Filho, 2020). Several factors, like management, regional climatic conditions, animal activity in the group, and the nutritive value and availability of the forage influence duration and intensity of the activities that sheep perform during the day (such as grazing, resting, and ruminating) (Dias-Silva and Filho, 2020).

This study focuses on management. Sheep can be grazed continuously, covering the entire year or grazing season on the same pasture, or rotationally. Rotational grazing or multi-paddock (MP) grazing is difficult to define as it tends to differ between systems, with the paddock size and grazing and rest periods depending on the needs and challenges faced by the farmer (Heady, 1961). Rotational grazing using separate pastures was introduced in Californian grazing systems around 1900, as a range improvement practice (Heady, 1961; Smith, 1895). Adaptive multi-paddock (AMP) grazing is a form of rotational grazing with short grazing periods, high stocking density, long recovery periods, and as conditions change, animal numbers, recovery periods, and other management elements are also adapted (Mosier et al., 2021; Teague and Barnes, 2017). AMP grazing is more labor intensive than continuous or less intensive rotational grazing, but resource use and forage nutritive value is often higher when a pasture is rotationally grazed than when it is continuously grazed (Paine et al., 1999; Teague et al., 2013). Multi-paddock (MP) or rotational grazing with short grazing periods and adequate recovery periods has a consistent advantage over continuous grazing for forage production and livestock weight gain (Teague et al., 2013; Wang et al., 2018). However, Briske et al. (2008) and Heady (1961) report no differences between rotational and continuous grazing management and in some instances higher stocking densities, often associated with MP grazing, can in fact reduce individual ADG compared to continuous grazing (Savian et al., 2014).

## 1.5. Preliminary exploratory study

This preliminary exploratory study addresses how solar panels and grazing management strategy affect the grazing behavior of sheep on a solar farm. While this multifunctional use of land – also referred to as agrivoltaics – has great potential, because the environmental impact from raising sheep and producing energy separately is reduced (Handler and Pearce, 2022), no research has yet been published on the impact of solar panels and grazing management on the grazing behavior of sheep. No scientific data hence exist informing contract grazers on how to manage sheep effectively on solar farms. The aim of this preliminary exploratory study was to investigate both the effects of solar panels (presence or absence of panels) and the grazing management strategy (i.e., intensive rotational grazing (1-day rotations) or rotational grazing (4-day rotations)) on the grazing behavior of sheep, with the aim of finding the best suited strategy for vegetation management on a solar farm through evidence-based grazing management techniques. We tested two hypotheses. Our first hypothesis was that solar panels would increase the total number of grazing hours per day as a result of protection from climatic conditions. We base this hypothesis on the fact that, in cattle, time spent grazing reduces with solar and heat exposure, as a behavioral response to increased heat load (air temperature > 30 °C) (Schütz et al., 2009). Our second hypothesis was that rotational grazing

(4-day rotations) would increase the total number of grazing hours per day compared with intensive rotational grazing (1-day rotations) because animals that rotate less often can spend more time browsing or selecting preferred plant species. Data loggers placed dorsally on the sheep's necks registered the upward and downward movements of the animals' neck. We assumed that an animal that was standing or walking slowly with their head down, was grazing/browsing. Because 'grazing' was not actually observed, but is a behavioral category estimated by data parameters that have an error component, where any variation of 'grazing' is given in quotes in this article, it will refer to behaviors identified as grazing from the HOBO Pendant G dataloggers (standing still or walking slowly with head down). With a higher stocking density, which is the number of animals per unit of land at a specific time, the pasture will be grazed more evenly because animal distribution improves with higher stocking densities, and selective grazing will be reduced, which increases the number of plant species grazed, weeds included (Olson and Lacey, 1994). When grazing intensity increases, there is less standing forage available per animal, which makes the animals less selective (Matches, 1992).

## 2. Methods

All procedures were approved by the IACUC (Institutional Animal Care and Use Committee) of California Polytechnic State University (IACUC approval #2009). Data were collected at Gold Tree Solar Farm in San Luis Obispo County, California, USA. The facility is a 4.5 MW solar photovoltaics power project and has ground-mounted, single-axis tracking solar panels which automatically orient towards the sun (California Polytechnic State University, 2020). This means that the panels have long shades in the early mornings and late afternoons, a rectangular shade right under the solar panels between noon and 13:00 h, and shades going from long to short in the morning and from short to long in the afternoon. The solar farm is constructed on 7.5 ha of sheep pasture owned by Cal Poly (California Polytechnic State University, 2020).

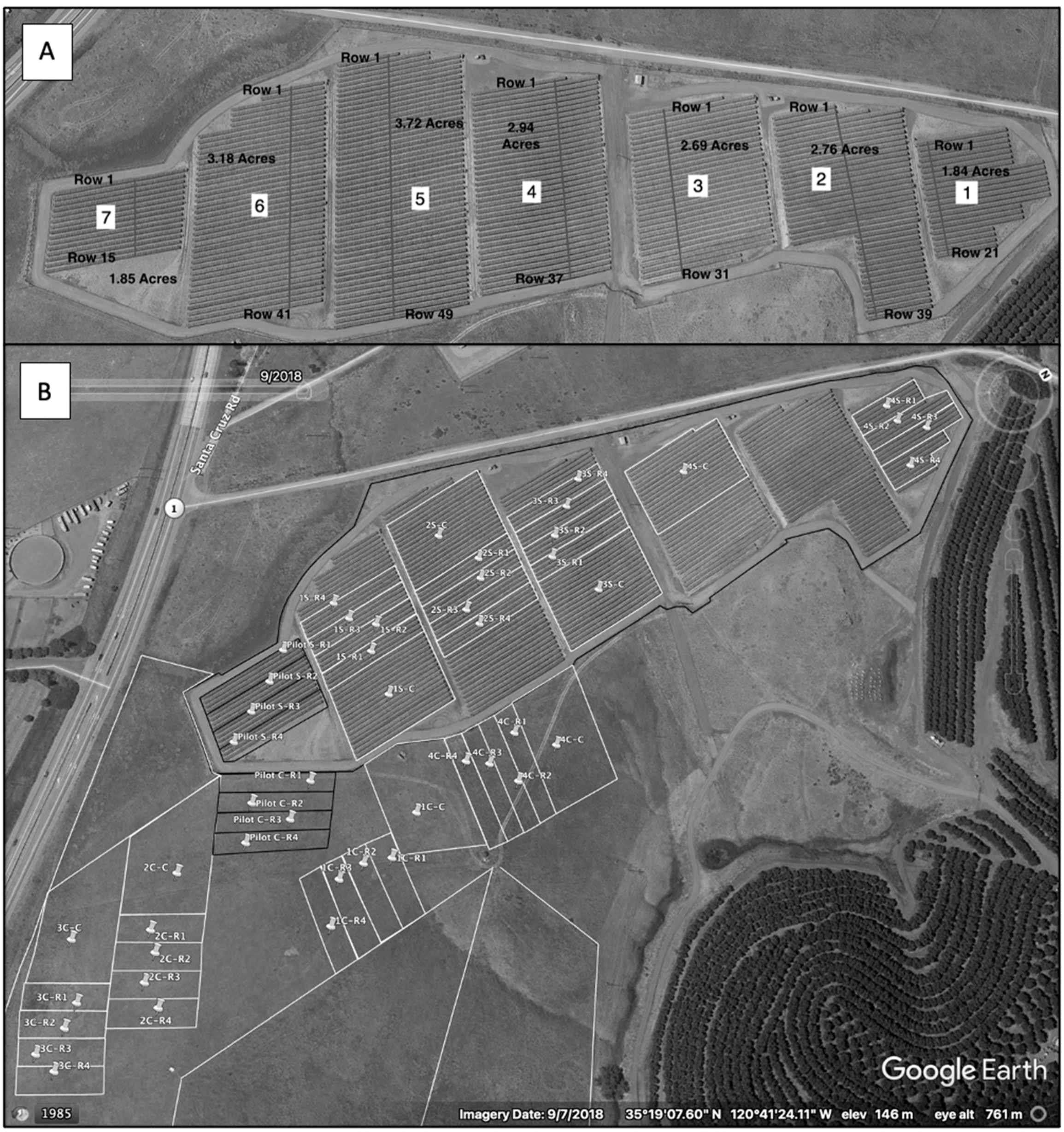


**Fig. 1.** **A** Solar arrays 1–7 of Gold Tree Solar Farm. **B** Paddocks for the pilot study (black lines) and the main study (white lines). The chain-link perimeter fence around the solar farm is shown in black.
(a) Source: Google Earth Pro (2020). (b) Source: Google Earth Pro (2020).

Usually, the sheep from Cal Poly's flock (n = 82) are used for grazing management on Cal Poly's rangelands and on Gold Tree Solar Farm. Thus, the management conditions for the current study when compared with normal management conditions were very similar.

Two experiments were conducted to investigate the effects of solar panels on sheep grazing behavior (time spent grazing) and which grazing management strategy is best suited for vegetation management on a solar facility. A pilot study was conducted in November 2020 to inform the design of the main study, which was conducted in January 2021. The sheep used in the pilot study (n = 42) were also used in the main study (n = 80). The sheep used in the main study were divided into four groups based on their weight, so the average sheep weight was similar between the four groups.

The study was a systems comparison between the solar grazing system (S) and the grazing system in native rangelands (NR), under rotational (4d) or intensive rotational (1d) grazing. This preliminary exploratory study provides valuable information for future studies.

### *2.1. Pilot study – testing the effect of solar panel presence on grazing behavior to inform the design of the main study*

Sheep (over 99% Dorper-based genetics; n = 42) were stratified by body weight (BW) (mean ± SEM = 78.3 kg ± 0.97) and age (range 1–8 years old) into two groups of equal size to one of the respective treatment grazing locations, solar farm (S), or native rangeland (NR) (Fig. 1B). The average weights ( ± SEM) of group $S_P$ and $NR_P$ were 78.5 kg ± 1.55 and 78.6 kg ± 1.55, respectively. The pilot study was conducted over a 4-day period during the third week of November 2020 on solar array 7 (Fig. 1A) of Gold Tree Solar Farm. Array 7 had not been grazed as often as the other arrays on the solar farm, so observed forage species diversity was limited and was therefore no suitable replicate for the main study, which is why this array was selected for the pilot study. Via visual observation of the pasture (forage length and forage mass for 20 ewes per 0.101 ha per day), it was determined that there was insufficient forage to support 20 ewes fully in terms of nutrition. All sheep were managed in an intensive rotational grazing system, whereby the sheep were moved to a fresh paddock at the start of each new day of the study (four paddocks in four days, sheep were moved between 10:00 h and 10:30 h each day; paddock size = 0.101 ha). The design of the pilot study was a repeated measures design. All eight paddocks were only grazed once. The sheep in both treatment groups were fed one bucket of almond hulls every morning between 07:00 h and 07:30 h and had ad libitum access to water.

The main ( ± SEM) temperature during manual observation during daytime (10:45 h - 17:30 h) was 17.5 °C ( ± 0.16), with main wind speed ( ± SEM) being 8.0 km/h ( ± 0.38). There was no precipitation.

#### *2.1.1. Pilot study results and discussion*

For the automated data collection using the HOBO Pendant G data logger, grazing behavior was expressed in both proportions of total time daily and in proportions of eleven set time periods of 2 h each for the pilot study. Because the sheep were moved to a new paddock between 10:00 h and 10:30 h every morning, the time period 09:00 h - 10:58 h was not considered in that analysis (Fig. 3). Logger data from the pilot study were not analyzed with a statistical test because the 20 sheep per group in the two treatment groups ($NR_P$ & $S_P$) could not be assumed as behaving independently from each other. Because the dataset for the pilot study was not large enough, the model did not converge. Therefore, only descriptive statistical results were reported. Most of the 'grazing' behavior (averaged over all sheep per treatment group and over all four days) was performed during daytime, between 07:00 h and 19:00 h, regardless of whether solar panels were present (Fig. 3). At night (19:00 h - 07:00 h), 'grazing' was still performed, but less than during daytime. Sheep increased 'grazing' activity in the period from 07:00 h to 8:58 h in both the $S_P$ and the $NR_P$ treatments. Both groups 'grazed' more at the end of the day, during the time period from 15:00 h to 16:58 h, just before sunset at 16:50 h. Logger data from the pilot study suggested that sheep 'grazed' more in the $NR_P$ treatments than in the $S_P$ treatments. The pilot study, however, ran for 4 days only, while the main study ran for a total of 16 days, and was performed with twice the number of animals than used in the pilot study, resulting in four replicates. For the manual data collection, scan sampling was practiced in the pilot study, informing the scan sampling procedures for the main study.

### *2.2. Main study*

Sheep (over 99% Dorper-based genetics; n = 80) were stratified by body weight (BW) (M ± SEM = 78.3 kg ± 0.97) and age (range 1–8 years old) to the respective treatment grazing locations, i.e. solar farm (S) or native rangeland (NR) (Fig. 1B), leading to a systems comparison. Grazing location treatments were then randomly assigned to the grazing management styles of rotational grazing management (4d; paddock size = 0.405 ha) or intensive rotational grazing management (1d; paddock size = 0.101 ha), resulting in a 2 × 2 factorial arrangement of treatments: Solar Rotational (S-4d), Solar Intensive Rotational (S-1d), Native Rangeland Rotational (NR-4d), and Native Rangeland Intensive Rotational (NR-1d). The mean weights ( ± SEM) at the start of the study of group 1, 2, 3, and 4 were 77.8 ± 2.31 kg, 78.0 ± 1.83 kg, 78.4 ± 1.81 kg, and 78.3 ± 1.95 kg, respectively. All sheep were mated with the ram in September 2020 and 76 out of 80 sheep conceived and delivered in February 2021. During the main study in January, sheep were in the final trimester of gestation. In all four groups, one sheep did not conceive. Sheep from group 1 gave birth to 26 lambs, group 2 to 28 lambs, group 3 to 30 lambs, and group 4 to 29 lambs. Data were collected during a period of 16 consecutive days in January 2021. All four treatments were applied to all four groups in a pseudo-randomized order (to control carry-over effects) across a period of 4 weeks (Fig. 1B), with 4 days per treatment. Every treatment was applied to each of the four experimental units (study flocks) in the order shown in Table 1. Due to drought causing the forage to be senescent, a management decision was made to supplement the sheep in the solar treatments with approximately 23 kg of alfalfa hay per treatment group (n = 20) on all treatment days except for the first day of every treatment period. The sheep in all treatment groups were fed one bucket of almond hulls every morning between 07:00 h and 07:30 h. All sheep had ad libitum access to water. The sheep in the intensive rotational treatments (S-1d and NR-1d) were moved to a new paddock between 08:30 h and 10:30 h every day, and the sheep in the rotational treatments (S-4d and NR-4d) were moved every 4 days to their next treatment period. For the 1d treatments this means that 20 sheep grazed 0.101 ha per day for a period of four days. For the 4d treatments, 20 sheep grazed 0.405 ha for a period of four days. This means that all sheep, regardless of their treatment, had

**Table 1**
Rotation schedule of sheep groups through the paddocks. (S = Solar; NR = Native Rangeland; 4d = Rotational; 1d = Intensive Rotational).

| Paddock | Week 1 (Jan. 3–6) | Week 2 (Jan. 7–10) | Week 3 (Jan. 11–14) | Week 4 (Jan. 15–18) |
|---|---|---|---|---|
| 1 S-4d | Group 1 | | | |
| 2 S-4d | | Group 2 | | |
| 3 S-4d | | | Group 3 | |
| 4 S-4d | | | | Group 4 |
| 1 S-1d | Group 2 | | | |
| 2 S-1d | | Group 4 | | |
| 3 S-1d | | | Group 1 | |
| 4 S-1d | | | | Group 3 |
| 1 NR-4d | Group 3 | | | |
| 2 NR-4d | | Group 1 | | |
| 3 NR-4d | | | Group 4 | |
| 4 NR-4d | | | | Group 2 |
| 1 NR-1d | Group 4 | | | |
| 2 NR-1d | | Group 3 | | |
| 3 NR-1d | | | Group 2 | |
| 4 NR-1d | | | | Group 1 |

access to the same amount of space during their treatment period.

### 2.3. The HOBO Pendant G data loggers (Onset Computer Corporation, Bourne, MA, USA)

All sheep (both in the pilot and the main studies) were equipped with a tri-axial accelerometer, the HOBO Pendant G data logger (hereafter data logger; Onset Computer Corporation, Bourne, MA, USA), attached dorsally on their necks using vet wrap bandages (Fig. 2). The X-axis of the device was aligned in the dorsoventral or vertical direction, the Y-axis was aligned with the mediolateral or transverse direction, and the Z-axis was approximately aligned with the craniocaudal direction (Hu et al., 2020), similar to how the data loggers were attached to the goats in the study of Moreau et al. (2009).

### 2.4. Validation of the HOBO Pendant G data loggers

In order to calibrate the data loggers (Moreau et al., 2009), manual observation was conducted by three trained observers over a period of four days for 30.5 h total. Ten sheep were placed in a pasture of approximately 0.101 ha in size. The behavior of three of these randomly chosen sheep, each one equipped with a data logger, was recorded with 2-minute intervals for 3 h per day over a 4-day period. Data logger output was combined with the manual observation data. Observations that were made were: lying, standing, grazing while standing, grazing while walking, and walking. Interobserver reliability was 100% between the three observers for an observation of 120 min using scan sampling at a 2-minute interval.

### 2.5. Automated data collection on grazing behavior

The grazing status (grazing behavior: grazing/non-grazing) of the sheep was determined with the use of the HOBO data loggers. Guo et al.

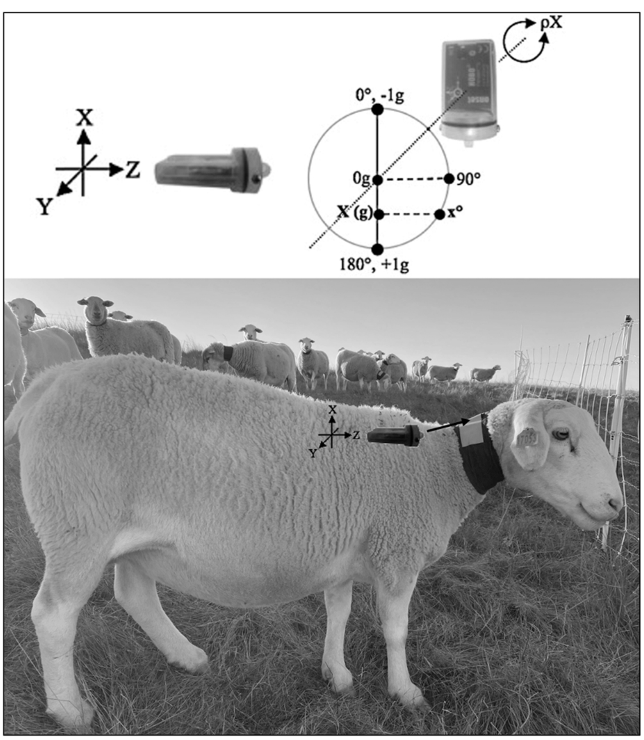


**Fig. 2.** Position of the HOBO Pendant G Data logger dorsally on the neck of the sheep. Picture derived from the article of Moreau et al. (2009). The X-axis of the data logger registers up to 90° (1 g) change deviated from the horizontal position, with head down position being a negative value between 0 and - 1 g and head up position being a positive value between 0 and 1 g.

(2018) reported consistency of observable behaviors attributed with grazing and non-grazing even before analyzing data from an accelerometer and gyroscope. During grazing, sheep kept their heads down to gather, bite, and swallow grass, while simultaneously walking at a slow pace or remaining at the same location (Guo et al., 2018). Data in the form of X/Y/Z-axis readings at a 2-minute interval, were translated into grazing and non-grazing behavior by reading the X-axis. A positive value was associated with non-grazing behavior (head up), while a negative value was attributed to grazing behavior (head down) with an accuracy of 90.25% (M. Weller, Scientific Programmer, University of Göttingen, personal communication, January 29, 2021; Moreau et al., 2009). Grazing behavior was expressed in proportions of total time daily.

### 2.6. Manual data collection

Manual observation data were acquired through scan sampling of all treatment groups during the grazing event, where the behavior of all sheep in each group was recorded at regular intervals (Gilby et al., 2011). All behaviors from the five categories (Table 2) were individually scored for all sheep by counting the number of sheep exhibiting the associated behaviors. The scan sampling data were, therefore, not at individual level, but at group level. The observations on location (i.e., whether the sheep were under the solar panels or in the alley between the solar panels) could only be done for the solar groups as the NR groups did not have access to solar panels. Behavior was recorded in scan samplings at a 30-min interval, from 11:00 h to 15:50 h (10 times per day per group), for 16 consecutive days during the main study. Scan sampling started every morning at 11:00 h for the S-4d group, at 11:05 h for the S-1d group, at 11:15 h for the NR-4d group and at 11:20 h for the NR-1d group.

### 2.7. Pasture biomass sampling

#### 2.7.1. Quantitative analysis

The forage intake of the sheep (i.e., the change in forage mass) per individual paddock was estimated through pasture biomass sampling using the clipping technique as described by Voelkel et al. (2018). The pasture biomass was sampled before and after the grazing event in each paddock. Biomass sampling was done through randomly selecting 12 locations per 0.405 ha rotationally (4d) grazed plot and three locations per 0.101 ha intensively rotationally (1d) grazed plot (adding up to 12 locations per four intensively rotationally grazed plots). According to Voelkel et al. (2018), a minimum of 12 clipped biomass samples representative for the plot should be taken per pasture. A 0.305 $m^2$ quadrat was randomly distributed in the pasture. The plant biomass at the location where the quadrat was dropped was clipped to 2.5 cm above the soil. Each sample was oven dried in an open paper bag for a minimum of 48 h at 55 °C. After drying, the samples were weighed on a scale with 1 g precision.

#### 2.7.2. Forage proximate analysis

Forage samples were ground using a Wiley mill (Thomas Scientific, Swedesboro, NJ). Biomass from all samples was homogenized and the homogenized ground samples were analyzed using an Ankom machine (ANKOM Technology Corp., Fairport, NY) to determine Neutral Detergent Fiber (NDF) content. The percentage of N and C in all samples, as well as the C/N ratio, were measured using an elemental analyzer (Elementar VarioMax, Langenselbold, Germany).

### 2.8. Statistical analysis

#### 2.8.1. Validation of the HOBO Pendant G data loggers

According to Moreau et al. (2009), the data loggers can, through measurements of acceleration and tilt, determine four mutually exclusive behaviors; grazing, lying, standing and walking. Due to low accuracy (< 50%) for other behaviors measured during the validation trials

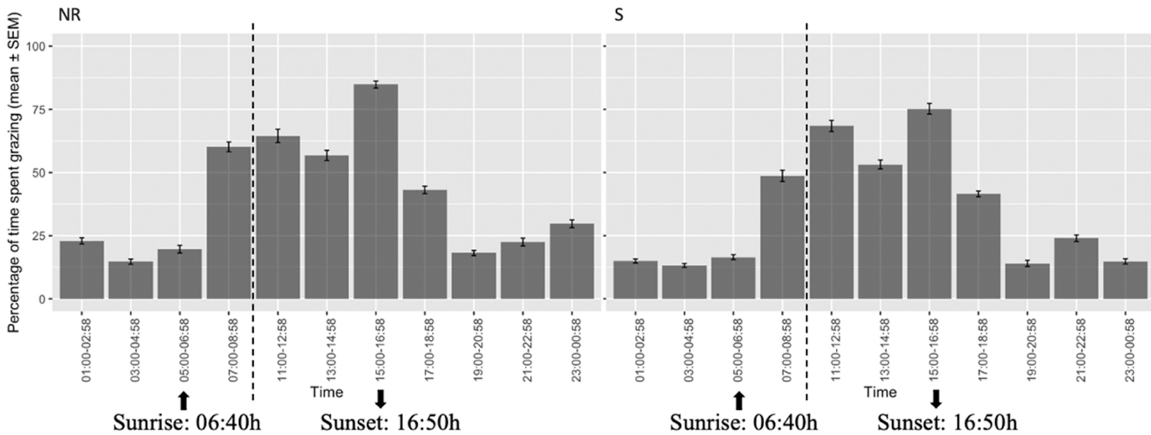


**Fig. 3.** Bar graphs showing the mean ( ± SEM) of the total percentage of time spent grazing per treatment (left: NR & right: S) during the pilot study, averaged over the grazing period of four days. Each bar entails a period of two hours. The dashed line indicates the sheep being moved to a different paddock every morning between 09:00 h and 11:00 h. The two groups of 20 sheep per group were all fed a bucket of almond hulls at 07:00 h. Sunrise and sunset took place at 06:40 h and 16:50 h, respectively. (S = Solar; NR = Native Rangeland).

**Table 2**
Behaviors scored during manual observation every day of the main grazing event from 11:00 h until 16:00 h. The behaviors in each category are mutually exclusive.

| Category/behavior | | Definition |
|---|---|---|
| Location | Panels | Percentage of sheep are with 1/2 or more of their body under the solar panels. |
| | Alley | Sheep are with less than 1/2 of their body under the solar panels. |
| Posture | Lying | Sheep are touching the ground with the entire bottom surface of their body. |
| | Walking | Sheep are moving faster than 0 km/h. |
| | Standing | Sheep are standing in the pasture without moving in any direction. |
| Activity | Grazing | Sheep are standing or walking in the pasture with their heads down, while pulling grass from the pasture with their mouths. |
| | Non-grazing | Sheep are not moving their heads down and are not pulling grass from the pasture with their mouths. |
| Proximity of sheep to each other | > 5 sheep-lengths away from each other | Sheep are more than five sheep-lengths away from all other sheep. |
| | < 5 sheep-lengths away from each other | Sheep are less than five sheep-lengths away from all other sheep. |

of the data loggers, only grazing behavior was further analyzed. Because ‘grazing’ was not actually observed, but is a behavior category estimated by data parameters that have an error component, where any variation of ‘grazing’ is given in quotes in this article, it will refer to behaviors identified as grazing from the HOBO Pendant G dataloggers (standing still or walking slowly with head down).

To validate the data loggers, the outputs of the data loggers were compared to the outcomes of 30.5 h, 2-min interval scan sampling observations of five sheep with three observers. One sheep was observed for a period of 2 h by all three observers to test interobserver reliability. The precision (the likelihood that grazing behavior recorded by the data loggers was also recorded through manual observation; formula 1), sensitivity (ability of the data loggers to correctly determine if a sheep was grazing; formula 2), specificity (the likelihood that non-grazing behaviors that were recorded by the data loggers were also recorded through manual observation; formula 3), and the accuracy (the ability of the data loggers to correctly differentiate between grazing and non-grazing behavior; formula 4) for grazing behavior were calculated for a 2-min recording interval.

$$Precision = \frac{\text{True Negative}}{(\text{True Negative} + \text{False Negative})} \tag{1}$$

$$Sensitivity = \frac{\text{True Positive}}{(\text{True Posivite} + \text{False Negative})} \tag{2}$$

$$Specificity = \frac{\text{True Negative}}{(\text{True Negative} + \text{False Positive})} \tag{3}$$

$$Accuracy = \frac{(\text{True Positive} + \text{True Negative})}{(\text{True Positive} + \text{True Negative} + \text{False Positive} + \text{False Negative})} \tag{4}$$

Eight data loggers had either shifted or fallen off due to sheep rubbing themselves against the metal poles on the solar farm. The data these loggers did not record were registered as missing values, which were excluded from the analysis.

### 2.8.2. Automated data collection

Grazing data (proportions of total time) recorded by the data loggers were analyzed using a general linear mixed model (GLMM) in R (version 4.0.2, R Core Team, 2020; model glmmPQL from the MASS package) specifying a binomial distribution with a logit link function. The family used was quasibinomial, which automatically estimates overdispersion. Fixed effects included treatment (S/NR), management (4d/1d), and group (1−4). Sheep ID was introduced as a random effect to account for the repeated measures on the individual sheep. Results of the GLMM were given on the log odds ratio scale. Outputs were considered significant when $\alpha < 0.05$.

## 2.9. Manual data collection

Behavior data from direct observations were at group level and could, therefore, not be statistically analyzed, with only 4 groups exposed to all treatments. However, the summary values (M ± SEM) are provided for discussion. Sheep whose data loggers fell off or shifted during the study were omitted from the data logger results, but these sheep were, nonetheless, still included in the manual data collection results.

## 2.10. Pasture biomass sampling

Pasture biomass data before and after the grazing event were reported in mean ( ± SEM) of the dry matter (DM) weight of forage samples taken in the 16 different paddocks from all four treatment groups. Weight of all forage samples in DM was averaged per treatment. An ANOVA was performed for both the forage quantitative (forage DM weight) and forage qualitative data.

## 3. Results

### 3.1. Validation of the HOBO Pendant G data loggers

The X-axis values from the data loggers (M. Weller, Scientific Programmer, University of Göttingen, personal communication, January 29, 2021) were compared to the behaviors obtained during manual observation. The data loggers assigned 93.5% of the behaviors correctly and were therefore deemed sufficiently valid. The precision for 'grazing' behavior was 96.7%, sensitivity 96.6%, specificity 90.6%, and accuracy 93.5% for a 2-min recording interval.

### 3.2. Environmental data

The main ( ± SEM) temperature during daytime manual observations (11:00 h - 16:00 h) over the entire data collection period was 20.1 °C ( ± 0.40) with variability in temperature among weeks: week 1 = 18.7 °C ( ± 0.17); week 2 = 22.1 °C ( ± 0.52); week 3 = 22.8 °C ( ± 0.33); and week 4 = 16.9 °C ( ± 0.59). In the first 3 weeks there was no rainfall, but during the last 2 days of week 4 there was some rain in the mornings, with a total 12.4 mm of rain on 22 January and 2.0 mm of rain on 23 January. The mean wind speed was 10.1 km/h ( ± 0.45) in week 1; 8.9 km/h ( ± 0.48) in week 2; 13.2 km/h ( ± 0.42) in week 3; and 7.6 km/h ( ± 0.39) in week 4, with the largest wind speeds often being in the mornings and evenings.

### 3.3. Grazing behavior

'Grazing' behavior, recorded by the data loggers, exhibited a treatment × management ($P < 0.01$) interaction (Fig. 4A). Sheep in S treatments (S-4d: Mean ± SEM = 45.65 ± 0.35% of total time and S-1d: 43.30 ± 0.46% of total time) spent more time 'grazing' than sheep in NR treatments (NR-4d: 44.02 ± 0.47% of total time and NR-1d: 39.95 ± 0.39% of total time). Similarly, sheep in both 4d management treatments (NR-4d and S-4d) spent more time 'grazing' compared to sheep in 1d management treatments (NR-1d and S-1d).

An analysis of the 'grazing' behavior from only the first day of all treatments (sheep in the solar treatments did not receive alfalfa supplementation on the first day of each treatment, while they did receive alfalfa supplementation on days 2, 3 and 4 of the solar treatments), shows that sheep 'grazed' more on day one in the S-4d treatments (47.50 ± 0.55) than in the NR-4d treatments (44.60 ± 1.04; $P < 0.05$), and more in the S-1d treatments (45.67 ± 1.29) than in the NR-1d treatments (38.39 ± 0.84; $P < 0.001$). Within the NR treatments, sheep 'grazed' more under 4d management than under 1d management ($P < 0.001$). No differences were observed in time spent 'grazing' between the 4d and 1d grazed sheep within the S treatments ($P = 0.18$) on the first day. These results are similar to the average results from all treatment days combined.

### 3.4. Scan sampling data

Means ( ± SEM) of repeated scan sampling data for all treatments are shown in Table 3. Treatment effects could not be tested due to insufficient replication. Walking, which was a short-term event behavior, was very rarely observed at our rate of scan sampling.

Qualitative observations of environmental influences: On dry days with an average temperature lower than 23 °C, but with a minimum average temperature of 12 °C, sheep spent 70.4% ( ± 3.87) of their time under the solar panels. However, on days with an average temperature above 23 °C, sheep spent 76.1% ( ± 2.70) of time under the solar panels and increased up to 91.7% ( ± 6.41) of the time under the solar panels during rainfall (≥ 1.0 mm in a 15-minute period).

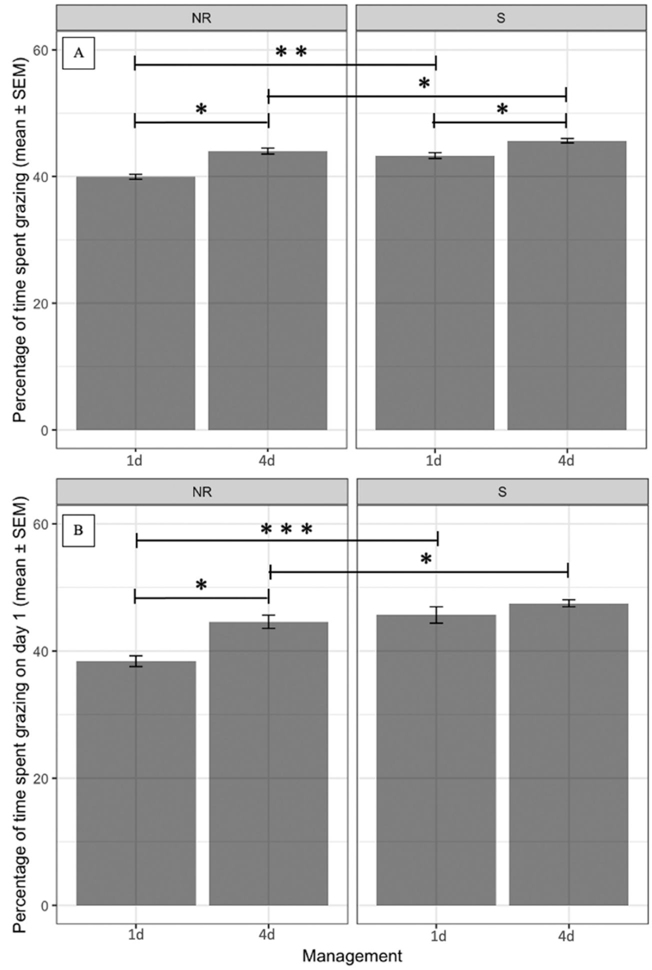


**Fig. 4.** Bar graphs showing the mean ( ± SEM) of the total percentage of time spent grazing during the main study over the total period of sixteen days of both treatment groups (NR & S) and both management types (4d & 1d). **A** Data from all treatment days. **B** Data from the first days of all four treatment weeks (when sheep were not supplemented with alfalfa hay).
* P < 0.0001, * * P = 0.0015, * ** P = 0.031. (S = Solar; NR = Native Rangeland; 4d = Rotational; 1d = Intensive Rotational).

### 3.5. Forage data

#### 3.5.1. Forage quantitative data

Forage mass was expected to be different between the S and NR pastures. A Shapiro-Wilk test showed that the data were approximately normal, W (377) = 0.844, $P < 0.001$. An ANOVA test indicated a difference in forage quantity between treatment groups. The NR sites produced 147% of the biomass measured in the solar sites (S (Mean ± SEM = 345.63 ± 224.13 g/ha) and NR (508.03 ± 229.67 g/ha), $P < 0.001$). Forage disappearance under grazing was 17% ((467.04 g/ha - 386.61 g/ha)/ 467.04 g/ha * 100), indicating that our sampling captured changes resulting from forage consumption (Fig. 5A). No differences were detected in forage mass between the 4d (412.57 ± 302.26 g/ha) and 1d (441.09 ± 248.04 g/ha) grazed pastures ($P = 0.087$).

#### 3.5.2. Forage quality data

There were no differences in forage digestibility (NDF content, %C, %N, C/N ratio) between the 4d and 1d pastures. There were, however,

**Table 3**
Percentage of sheep (M ± SEM) out of 20 sheep per group that perform a certain (mutually exclusive per category) behavior as observed through manual observation every day of the main grazing event from 11:00 h until 16:00 h. (S = Solar; NR = Native Rangeland; 4d = Rotational; 1d = Intensive Rotational).

| Category/behavior | | S | | NR | |
|---|---|---|---|---|---|
| | | 4d M ± SEM | 1d M ± SEM | 4d M ± SEM | 1d M ± SEM |
| Location | Panels | 71.5 ± 1.28 | 72.8 ± 1.29 | – | – |
| | Alley | 27.6 ± 1.20 | 26.0 ± 1.14 | – | – |
| Posture | Lying | 24.3 ± 2.21 | 26.3 ± 2.17 | 15.1 ± 1.85 | 15.4 ± 1.74 |
| | Walking | 1.1 ± 0.33 | 1.8 ± 0.51 | 0.7 ± 0.21 | 0.4 ± 0.19 |
| | Standing | 73.6 ± 2.28 | 71.1 ± 2.24 | 84.5 ± 1.85 | 84.2 ± 1.74 |
| Activity | Grazing | 71.5 ± 2.48 | 67.9 ± 2.44 | 82.0 ± 2.05 | 82.0 ± 1.87 |
| | Non-grazing | 27.2 ± 2.41 | 31.3 ± 2.34 | 17.9 ± 2.06 | 17.9 ± 1.88 |
| Proximity of sheep to each other | < 5 sheep-lengths away from each other | 70.2 ± 1.49 | 85.0 ± 1.01 | 87.8 ± 0.67 | 94.0 ± 0.44 |
| | > 5 sheep-lengths away from each other | 28.7 ± 1.37 | 13.8 ± 0.68 | 12.3 ± 0.67 | 6.0 ± 0.44 |

differences between forage digestibility between S and NR pastures. NDF content (Fig. 5B) in the forage DM was not significantly higher in the NR pastures (M ± SEM = 76.33 ± 1.57) than in the S pastures (74.11 ± 4.17, $P = 0.059$). Nitrogen (Fig. 5D), used to estimate protein content (Fig. 5F), was 172% higher in the forage in the S pastures (1.12 ± 0.18%) than in the NR pastures (0.65 ± 0.13%). Carbon (Fig. 5C) was only 103% higher in the forage in the NR pastures (40.26 ± 0.24%) than in the S pastures (39.07 ± 1.60%; $P < 0.05$), while the C:N (carbon to nitrogen) ratio (Fig. 5E) was 180% higher in the forage in the NR pastures (64.20 ± 13.30) than in the S pastures (35.64 ± 5.70; $P < 0.001$). The high NDF content of the forage in both S and NR pastures indicates that the forage was senescent and of low quality. However, protein content of the forage was higher and both %C and C:N ratio were lower in the S pastures than in the NR pastures, indicating that the S pastures had a higher forage quality and digestibility than the NR pastures.

## 4. Discussion

The aim of our study was to explore the effects of solar panels and grazing management strategy on the behavior of sheep. Photovoltaics is considered one of the most promising renewable energy sources due to the continuous technological developments and efficiency gains (Shubbak, 2019), the relatively low cost and adoption in a quickly growing number of regions around the world (Breyer et al., 2017; Shahabuddin et al., 2021), and the low environmental footprint compared to other renewable energy technologies (Creutzig et al., 2017). However, large utility-scale solar farms, which typically produce > 1 Megawatt (MW) and are placed outside of urban areas (Hernandez et al., 2014), are controversial because they could potentially threaten natural ecosystems through fragmentation of habitats or displace other human land-uses (Cameron et al., 2012). For instance, they are often built on existing agricultural grassland and marginal lands (Montag et al., 2016), but the actual use of these lands is highly debated (Muscat et al., 2022). Agrivoltaics is the multifunctional use of land for both energy production through solar panels and agricultural production, for example through grazing. Most of these agrivoltaic sites have specific demands for grazing outcomes that are dependent on the site management. The novelty of this work relates to different grazing strategies that meet the demands of the agrivoltaic site managers and animal managers. Vegetation management through grazing on solar farms serves a dual purpose: providing nutrients to the sheep as well as providing a service to the electrical company. One of our main objectives was to use an evidence-based approach to grazing management to meet the needs of both parties. We found that sheep spent more time 'grazing' in the S treatments than in the NR treatments and that sheep in the 4d treatments spent more time 'grazing' than sheep in the 1d treatments during senescent forage conditions.

### 4.1. *The effects of solar panels on sheep grazing behavior*

We hypothesized that solar panels would increase the total number of grazing hours per day as a result of the protection from sun, wind, and rain the solar panels provide the sheep. Evidence supporting this hypothesis was provided by data logger results. Direct scan sampling data indicate that sheep in the NR treatments grazed more, which suggests that the results are sensitive to the method, indicating that differences in time spent grazing are relatively small between treatments. Logger data, and the corresponding statistical analysis, show that sheep in the S (S-4d and S-1d) paddocks spent more time 'grazing' than sheep in the open fields (NR-4d and NR-1d; Fig. 1), which confirm our initial hypothesis. This difference can be explained by four factors: forage availability, forage quality, time, and weather.

#### 4.1.1. *Forage availability*

There was a lower forage availability in the S paddocks than in the NR paddocks (Fig. 5A), which could have caused the sheep to search for longer periods to find sufficient forage. Total daily foraging time of large herbivores correlates with total daily intake (Iason et al., 1999; Newman et al., 1995). When forage availability decreases, sheep have been shown to increase their daily foraging time to compensate (Allden and McDWhittaker, 1970; Arnold and Birrell, 1977; Penning, 1986; Penning et al., 1991).

The study was originally planned for the forage growing season. However, due to drought, the rainfall started during the last 2 days of the data collection period, causing the forage to be in a senescent condition leading to insufficient forage availability on the solar farm. The solar pastures had also been grazed regularly, while the NR area had not been grazed as intensively in previous grazing periods. A management decision was made to supplement the sheep in the solar treatments with alfalfa hay. Hence, all treatment groups on the solar farm (S-4d and S-1d) were fed approximately 23 kg of alfalfa hay between 17:30 h and 18:30 h on the 2nd, 3rd, and 4th day of the 4-day treatment week because of a lack of forage availability on the solar farm. The alfalfa hay provided approximately 50% of the sheep's DMI. Some S paddocks contained more forage than other, but all S paddocks received the same alfalfa supplementation. The sheep in the NR treatments did not have to be fed alfalfa hay since there was enough accumulated residue vegetation from previous years available in the open pastures. The consumption of hay was recorded by the data loggers as grazing and the hay was consumed very quickly (in ± 30 min from the time of feeding all hay fed was consumed).

Results of 'grazing' behaviors recorded only on the first day of every new treatment week (none of the sheep received alfalfa supplementation on the first day of every week; Fig. 4B), produced similar results to the average of all treatment days (Fig. 4A), indicating that the management decision to supplement the sheep in the solar treatments with alfalfa hay did not significantly impact sheep 'grazing' behavior in this research.

#### 4.1.2. *Forage quality*

Botanical composition of the sward may have impacted the nutritive value of the forage (Graham et al., 2021) and, therefore, influenced the time spent grazing between the sheep in the S paddocks and the sheep in the NR paddocks. Solar panels can create micro-climates, in part because they provide shade, promoting higher soil moisture levels, and in part

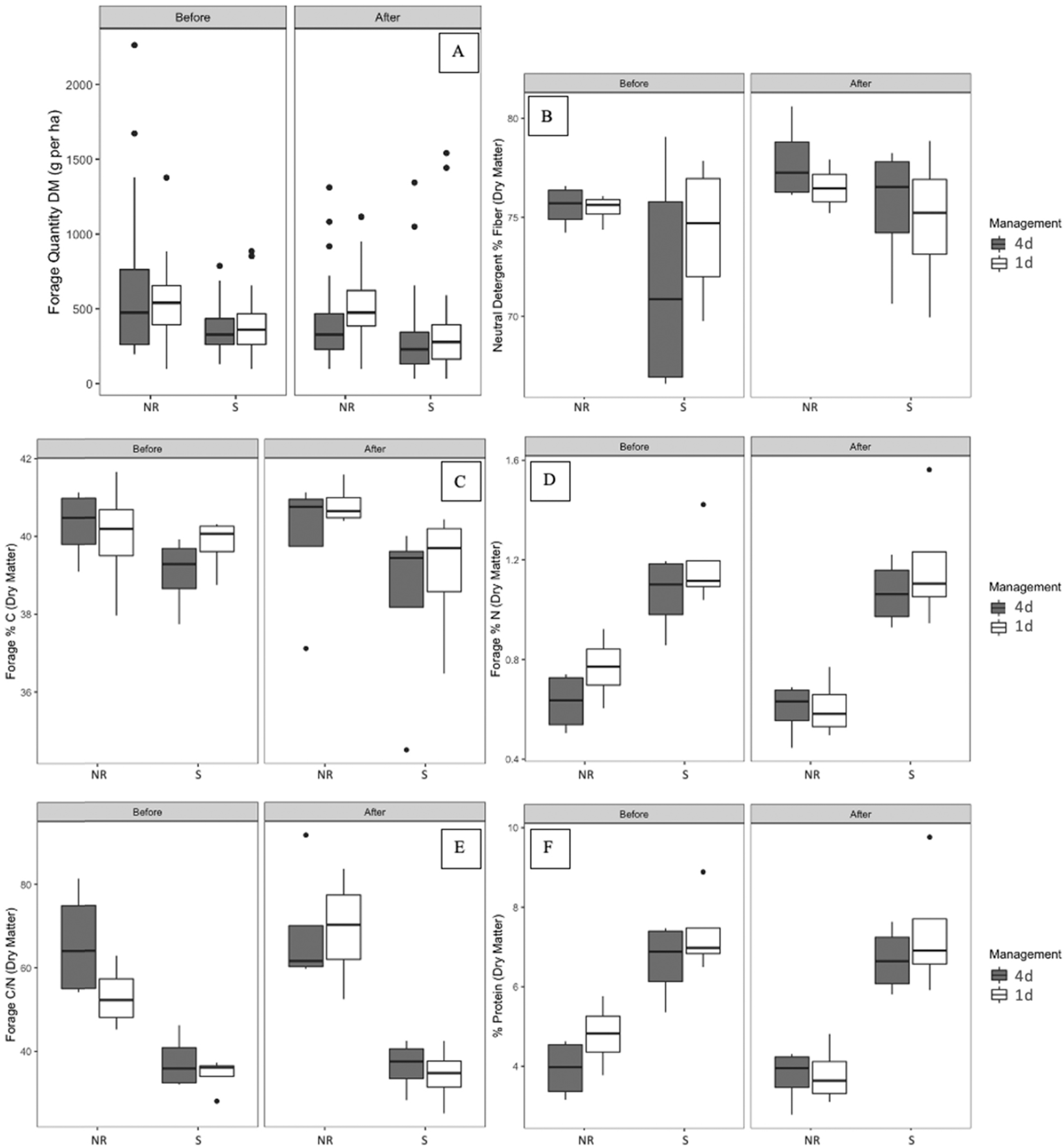


**Fig. 5.** Bar graphs showing the mean ( ± SEM) of **A** Forage quantity, **B** Neutral detergent % fiber, **C** Forage %C, **D** Forage %N, **E** Forage C/N, and **F** % Protein in forage, in forage dry matter. (S = Solar; NR = Native Rangeland; 4c = Rotational; 1d = Intensive Rotational).

because during the night, dew accumulates on the solar panel surfaces, which drips down the edge and creates moist soil beneath the panels in which fresh, more protein-rich vegetation grows (Armstrong et al., 2016; Marrou et al., 2013; Santra et al., 2017). Qualitative forage data showed that %N was higher in the standing forage in the S pastures than in the NR pastures, while %C and C/N content were higher in the NR pastures than in the S pastures. This indicates a higher forage digestibility in the S pastures, which caused the sheep to be able to ingest more forage, which may have caused the sheep to be able to spend more time grazing.

#### 4.1.3. *Time*

Sheep in the pilot study in the $S_P$ paddocks ‘grazed’ more than the sheep in the $NR_P$ paddocks in the morning after the sheep in the $IR_P$ treatments were moved to a new paddock (the period from 11:00 h to 12:58 h; Fig. 3). Sheep in the $NR_P$ paddocks, on the other hand, ‘grazed’ more in the afternoon in the period from 15:00 h to 16:58 h before sunset. This could also be influenced by the difference in intensity of the solar radiation between the morning and the afternoon (Cedar Lake Ventures Inc, 2022). Sheep in the $NR_P$ treatments grazed more just before sunset, potentially because the temperature went down by 1 °C on average during the time period 2 h before sunset (between 15:00 h and 16:45 h) compared to the temperature during the 2-hour period before (13:00 h – 14:45 h), making it easier for the sheep to regulate their body temperature and therefore be able to spend more energy on grazing (Bhattacharya and Hussain, 1974). Likewise, in the main study, sheep in the S paddocks possibly grazed more in the morning and ruminated more in the afternoon.

#### 4.1.4. Weather

Approximately 60% of the surface area in the paddocks was covered by solar panels and 40% was exposed (Grading and Drainage Plans for Cal Poly Solar Farm, 2018), which means that the random chance of the sheep being under the solar panels was higher than the random chance of the sheep being in the alley between the panels. However, according to means comparison of the scan sampling data, sheep in the S treatments spent most of their time (> 70%) under the solar panels, suggesting that the sheep preferred being under the solar panels as opposed to being in the alley between the panels. Data also indicate that sheep prefer being beneath the solar panels under unfavorable weather conditions of heat and rain. The presence of solar panels may have provided relief from heat (Sharpe et al., 2021), wind, and rain to the sheep, which could have caused the sheep in the S groups to graze more. Solar panels provide protection from poor weather, and therefore most sheep will be found under the solar panels in circumstances of intense solar radiation or heavy rain. Because this study was conducted in January, the solar radiation was likely much less intense than in the spring and summer months. This may have influenced the amount of time that the sheep sought refuge under the solar panels. Additionally, there were more fresh weeds under the solar panels than in the alleys, which may also have caused sheep to spend more time under the solar panels. However, during visual observations, sheep were observed to also spend a lot of lying time under the solar panels (Table 3), during which they potentially ruminated, suggesting that the sheep preferred resting under the panels. Sheep in the S treatments (4d: 24.3 ± 2.21, 1d: 26.3 ± 2.17) spent more time lying/ruminating than sheep in NR treatments (4d: 15.1 ± 1.85, 1d: 15.4 ± 1.74), while sheep in NR treatments (4d: 84.5 ± 1.85, 1d: 84.2 ± 1.74) spent more time standing idle than sheep in S treatments (4d: 73.6 ± 2.28, 1d: 71.1 ± 2.24; Table 3). Standing idle has been suggested as an indicator of reduced welfare as inactivity could be a strategy to cope with sub-optimal conditions (Webb et al., 2017).

### 4.2. The effects of grazing management strategy on sheep grazing behavior

Intensive rotational grazing typically increases grazing pressure and therefore alleviates undesirable selective grazing (Bailey and Brown, 2011). We expected that the number of 'grazing' hours per day would increase when the animals were grazed 4d compared with 1d. Animals that rotate less often can spend more time browsing or selecting preferred plant species, which they will do with their head down, which is picked up by the data loggers as 'grazing'. Sheep under 1d grazing management (NR-1d: 39.95% ± 0.39% and S-1d: 43.30% ± 0.46%), spent respectively approximately 4% and 2.3% less time 'grazing' when compared with the 4d management strategy (NR-4d: 44.02% ± 0.47% and S-4d: 45.65% ± 0.35%; Fig. 4A). This difference between the 'grazing' results of the 1d and 4d treatments may partially be in response to the sheep in the 1d treatments being moved to a new paddock with fresh forage every morning, likely stimulating grazing for a short period of time in anticipation of movement. Sheep in the 1d treatments may have ingested most of the forage material with high nutritive value in the morning, leaving the less palatable materials for the rest of the day (Penning et al., 1994). This may have caused them to be more satiated for the rest of the day and, therefore, causing them to rest/ruminate more. Another reason why sheep in the 4d management strategy 'grazed' more than sheep in the 1d strategy could be that because sheep in the 4d management strategy stayed in the same paddock for four consecutive days, the sheep had consumed the plant material with grater nutritive value on the first day, leaving forage with lower protein content. Sheep in the 4d grazed groups likely had to graze more on the other three days of the treatment to satisfy their nutrient needs, possibly distributing grazing behavior over those three entire days. There were no differences in forage mass and forage digestibility (NDF content, %C, %N, C/N ratio) between the 4d and 1d pastures.

### 4.3. Vegetation management strategies in solar farms

Different parties have different aims for solar grazing. Solar system managers need to prevent shading on their panels. Contract grazers are hired to prevent vegetation from doing this. Therefore, their aim is also to keep biomass low, while simultaneously fattening their sheep to sell the lambs for meat. Having sheep graze on solar farms could be a beneficial opportunity for both contract grazers and solar developers (Kochendoerfer and Thonney, 2021). We found that sheep grazed well on a solar farm and that they spent most of their time under the solar panels, protected from climatic conditions. Solar developers, on the other hand, are benefitted by the grazing efficiency of sheep. Furthermore, a reduction in maintenance expenses can be accomplished via the use of sheep for vegetation management instead of mowers that have to maneuver between the panels and in some cases on steep hills (Agrivoltaic Solutions, 2020; Kochendoerfer et al., 2019; Pascaris et al., 2021). Using sheep for vegetation maintenance on solar farms can also assist in improving biodiversity and soil activity if grazing pressure is not too high. Sheep can create micro-climates with their hooves in the soil, spread seeds with their wool, and spread diaspores from some plants with their hooves and feces (Peschel et al., 2019). Thus, there needs to be a balance between biomass management and stocking rate.

Sharrow (1983) mentions that during the dry-feed period (intensively) rotationally grazed sheep have less opportunity for dietary selectivity than continuously grazed sheep, and, therefore, have a lower quality diet. The current study was conducted when forage was senescent, which could have led to the sheep in the 1d treatments having a lower quality diet than sheep in the 4d treatment. On solar farms and other native rangelands with climate conditions similar to those at the Central Coastal region in California, i.e., Mediterranean climates, the current study indicates that sheep graze most when they are grazed in less intensive rotational management systems during the senescent stages of forage growth. However, future studies must be conducted over longer periods of time, during different stages of forage growth.

### 4.4. Research agenda

To draw clearer conclusions about vegetation management strategies on solar farms, the study should be repeated across different climates, over longer periods of time, and during different stages of forage growth. The study should be repeated in every season of the year in order to assess seasonal variation in sheep grazing behavior. Behavioral indicators of thermal stress between groups should be recorded, as well as air temperature under the solar panels, in the alleys between the panels, and in the native rangeland. With further research we may be able to identify further grazing management practices considering season, breeding cycle of the sheep, and growth stage of the forage. The forage in the treatments should be prepared well in advance. The S treatment will always have intensive weed management and the sward will not be above a certain height, to prevent shading of the solar panels. Therefore, the NR paddocks should be managed in the same way as the S paddocks in preparation of the study in order to limit systematic error. If all treatments are managed in the same way before the start of the study, the sheep should not have to be supplemented with alfalfa hay. Soil and forage health should be analyzed in both 1d and 4d treatments on solar farms to determine if management influences soil health and pasture production on solar farms.

The difference in sheep weight was not measured in this study because most of the sheep were approaching the final trimester of gestation and started lambing in February. These sheep put on extra weight that was not due to grazing over the course of the grazing period. The average number of lambs per grazing group was similar, while the number of lambs per sheep ranged from 0 to 3. A future study should be done that looks at the differences in weight in sheep having 1, 2, or 3 lambs. To estimate the forage intake of the sheep, both the difference in forage DM mass and their body condition score (BCS) should be measured before and after treatment. When using lambs for vegetation management, the difference in sheep weight before and after each treatment (i.e. average daily gain (ADG)) should be measured. BCS for adult sheep and ADG for lambs would be valuable information for future studies if sheep can be weighed in a manner that does not cause much stress for the sheep.

Future work could also include research into how the use of sheep for vegetation management on solar farms impacts the public image and acceptance of solar farms. Moreover, the impact of solar grazing on environmental sustainability (greenhouse gas mitigation (life cycle assessment (LCA)), and opportunities for biodiversity) should be evaluated, as well as other animal welfare benefits that solar grazing practices may provide, like sheep being able to scratch themselves against the poles on which the solar panels are mounted. Lastly, socio-economic aspects of solar grazing in the sense of labor and profitability, for both sheep farmers and solar farm owners, should be investigated.

## 5. Conclusions

In this preliminary exploratory study, we hypothesized that sheep spend more time grazing in solar treatments than in natural rangeland pastures without solar panels or any other form of shade and the results of the experiment confirmed this. The second hypothesis was that sheep in 1-day intensive rotational treatments spend more time grazing than sheep in 4-day rotational treatments. Sheep in the 1d treatments spent less time 'grazing' than sheep in the 4d treatments. This may be caused by the grazing pressure in the 1d treatments being higher than in the 4d treatments, which decreases the amount of time animals can spend browsing or selecting preferred plant species (Lin et al., 2011). 4d grazing may therefore be most effective during the senescent stages of the forage, which was the case during the experiment. We carefully conclude based on this preliminary systems comparison that solar panels may lead to an increase in time spent grazing in sheep. This study is a preliminary systems comparison and further experimental research with control treatments is warranted to pinpoint precisely which factors led to our specific findings. The limitations of this project relate to grazing behavior in specific climate conditions (drought, senescent forage, alfalfa hay supplementation). Therefore, future research should assess sheep grazing behavior in solar farms in different seasons and in different climates to draw conclusions that are applicable to solar farms established in open rangelands across the globe. We recommend that soil and forage health, environmental sustainability, animal welfare, potential facility infrastructure, public image and acceptance, and socio-economic aspects of solar grazing be part of this work.

## Declaration of Competing Interest

The authors report no known or perceived conflicts of interest.

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