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# Forage Biomass and Nutritive Value of Grasses and Legumes Grown Under Agrivoltaic Systems

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**Abstract.** Forage crops grown underneath ground-mounted photovoltaic systems (PV) may provide a feed source for livestock production. The objective was to evaluate forage biomass and nutritive value of crops, grasses and legumes grown under different PV conditions. Forages were planted underneath a 30-kilowatt PV site (30kW), a 50-kilowatt PV site (50kW) and one control site without PV (CON) in May 2022 with four replicates per site. Forage crops included alfalfa, field peas, meadow fescue, orchard grass, red clover, brown midrib sorghumsudan grass, white clover and 3 grass and legume mixes with either alfalfa, red clover, or white clover. Biomass samples were clipped at appropriate maturity levels for grazing. Samples were sorted for botanical composition and analyzed for nutrient value. Crop biomass, dry matter and nutrient values were analyzed with PROC Mixed of SAS with the fixed effects of site (30kW, 50kW, or Con), crop nested within site, and cutting (1st or 2nd) and the random effect of replicate nested within site. Forages produced less biomass at the 30kW (563.7 kg/ha) and 50kW (446.4 kg/ha) solar sites compared to CON (1099.7 kg/ha). The 50kW forages had greater crude protein on a dry matter basis (25.8%) than the 30kW (21.4%) and CON (20.9%). The 50kW (57.1%) forages also had greater total tract neutral detergent fiber (NDF) digestibility than the 30kW (52.5%) and CON (51.0%). Additionally, the 50kW forages had greater percent calcium (1.05%) compared to the 30kW (0.75%) and CON (0.84%). Forage biomass and nutrient values varied based on the solar array design and amount of sun exposure.

**Keywords:** Forages, Agrivoltaic Systems, Organic

## 1. Introduction

Increasing land availability pressures demand the sustainable intensification of agriculture. Solar energy sites which take arable land out of agriculture cultivation minimize food production potential. At the same time, climate change and population increases are decreasing available arable land [1]. Renewable solar energy replaces greenhouse gas emitting fossil fuels. However, Agrivoltaics (AV), which combines solar energy and agricultural production on one site, accomplishes both food production and clean energy goals while providing flexible economic opportunities to farmers. Modeling suggests that AV systems could increase land productivity from 35-73% worldwide [2], [3], [4]. This estimate does not account for newer spectral-splitting solar panels which have been documented to increase plant biomass compared to open air controls. This technology allows a specific range of the light spectrum useful for photosynthesis to pass through the panel while the rest of the spectrum is reflected for energy production increasing the efficiency of the system [5]. Other studies record land equivalent ratios (LER) greater than 1.5 for both crop and livestock production in AV systems indicating synergistic benefits of solar energy and agriculture colocation [3], [6], [4]. Adopting AV systems reduces greenhouse gas emissions while increasing revenue for farmers [7]. For example, AV systems incorporating vegetable farming or livestock grazing produce greater income by 2.5-35% compared to conventional systems [8], [9]. Agrivoltaic systems can increase land efficiency and improve farm income. However, further documentation of the agronomic potential of these systems is needed.

Agronomic conditions in AV systems affect crop biomass production and nutritive value. The AV system decreases air and soil temperature and increases soil moisture [10], [11]. This microclimate produces favorable conditions for certain crops like winter wheat, potatoes, and celeriac especially in drought years [3], [4], [12]. Additionally, the reduction in air temperature due to the inclusion of plants for ground cover minimizes heat stress of the solar panels increasing energy production [11], [13]. However, decreases in yield are expected due to less solar radiation. Forage crops grown underneath ground-mounted photovoltaic (PV) systems could provide a feed source and shade for livestock production, a green energy source for farms and additional income for farmers [14]. However, yield response to varying levels of shade for common forage and grain crops is scarcely documented. Therefore, to sustainably intensify AV, crops must be evaluated for their biomass and nutritional value potential when grown at varying AV sites.

## 2. Materials and Methods

During May of 2022, 7 forage species and 3 mixes of grass and legume species were planted underneath 2 different solar sites and 1 control site without shade. Forage crops included alfalfa, field peas, meadow fescue, orchard grass, red clover, BMR sorghum-sudan grass, white clover and 3 meadow fescue, orchard grass, and legume mixes with either alfalfa, red clover, or white clover. One solar site was two 15-kilowatt (kW) fixed solar arrays mounted at 35 degrees south and 2.5-3.0 meters off the ground to allow for grazing of dairy cows underneath (30kW; Fig. 1). The 30kW site is partially shaded. The other solar site was a 50kW square shaped, flat top array using reflectors mounted 2.5-3.0 meters off the ground without grazing cattle underneath (50kW; Fig. 2). The 50kW site is shaded completely. The control site with no solar array was established in a pasture with minimal slope (CON).

The soil at all sites were tilled once and the 10 forage crops were planted with a Carter plot seeder at an appropriate species seeding rate. All crops were managed on certified organic land. There were 4 replicates of each crop representing a row within the site. Each row contained 10 plots, one for each crop which were randomized within row. Individual plots were 5.5m by 1.8m. The 50kW site was planted without the 3 grass, legume mixes and field peas due to size constraints.

Two biomass samples were clipped of each forage from each plot using a 0.23 $m^2$ square when grasses reached the V3 stage. The entire plot was mowed to 10 cm stubble height after sampling. Perennial forages were sampled twice during the growing season. Samples were dried at 60°C for 48h to calculate dry matter percent. One of the 2 samples from each plot was randomly selected and sorted for botanical composition. The weed weight was subtracted from the forage biomass weight. Once sorted samples were ground with a 1 mm screen (Model 4, Wiley Mill, Thomas Scientific, Swedesboro, NJ, USA). Samples were analyzed for nutritive value by the Rock River Laboratory, Inc. (Watertown, WI, USA). To analyze forage biomass, dry matter and nutritive value, the independent variables included the fixed effects of site (30kW, 50kW, or CON), forage species (alfalfa, field peas, meadow fescue, orchard grass, red clover, BMR sorghum-sudan grass, white clover, grass alfalfa mix, grass red clover mix, or grass white clover mix) nested within site, and cutting (1 or 2) and the random effect of replicate (1, 2, 3, or 4) nested within site. The PROC MIXED procedure of SAS 9.4 was used.

**Figure 1.** Forages underneath the 30kW solar ground-mounted array site at the University of Minnesota West Central Research and Outreach Center in Morris, Minnesota, USA.

**Figure 2.** Forages underneath the 50kW solar ground-mounted flat top site at the University of Minnesota West Central Research and Outreach Center in Morris, Minnesota, USA.

## 3. Results

The 30kW (564 kg/ha) and 50kW (446 kg/ha) AV sites produced 50% less aboveground biomass ($P<0.05$) than CON (1,100 kg/ha) due to the lack of solar radiation reaching the plant-level. The sorghum-sudan grass produced the greatest biomass in all three sites (Table 1). However, the sorghum-sudangrass had similar biomass in the 50kW compared to other forages as it received less sunlight. Sorghum-sudangrass is a summer annual grass that requires greater sun exposure compared to cool season perennial grasses such as orchardgrass and meadow fescue. When comparing the two AV sites, the 50kW favored greater biomass compared to the 30kW for alfalfa, meadow fescue, orchardgrass, red clover and white clover (Table 1). The 50kW site has a larger area under shade which could have reduced weed pressure in this site due to the lack of sunlight. Reduced weed pressure allows for greater biomass production of the intended crop, especially in an organic system in which chemical weed management is not employed.

Percent dry matter on average was highest for CON (25.1%; $P<0.05$) followed by 30kW (16.8%) and 50kW (12.8%). Differences in dry matter could be affected by soil moisture retention which is greater in the AV sites. Increased shade in the AV sites decreases evapotranspiration as well.

Although the AV sites produced less kilograms per hectare compared to CON they recorded greater forage crude protein. Average crude protein (CP) for forages in the 50kW (25.8 % of DM) was higher ($P<0.05$) than the 30kW (21.4 % of DM) and CON (20.9 % of DM). A similar trend is noted for individual species (Table 1).

Neutral detergent fiber (NDF) content was highest ($P<0.05$) for the 30kW (52.7 % of DM) forages, intermediate for the CON (47.9 % of DM) and lowest for the 50kW (44.9 % of DM). The legume forages had lower NDF values compared to the grasses and field peas (Table 2). The digestibility of NDF was measured by the total tract NDF digestibility (TTNDFD) metric. The CON (51.0 % of aNDF) and 30kW (52.5 % of aNDF) had similar TTNDFD while the 50kW (57.1 % of aNDF) had higher ($P<0.05$) digestibility for its forages. The forages with the most highly digestible TTNDF were the sorghum-sudan grass and orchardgrass in the 30kW, the white clover and sorghum-sudan grass in the 50kW and the meadow fescue and sorghum-sudan grass in the CON (Table 2).

Mineral content was also analyzed for forages in each site (Table 3). The CON (0.84 % of DM) and 30kW (0.75 % of DM) had similar forage calcium (Ca) levels while the 50kW (1.05 % of DM) forages had higher ($P<0.05$) Ca content. The forages with the highest Ca levels were the red clover and field peas in the 30kW and CON and the red clover and alfalfa in the 50kW (Table 3).

**Table 1.** Least squares means of forage biomass, dry matter and crude protein for 30kW, 50kW and control sites.

| | Biomass, kg/ha | | | Dry Matter, % | | | Crude Protein, % of DM | | |
|---|---|---|---|---|---|---|---|---|---|
| Forage Species | 30kW | 50kW | Control | 30kW | 50kW | Control | 30kW | 50kW | Control |
| Alfalfa | 53.6$^{a}$ | 234.1$^{a}$ | 284.7$^{a}$ | 18.8$^{a}$ | 12.5$^{b}$ | 23.7$^{c}$ | 22.5$^{a}$ | 26.7$^{b}$ | 24.5$^{ab}$ |
| Field peas | 265.7$^{a}$ | -- | 3356.0$^{b}$ | 17.6$^{a}$ | -- | 19.8$^{a}$ | 19.5$^{a}$ | -- | 17.1$^{a}$ |
| Meadow fescue | 220.7$^{a}$ | 465.0$^{a}$ | 136.5$^{a}$ | 16.0$^{a}$ | 13.1$^{a}$ | 30.5$^{b}$ | 22.2$^{a}$ | 24.9$^{a}$ | 21.6$^{a}$ |
| Orchardgrass | 376.7$^{a}$ | 674.9$^{a}$ | 455.3$^{a}$ | 13.4$^{a}$ | 16.0$^{a}$ | 24.3$^{b}$ | 24.3$^{ab}$ | 24.5$^{b}$ | 20.9$^{a}$ |
| Red clover | 23.1$^{a}$ | 293.9$^{a}$ | 225.5$^{a}$ | 17.2$^{a}$ | 12.1$^{b}$ | 25.2$^{c}$ | 24.4$^{ab}$ | 28.0$^{b}$ | 24.0$^{a}$ |
| Sorghum-sudan grass | 2813.1$^{a}$ | 740.6$^{b}$ | 4729.7$^{c}$ | 16.8$^{a}$ | 12.9$^{b}$ | 18.5$^{a}$ | 11.9$^{a}$ | 23.6$^{b}$ | 12.7$^{a}$ |
| White clover | -- | 270.2$^{a}$ | 8.4$^{a}$ | -- | 9.8$^{a}$ | 40.3$^{b}$ | -- | 27.0 | -- |
| Grass alfalfa mix[1] | 409.0$^{a}$ | -- | 624.8$^{a}$ | 16.5$^{a}$ | -- | 24.8$^{b}$ | 22.3$^{a}$ | -- | 22.2$^{a}$ |
| Grass red clover mix[2] | 445.6$^{a}$ | -- | 636.15$^{a}$ | 17.0$^{a}$ | -- | 20.6$^{b}$ | 23.1$^{a}$ | -- | 23.0$^{a}$ |
| Grass white clover mix[3] | 465.7$^{a}$ | -- | 539.8$^{a}$ | 17.8$^{a}$ | -- | 23.7$^{b}$ | 22.6$^{a}$ | -- | 22.5$^{a}$ |

$^{a-c}$ Means within a row with different superscripts are different at $p < 0.05$. SE = standard error; DM = dry matter.

[1] Mixture of meadow fescue, orchard grass and alfalfa

[2] Mixture of meadow fescue, orchard grass and red clover

[3] Mixture of meadow fescue, orchard grass and white clover

-- Insufficient sample available for analysis or space within site for species

**Table 2.** Least squares means of forage ADF, NDF, Lignin and TTNDFD for 30kW, 50kW and control sites.

| | ADF, % of DM | | | NDF, % of DM | | | TTNDFD, % of aNDF | | |
|---|---|---|---|---|---|---|---|---|---|
| Forage Species | 30kW | 50kW | Control | 30kW | 50kW | Control | 30kW | 50kW | Control |
| Alfalfa | 33.2$^{a}$ | 31.2$^{b}$ | 32.7$^{a}$ | 39.7$^{a}$ | 37.9$^{a}$ | 37.8$^{a}$ | 52.1$^{a}$ | 52.0$^{a}$ | 48.6$^{a}$ |
| Field peas | 34.3$^{a}$ | -- | 34.1$^{a}$ | 46.7$^{a}$ | -- | 44.7$^{a}$ | 44.3$^{a}$ | -- | 38.0$^{b}$ |
| Meadow fescue | 35.3$^{a}$ | 37.4$^{b}$ | 33.2$^{c}$ | 57.6$^{a}$ | 52.2$^{b}$ | 51.3$^{b}$ | 55.2$^{a}$ | 58.0$^{a}$ | 59.5$^{a}$ |
| Orchardgrass | 36.4$^{ab}$ | 36.6$^{b}$ | 34.9$^{a}$ | 59.6$^{a}$ | 56.1$^{a}$ | 52.3$^{b}$ | 57.7$^{a}$ | 55.5$^{a}$ | 55.8$^{a}$ |
| Red clover | 34.6$^{a}$ | 32.7$^{a}$ | 32.7$^{a}$ | 36.7$^{a}$ | 35.6$^{a}$ | 35.1$^{a}$ | 38.7$^{ab}$ | 45.6$^{b}$ | 34.5$^{a}$ |
| Sorghum-sudan grass | 38.4$^{a}$ | 37.6$^{a}$ | 35.7$^{b}$ | 61.3$^{a}$ | 56.2$^{b}$ | 58.9$^{ab}$ | 57.2$^{a}$ | 60.1$^{a}$ | 58.2$^{a}$ |
| White clover | -- | 29.1 | -- | -- | 31.6 | -- | -- | 71.4 | -- |
| Grass alfalfa mix | 36.8$^{a}$ | -- | 34.3$^{b}$ | 58.1$^{a}$ | -- | 49.0$^{b}$ | 55.9$^{a}$ | -- | 55.3$^{a}$ |
| Grass red clover mix | 37.2$^{a}$ | -- | 34.7$^{b}$ | 57.5$^{a}$ | -- | 48.8$^{b}$ | 56.6$^{a}$ | -- | 51.8$^{b}$ |
| Grass white clover mix | 35.7$^{a}$ | -- | 34.8$^{a}$ | 56.8$^{a}$ | -- | 53.1$^{a}$ | 54.6$^{a}$ | -- | 57.6$^{a}$ |

$^{a-c}$ Means within a row with different superscripts are different at $p < 0.05$. SE = standard error; DM = dry matter; ADF = acid detergent fiber; NDF = neutral detergent fiber; TTNDFD = total tract NDF digestibility.

[1] Mixture of meadow fescue, orchard grass and alfalfa

[2] Mixture of meadow fescue, orchard grass and red clover

[3] Mixture of meadow fescue, orchard grass and white clover

-- Insufficient sample available for analysis or space within site for species

**Table 3.** Least squares means of forage Calcium, Phosphorus, Magnesium and Potassium for 30kW, 50kW and control sites.

| | Calcium, % of DM | | | Phosphorus, % of DM | | | Potassium, % of DM | | |
|---|---|---|---|---|---|---|---|---|---|
| Forage Species | 30kW | 50kW | Control | 30kW | 50kW | Control | 30kW | 50kW | Control |
| Alfalfa | $1.05^{a}$ | $1.49^{b}$ | $1.30^{c}$ | $0.37^{a}$ | $0.48^{b}$ | $0.32^{a}$ | $3.94^{a}$ | $4.98^{b}$ | $3.39^{a}$ |
| Field peas | $1.22^{a}$ | -- | $1.32^{a}$ | $0.50^{a}$ | -- | $0.35^{a}$ | $4.75^{a}$ | -- | $2.44^{b}$ |
| Meadow fescue | $0.50^{ab}$ | $0.65^{b}$ | $0.40^{a}$ | $0.43^{ab}$ | $0.47^{b}$ | $0.40^{a}$ | $4.04^{a}$ | $4.59^{a}$ | $4.19^{a}$ |
| Orchardgrass | $0.43^{a}$ | $0.50^{a}$ | $0.45^{a}$ | $0.39^{a}$ | $0.39^{a}$ | $0.31^{b}$ | $4.66^{a}$ | $4.10^{a}$ | $3.94^{a}$ |
| Red clover | $1.71^{a}$ | $1.66^{a}$ | $1.66^{a}$ | $0.28^{ab}$ | $0.38^{b}$ | $0.27^{a}$ | $4.24^{ab}$ | $4.53^{b}$ | $3.39^{a}$ |
| Sorghum-sudan grass | $0.45^{a}$ | $0.55^{a}$ | $0.50^{a}$ | $0.42^{a}$ | $0.60^{b}$ | $0.30^{c}$ | $3.34^{a}$ | $4.04^{b}$ | $3.09^{a}$ |
| White clover | -- | 1.44 | -- | -- | 0.42 | -- | -- | 5.78 | -- |
| Grass alfalfa mix | $0.46^{a}$ | -- | $0.67^{b}$ | $0.38^{a}$ | -- | $0.35^{a}$ | $3.99^{a}$ | -- | $3.36^{a}$ |
| Grass red clover mix | $0.48^{a}$ | -- | $0.77^{b}$ | $0.37^{a}$ | -- | $0.35^{a}$ | $4.16^{a}$ | -- | $3.71^{a}$ |
| Grass white clover mix | $0.45^{a}$ | -- | $0.49^{a}$ | $0.35^{a}$ | -- | $0.34^{a}$ | $3.47^{a}$ | -- | $3.65^{a}$ |

$^{a-c}$ Means within a row with different superscripts are different at $p < 0.05$. SE = standard error; DM = dry matter.

[1] Mixture of meadow fescue, orchard grass and alfalfa

[2] Mixture of meadow fescue, orchard grass and red clover

[3] Mixture of meadow fescue, orchard grass and white clover

-- Insufficient sample available for analysis or space within site for species

## 4. Conclusion

Although less biomass was produced in the AV sites compared to the open air control, forages were of high quality based on similar or higher crude protein, fiber content and digestibility, and mineral levels of the forages in the 30kW and 50kW sites. Agrivoltaics in the form of forage production grown underneath ground-mounted photovoltaic systems can provide a suitable feed source for organic livestock production, a renewable energy source for farms and economic opportunity for farmers.

## Data availability statement

Data available upon reasonable request.

## Author contributions

S. L. P. was involved in data curation, formal analysis, investigation, project administration, visualization, and original draft writing. B. J. H. was involved in conceptualization, formal analysis, funding acquisition, investigation, project administration, resources, supervision, visualization and writing review and editing. E. S. B. and M. H. R. were involved in conceptualization and funding acquisition.

## Competing interests

The authors declare no competing interests.

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