Electrical consumption on Midwestern dairy farms in the United States and agrivoltaics to shade cows in a pasture-based dairy system

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ABSTRACT

The objectives of the thesis were to investigate electrical energy use on dairy farms located in west central Minnesota and to evaluate the effects of shade use by cattle from solar photovoltaic systems. As the push for sustainable food production from consumers continues to grow, food industries and processors are looking for ways they can be more marketable to consumers. Not only do food industries investigate sustainable practices within their own systems, they also push their suppliers to explore ways to lower their farms’ carbon footprints. Measurements of baseline fossil fuel consumption within dairy production systems are scarce. Therefore, there is a need to discern where and how fossil fuel-derived energy is being used within dairy production systems. Baseline energy use data collection is the first step in addressing the demand for a reduced carbon footprint within dairy production systems. Energy use on five Midwest dairy farms was evaluated from July 2018 to December 2019. Through in-depth monitoring of electricity-consuming processes, it was found that electricity use can differ quite drastically in different types of milking systems and farms. Electricity on an annual basis per cow ranged from 400 kWh/cow in a low-input and grazing farm to 1,145 kWh/cow in an automated milking farm. To reduce electrical energy consumption as well as reduce the effects of heat stress in pastured dairy cows, producers may investigate using an agrivoltaic system. Biological effects of internal body temperature, milk production, and respiration rates and behavioral effects of activity, rumination, fly avoidance behaviors, and standing and lying time of the solar shade were evaluated. Treatment groups were shade or no shade of cattle on pasture. The results of this agrivoltaic system suggested that grazing cattle that have access to shade had lower respiration rates and lower body temperatures compared to cattle that do not have access to shade. Electricity used in dairy farms was examined to help producers find areas in their farms that have the potential for reduced energy consumption. Furthermore, the use of an agrivoltaic system on a pasture-based dairy was studied for its shading effects on the health and behavior of dairy cows.

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LITERATURE REVIEW

Introduction

One of the biggest dilemmas mankind faces today is how to feed the ever-growing population while producing our food in a manner that is environmentally, socially, and economically viable. Consumers have become increasingly concerned about how their food is produced, where it is produced and in what manner it is produced. Food that is produced utilizing environmentally conscious methods is often sought after in grocery stores. Pressure on the dairy industry is building as the cost of production continues to rise along with rising energy prices all of which is further complicated by inadequate prices of milk (Oenema et al, 2011). Some producers have been searching for methods to reduce fossil fuel-derived energy use on-farm to become more appealing to consumers. Assisting farmers in finding areas within their operations with potential for increased energy efficiency, or by proposing novel ideas on energy generation or utilization which is ultimately backed by research, could help increase both the producer's profitability and appeal to consumers. At the farm level, producers may be unsure of where they might make adjustments to reduce energy use as on-farm electricity use data in the United States are scarce. When producers receive their electricity bill, they see the total cost and total amount of electricity used. However, farmers are generally unaware of where, specifically, that electricity is being used on their farm. Daily and seasonal electricity consumption trends could help in targeting areas within a farm where there is potential to reduce fossil fuel use. To be more appealing to consumers, some producers within the dairy industry have already made adjustments to rely less on fossil-fuel generated electricity or have adopted methods which ultimately emit less greenhouse gases (GHGs). Some of these adjustments may include converting lighting systems to light emitting diodes (LEDs), installing and using methane digesters, installing variable frequency drives on motors, implementing behavioral changes, or installing renewable energy systems. Renewable energy generation is an option to reduce reliance on fossil fuel reserves. Solar energy systems can be placed on the roof of buildings or mounted on the ground. For pasture-based dairy systems, this could provide a unique opportunity to not only generate electricity onsite, but could also provide shade to cattle in a warm climate, whether housed on a pasture or in a dry lot. The dual-use of solar systems in pastures could increase the efficiency of land use while increasing profitability for the producer, and ultimately, promoting a healthier cow.

Consumers and farm energy use

The global human population is expected to grow from 7.7 billion in 2019 to 9.7 billion people by 2050 (UN, 2019). As the human population grows, the demand for agricultural products is expected to grow by 50% compared to 2013 (FAO, 2017). As the demand for agricultural products rises, the degradation of natural resources, loss of beneficial plant and animal species, and spread of agricultural pests and diseases will likely continue to occur as well as an increased output in GHGs if management and land-use practices remain unchanged (FAO, 2017).

Now more than ever before, consumers are interested in where their food originates from, how their food is produced, and how their food appears on their plate. Along with consumer curiosity and the demand for transparency as it pertains to food production, consumers are becoming more aware of the environmental impacts their food choices may incur, and more than one-third of consumers have indicated that they are willing to pay more for environmentally- safe products (Network for Business Sustainability, 2010). Food companies recognize these consumer demands and are looking within their supply chain to determine where they might lower fossil-energy use. As an example, the United States dairy industry is working to improve the sustainability of its supply chain to be more marketable to food companies and consumers. Along with investigating fossil energy use within their own operations, food companies have been putting pressure on the producers who provide them with their raw materials to reduce fossil energy use on the farm.

In the United States, 28% of GHGs are emitted while burning fossil fuels to produce electricity (EPA, 2019). Electrical energy consumption is a logical place to begin to search for areas to lower indirect fossil energy use on the farm. In a world which demands increased food production while reducing GHG emissions, producers face many challenges. If a producer is to address supply chain and, ultimately, consumer demands of reducing fossil energy use, it is critical to understand how energy is used and where energy is used at the farm level. Daily and seasonal electricity consumption patterns will help pinpoint electrical loads or areas within a dairy farm that have the potential for increased efficiency. Actual energy use, focusing on electricity use, at the dairy farm level is not an area that has been thoroughly investigated in the United States.

Energy use in Irish, Italian, and Canadian dairies

The country with the most detailed research on energy use in dairies is Ireland. Upton et al. (2013) collected energy data from 22 Irish dairy farms by installing energy monitoring systems on-farm. The authors found that 25% of energy used along the cradle-to-farm-gate life cycle of milk in pastured dairies was electricity consumption. Of the total energy used on the farm to produce milk, 60% was electrical energy. Of total electricity used on-farm, milk cooling accounted for 31%, water heating accounted for 23%, milking processes accounted for 20%, pumping water used 5%, lights accounted for 3% of electricity use on farm, and all other miscellaneous electrical loads consumed 18% of the total electricity used by the farms. Energy studies from Ireland were conducted in pasture-based herds so the milk harvesting process is the substantial user of total electricity. Average electricity required to produce one liter of milk across the 22 farms was 42.34 Watt-hours. The month which used the most electrical energy across the 22 farms was April because electricity consumption tended to follow the milk production curves of the farms. Daily electrical energy consumption was highest during peak milking hours which occurred in both morning and evening. Electricity use peaked between the hours of 7:00 to 12:00 and again from 16:30 to 19:30. The authors also found that 20% of electrical energy consumption was independent of the amount of milk produced, while other loads such as water heating, milk cooling, and vacuum pumps mirrored the milk production curve.

A study conducted by Shortall et al. (2017) investigated the daily and seasonal trends of electricity used on pasture-based automated milking (AMS) dairies in Ireland. The authors utilized electric energy meters installed on 7 pasture-based farms across Ireland with an average herd size of 114 cows. Total electricity used to produce 1 liter of milk was 62.6 Watt-hours. The milking process (vacuum and milk pumping, with water heating components) accounted for the largest percent of total electricity used at 33%. Air compressors used 26% of total electricity, milk cooling used 18% of total electricity, auxiliary water heating used 8% of total electricity, water pumping used 4% of total electricity, and all other miscellaneous electrical loads used 11% of total electricity. Total daily electrical consumption peaked during the hours of 0100, 0800 and between 1300 and 1600 when the AMS saw its heaviest cow traffic. Annual electricity required to power the milk harvesting process was 111 kWh/cow, air compressors was 87 kWh/cow, milk cooling components accounted for 60 kWh/cow, and water heating accounted for 27 kWh per cow. On an annual basis, the Irish AMS dairies consumed an average of 7,361 kWh/year on the average farm, 9,186 kWh/year on the farms with one AMS, and 5,992 kWh/year on the farms with two AMS. The two AMS system used less electricity, as the milkings were spread out across the two units and stocking densities were lower, which lowered the electricity used by each single AMS. During January, the AMS farms used the least amount of electricity and used the highest amount of electricity during the month of May following the milk production curve. The authors found this seasonal trend was the inverse of the milk production curve when examined on the basis of Wh/L of milk produced. Therefore, when milk production was highest, less electricity was required to produce 1 L of milk. The authors indicated that other electrical loads remained constant, despite changes in the number of milking cows. This is further evidence that as the number of milkings per AMS increased, the electricity consumption per liter of milk decreased.

A study by Tangorra and Calcante (2018) investigated electric energy consumption of an automated feeding system (AFS) compared with a conventional feeding system (CFS) on a dairy farm in Italy. The monitored AFS was a Lely Vector system, and the CFS was a tractor-operated mixing wagon system which used a telehandler for loading. The authors found the AFS consumed 40.2 kWh/day compared to the CFS energy use converted to electricity consumption of 1,388 kWh/day which was a 97% reduction in electrical energy use. Furthermore, the AFS reduced the daily cost for feeding by 33% (Tangorra and Calcante, 2018). Studies on dairy farms conducted in Ontario, Canada, found that dairy farms use an average of 800-1,400 kWh/cow/year (Clarke et al., 2010). In a tie stall dairy, the average annual electrical use per cow was 1,417 kWh of electricity. In freestall dairies, this use was 837 kWh/cow/year. The authors found five areas of dairy operations that accounted for 90% of total electricity used in the farms. These five areas were: milk cooling, vacuum pumps, water heating, lighting, and ventilation. Of the dairy farms that were audited, 23% of total electricity was used to power the milking system which included vacuum pumps, 21% of total electricity used by the farms was used to power milk cooling systems, 15% of electricity was used for heating water, 14% of total electricity used by the farms was for lighting, and 12% of total electricity was used for ventilation. The remaining electrical loads accounted for 9% of total electricity use and included feed handling and manure handling systems.

Another study of electricity use on dairy farms in Nova Scotia used a survey to determine electrical energy expense on dairy farms. The producers reported that 37.9% of the total cost of fossil-derived energy on farm was attributed to electrical energy. When the producers were asked to select the top three fossil energy uses on the farm, producers included electrical consumption in the top three categories. The producers reported using 1,069 kWh of electricity/ cow on an annual basis (Bailey et al., 2008). Another study conducted on a 95 cow dairy on Prince Edward Island, Canada (Houston et al., 2014), found annual electricity consumption to be 123,712 kWh. On further investigation, electrical energy accounted for 89% of the on-farm total energy use. On an annual basis, the farm used 1,302 kWh/cow. During spring and summer months, cows were housed outdoors on pasture, and therefore, the farm used the most electricity during the winter months when more energy was required for lighting and heating after the cows were moved back in to the barn. Based on estimated operating hours and equipment ratings, compressors for milk cooling used 29,025 kWh of electricity on an annual basis, which was the largest user of total electricity on the farm. Following compressor use was electricity used by fans (14,920 kWh), electricity used by the vacuum pump (12,253 kWh), and, lastly, electricity used for lighting (11,563 kWh).

Energy use in United States dairies

Direct greenhouse gas emissions (GHGs) from agriculture contribute 10 to 12% of the total global GHG emissions (Bellarby et al., 2008). Within the United States, approximately 9% of GHGs are emitted by agricultural practices (EPA, 2017). Dairy farms in the United States face many challenges and opportunities led by shifting consumer attitudes and rising energy costs. The dairy industry in the United States has adopted practices to reduce the carbon footprint of the industry in a way that is economically feasible for producers while also appealing to consumers. Dairy farmers should analyze their energy inputs and uses to reveal potential conservation and energy efficiency measures on the farm.

The United States dairy industry has been the base for many life cycle assessment LCA studies which assist in targeting areas within the milk production system where there is potential for fossil energy reduction or energy efficiency measures (de Boer et al., 2003, Gerber et al., 2010, Thoma et al., 2010). In investigating GHG emissions used to produce 3.8 L of milk in the United States, 20.3% is emitted while producing feed, 51.5%

is emitted during the milk production process, 5.7% is emitted during processing which includes hauling from farm to processor, 3.5% is emitted during packaging, 7.7% transporting the product to the store, 6.5% at the grocery store, and 4.9% by the consumer. Direct electricity used by the farm accounts for 3.6% of the total GHGs emitted to produce 3.8 L of milk. This life cycle assessment study found that total U.S. dairy GHG emissions are approximately 2 percent of total U.S. emissions. (Thoma et al., 2010).

Although LCA studies and energy audits have been conducted on U. S. dairies, scientific literature utilizing actual electricity data which has been analyzed on a per load basis on U. S. dairies is absent. Typically, fossil energy use is estimated by relying on prior studies, based on modeling of data, a combination of brief energy audits, equipment specifications and estimated run-time, or by observing utility electric bills. An energy audit conducted by the Minnesota Department of Commerce in 2015 on 30 dairies in Minnesota estimated annual electricity on a per cow basis to range from 400 to 1,700 kilowatt-hours (kWh). Further, the MN Department of Commerce found that water heating made up 22% of total electricity used on the farm, 17.6% of total electricity was used for milk cooling components (compressors and chillers), ventilation accounted for 18.8% of total electricity use, vacuum pumps used 14.6% of total electricity use, and lighting was 12.9% with the remaining 14.1% being made up of miscellaneous electrical loads such as waterers, laundry, etc (MN Dept. Commerce, 2015). Electricity used on Midwest dairy farms ranged from 2 to 5% of a dairy farm’s production costs (WI Dept. of Ag, Trade, & Consumer Protection, 2006).

A study on dairy farms in Wisconsin by Peebles and Reinemann (1994) found that milk cooling and water heating can account for 40 to 60% of total electricity used on the farm. The authors estimated that vacuum pumps account for 15% of total electrical use. On a per cow basis, milk cooling accounted for 140 kWh/cow/year, water heating accounted for 203 kWh/cow/year without heat recovery, and vacuum pumps accounted for 190 kWh/cow/yr. In modeling electricity used by a 200 cow farm, the authors found that electricity use could range from 49,505 kWh using energy efficient measures to 119,026 kWh of electricity/year using inefficient means across the various electrical components. In modeling a 400 cow farm, the authors found electrical consumption could range from 92,727 kWh using various energy efficiency measures to 226,648 kWh of electricity/year with an inefficient system. The authors also used a model across all dairy farms in Wisconsin to determine that fans were the largest end user of total annual electricity (508,382 MWh) followed by water heating (372,197 MWh).

In 2003, the New York State Energy Research and Development Authority (NYSERDA, 2003) conducted a study which utilized energy audits from 32 dairy farms located in New York. The authors found that milk cooling, lighting, ventilation, and vacuum pumps combined accounted for 88% of the total electricity used on the farm. The annual energy use on farms in the study ranged from 29,805 kWh to 775,909 kWh of electricity per year. The study found that the annual electricity required on a per cow basis ranged from 800 kWh to 1,200 kWh per cow. The electricity used by equipment category is as follows: 25% of electricity was used for milk cooling components, 24% of electricity was used for lighting, 22% was used for barn ventilation, 4% was used for electric water heating, 4% was used for manure handling, and feeding equipment and miscellaneous loads used 4% of the total electricity used by the entire barn. The comparison of tiestall to freestall barns was also made in the New York study. Milk cooling was the largest user of total electricity in both the tiestall (23%) and freestall (27%) system. In combination, milk cooling, vacuum pumps, ventilation, and lighting accounted for 92% of the total electricity used within freestall barns. On tiestall farms, the same combination of electrical components comprised 79% of total electricity used. Water heating, feeding, manure systems and miscellaneous comprised the final 21% of total electricity used.

Solar energy in agriculture

Energy produced by renewable sources has been expanding largely to alleviate the impacts of climate change and lessen dependence on finite fossil fuels (IPCC, 2011). In the United States, 17% of electricity is generated by renewable energy sources, with 2% being produced by solar photovoltaic (PV) energy (EIA, 2019). The technology which is used to produce solar panels has become more economically feasible and accessible to homeowners and farmers across the United States. As solar PV systems are becoming more available and affordable to consumers, installations of these systems have been increasing (IRENA, 2019, EIA, 2019), and solar PV is the fastest growing power generating technology today (REN21, 2017). Today, solar systems in the United States produce enough electricity to power 12 million homes (SEAI, 2019). The cost of solar panels has dropped by 50% since 2014 (NREL, 2019) which has further accelerated solar PV installations. Not only do solar energy technologies produce electricity, they also have the potential to be utilized as a dual-use structure. Solar panels have provided protection for vehicles when mounted on parking lot scaffolding and solar cell shingles have been mounted on roofs of houses replacing traditional shingles (Hezel, 2003).

Combining solar energy with agriculture, known as agrivoltaics, could play a key role in meeting global food demands while simultaneously meeting global energy demands. The photosynthetic process of plants yields an efficiency of around 3%, whereas solar PV panels yield an efficiency of around 15%. Therefore, it is hypothesized that large solar systems could compete with agriculture for land in the future (Dupraz et al., 2011). Instead of competing against one another, some studies suggest using solar energy technologies and agriculture together could improve the global food, water, and energy nexus (Dupraz et al., 2011; Marrou et al., 2013; Amaducci et al., 2018; Walston et al. 2018).

Agrivoltaics is a relatively new idea in which agricultural systems are combined with the use of solar systems to maximize land use. Some purposes which have been used in combination with agriculture include pollinator habitats, gardens, and cropping systems (Dupraz et al., 2011; Walston et al. 2018). Researchers from The University of Arizona found that plants grown under the shade cast by solar panels require less water while simultaneously cooling the underside of the solar panels. Solar panel modules can lose efficiency while operating in extreme heat conditions. However, the cooling effect provided by the plants allows the cooled solar panels to capture more solar energy, thereby performing at a higher level (Dinesh and Pearce, 2016). Shading provided by solar panels may improve the soil and water balance, further increasing water savings (Amaducci et al., 2018). As the climate warms, nighttime temperatures remain persistently high with the probability of extremely warm nights increasing (IPCC, 2013).

Higher nighttime temperatures cause wasteful respiration, resulting in premature crop maturation, which shortens the grain filling period (Lindsey and Thomison, 2018). Research by Marrou et al. (2013) demonstrated that solar panels can reduce the day/night amplitude of crop temperature and decrease soil temperature, which has the potential to improve crop health.

Dupraz et al. (2011) modeled a combined solar and cropping system to determine the efficiency of land productivity. The authors found that land productivity globally could increase between 35-75% while utilizing solar PV and different mono-cropping systems in combination. The National Renewable Energy Laboratory and United States Department of Energy have estimated that solar photovoltaic panels on just 0.6% of the United States' total land area could supply enough electricity to power the entire United States (NREL and DOE, 2012). These findings have the potential to change the landscape as we know it. Although research has shown that agrivoltaics may be an efficient way to produce crops and energy, scientific literature is lacking in regards to another large aspect of United States agriculture: utilizing agrivoltaics within pastured lands that account for 27% of the total acreage of the contiguous 48 states (USDA, 2020).

Using agrivoltaics to reduce heat stress in dairy cows

During the last 30 years, heat waves occurring in the Midwest region of the United States have killed thousands of feedlot cattle (Hahn, 1999). With climate change causing areas of the United States to experience rising temperatures, mitigating heat stress in dairy cattle is now more important than ever. Heat stress has a considerable effect on the dairy industry in the United States with production losses costing the United States more than $900 million annually (St-Pierre et al., 2003). As metabolic heat production has increased in parallel with large increases in average milk production per cow and by digesting roughage, which causes body temperature to rise, dairy cows face even greater challenges in heat stress (Ammer et al., 2018 and Mader and Davis, 2004). Dairy cows challenged with heat stress can have a reduction in milk production, decrease in fat and protein content in the milk, lower reproductive performance, increased somatic cell count, increased incidence of lameness, and lower immune system functioning (Hahn, 1999, Ravagnolo et al., 2000, Cook et al., 2007, and Bertocchi et at., 2014) than dairy cows provided with heat abatement. Feed intake decreases when air temperature reaches 25 ˚C and decreases severely when the air temperature rises above 40 ˚C. Feed intake can be 20 to 40 % lower for a heat-stressed cow than under thermoneutral conditions (Hahn, 1999).

An indicator of thermal stress, body temperature of dairy cows can be very susceptible to hot and humid weather (Akari et al., 1984). The main environmental factors which cause body temperature of cows to rise are ambient air temperature, humidity, and the calculated temperature-humidity index (THI). THI scales have long been used to determine when a dairy cow may experience environmental conditions outside of her comfort zone (thermo-neutral zone). THI is used frequently to estimate effects of heat stress on milk production, dry matter intake, behavior, reproduction, health, and welfare (McDowell et al., 1976, West et al., 2003, Cook et al., 2007, Bohmanova et al., 2007, and Tucker et al., 2007). According to Armstrong (1994), THI below 71 is within a cow’s comfort zone, a THI between 72 to 79 results in mild stress, 80 to 89 causes moderate stress, and values above 90 cause severe stress.

Cows experiencing heat stress have been observed to spend more time standing. The increased standing times have been found to cause higher incidences of lameness in dairy cows housed in freestall barns (Leonard et al., 1996, Cook et al., 2007). Presumably, cows stand as a way to maximize surface area of the body that is exposed to the environment, which increases airflow around the body (Ansell, 1981). Furthermore, a study from the United States used 119,337 milk production records to determine that fat and protein contents in milk decreased by 0.012 kg and 0.009 kg for each unit of increase in a temperature-humidity index above 72 (Ravagnolo et al., 2000). Garcia-Ispierto et al. (2006) found that a THI above 69 causes the risk of a cow aborting a pregnancy to be 2% higher compared to a cow under thermoneutral conditions. Heat stress further affects reproduction by reducing behaviors centered around estrus, altering follicular development, and can inhibit development of the fetus (Hansen et al., 2001, Wolfenson et al., 1995, and Garcia-Ispierto et al., 2006). Studies have also shown that the calf of a gestating cow that experienced heat stress in utero may have lower developing body weights and compromised passive immune transfer as well as lower milk production when it enters the milking herd (Collier et al., 1982, Monteiro, et al., 2016, Dahl et al., 2016).

Agrivoltaics is one way producers might be able to increase energy dependence, lower electricity production costs, increase land efficiency, and increase milk production and health in dairy cows. Using a ground-mounted PV system in a pasture-based dairy could provide shade to dairy cows during heat events. Many studies have reported benefits of heat abatement techniques to dairy cows, which may include fans, sprinklers, or fog misters. However, there are few which investigate the benefits of providing shade to dairy cows on pasture or housed outdoors. Shütz et al. (2008) found that shade was of the utmost importance to dairy cows housed on pasture. The study showed that cows which were deprived of lying for 12 hours chose to stand under a shade structure during hot days when they had the option to lay down in an area devoid of shade. Tucker et al. (2007) found that pastured dairy cows utilized shade structures more often when ambient solar radiation levels were highest during the day. Shütz et al. (2009) found that cows on pasture preferred a shade cloth that blocked 99% of solar radiation over a shade cloth which only blocked 25% of solar radiation. These authors found that cows spent significantly more time in the shade on days with high solar radiation levels and used the shade during 29.8% of the day. Further, body temperatures of cows increased significantly in parallel with increasing THI and ambient air temperature.

Kendall et al. (2007) found that shade treatments significantly reduced respiration rates of pastured cows by 30%, and a combined sprinkler and shade system reduced respiration rates of cows by 60% as compared to uncooled cows. These authors found that milk production declined significantly from 16.1 kg to 11.2 kg over the duration of the 35 day experiment, and somatic cell counts were significantly lower in shaded cows. Palacio et al. (2015) researched the effects of providing a portable shade structure to Canadian cows on pasture. Cows with access to the shade were observed drinking water 6.4 times less than unshaded cows. However, providing shade had no effect on lying time, fly intensity, vaginal temperature, or milk production of cows.

A lone study available in the literature investigated using agrivoltaics for livestock. The study investigated behavioral effects of shade from photovoltaic panels on grazing sheep in Brazil. The study by Maia et al. (2020), found that grazing sheep preferred shade cast by PV panels over shade provided from classic 80%-blockage material. The authors concluded that sheep spent less than 1% of the time under the shade cloth compared to 38% of the time under the shade from the PV panels. This study is the first of its kind to investigate the use of shade from PV by grazing sheep. No research has been done on the effects of using agrivoltaics as a means for shading in a pasture-based dairy setting. Using an agrivoltaic system for pastured cows could provide an adequate means of heat abatement while reducing grid-tied electricity consumption.

Conclusions

Data on electricity use of dairy production systems in the United States are scarce. With consumers pressuring food companies and producers to reduce their carbon footprint, more investigation needs to be conducted to determine where on-farm electricity consumption can be reduced. Results could determine specific electrical loads or processes that have the potential to reduce use of electricity. Reducing energy use will allow milk producers to reduce their dependency on finite fossil fuels, increase their profitability, and be more marketable to consumers. In the future, novel ways of thinking and producing food will be required due to rising pressures from consumers and vanishing finite fossil fuels. Agrivoltaics is one method that producers could use to achieve multiple benefits: increase land use efficiency, reduce grid-tied and fossil fuel-produced electricity use, and increase consumer acceptance all while providing heat abatement to cattle which has the potential to increase milk production, health, and welfare of dairy cows.

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Manuscript 1

Electricity consumption on Midwestern dairy farms in the United States

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Interpretive Summary

Electricity consumption on Midwestern dairy farms in the United States. By Sharpe et al. (2020). The objective of this study was to evaluate electricity use on five dairy farms in the Midwestern United States. Fans for cow comfort had the largest use of electricity on farms and ranged from 15 to 38%. Milk cooling ranged from 6 to 32%, and lighting ranged from 3 to 37% of total electricity on farms. The results of this study provide contemporary energy usage that can be used as farm energy benchmarks that can inform decisions to reduce energy usage in dairy production systems.

SUMMARY

The objective of this study was to evaluate electricity use on five dairy farms in the Midwestern United States. Data were collected from commercial farms representative of typical Midwestern dairy farms and located in west central Minnesota. Farm A was a 9,500-head, cross-ventilated barn with a rotary milking parlor, Farm B was a 300-head, naturally-ventilated barn with 6 automatic milking systems, Farm C was a 200-head, naturally-ventilated barn with a parabone milking parlor, Farm D was a 400-head, naturally-ventilated barn with a parallel milking parlor, and Farm E was a 275-cow, low-input grazing herd with a swing-9 parabone milking parlor. Multiple electric loads across all dairy farms were monitored from July 2018 to December 2019 on the farm side of the electric utility meter at circuit panels to determine electrical usage. Monthly electricity data were summed across farms and averaged per cow, per kg of milk produced, and per kg of fat plus protein produced. Hourly data were analyzed with PROC MEANS of SAS to determine seasonal and hourly trends on farms. Fans for cow comfort had the largest use of electricity on farms A, B, and C, and ranged from 15 to 38% of total electricity used across farms. The automated milking system on Farm B, consumed 14% of total electricity. On Farm D, a manure composter used the greatest percentage of electricity (34%). On Farm E, milk cooling (38%) had the highest percentage of total electricity usage. Milk cooling from compressors and chillers ranged from 6 to 32% of total electricity on farms. On a monthly basis, electricity from lighting ranged from 3 to 37% and manure handling systems ranged from 0.02 to 55% of total electricity usage on farms. Monthly total electricity use per cow ranged from 20 kWh on Farm E to 139 kWh on Farm B. Monthly electricity per kg of fat and protein produced averaged 1.24 kWh on

Farm A, 1.25 kWh on Farm B, 0.64 kWh on Farm C, 0.92 kWh on Farm D, and 0.94 kWh on Farm E. The results of this study provide contemporary energy usage that can be used as farm energy benchmarks which then can inform decisions to reduce energy usage in dairy production systems.

(**Key words:** dairy, energy, electricity, sustainability)

INTRODUCTION

Consumer interest and concern is growing in regard to the carbon footprint of livestock systems (Forsman-Hugg et al., 2008). Subsequently, consumer demand for increased sustainability and reduced carbon emissions within livestock production systems has been rising along with an increased demand for food products due to population growth. Global food requirements are predicted to rise by 70% in the future (FAO, 2009). To address consumer demands, producers may have to investigate areas within their own production systems that have the potential for reduced energy consumption. However, baseline data on fossil fuel use within dairy production systems is scarce, and there is a need to determine where and how fossil energy, namely electricity, is used on dairy farms.

Electricity used on-farm may be a small portion of total energy used to produce milk; however, recent studies have evaluated electricity use on dairy farms around the globe. Electricity use on dairy farms was 25% of total energy use on New Zealand dairy farms (Wells, 2001). A study on Irish dairy farms found electricity accounted for 12% of total energy use of which milk cooling accounted for 31%, water heating accounted for 23%, and the milking process accounted for 20% of total electrical use (Upton et al., 2013). On pasture-based automated milking farms in Ireland, vacuum and milk pumps had the largest electrical use (33%), followed by air compressors (26%) and milk cooling (18%; Shortall et al., 2018).

Electricity costs in the United States are expected to rise due to forecasted increases in natural gas prices (EIA, 2020), which may force producers to investigate methods to reduce electrical use on farm. Most energy studies conducted on dairy farms in the United States are outdated and were done using brief audits, manufacturer specifications on equipment, and whole farm usage from electric bills. Electricity costs on dairy farms in the Midwest region of the United States ranged from 2 to 5% of all milk production costs and translated into an annual electricity use of 700 to 900 kilowatt-hours (kWh) per cow (WI Dept. of Ag., 2006). Baseline electricity use data from specific loads and across hours and seasons is needed to accurately determine where and how energy is used on the farm. As dairy farms have adopted new technologies such as automatic milking systems, cow monitoring systems, or improved building designs, current electrical use data may be useful in assisting producers to find locations on farm to reduce energy consumption. Daily and seasonal electricity use may be helpful to determine areas of high electrical use across the year and throughout day-to-day farm operations. Therefore, the objective of this study was to measure total electricity use and determine areas of energy consumption on five dairy farms in the Midwestern United States. The results of the study may provide recent electrical energy use for farm energy benchmarks, agricultural energy policy deliberations, economic evaluations, renewable energy opportunities for on-farm production, and further research into dairy farm energy.

MATERIALS AND METHODS

Dairy farms

Five dairy farms located in west central Minnesota were contacted to participate in electricity monitoring on their farm, and after consultation, farm owners gave their approval for researchers to evaluate electrical consumption on farm. Dairy farms of various sizes and with various milking and ventilation systems were selected to represent a wide range of commercial dairy farms and were typical of those located throughout the upper Midwest region of the U. S. Electricity use on farms was recorded from July 2018 through December 2019. Additionally, cow numbers, milk production, and milk components were obtained from the producers. The project was approved by the University of Minnesota Institutional Animal Care and Use Committee (#1709-35099A).

Farm A

Farm A had 9,500 Holstein and Jersey crossbred dairy cows, and 90% of cows were lactating over the duration of the study. Mean milk production was 25.8 kg/cow/day. The cross-ventilated free stall barn had 12 pens with 24 rows of stalls for lactating cows. There were another 12 pens of dry cows, which had approximately 1/5 the number of stalls as the lactating cow pens. The barn had 17 rows of light emitting diode (LED) lights over the stalls. The barn had 400 exhaust fans (145 cm diameter) located on the north side of the barn and were 1.5 kilowatts each. The fans in the barn did not have variable-frequency drives (VFDs) installed, and the fans were not activated in stages on thermostats. All fans were instead managed according to decisions made by farm herdsmen and were typically run at maximum ventilation when the outside ambient air temperature was greater than 1.6°C. Cows were milked twice per day in a 106-stall DeLaval rotary parlor (DeLaval, Kansas City, MO), and the milking parlor had 3 wall fans (50.8 cm diameter). The rotary parlor was in operation 22 hours per day with a one hour wash in between milkings. Additionally, the holding pen had 38 exhaust fans (145 cm diameter; 1.5 kW), and the milking parlor had a 36 kw boiler for in-floor heat.

The milking system had 2 air compressors (22 kW/compressor), 3 vacuum pumps (11.2 kW/pump), and 4 compressors for milk cooling (18 metric ton per compressor). The plate cooling system had 1 well water pump (11.2 kW), 2 glycol pumps (11.2 kW/pump) and 2 condensing units (11.2 kW/unit). The glycol pump was used to transfer heat from the plate exchanger to the condensing units. The condensing units released heat into the plate exchanger room during cold months and released heat outdoors during warm months. The plate exchanger room had 2 exhaust fans (145 cm diameter/fan). Milk from this dairy was transferred directly into milk tankers, and therefore, there was no on-site milk storage. Wash water was heated with 2, tank water heaters (15 kW/heater). Manure was collected by a manure vacuum system (Mensch Manufacturing, Hastings, MI). The components of the manure system were 2 effluent pumps (7.5 kW/pump), 1 agitator (18.6 kW), 2 separator pumps (15.0 kW/pump), 10 separator motors (11.2 kW/motor) for manure separated solids, 1 stacking pad motor (11.2 kW), and a 36 kW boiler for in-floor heat.

Furthermore, the farm had a hoof-trimming area equipped with 3 electric radiant heaters (4.8 kW/heater) and 4 exhaust fans (91 cm diameter; 0.75 kW/fan). The maternity calf room had 19 electric radiant heaters (4.8 kW/heater) and 1 wall fan (51 cm diameter; 1.1 kW). The fresh cow hospital and veterinary room had a 16 stall single-sided milking parlor with a 7.5 kW vacuum pump, a 3,785 L bulk tank, 5 electric radiant heaters (4.8 kW/heater), and a 0.2 kW air compressor. The electrical circuits for the hoof trimming area and calf room were located within the veterinary room. Subsequently, electrical monitoring for all three rooms were combined within the veterinary room.

Farm B

Farm B had 300 lactating Holstein cows, and mean milk production was 38.5 kg/cow/day. The naturally-ventilated freestall barn had 2 pens with 6 rows of stalls in the barn. There were 27 panel fans above the stalls (122 cm diameter; 0.7 kW/fan) for air movement. Furthermore, 5 panel fans (1.5 kW/fan) were located above the cow pens. Dry cows were housed in a separate, 3-row freestall barn with 8 panel fans (122 cm diameter; 0.7 kW/fan). The fans did not have VFDs and were activated by thermostats. Twenty percent of the lights in the freestall barn had been converted to LEDs.

Furthermore, Farm B had 6 automated milking systems (AMS; Lely North America, Pella, IA). Two of the AMS rooms had 2 AMS in each room and the other 2 rooms had 1 AMS system. All AMS rooms each had 8 LED lights, 1 exhaust fan (51 cm), and 1 electric wall heater (4.8 kW). The harvested milk was stored in a 27,255 L bulk tank and was cooled with 1 constant 3.7 kW and one variable rate 3.7 kW compressor for milk cooling.

Farm C

Farm C had 200 lactating Holstein cows, and mean milk production was 33.6 kg/cow/day. Cows were milked twice per day with a double-eight parabone milking parlor. The naturally-ventilated freestall barn had 2 pens with 4 rows of stalls in the barn. There were 14 panel fans above the stalls (122 cm diameter; 0.7 kW/fan). Furthermore, there were 2 panel fans (122 cm diameter; 0.7 kW/fan) in the holding area and 5 panel fans (91 cm diameter/fan) in a separate maternity area, and all fans had VFDs. Additionally, all lights in the freestall barn were LEDs. Milk was harvested with a 3.7 kW vacuum pump and was stored in either a 7,570 L bulk tank or a 4,732 L bulk tank. Each bulk tank had 1 compressor for milk cooling (3.0 kW).

Farm D

Farm D had 400 milking Holstein cows. Mean milk production was 33 kg/cow/day. Cows were milked twice daily in a double-eight herringbone milking parlor. The naturally-ventilated and insulated freestall barn consisted of 9 rows of stalls. There were 47 panel fans (122 cm diameter; 0.7 kW/fan) above the stalls and 2 fans in the milking parlor. All fans were equipped with VFDs and all lights in the barn were LEDs. Milk was harvested with a vacuum pump (7.5 kW) and stored in a 15,142 L bulk tank. Two 3.7 kW compressors were used to cool the milk. The manure system had a 37.0 kW manure pump and a BeddingMaster manure composting system (BeddingMaster, Daritech Inc., Lynden WA) which supplied the farm with bedding in stalls for cows.

During the last 2 months of data collection, Farm D retrofitted the freestall barn and added 7 AMS (Lely North America, Pella, IA) in October 2019. Additional energy meters and sensors were not added to monitor the AMS system. Therefore, the data reflects the drop in electricity used at Farm D that occurred when the herringbone milking parlor was decommissioned.

Farm E

Farm E was the experimental dairy herd at the University of Minnesota West Central Research and Outreach Center in Morris, MN, USA, and had 275 Holstein and crossbred cows, and cows were milked twice daily in a swing-9 parabone parlor. Mean milk production was 16 kg/cow/day. The farm was a pasture-based system, and therefore, the cows were housed outdoors on pasture or in a dry lot during the summer and winter, respectively. The farm calved seasonally, and therefore, milking cow numbers fluctuated throughout the year. The main electrical components of this farm were used to operate the milking system and cool and store the milk. The milking parlor had 3 panel fans (61 cm diameter; 0.7 kW/fan) and 5 exhaust fans (61 cm diameter; 0.7 kW/fan), a natural gas furnace, and 2 space heaters (1.5 kW/heater) used during the winter months to prevent water pipes from freezing in the mechanical room. The vacuum pump was 5.5 kW, and there were 2 scroll compressors (3.7 kW/compressor) to cool the milk which was stored in 2 bulk tanks (6,057 L/tank).

Monitoring of electricity and data analysis

Electrical loads were monitored at circuit panels on the 5 farms. Twenty-one eGauge meters were installed across the farms to collect electricity data. At the four commercial farms, eGauge meters (models EG4015 and EG4130, eGauge Systems LLC, Boulder, CO) were mounted inside weatherproof electrical boxes which were mounted on the wall outside of the electrical panel. At Farm A, 71 electrical loads were monitored on five eGauge Meters. At Farm B, 69 electrical loads were monitored on four eGauge Meters. At Farm C, 39 electrical loads were monitored on six eGauge Meters. At Farm D, 39 electrical loads were monitored on four eGauge Meters. At Farm E, two eGauge Meters (EG3000) were installed in the same manner as the other farms. Additionally, at Farm E only, a Campbell Scientific (CS) CR3000 data logger (CR3000 Micrologger, Campbell Scientific, Logan, UT) was inside a weatherproof electrical box and mounted outside of the circuit panels. A total of 28 electrical loads were monitored on Farm E.

The eGauge meters were powered through a specific circuit within the circuit panel so that the eGuage measurement system did not influence any component measurements. The eGauge meters, rated at ANSI C12.20, automatically stored data at a frequency of 1 second. Electrical current transformers (CT; J&D Smart Sensing, Jungwon-gu, South Korea), with an accuracy of ± 1% were connected to twisted pair wire and a 2-pin CT plug which plugged into the eGauge meter. True power and power factors were calculated by the eGauge from the sensors, and data were stored in instantaneous (kW) or cumulative form (kWh).

In addition to 8 electrical loads monitored by eGauges at Farm E, 20 loads were monitored by the CS logger. The CS was attached to current sensors (CR Magnetics, St. Louis, MO) which were rated with an accuracy of ±2% at full scale. The CS was programmed to read electrical current every 30 seconds which was then averaged and stored every 10 minutes.

Contrary to the eGauge Meters, the CS was unable to calculate the kW or kWh used by each load. Therefore, additional calculations were necessary after the data were downloaded and exported into Microsoft Excel (Microsoft Excel, 2016). The 10-minute average electrical current recorded by the CS was converted from current (amperes) to power with the equation: Power (watts) = voltage (line to ground) × current (on one phase) × phase (number of phases in the circuit) × power factor (U.S. Department of Energy, 2001). To determine energy in kilowatt hours (kWh), power was multiplied by 1/6 of an hour. Hourly and daily cumulative kWh data were used in the current study and were collected monthly from all energy meters and exported into Microsoft Excel (2016) and summed to obtain monthly totals. Hourly data were downloaded into Microsoft Excel (Excel, 2016) and analyzed with PROC MEANS of SAS (SAS Institute, 2016) to determine seasonal trends by hour. Across all farms, electric loads were separated into categories based on function and use: fans, heaters, milk cooling, lights, vacuum pumps, manure systems, AMS, vet room, and other uses. Other uses included all loads that used less than 10% of the electricity used by the farm.

RESULTS AND DISCUSSION

Farm A

Farm A used a consistent amount of electricity across the study period (Figure 1). Total kWh of electricity used ranged from 582,032 kWh of electricity in February 2019 to 768,425 kWh in October 2018. Total electricity use was lowest during February 2019 due to the lowest fan use (4% of total electricity used by the farm). Fan use and total electricity used in the Vet Room was high in October, because three of the areas in the Vet Room utilized electric radiant heaters. Heating and cooling was high due to cooling the cows and heating for the calves because of cool nights and warm days during October which is a transition month for weather in the upper Midwest. Heaters (boilers, water heaters, and room heaters) were lowest during July and August of both years (1%) and increased to a high of 8% of total electricity in February 2019. The heaters category did not include heaters located within the Vet Room because the Vet Room was monitored as a whole which included heaters.

Across the months of the study, LED lighting used 11% during August 2018 to 20 % during February 2019. The manure system had 8 to 12% of total electricity used by month. Milk cooling components (including compressors, conditioning units, and chiller pumps) used 6 to 9% of total electricity during the entire study period. Electricity used for water purposes (wells, sprinklers, water pumps, pressure washers, holding pen flushes, and agitators) was consistent throughout the study period, and fluctuated between 2 and 3% of total electricity used. Furthermore, the electrical consumption of other loads (vacuum pumps, milk pump, rotary, surge protectors, controls, and dryers) was consistent at 2% of total electricity used on farm during the study period.

The total electrical usage from Farm A is considerably greater than previously reported results that found electricity usage averaged 98,207 kwh/year in Nova Scotia, Canada dairy farms (Corscadden et al., 2014). Furthermore, Capareda et al., (2010) reported California dairy farms averaged 48,510 kwh/month to 120,447 kwh/month with herd sizes that ranged from 735 to 3,500 cows. Recent studies have reported that milk cooling and harvesting has the largest energy consumption on dairy farms (Todde et al., 2018; Shine et al., 2020). However, the current study found that ventilation fans and lighting had the greatest electrical energy usage, which is contrary to reported studies. This is the first study to report electrical energy usage from large commercial dairy farms with large capital housing investments, and therefore, provided insight into current dairy management practices. The results of the current study for water heating and milk cooling are lower than previous reported results (Edens et al., 2003; Todde et., 2018; Shine et al; 2020) quite possibly because of improvements to milk cooling and water heating efficiencies. Furthermore, milk cooling was lower on Farm A because milk was pumped directly into milk tankers and not in bulk tanks which require additional cooling. Contrary to Todde et al. (2018), the current study reported more electrical energy use for lighting and fans from Farm A. An energy audit conducted by Peebles and Reinemann (1994) found lighting use to account for about 18% of total electricity used on dairy farms across Wisconsin which is comparable to the 15% of total electricity from lighting use in the current study for Fam A. Peebles and Reinemann (1994) also found fans used 34% of total electricity, which is similar to fan use on Farm A (38%). The comparisons of these audited studies to the current study indicate the need for actual electrical energy use data in order to accurately determine trends and uses of electricity on farm.

Electricity used for lighting, the manure system, milk cooling, the water system, and other uses throughout the day varied across seasons of the year (Figure 2a, 2b, and 2d). Fan use for ventilation was greater during the summer months than during the winter months; however, fan use was consistent throughout the hours of the day. During the afternoon hours in the spring (March, April, May) when outside temperatures increased, fan use subsequently increased at 1200 h. A rise in Vet Room electricity usage from 0700 and 0800 h was likely due to the milking parlor being used to milk hospital and fresh cows. During 0600 h of each season, more lights were turned on in the barn. A clear drop in electricity use occurred around 1300 h of each day in each season in the manure and milk cooling categories. This is likely since Farm A washes milking equipment on the rotary from 1200 to 1300 h. Because the milking parlor was not used during the hour long break because of a full system wash of the milk lines, electricity used for heating increased slightly during the 1300 h period. Electricity used for fans during the summer months (Figure 2c) was higher than days during the other seasons and remained constant throughout the day and accounted for approximately 50% of total electricity used on the farm. During the spring and winter months (Figure 2b and 2d), electricity used in the Vet Room was high because of the electric radiant heaters in the hoof trimming area, the sick and fresh cow milking parlor, and the calf area.

Farm B

Results for electrical use across the 18 months of the study from Farm B are in Figure 3. Fan use was greater for the warmer months and had the highest electricity consumption across the study period. Total kWh used on a monthly basis ranged from 19,341 kWh of electricity in October 2018 to 45,779 kWh of electricity in July 2019. Fan use ranged from a low of 6% during December 2018 and January and November 2019 to a high of 52% during August 2018. Milk cooling use was at its lowest during the month of August 2018 (12%) and was the highest during October 2019 (32%). Heaters (including the generator block heater, miscellaneous milk house heaters, AMS room heaters, and water heater) fluctuated from 2% of total electricity use during August 2019 to 42% of total electricity use during February 2019. However, higher than expected electricity usage for heating occurred during July and August 2018 as well as June and July of 2019. Upon further investigation of the data, a switch for the generator block heater thermostat was found to be faulty. The faulty switch resulted in the block heater running constantly, and therefore, caused the producer higher than usual electricity bills. Total electricity used for lighting varied from a low of 3% during July and August 2018 to a high of 12% during November and December 2019. The results for Farm B are similar to some of the farms from Capareda et al. (2010) who reported electrical energy use range averaged 47,500 kwh/month for smaller herd size dairy farms in California and Texas. Results for lighting and milk cooling from Farm B are similar to Todde et al. (2018) who reported an average of 4% total electrical use from lighting and 19% total electrical use from milk cooling for 285 southern Italy dairy farms.

Electricity used by the 6 AMS averaged 13% of total electricity use on Farm B. Electricity for water uses (cattle waterers, well, etc.) ranged from 4 to 9% of total electricity used by Farm B. The manure system averaged 2% of total electricity, and other electrical loads (office, feed augers, controls, cow brush, feed pushing robot, refrigerator, silage feed pump, and dryer) averaged 3% of the total electricity used in Farm B. Shortall et al. (2013) reported similar results for milk cooling on pasture-based AMS Irish dairy farms (18%) which is comparable to the 23% of electricity used in the current study. The results indicate similarities in electricity use of AMS systems regardless of housing system.

Electricity used by the AMS increased dramatically at 0600 and 1800 h across all seasons (Figure 4) likely due to farm employees entering the barn and conducting maintenance or other routine operations and pushing cows through the AMS. Subsequently, electricity used for milk cooling increased at 0700 h and slightly increased at 1800 h. Because operations began on the farm at 0400 h, the lights and the manure system increased in use. Conversely, during the 2200 h, electricity used for lighting and the manure system declined. Electrical loads that were constant throughout the day included heat, water use, and other use. During the winter months (Figure 4d) electricity for fans remained constant. During fall (Figure 4a), spring (Figure 4b) and summer (Figure 4c) months, electricity for fans increased because of an increase in outside ambient air temperature during the afternoon. Total hourly electricity usage for fans was high during the summer, which was twice as much as the other electrical loads. Conversely, electricity usage for heating was twice as much as the other electrical loads during the winter months. In a study of Irish pasture-based and AMS dairy farms, Shortall et al. (2017) found total daily electrical consumption peaked during the hours of 0100, 0800 h, and between 1300 and 1600 h because of AMS utilization by cows. Conversely, Farm B had peak electrical consumption during 0600 and 0700 h and 1700 and 1900 h. Shortall et al. (2017) also noted multiple smaller peaks in electricity consumption each day, whereas the current study found the largest peaks occur during the two hours each day as described above. This could be due to differences in management of freestall barns versus pasture-based farms and workers moving cows through the AMS or working in the AMS rooms during those times.

Farm C

Farm C results for electrical use across the 18 months of the study are in Figure 5. Total electricity used on a monthly basis was lowest during February 2019 (5,999 kWh) and was highest during July 2018 (13,025 kWh). Electricity used for fans was minimal during winter months and averaged 1% of total electricity used. Conversely, a high of 47% of total electricity used by Farm C powered fans during July 2018. Electricity for wash water, cattle waterers, well, washing machine, etc. fluctuated from 7% in August 2019 to 16% of total electricity used by the farm in December 2018 and February 2019, respectfully, and ranged from 887 kWh during August 2019 to 1,145 kWh during December 2019. Electricity used to power heaters (water heaters, break room heaters, and parlor heat) ranged from 13% of total electricity used during July 2019 to 36% during February 2019. Electricity used for heating during the warmer months was largely due to heating of water, and during colder months, heater use increased because of the demand for air and water heating.

Upton et al. (2013) reported water heating required the second highest percentage of total electricity (23%) used in pasture-based Irish dairy farms compared with 15% on Farm C in the current study. Because the farms in Upton et al. (2013) were outdoor systems, the water heating system located inside Farm C quite possibly had more insulation from the elements. Farm C had LED lights and total electricity ranged from 7% of total electricity during both July months to 16% during December 2018. Throughout the study period, compressors used for milk cooling, vacuum pumps, and the other category remained constant. Milk cooling averaged 17% of the total electricity used by Farm C. Vacuum pumps averaged 6%, and other (auger motor, break room, and manure pumps) averaged 9% of the total electricity used. The results are similar to Corscadden et al. (2014) who reported total monthly electrical use of 5,033 kwh to 10,695 kwh for dairy herd size of 85 to 125. An electrical energy audit by Peebles and Reinemann (1994) estimated electricity used by a 200 cow farm. The authors reported energy used by fans accounted for 5% of total electricity used on the farm, 32% of total electricity was used for lights, 20% of electricity use for milk cooling and water heating, and 15% of total electricity for the vacuum pump. This indicated that modeling of electricity use on farm that used estimated run times and equipment specifications may not be as useful as actual electrical consumption data as measured in the current study.

During all seasons for Farm C, electricity used for heat increased during 0300 h due to the pipeline wash cycle (Figure 6). Two peaks for hot water heaters occurred at 1000 and 2000, again due to hot water heating for the pipeline wash cycles. Following the rise in heating use, other use, vacuum pump use, and electricity for water uses all increased at 0300 h. Around 0500 h, another increase in heat, lights, vacuum pumps, fans, and milk cooling occurred because the morning milking started. Milk cooling peaked around 0800 h, and after 0900 h, all electrical loads besides heat decreased. Again, at 1600 h, a rise in electricity across all electrical loads occurred because of the afternoon milking. During the summer months (Figure 6c), fans used twice as much of the total electricity compared to the other electrical components.

Farm D

During the study period, Farm D used the most electricity during the month of July 2019 (32,851 kWh; Figure 7). Farm D transitioned from a double-8 herringbone parlor to 7 AMS the last three months of data collection, and therefore, there was a reduction in electricity use because the new AMS was not monitored. The manure composting system used the greatest amount of electricity (~30%) across the 18-month study period. During the month of July 2018, a lightning strike on the manure composting system circuit panel caused the system to be non-operational for the month. During September, October, and November of 2019, data from the manure composting system were lost because the power supply was switched off within the circuit panel. During all other months, the manure system was constant and averaged 30% of the total electricity used by the farm. Fan use on Farm D ranged from 6% during November 2018 to 35% during July 2018. Electricity used for lighting was constant throughout the study period and averaged 18% of total electricity used. The highest month for lighting use was during October 2019, when the 7 AMS system was installed into the barn.

Milk cooling (compressors) were constant throughout the study period and averaged 15% of total electricity used. Electricity used for milk cooling decreased during October, November, and December 2019 because of the AMS installation. Electricity for water use (cattle waterers, tank washer, etc.) was constant and averaged 6% of total electricity used. Lastly, electricity to run heaters and other (crowd gate, Lely Juno automatic feed pusher, office, and hydraulic doors) use were constant throughout the period from 4% and 6% of total electricity use, respectively. The results differed from those of Upton et al. (2013), which monitored electricity used by pasture-based AMS dairy farms, and reported 80% of electricity use was related to water heating, cooling milk, and milking. Conversely, the largest electricity consumer in Farm D was the manure composter. This was expected as pasture-based dairy farms typically do not need to account for manure aggregation in the barn. Results from Farm D are similar to results found by the Minnesota Department of Commerce (2015) that reported milk cooling averaged 17.6% of total use and lighting used 12.9% of total electrical use. Peebles and Reinemann (1994) estimated energy use on a 400 cow dairy using an electric energy audit. The authors found that 29% of total electricity used by the farm was used for milk cooling, 16% of electricity was used for heating water, 32% of electricity was used to power all lights, 4% was used for fans, and 18% of total electricity was used for the vacuum pump. Although Farm D had a manure composting system, the estimates of Peebles and Reinemann (1994) were not comparable to any of the electrical consumption patterns in the current study. However, the results from Farm D are comparable to Todde et al (2018) and Shine et al. (2020) who reported that milk cooling has the greatest electrical energy consumption on dairy farms.

Across all seasons, daily electricity use in Farm D was consistent, regardless of season (Figure 8). Electricity used for lighting increased at 0400 h and remained unchanged until 2400 h when lighting drastically decreased. Electricity for vacuum pumps, milk cooling, and heating increased during 0500 h following the morning milking schedule. Electricity used for water purposes increased again during 1000 h, because of the cleaning period after milking. Again at 1800 h, vacuum pumps and the milk cooling process began because of the afternoon milking. During the fall and spring seasons (Figure 8a and 8b), the thermostatically controlled fans used more energy as the day progressed, typically around 1200 h. During the summer months (Figure 8c), fan use increased at 0400 h and increased at 1700 h. Farm workers manually switched on the non-thermostatically controlled fans in holding area because of the milking process. The manure system increased electricity used throughout the day during 0600 and 1600 h, likely when workers cleaned manure from the pens in the freestall barn.

Farm E

Total electricity used by Farm E ranged from 4,619 kWh in October 2018 to 10,780 kWh in May 2019 (Figure 9). Milk cooling was the largest proportion of total electricity during every month of the study period and ranged from 29% in August 2018 to 45% in October 2018 and November 2019. The milk cooling component of Farm E was highest because less ventilation and manure management were needed for cows housed outdoors. Furthermore, Farm E installed a fully electric heat pump system to transfer heat from milk to a warm water storage tank, which was used to heat water for cleaning purposes. Milk cooling results were similar to Upton et al. (2013) who reported milk cooling was the largest user of electricity in pasture-based dairy farms. Furthermore, Edens et al. (2003) reported milk cooling and vacuum pumps consumed the largest electrical energy on an experimental farm at the University of Tennessee in the US, which is similar to the results of the experimental herd in the current study (Farm E). Heaters (furnace, milk house heaters, bathroom heater, water heaters) used the second largest amount of total electricity, ranging from 1% to 40% of total electricity used during October 2018 and February 2019, respectfully. Heaters consumed a large amount of electrical energy because of supplemental space heaters that were used to prevent water lines from freezing in the utility room of the barn during winter months. Fan use ranged from 4% during winter months to 26% of total electricity used during July 2018.

Interestingly, vacuum pump use had large fluctuations in energy use and ranged from 2% during April 2019 to 17% of total electricity during November 2019. Electrical loads which remained constant throughout the period were the clothes dryer for drying towels (average of 12%), electricity for water uses (tank wash, washing machine, and electric pressure washer; 3%), and other use (lights, office, and barn cleaner; 10%). During the summer months, Farm E averaged 8% of total electricity to heat water. Minnesota dairy farms reported average fan use of 18% and vacuum pump use of 14% (Minnesota Department of Commerce, 2015) which was greater than fan use of 14% and vacuum pump use of 8% of total electricity used on Farm E.

Electrical energy consumption and trends in individual components were consistent on Farm E, regardless of season (Figure 10). From 0500 h to 0600 h, electrical energy increased from use of the dryer, and vacuum pump as the morning milking cycle began. Milk cooling increased during 0600 h because of increased energy use from milk bulk tanks to cool milk. Dryer use fluctuated throughout the day as employees washed and dried towels used for milking. Electricity use increased at 1100 h because the milking cycle ended and the milk pipeline system cleaning cycle started. At 1600 h, electricity for milk cooling and vacuum pumps increased because the evening milking cycle began. Parlor cleaning typically occurred at 2000 h because increased use of electricity used for water and towel dryer.

Total electrical use across a 24-hour period

Total hourly electricity usage for each farm across a 24-h period is shown in Figure 11. Farm A had an average hourly electrical use that ranged from 880 to 950 kwh, and the highest amount of electricity use was during 0900 and 1700 h. The rotary milking parlor was in use 22 of 24 hours and employees were on the farm all 24 hours. However, most employees had a more typical schedule and started work during 0600 or 0700 h and ended during 1700 or 1800 h. This might be represented by the increased electricity usage during the daylight hours with additional employees conducting maintenance work, hoof trimming, and cleaning. Farm A used 19 times more electricity than Farm B, 38 times more electricity than Farm C, 20 times more electricity than Farm D, and 56 times more electricity than Farm E.

Although Farm B had 6 AMS, an increase in electricity was observed in 0400 h and 1600 h (Figure 11). This is likely due to employees that fetched cows and moved un-milked cows through the AMS, as well as an increase in electrical energy use from motors to feed cows and clean equipment. Electricity used on Farm C and D increased during the morning and the evening because of the increased energy use from vacuum pumps and compressors to milk cows and cool the milk. On a daily basis, Farm E used the least hourly total electricity compared to the other farms. Again, energy usage peaked in the morning and evening hours because of milking and milk cooling. The hourly electricity consumption trends found in this study are similar to those trends reported by AMS farms in Upton et al. (2013). The authors reported peaks in electricity were from 0700 to 1200 h and from 1630 and 1930 h.

Total annual electricity use per cow was 965 kWh for Farm A, 1,145 kWh for Farm B, 574 kWh for Farm C, 775 kWh for Farm D, and 400 kWh for Farm E. The findings from Farm A and Farm B are comparable to energy audits completed on 32 dairy farms in New York (NYSERDA, 2003) that reported annual electricity on a per cow basis ranged from 800 kWh to 1,200 kWh per cow. The electricity use per cow on

Farms C, D, and E were all lower than the electrical consumption per cow found in the New York study. The energy use per cow on Farm A and Farm B further align with the results of Bailey et al. (2008) who found that dairy farms in Nova Scotia used 1,069 kWh/cow/year and Clarke et al. (2010) reported that dairy farms in Ontario used 800 to 1,400 kWh/cow/year. However, Farm C, D, and E were all slightly lower on an electricity use per cow basis, and Capareda et al. (2010) reported 280 kWh/cow for a pasture based dairy in Texas which is lower than the pasture-based dairy herd (Farm E) in the current study. Farm E used 395 kWh/cow/year because supplemental heat would be required in colder climates in pasture-based dairies. The kWh/cow/year ranged from 379 to 832 kWh in California dairy farms and ranged from 268 to 753 kWh/cow/year on Texas dairy farms (Capareda et al., 2010).

Across the study period, monthly total electricity on a kWh per cow and kWh/kg of fat plus protein varied across the five farms (Table 1). Farm A used the most electricity per cow during the month of October for both years in the study, because of increased fan and heater use. The lowest monthly demand for electricity on Farm A was during the winter months when fan use decreased. Furthermore, Farm B and Farm E had the lowest energy use per cow during the winter months when fan use was lowest.

Upton et al. (2013) reported that electrical use trends in Irish dairy farms should be applicable to other global milk producers, which was contrary to the current study. The authors found that the largest portion of total electricity usage was milk cooling components because the Irish dairy farms were pasture-based systems, which is similar to the findings only on Farm E in the current study. However, the current study found that fan and lighting use were the largest portions of electrical energy consumption on farm, which is contrary to reported studies in the literature.

On a kWh/kg of fat plus protein produced, all five farms were similar in seasonal fluctuations. All farms used the least amount of electricity per kg of fat plus protein during autumn and winter months when fat and protein production were the highest. Conversely, all five farms experienced higher electricity use per kg of fat plus protein during the warmer Midwestern months when fat and protein composition was low and fans used for heat stress mitigation in the freestalls was the highest. Apart from the Irish studies by Upton et al. (2013) and Shortall et al. (2017), all other studies compared to with the current study were conducted using energy audits which estimated electricity use on-farm. Some of the findings in the current study were comparable to prior energy audits, however, actual electrical use data are unique to this study and the Irish studies. Therefore, it was difficult to compare results from this study to available energy audits.

CONCLUSIONS

Electricity used on dairy farms may fluctuate based on many factors that include milking system, barn structure, fan types and sizes, management decisions, hour of day, number of cows, manure management, and season. For total electricity, fans were the largest load across Farms A, B, and C. A manure composting system on Farm D used the highest proportion of total electricity. The milk cooling system in the low-input dairy (Farm E) had the highest percent of total electricity used by the farm. By focusing on areas that have the potential for reduced electrical use or improved efficiency, producers have the tools they need to reduce their carbon footprint directly on farm. Hourly data provided insight into operations on a daily basis at all farms and which components use the most electricity at different times. This could assist producers to discover periods during the day when electricity use is high, which could help in reducing their peak demand. The results from this study provide recent electrical energy usage data for farm energy benchmarks, agricultural energy policy, economic evaluations, and baseline data for life cycle assessment analysis. More research into the daily and seasonal electricity use trends is needed to target specific time periods when electricity use can be reduced. Additionally, further research on energy efficiency measures and renewable energy systems on-farm should be investigated.

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Table 1. Monthly total electricity (kWh/milking cow and kWh/kg of fat + protein) for 5 farms during July 2018 to December 2019.

	kWh/cow					kWh/ kg fat plus protein				
Month	Farm A	Farm B	Farm C	Farm D	Farm E	Farm A	Farm B	Farm C	Farm D	Farm E
2018										
July	82.0	137.1	69.7	58.6	34.0	1.33	1.79	0.96	0.88	0.99
August	83.0	128.7	66.8	78.5	36.6	1.32	1.88	0.96	1.17	0.96
September	78.1	92.9	58.4	81.2	30.7	1.25	1.75	0.78	1.17	0.93
October	91.9	62.5	37.5	72.7	19.7	1.36	1.19	0.49	1.04	0.50
November	74.8	70.5	35.5	64.5	22.9	1.16	0.79	0.48	0.92	0.54
December	73.8	84.8	35.6	70.2	27.6	1.11	0.83	0.50	0.95	0.59
2019										
January	73.8	95.6	35.7	73.3	36.0	1.11	0.98	0.47	0.98	0.81
February	68.4	89.6	32.1	61.8	36.0	1.14	1.24	0.47	0.92	0.99
March	82.8	79.7	36.9	64.6	39.1	1.25	1.05	0.50	0.88	1.06
April	81.6	83.0	37.6	60.7	33.6	1.29	1.01	0.49	0.88	1.00
May	84.7	92.6	41.5	63.3	38.1	1.31	0.97	0.53	0.89	1.08
June	79.2	122.7	64.1	72.9	38.4	1.28	1.14	0.86	1.08	1.00
July	80.8	139.1	68.1	77.6	36.4	1.29	1.55	0.98	1.11	1.21
August	82.0	121.2	64.7	73.0	41.9	1.23	1.70	0.83	1.04	1.33
September	84.0	99.6	57.0	62.0	40.5	1.27	1.53	0.76	0.89	1.33
October	90.4	69.6	42.5	37.0	28.5	1.29	1.23	0.54	0.53	0.94
November	82.8	73.5	36.9	47.1	27.4	1.26	0.89	0.47	0.67	0.74
December	73.4	74.5	41.0	43.8	32.9	1.10	0.91	0.50	0.60	0.83

Figure 1. Monthly total electricity usage from July 2018 to December 2019 by category for Farm A (green= fans, yellow= lights, brown= manure, pink= vet room, light blue= milk cooling, red= heaters, dark blue= water, and grey= other).

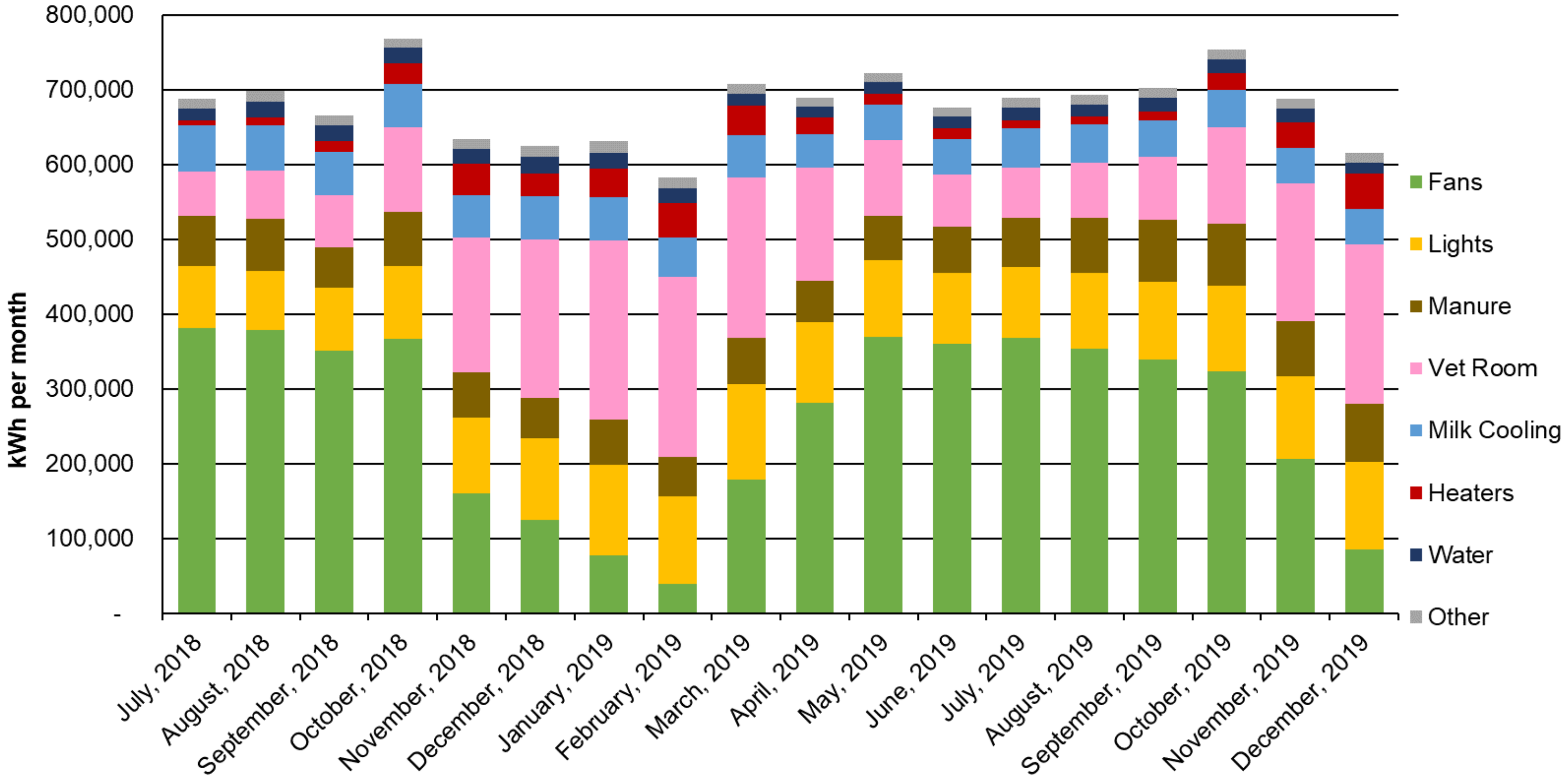


Figure 2. Seasonal average hourly electricity use for Farm A across the 18-month study period (**a.**= September, October, and November; **b.**= March, April, and May; **c.**= June, July, and August; **d.**= December, January, and February).

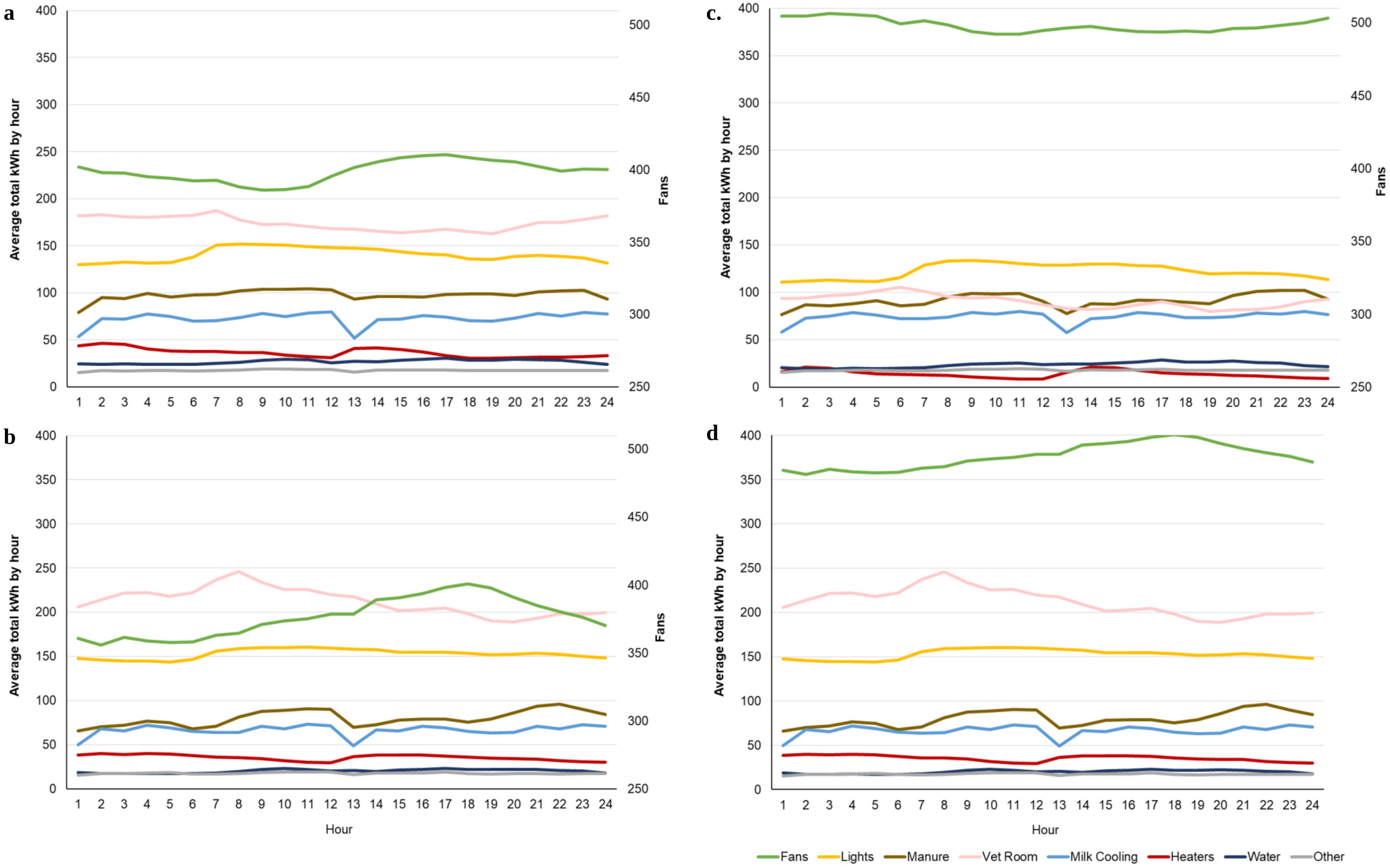


Figure 3. Monthly total electricity usage from July 2018 to December 2019 by category for Farm B (light blue= milk cooling, green= fans, red= heaters, yellow= lights, brown= manure, orange= AMS, dark blue= water, and grey= other).

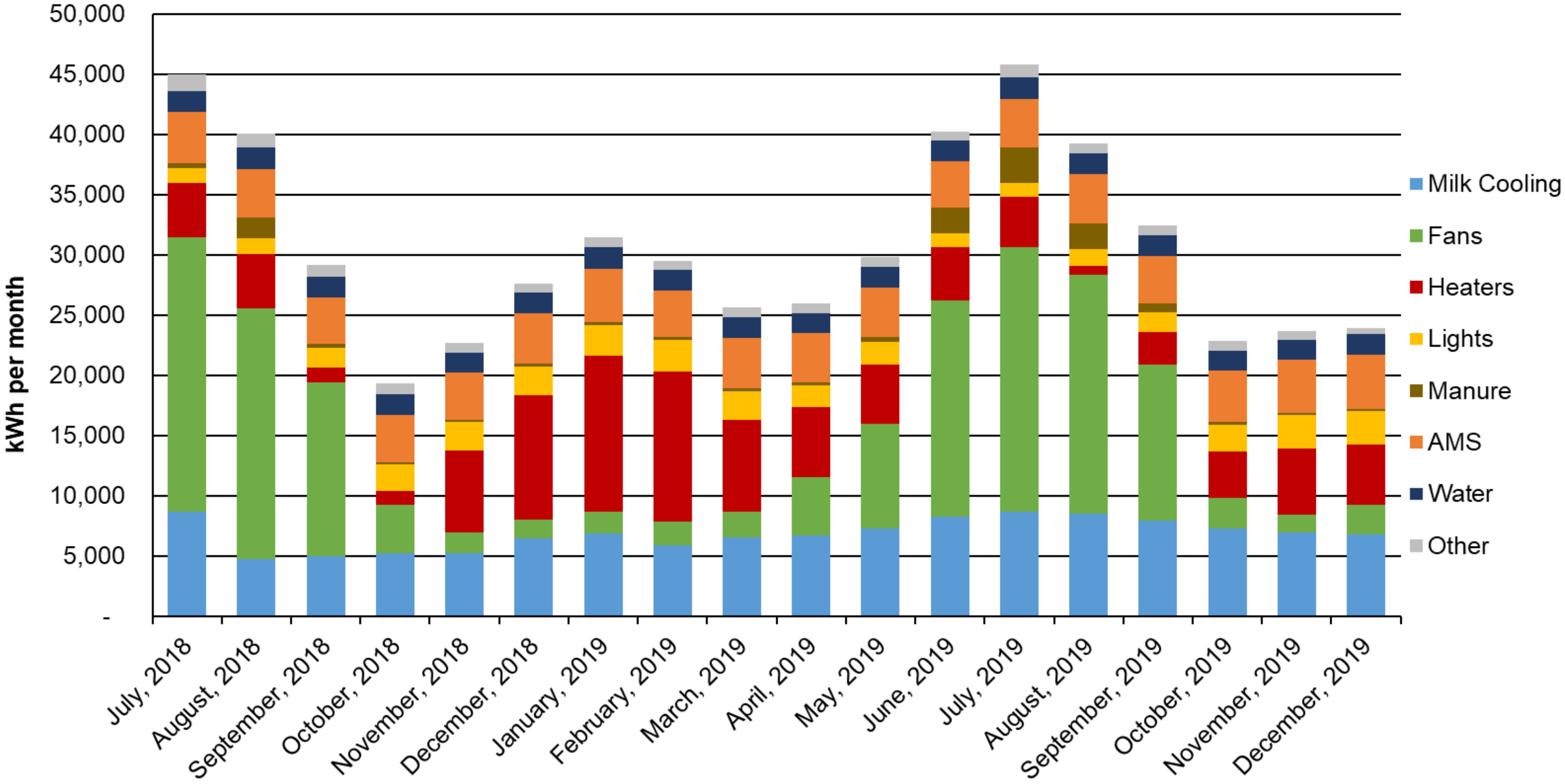


Figure 4. Seasonal average hourly electricity use for Farm B across the 18-month study period (**a.**= September, October, and November; **b.**= March, April, and May; **c.**= June, July, and August; **d.**= December, January, and February).

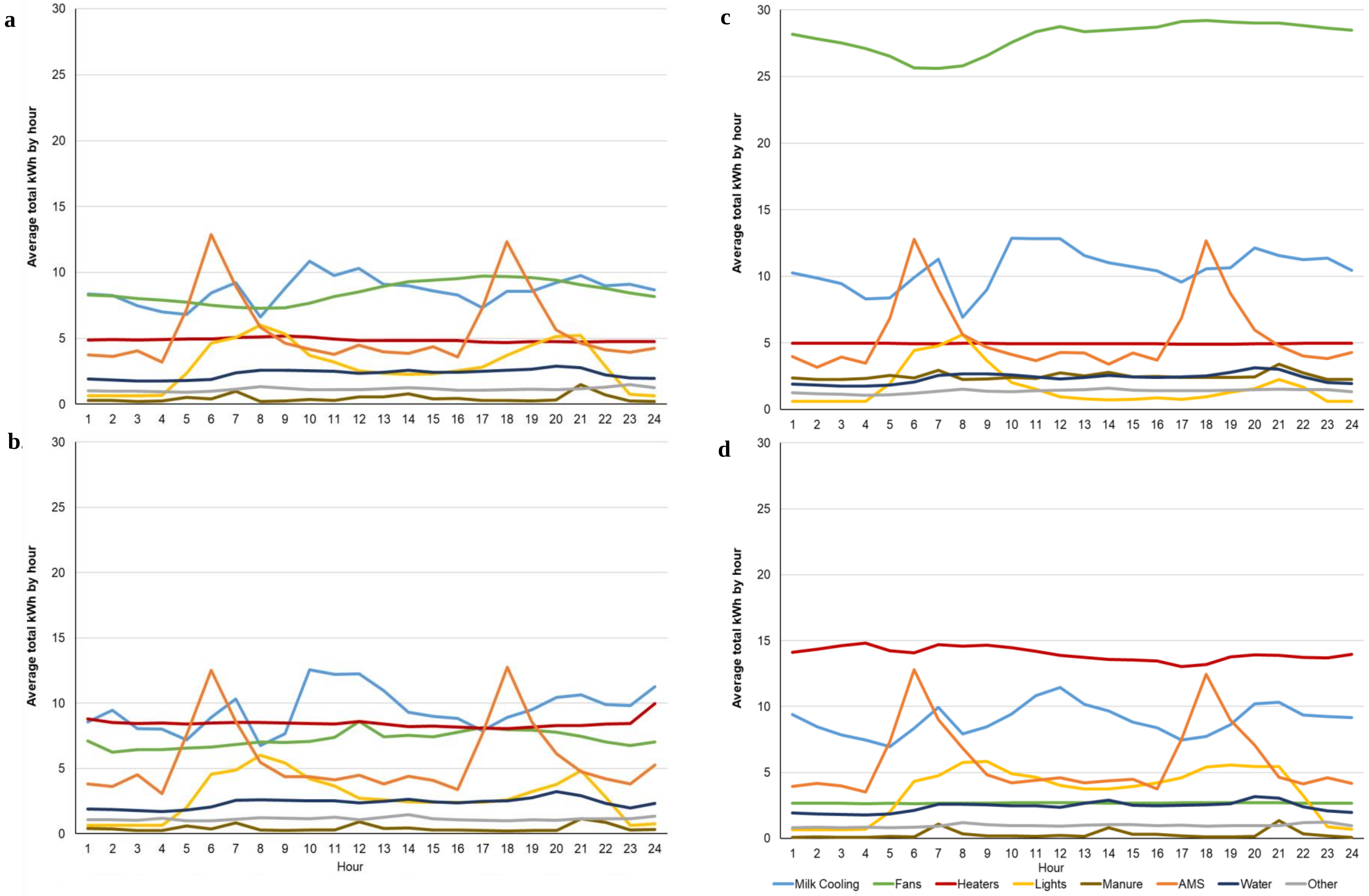


Figure 5. Monthly total electricity usage from July 2018 to December 2019 by category for Farm C (green= fans, dark blue= water, red= heaters, light blue= milk cooling, yellow= lights, purple= vacuum pumps, and grey= other).

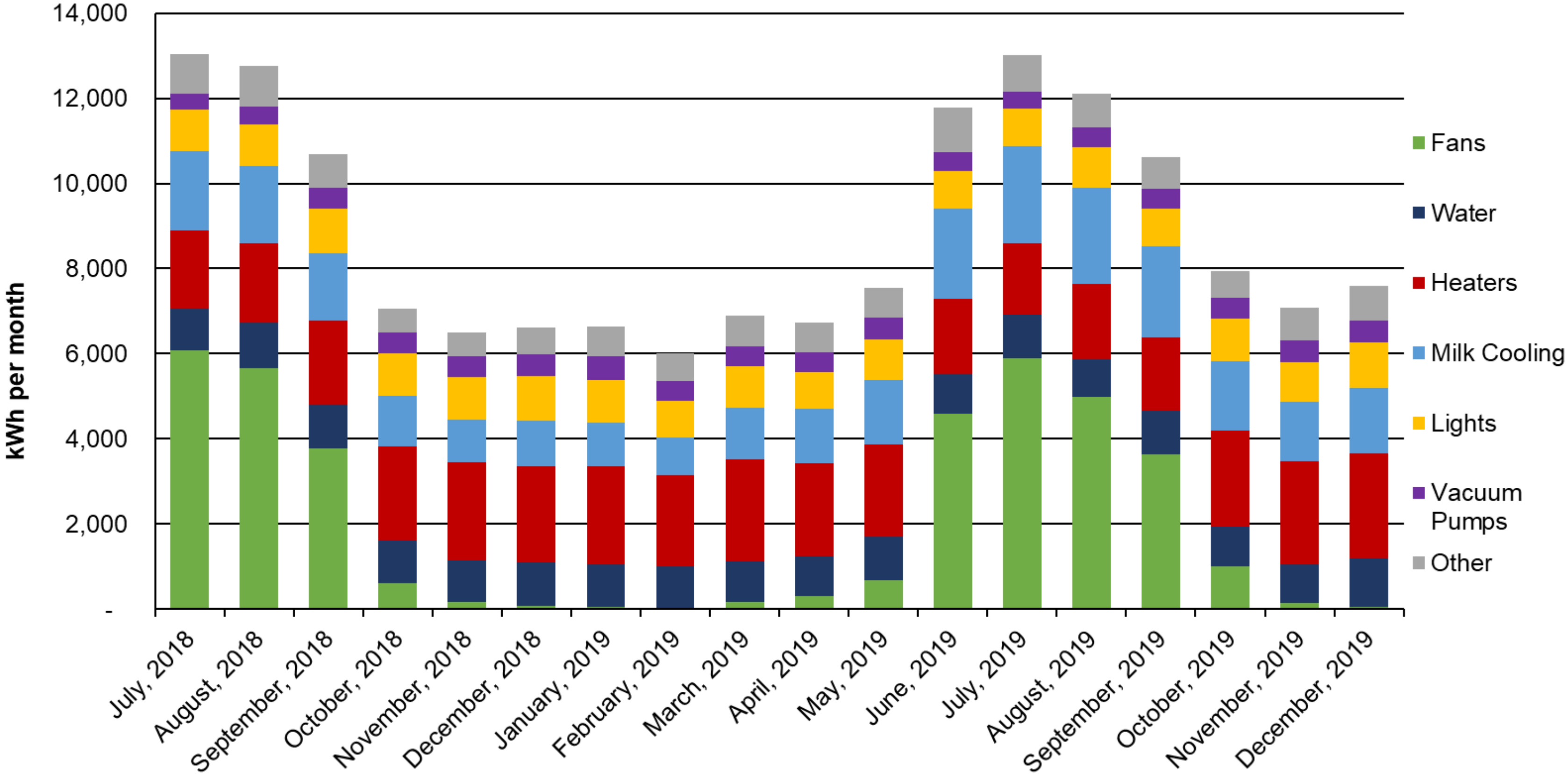


Figure 6. Seasonal average hourly electricity use for Farm C across the 18-month study period (**a.**= September, October, and November; **b.**= March, April, and May; **c.**= June, July, and August; **d.**= December, January, and February).

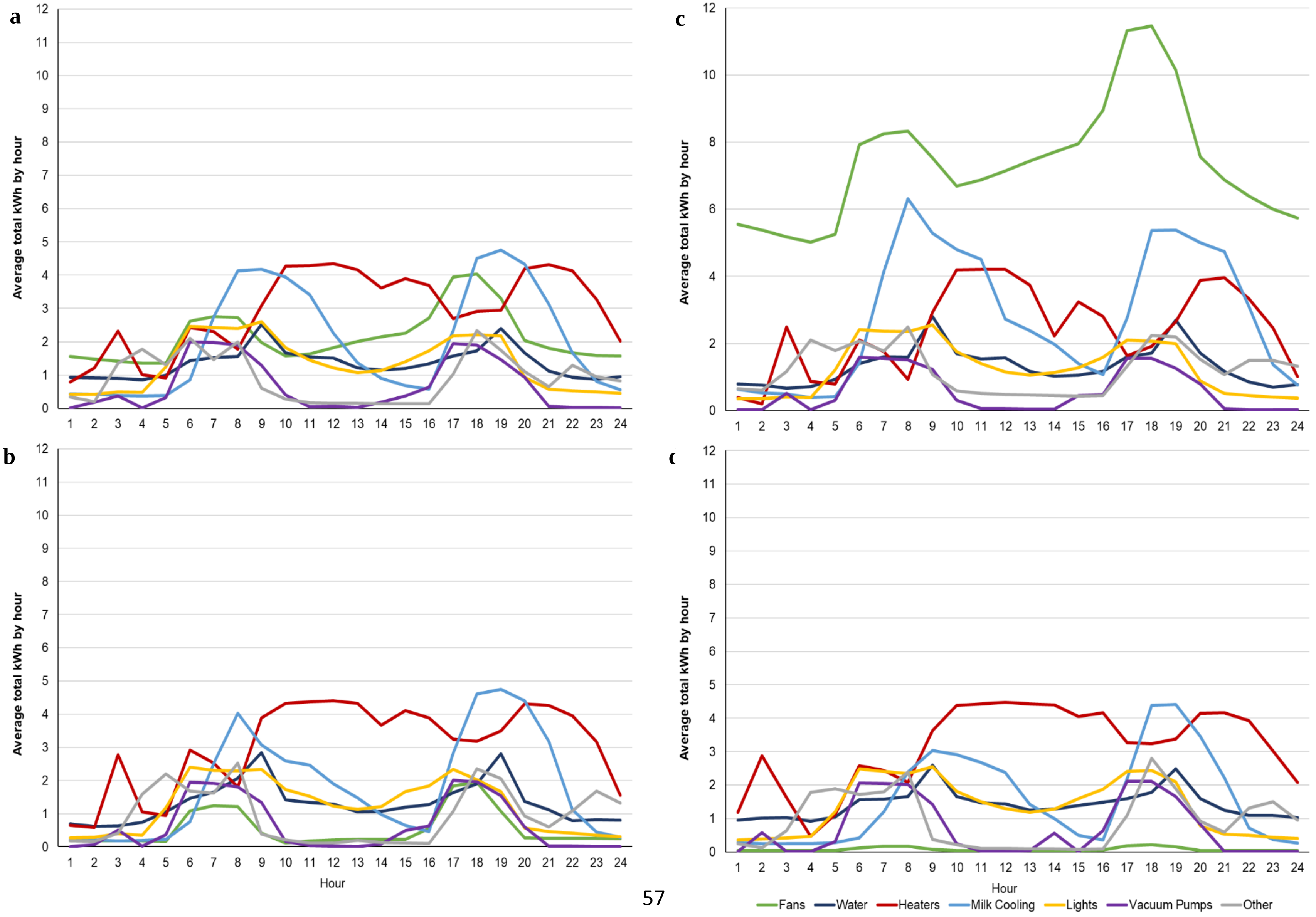


Figure 7. Monthly total electricity usage from July 2018 to December 2019 by category for Farm D (brown= manure, green= fans, yellow= lights, light blue= milk cooling, purple= vacuum pump, dark blue= water, red= heaters, and grey= other).

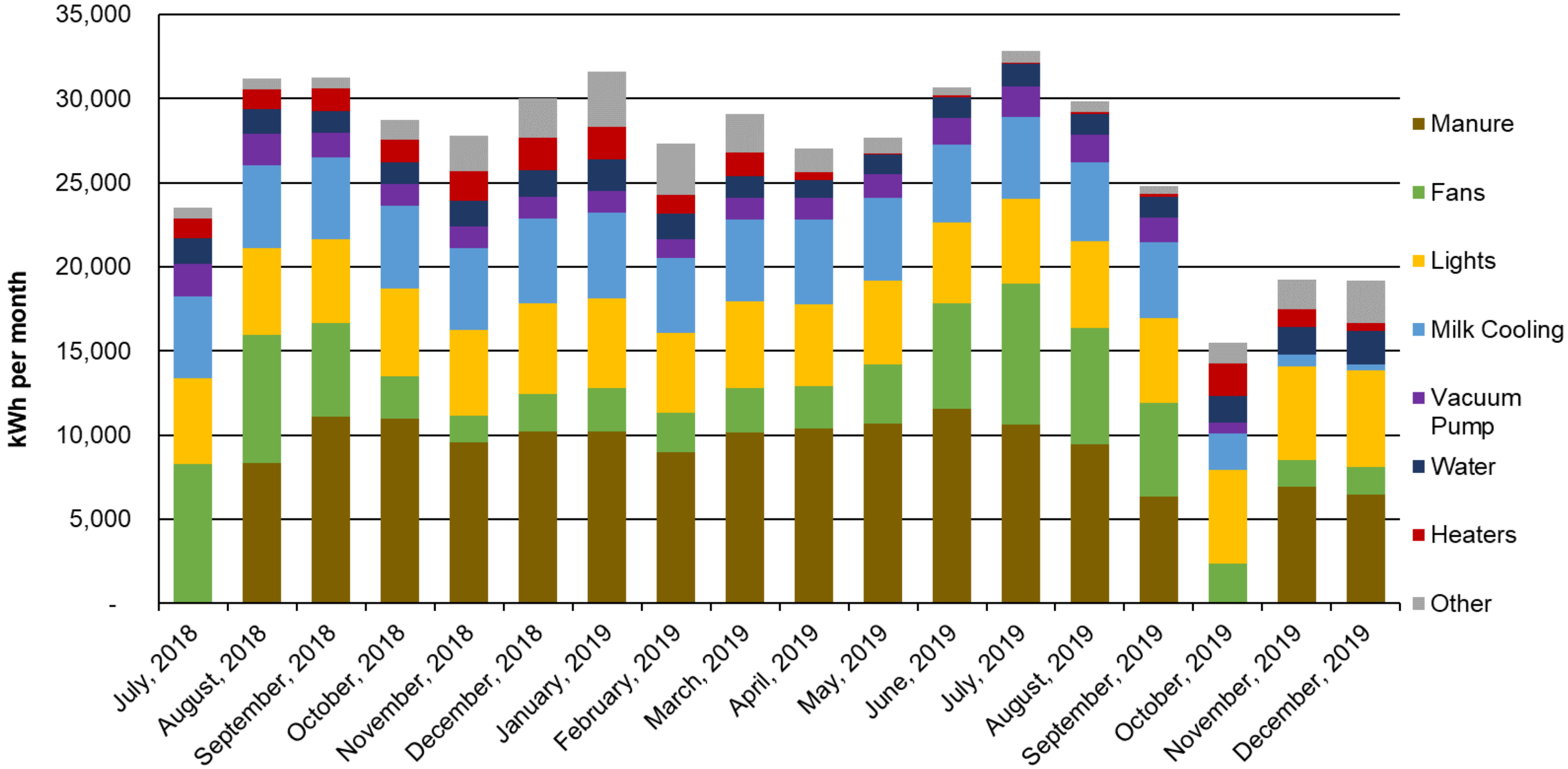


Figure 8. Seasonal average hourly electricity use for Farm D across the 18-month study period (**a.**= September, October, and November; **b.**= March, April, and May; **c.**= June, July, and August; **d.**= December, January, and February).

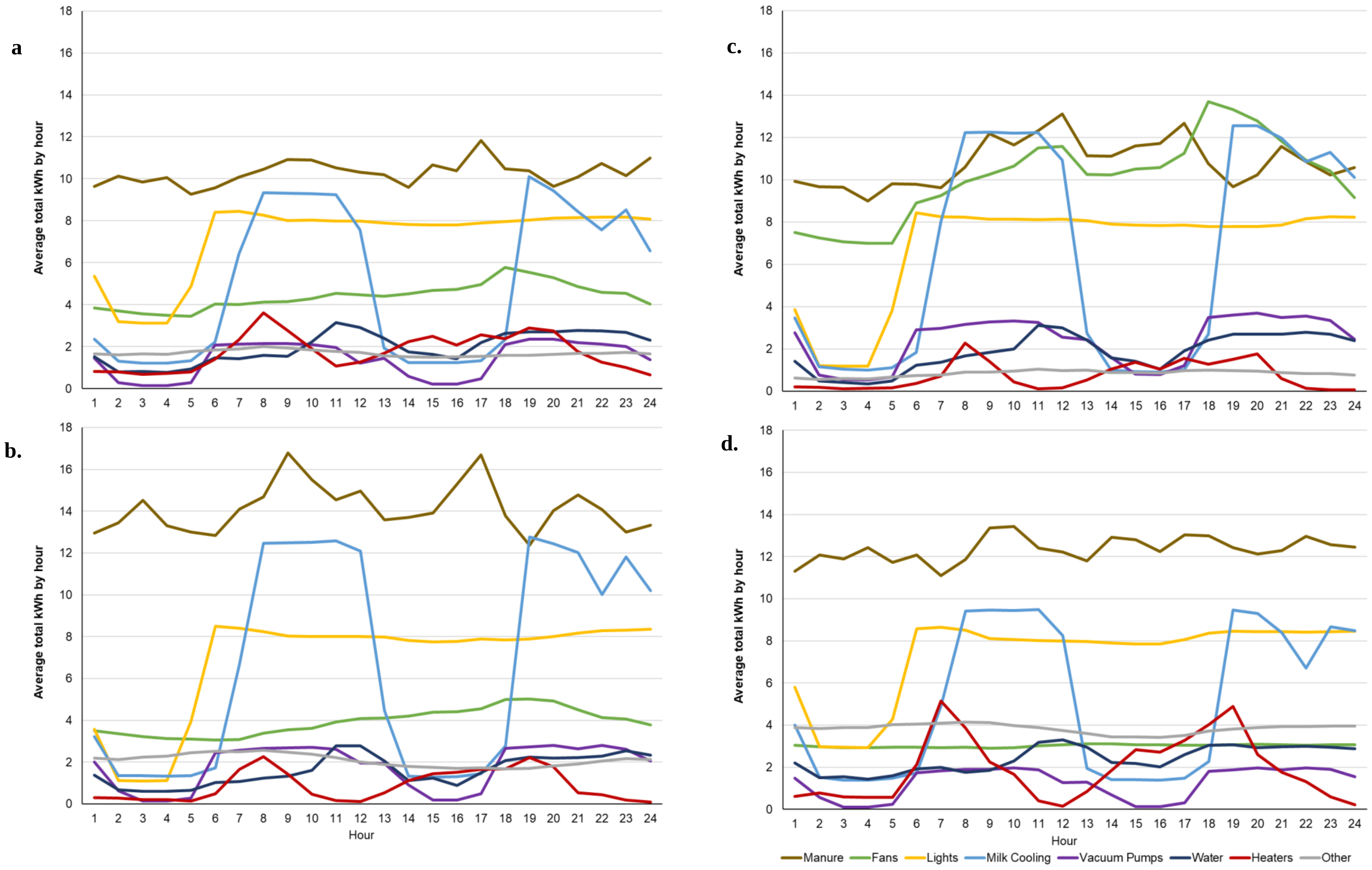


Figure 9. Monthly total electricity usage from July 2018 to December 2019 by category for Farm E (light blue= milk cooling, red= heaters, green= fans, purple= vacuum pumps, light orange= dryer, dark blue= water, and grey= other).

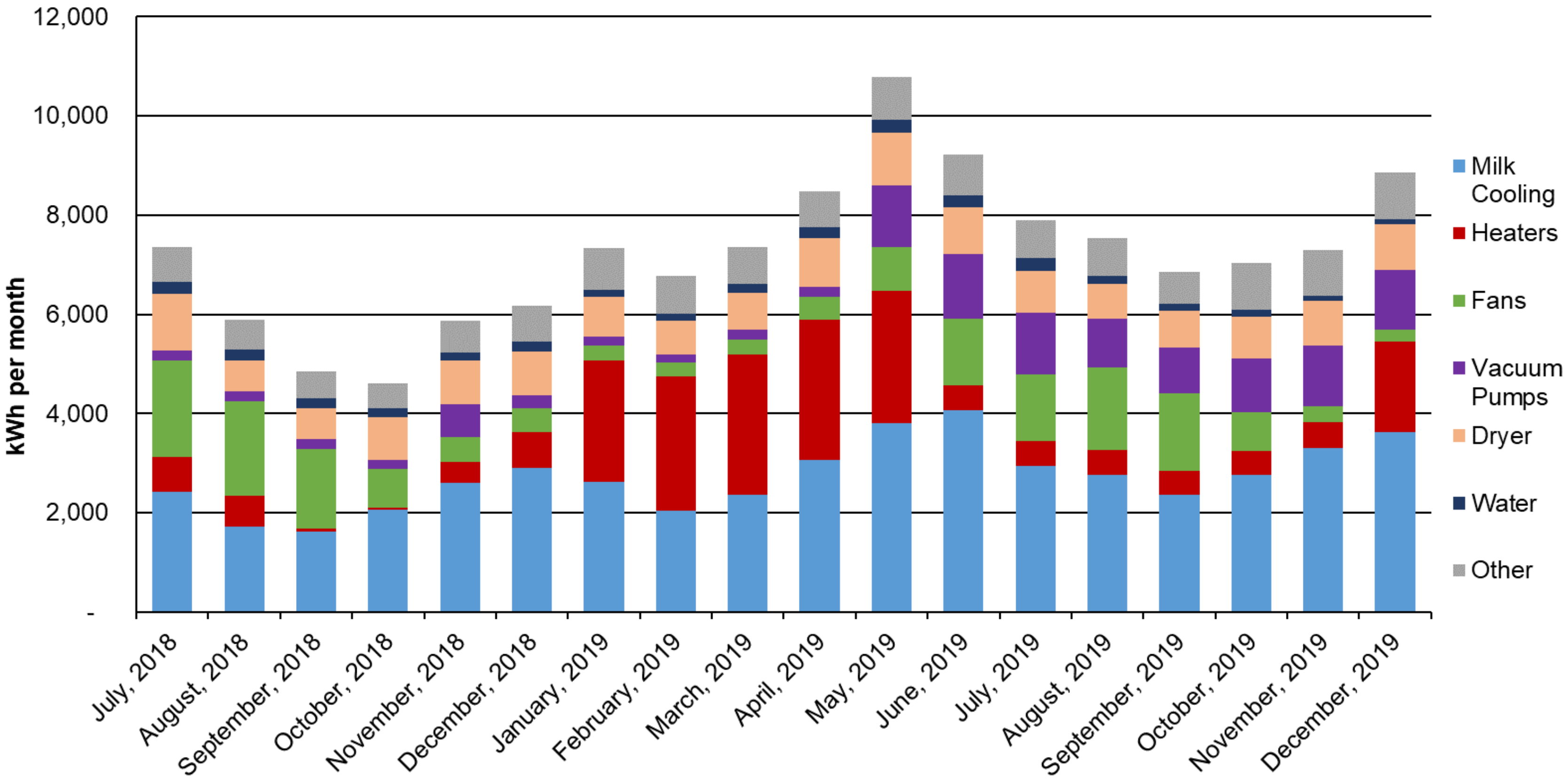


Figure 10. Seasonal average hourly electricity use for Farm E across the 18-month study period (**a.**= September, October, and November; **b.**= March, April, and May; **c.**= June, July, and August; **d.**= December, January, and February).

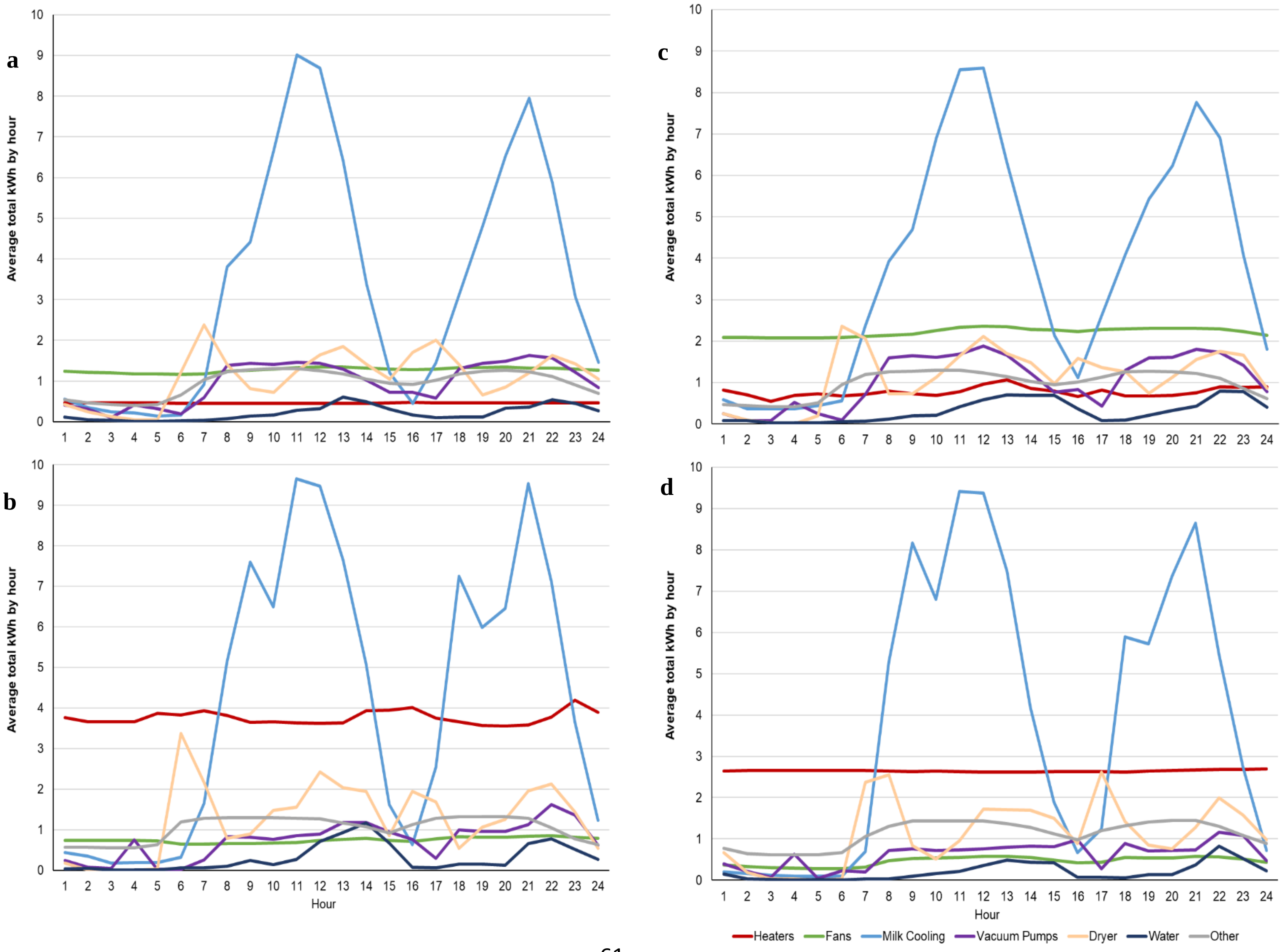
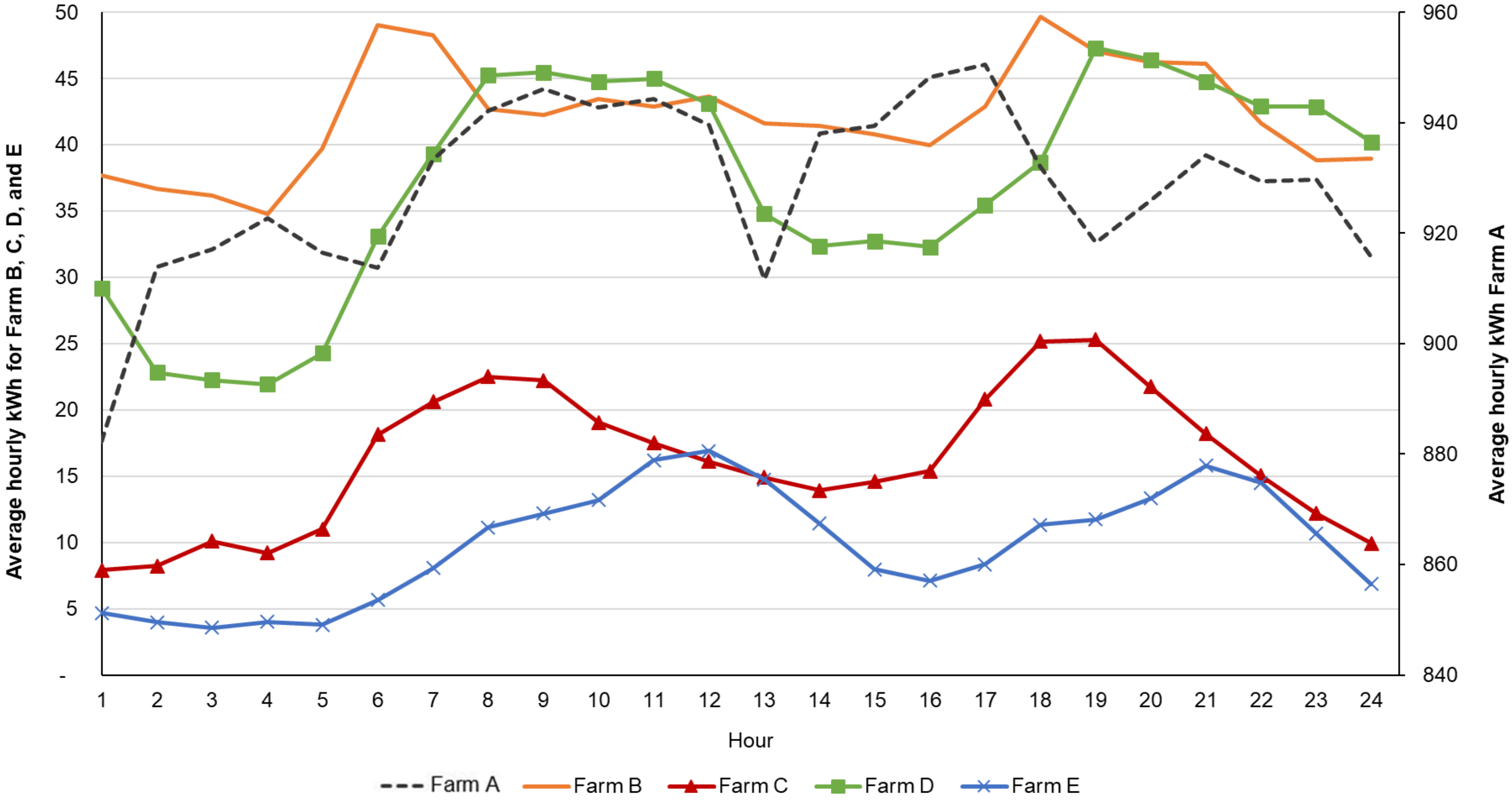


Figure 11. Average total electricity use by hour farms (orange= Farm B, red triangle= Farm C, green square= Farm D, blue X= Farm E, and on the secondary axis, dashed black= Farm A).



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Manuscript 2

Agrivoltaics to shade cows in a pasture-based dairy system

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Interpretive Summary

Agrivoltaics to shade cows in a pasture-based dairy system. By Sharpe et al. (2020). The objective of this study was to evaluate grazing cattle under shade from a solar photovoltaic system. Cows with access to solar shade were similar for behavior characteristics, fly counts, and milk production compared to cows with no access to shade. Cows with access to solar shade had lower internal body temperatures and respiration rates during the hottest parts of the day than cows with no access to shade. Incorporating agrivioltaics into pasture dairy systems may reduce intensity of heat stress in cows.

SUMMARY

The combined use of solar photovoltaics and agriculture may provide farmers with an alternative source of income and reduce heat stress in dairy cows. The objective of this study was to determine the effects on grazing cattle under shade from a solar photovoltaic system. The study was conducted at the University of Minnesota West Central Research and Outreach Center, Morris, MN grazing dairy. Twenty-four crossbred cows were randomly assigned to 2 treatment groups (shade or no-shade) from June to September 2019. The replicated (n = 4) treatment groups of 6 cows each were provided shade from a 30-kilowatt photovoltaic system. Two groups of cows had access to shade in paddocks and two groups of cows had no shade in paddocks and cows were located in the same pasture during the study period. Behavior observations and milk production were evaluated for cows during four periods of summer. Smaxtec boluses (smaXtec, Graz, Austria) and an eartag sensor (CowManager SensOor, Agis Automatisering BV, Harmelen, the Netherlands) monitored internal body temperature and activity and rumination on all cows, respectively. Data were analyzed with PROC MIXED of SAS. Independent variables were the fixed effects of breed, treatment group, coat color, period, and parity, and random effects were replicate group, date, and cow. No differences in fly prevalence, milk production, fat and protein production, body weight, body condition score, drinking bouts, hock lesions, or locomotion were observed between the treatment groups. Shade cows had more ear flicks (11.4 ear flicks/30 sec) than no-shade cows (8.6 ear flicks/30 sec) and had dirtier bellies and lower legs (2.2 and 3.2, respectively) than no-shade cows (1.9 and 2.9, respectively). During afternoon hours, shade cows had lower respiration rates (66.4 breaths/min) than no-shade cows (78.3 breaths/min). From 1200 to

1800 h and 1800 to 0000 h, shade cows had lower body temperature (39.0 and 39.2˚C, respectively) than no-shade cows (39.3 and 39.4˚C, respectively). Furthermore, during daylight hours and between milkings, the shade cows had lower body temperature (38.9˚C) than no-shade cows (39.1˚C). Agrivoltaics incorporated into pasture dairy systems may reduce the intensity of heats stress in dairy cows and increase well-being of cows and increase the efficiency of land use.

(**Key words:** dairy, heat stress, pasture-based, solar photovoltaic)

INTRODUCTION

Global warming has occurred on every continent, and higher than average warming has occurred over land than over oceans (Allen, 2018). Climate change is expected to cause higher than average maximum temperatures, higher than average minimum temperatures, and less than average cool days. An increase in the duration and intensity of heat waves and droughts are also likely to occur in most land regions (IPCC, 2007).

Thermal balance is the difference between heat production and loss from metabolism and heat transfer with the outside environment (National Research Council, 1981). Increased temperatures move dairy cows out of their zones of thermal comfort, and heat stress typically occurs above 25˚C for cows (West, 2003). Some producers may modify barns with heat abatement measures such as sprinkler systems, fans, and utilize evaporative cooling techniques. However, for pasture-based dairy systems, heat abatement for cows may pose a challenge. As temperatures increase, cow cooling for pasture-based systems necessitates further exploration.

Heat stress has been estimated to cost the dairy industry in the United States more than $900 million annually due to production losses (St-Pierre et al., 2003). The main contributors to heat stress are temperature, humidity, and temperature-humidity index (THI), and THI is used to estimate effects of heat stress on milk production, nutrition, behavior, reproduction, and overall health of cows (West, 2003, Garcia-Ispierto et al., 2006, Cook et al., 2007, Tucker et al., 2008). Bohmanova et al. (2007) found that THI greater than 72 induced heat stress in dairy cows and decreased milk production. Garcia-Ispierto et al. (2006) reported the risk of abortion in cattle was 2% higher for THI greater than 69. Allen et al. (2015) reported cows that experienced heat stress had greater standing time per day, and reductions in lying time were negatively associated with increased lameness (Leonard et al., 1996, Cook et al., 2007). Prior research has been conducted on heat abatement measures in freestall barns with sprinklers, evaporative cooling, and fan design (Brouk et al., 1999, Smith et al., 2007). However, pasture-based research efforts on heat abatement are limited and have investigated fabric and trees for shade and sprinklers (Palacio et al., 2015, Shütz et at., 2009, Shearer et al., 1991, Kendall et al., 2007, Tucker et al., 2008).

Agrivoltaics is the combined use of solar photovoltaic (PV) and agricultural systems that provide mutual benefits (Adeh et al. 2018). Dupraz et al. (2011) determined that agrivoltaic systems have the potential to increase land productivity and efficiency by 60 to 70%. A study by Maia et al. (2020) utilized an agrivoltaic system to investigate the behaviors of sheep that had access to shade from solar panels or a shade cloth that blocked 80% of solar irradiation. The authors found benefits of shade for sheep and reported that the solar system provided a resource for generating electrical energy, and thus reducing the carbon footprint of the farm. No research in the scientific literature has investigated the use of shade from a ground-mounted solar PV system and the effects on dairy cows. The hypothesis of the current study was that shade from solar panels for dairy cows would reduce the intensity of heat stress indicated by reduced respiration rates, internal body temperatures, and drinking events. Therefore, the objective of this study was to investigate the effects of shade from solar PV on the production, health, and behavior of pastured dairy cows.

MATERIALS AND METHODS

Experimental design and collection of data

The study was conducted at the University of Minnesota West Central Research and Outreach Center (WCROC) dairy farm in Morris, MN. Animal care and management were approved by the University of Minnesota Institutional Animal Care and Use Committee (#1709-35099A). The WCROC dairy maintains 300 cows in a low-input, grazing-based system. The herd is composed of crossbred cows, and details on herd management and breed groups are reported in Pereira and Heins (2019). During the summer of 2018, a 30 kilowatt ground mounted solar system was installed in a pasture at the WCROC (Figure 1). To optimize solar energy collection, the panels were mounted at a 35˚ angle facing due south. The solar panels were mounted 2.4 to 3 m from the ground so cows could not reach the panels. The solar panels were Heliene panels (Heliene Photovoltaic Modules, Marie, Ontario) using Solar Edge (Solar Edge, Fremont, CA) inverters and optimizers and were installed by Zenergy (Zenergy, Sebeka, MN).

The study was conducted from June 2019 through September 2019. Twenty-four crossbred cows were enrolled and were randomly balanced across treatments by parity, breed group, days in milk, and coat color. All cows calved during the spring (March to May) of 2019. The cows were separated into four balanced and replicated groups, and each group had six cows. Replicated groups of six cows had an equal number of breed groups and parity of cows and an equal number of cows determined to have either a minimum of 50% of a light colored coat, 50% of a dark colored coat, or a mixture of both light and dark on their coats. Coat color was determined from visual analysis of photographs taken of the left and right side of each cow. The cow was determined to have a light coat color if over 50% of the coat was white or light colored. Dark colored coats were over 50% dark brown, black, or red. Mixed coats had an even amount of both dark and light coloring. The cows were from the certified organic herd at the WCROC and, during the study months, were required to be housed on pasture and were required to have at least 30% DMI from pasture (USDA-NOP, 2019). All cows had access to 3,500 kg of dry matter per hectare from pasture and forages were smooth bromegrass (Bromus inermis), orchardgrass (Dactylis glomerata), meadow fescue (Festuca pratensis), quackgrass (Elymus repens), red clover (Trifolium pretense) and kura clover (Trifolium ambiguum M. Bieb.). All cows were located in the same pasture; however, each group was provided a different paddock of 5,030 square meters in area. Cows were assigned to one of two treatments: shade or no-shade. Shade cows had access to the shade from the solar PV system on pasture. The no-shade cows did not have access to any shade while on pasture. All treatment groups were provided a water tank and ad libitum access to a trace mineral mix. No grain or TMR was offered to cows. The cows were milked from 0600 to 0800 h and from 1600 to 1800 h.

Cows were provided access to pasture with the shade and no-shade treatments during 4 periods of the summer. Period 1 was from June 3, 2019 to June 10, 2019, Period 2 was from July 8, 2019 to July 12, 2019, Period 3 was from August 12, 2019 to August 17, 2019, and Period 4 was from September 16, 2019 to September 20, 2019. When cows were not on the study periods, they were combined with the remaining organic cows at the WCROC which were housed on alternative pastures. The cows were with the same treatment groups during each period of the study.

Weather data

Weather data were collected for each period during the study from the weather station at the WCROC located at 45° 35́’44″ N and 95° 52’53″ W (Table 1). Data recorded included temperature, relative humidity (%), total precipitation, and solar irradiation (W/m^2). Temperature humidity index (THI) for each period was determined using the following equation from Kendall et al. (2006): $THI = (1.8 \times T + 32) - ((0.55\text{-}0.0055 \times RH) \times (1.8 \times T - 26))$

where T = air temperature (°C) and RH = relative humidity (%).

Behavioral and biological measurements

Fly counts and fly avoidance behaviors

Four observers were trained to collect biological and behavioral measurements prior to the first study period. All cows were observed for fly incidence and fly avoidance behaviors. Fly counts on cows were recorded before the observer watched cows for fly avoidance behaviors and again after behavior observations. Observers distinguished horn flies from face flies and stable flies. Horn flies were counted individually or in groups of 10 on one side of each cow. Face flies were counted on the faces of cows viewed head on. Stable flies were counted on the visible faces of the front and rear legs separately viewed from the side of the cow. Fly counts were made from a distance of 2 to 4 m (Kienitz et al., 2018; Perttu et al., 2020).

Fly avoidance behaviors included head tosses, skin twitches, tail swishes, front leg stomps, and back leg kicks. A head toss was recorded if the animal's head was thrust back toward its body, far enough that the nose crossed an imaginary plane across the front of the cow's chest (Mullens et al., 2006). A skin twitch occurred if an isolated twitch took place in a localized area or as a continuous shiver over the whole flank for several seconds (Dougherty et al., 1995). A tail swish occurred if the tail was moved from its resting position to one side of the cow's body; a separate swish occurred if the tail crossed to the opposite side of the body (Dougherty et al., 1994). A front leg stomp was defined as a raising of either front leg (while standing) followed by a forceful thrust back to the ground. A hind leg kick occurred if either hind leg was thrust upward toward the cow's belly (Dougherty et al., 1995). Leg stomps and leg kicks were combined for analysis. Five sessions of behavior observations were conducted twice per day on every cow; once in the morning and once in the afternoon. An observer watched each cow continuously for 30 seconds and recorded counts of ear flicks, tail swishes, foot stomps, head tosses, and skin twitches. After 12 minutes, another session of observations would begin with the first observed cow.

Respiration rates, hygiene, hock lesions, and locomotion scoring

Respiration rates of all cows were recorded once each morning and afternoon. The same four observers counted the number of breaths for each cow for 30 seconds (flank movements/30s; Nienaber et al., 2003). During afternoon observations, hock lesion, hygiene, and locomotion scoring were conducted on each cow. The tailhead, upper leg (thigh), abdomen, udder, and lower hind leg, were all scored for hygiene, with 1 = clean to 5 = dirty (Reneau et al., 2005). Hock lesions were classified as 1 = no lesion, 2 = hair loss (mild lesion), and 3 = swollen hock with or without hair loss (severe lesion; Lobeck et al., 2011). Locomotion or lameness was evaluated using a 5-point locomotion scoring method (Flower and Weary, 2006), with 1 = normal locomotion, 2 = imperfect locomotion, 3 = lame, 4 = moderately lame, and 5 = severely lame.

Body Weight, body condition scores, and milk production

Prior to grazing for each period, cows were weighed using a digital scale (Tru-Test XR5000, Auckland, New Zealand) as cows exited the milking parlor in the morning. To evaluate health, body condition was scored by a trained evaluator at the same time as body weights were recorded. Body condition scores were: 1 = excessively thin to 5 = excessively fat, in increments of 0.25 (Wildman et al., 1982). On the last day of each study period, body weights and body condition scores were recorded in the same manner. Daily milk production from individual cows was measured with a Boumatic Smart Dairy system (Madison, WI) and monthly DHI measures of milk, fat, and protein.

Sensors for monitoring body temperature, activity, and rumination

All cows had a CowManager ear-tag sensor (CowManager SensOors, Agis, Harmelen, the Netherlands), and the sensor was mounted into a blank radio frequency identification tag first and then placed on the right ear of each cow. Data from the sensor were transmitted wirelessly through a plug and play router or solar powered router to a base computer in the milking parlor and made available through a web-based application (Pereira et al., 2018). The sensor detected and identified ear and head movements and through algorithms classified data as ruminating, eating, not active, active, and high active behaviors. Agis Automatisering BV provided raw hourly data for ruminating, eating, not active, and active behaviors for all cows.

HOBO Pendant G loggers (Onset Computer Corp., Bourne, MA) were used to record lying time and standing time of all cows during the study periods. The loggers were programmed with a logging interval of 60 seconds. The loggers were wrapped in a piece of SyrFlex (SyrVet Inc., Waukee, IA) cohesive bandage to reduce friction and attached to the right side of the right rear leg of each cow using SyrFlex bandage. The logger was oriented so that the X- axis of the logger was parallel to the ground pointing towards the cow's head. The loggers track the X, Y, and Z-axis on the cow which converted into standing and lying behaviors. The loggers were attached to the cows during the morning milking of the first day of each study period and removed during the afternoon milking on the last day of each study period. After removal, the data were downloaded with Onset Hoboware software and exported to Microsoft Excel (Microsoft Corp., Redmond, WA). Daily lying times, frequency of lying bouts, and lying-bout duration were computed for each cow using a macro in SAS (SAS Institute, 2016) developed by N. Chapinal (Universtiy of British Columbia, Vancouver, BC, Canada).

SmaXtec boluses (smaXtec Classic Bolus, Graz, Austria) were administered to each cow one week before the first study period. Boluses were placed in the reticulum of the cow and recorded internal body temperature and a proprietary activity measurement of the cows. Data from the boluses were downloaded by a repeater that transmitted data to the server located in the dairy barn office and stored data in an online database. Data were downloaded onto the server twice per day during the morning and afternoon milkings as each cow passed the repeater located in the milking parlor. Additionally, as the bolus resided in the reticulum, researchers were able to determine number of drinking bouts for each cow indicated by sharp drops in body temperature. Daily drinking events were identified when the body temperature of the cow was below 37.7˚C (Bewley et al., 2008; Cantor et al., 2018). Data were downloaded weekly from the online server into Microsoft Excel (Microsoft Excel, 2016).

Body temperature and activity from the smaXtec bolus were analyzed in one hour blocks throughout the day. Body temperature and activity of shade and no-shade cows were during the hour blocks: 1) 0000 to 0600 h, 2) 0600 to 1200 h, 3) 1200 to 1800 h and 4) 1800 to 0000 h. Furthermore, body temperatures were compared during the daylight hours between milking times (0800 to 1600 h), nighttime hours between milking times (1800 to 0600 h) and during milking time (0600 to 0800 and 1600 to 1800 h). Lastly, body temperatures and activity were investigated during every hour of the day.

Shade use

For the cows in the shade treatment group, shade use observations were conducted by locating cows every 10 minutes for two 180 minute periods to determine if cows were utilizing the solar shade. Shade use observations were recorded once in the morning and once in the afternoon. Shade use methods were adapted from Tucker et al. (2008), and cows that had at least one hoof within the shadow from the solar panels or if at least one hoof was directly below the solar panels was recorded as shade utilization.

Statistical analysis

Square root transformations of fly counts were used to satisfy analytical assumptions of equal variance and normal distribution of errors. The transformed fly count data were analyzed with PROC GLIMMIX in SAS (SAS Institute, 2016). Independent variables were the fixed effects of shade treatment, period, time of day, coat color, and the interaction of time of day by treatment with a Poisson distribution. The random effect was cow nested within replicated group by treatment.

Respiration rate per 30 seconds was multiplied by two to obtain the respiration rate for 1 minute. Data were analyzed with PROC MIXED of SAS (SAS Institute, 2016) with the fixed effects of treatment, coat color, period, time of day, and the interaction of time of day by treatment. Random effects were cow nested within replicated group by treatment and date nested within period.

Hock lesion, hygiene, and locomotion scores, body weight, BCS, and milk, fat, and protein production were analyzed with PROC MIXED of SAS (SAS Institute, 2016). The independent variables were the fixed effects of breed, parity, coat color, period, and treatment, and random effects were cow nested within replicated group by treatment and date with repeated measures. The autoregressive covariance [AR(1)] structure was used because it resulted in the lowest Akaike's information criterion (Littell et al., 1998).

Daily drinking bouts were analyzed with PROC MIXED of SAS (SAS Institute, 2016) and fixed effects were coat color, treatment, period, and the interaction of treatment by period, and random effects were cow nested within replicated group by treatment and date. For analysis of lying behavior (daily lying time, number of lying bouts per day, and lying-bout duration), independent variables were fixed effects hour, period, treatment and the interaction of treatment and hour and cow nested within replicated group by treatment as a random replicate effect. The compound symmetry covariance structure was used because it resulted in the lowest Akaike information criterion for repeated measures (Littell et al., 1998.)

For analysis of SmaXtec body temperature and activity and CowManager activity, eating, and rumination, fixed effects were coat color, treatment, and period with replicated group by treatment nested within cow and period nested within date were random effects. For the hour and hour block analysis of temperature and activity, fixed effects were coat color, treatment, period, hour, and the interaction of treatment by hour or hour block. The random effects were replicated group by treatment nested within cow and period nested within date with PROC MIXED of SAS (SAS Institute, 2016). Furthermore, separate regression analyses evaluated the effect of body temperature on air temperature, solar radiation, and temperature humidity index (THI) independently. All results from all analyses were reported as least squares means, with significance declared at $P < 0.05$.

RESULTS AND DISCUSSION

Weather data

Weather data for all periods of the study are summarized in Table 1. Mean temperature ranged from 21.0˚C in Periods 1 and 3 to 21.6˚C during Period 4. Period 1 had the lowest recorded individual low temperature (10˚C). Period 3 had the highest mean humidity (86%), and the humidity ranged from 96.9% in Period 1 to 102.8% relative humidity in Period 4 which was due to air supersaturation. The highest mean THI of 68.1 was during Period 2, though the highest THI was during Period 3 (77.4). Total precipitation ranged from a low of 11.7 mm in Period 2 to a high of 45 mm in Period 3. Solar irradiation was highest during Period 1 (983 W/m^2) and lowest during Period 4 (747 W/m^2). Armstrong (1994) determined THI below 71 was within the comfort zone of cows, and a THI between 72 to 79 caused mild stress, a THI of 80 to 89 caused moderate stress, and THI above 90 caused severe heat stress. Cows in the current study experienced mild heat stress as all high recorded THIs were between 73.3 and 77.4. Bohmanova et al. (2007) found that a THI greater than or equal to 72 induced heat stress in dairy cows and decreased milk production.

Fly avoidance behaviors, fly counts, and respiration rates

Table 2 has least squares means and standard errors of means for fly avoidance behaviors, stable, face, and horn fly counts, and respiration rates for shade and no-shade cows for morning and afternoon observations. The shade and no-shade cows were similar ($P > 0.10$) for tail swish, foot stomp, head toss, and skin twitch behaviors during the morning and afternoon observations. During the afternoon observations, the number of ear flicks was higher ($P < 0.05$) for the shade cows (11.4 ear flicks/ 30 sec) than for the no-shade cows (8.6 ear flicks/ 30 sec). Furthermore, shade and no-shade cows had similar ($P > 0.10$) number of stable flies, face flies, and horn flies during the morning and afternoon hours. Kendall et al. (2007) found no differences in hoof stomps and tail flicks for shade versus no-shade cows. Similar to the current study, Palacio et al. (2015) found no differences in fly intensity between shade and no-shade cows. As the shade and no-shade cows were located in the same pasture, it was hypothesized that no differences were found in fly counts or the majority of fly avoidance behaviors because the flies were easily able to transfer between each group of cows.

Respiration rates for shade (50.9 breaths/min) and no-shade (52.5 breaths/min) cows were similar ($P > 0.10$) during the morning hours. (Table 2). However, during the afternoon, the shade cows had lower ($P < 0.05$) respiration rates (66.4 breaths/min) than no-shade cows (78.3 breaths/min). Similar to the current study, Kendall et al. (2007) found that cows with no access to a shade structure had higher respiration rates than cows with access to shade. Furthermore, Muller et al. (1994) found that shade reduced respiration rates in cows, but only for temperatures greater than 25˚C. Hahn et al. (1997) found that respiration rates under 60 breaths/min in dairy cows were indicative of minimal to no thermal stress which indicated that both the shade and no-shade cows in the current study experienced heat stress conditions during the afternoon.

Hygiene and body measurements

The shade and no-shade cows had similar (*P* > 0.10) tailhead, upper leg, and udder hygiene scores (Table 3). However, the shade cows had (*P* < 0.05) dirtier bellies and lower legs (2.2 and 3.2, respectfully) than did no-shade cows (1.9 and 2.9, respectfully). Shade cows utilized the shade for resting times during the study period, and as the cows defecated and urinated directly under the panels, bellies and lower legs became dirty as cows laid down to rest. The cooler and wetter ground under the solar panels combined with the reduced spread of cows furthered the dirtier conditions. Hock lesion scores, locomotion scores, milk, fat, and protein production were not different (*P* > 0.10) between shade and no-shade cows (Table 3). Quite possibly, no difference was observed for milk production between treatment groups because cows were only under the shade for 28 days during the summer and for 7 days during each study period. Long term effects of milk production may have been observed had cows been under the shade for the entire summer. Kendall et al. (2007) reported no difference in daily milk production between shade (14.0 kg/d) and no-shade (13.2 kg/d) cows. Furthermore, Muller et al. (1994) found no difference in milk production or fat and protein in milk between shade and no-shade cows.

Mean body weight and BCS of shade cows (441.8 kg ± 15.7; 3.2 ± 0.2) and no-shade cows (465.8 kg ± 16.7; 2.9 ± 0.2) were not different (*P* > 0.10), respectively. Cook et al. (2007) found cows that experienced heat stress tended to stand for longer periods of time that resulted in higher lameness scores of 2 or 3. Contrary to the findings in this study, Shwartz et al. (2009) found BCS and body weight decreased in Holstein cows during periods of heat stress. Long term effects on body weight and BCS may have been observed if cows had been in the treatment groups during the entire summer for the current study.

Drinking bouts, activity, rumination, and lying time

Table 4 has least squares means and standard errors of means for drinking bouts per day from smaXtec Bolus, and activity, eating, and ruminating behaviors from CowManager ear tag, and lying and standing time from HOBO Loggers for shade and no-shade cows. The number of daily drinking bouts were similar ($P > 0.10$) between shade and no-shade cows. Arias and Mader (2014) found that feedlot cattle finished during summer months consumed 87.3% more water than those finished during winter months. Hourly activity, eating, rumination, and no activity across a 24-h period from the CowManager eartag were similar ($P > 0.10$) for shade and no-shade cows. However, the shade cows had less ($P < 0.05$) high activity (6.7 min/hr) than did no-shade cows (7.8 min/h). This could be due to bunching behavior that cattle exhibit which is thought to reduce radiant heat absorption as cattle provide shade for each other (Lefcourt and Schmidtmann, 1989).

Across the study period, the shade cows and no-shade cows had similar ($P > 0.10$) lying (51.1 min/h and 51.4 min/h, respectively) and standing time (8.9 min/h and 8.6 min/h, respectively). Palacio et al. (2015) also found no difference in lying times across a study period between shade and no-shade cows. Figure 2 has mean lying time for shade and no-shade cows across a 24-h period. The shade cows had higher ($P < 0.05$) lying times during 1000 and 2400 h than did no-shade cows. Conversely, no-shade cows had higher ($P < 0.05$) lying times during 1300, 1500, and 1600 h than did shade cows. Allen et al. (2015) found that hour of the day affected lying and standing times of cows exposed to mild and moderate heat stress and reported that cows that had higher body temperatures and were more heat stressed, tended to have lower lying times. Cows in the current study tended to lay less during the hottest parts of the day, and standing time peaked between 1200 to 1800 h. The higher lying time observed in the current study of the no-shade treatment cows during 1500 and 1600 h could be because the no-shade cows were fatigued after standing during the previous hours. Allen et al. (2015) also found that cows were more willing to lie down during 1600 h, which was observed in the current study.

Figure 3 has average hourly rumination and Figure 4 has average hourly eating from the CowManager ear tag during a 24 h period. During 0200, 0300, 0400, 0900, 1500, and 2200 h, shade cows had less ($P < 0.05$) rumination than did no-shade cows. However, the shade cows had greater ($P < 0.05$) rumination than no-shade cows during 1300 and 1700 h. Rumination of shade cows was higher than no-shade cows during 1300 h which was one of the hottest parts of the day. During 0100, 0200, 0300, 1200, 1500, 1600, 1900, and 2200 h, shade cows had greater ($P < 0.05$) eating time than did no-shade cows (Figure 4). Conversely, during 1300, 1700, and 2300 h, no-shade cows had more ($P < 0.05$) eating time than did shade cows. Hourly activity data from the CowManager ear tag (Figure 5) found no-shade cows were more active ($P < 0.05$) than shade cows during 0100, 0200, 0300, 1300, 1400, 1500, 1700, and 2400 h. Again, this could be due to no-shade cows that exhibited bunching behavior or more frequent standing and lying bouts.

Shade use

Least squares means for shade use for the shade cows are shown in Table 5, and during period 1, cows had more time not in the shade (111.2 min) ($P < 0.05$) than in the shade (68.8 min). Similarly, during period 3, cows had more ($P < 0.05$) minutes not in the shade (107.0 min) than in the shade (71.0 min). During period 4 cows had more ($P < 0.05$) minutes not in the shade (109.8 min) than in the shade (70.2 min). Cows had similar times for shade and no shade use during period 2. Period 2 had the highest mean temperature and humidity, THI and high solar radiation which was likely why cows had more time under shade during period 2 than the other periods. Similarly, Tucker et al. (2007; 2008) found that cows had more time under shade on days with higher solar radiation levels, higher ambient air temperatures, and higher THI. In the current study, cows had 38% (Period 1) to 44% (Period 2) of the time in the shade during the observation periods. The percent of time cows used shade in this study was slightly higher than that found in Shütz et al. (2009) which found cows used shade 30% of the time during the observation period. Tucker et al. (2007) found shade use by cows ranged from 0% to 54% of total daily time. Quite possibly, shade cows had more time under the shade in the current study compared to prior studies due to higher mean temperatures, THI, and solar radiation observed in this study.

Body temperature and activity from smaXtec

Least squares means for body temperature and activity of cows from Smaxtec bolus during specific periods during the day for shade and no-shade cows are in Table 6. From 0000 to 1200 h, body temperatures of shade and no-shade cows were similar ($P >$

0.10). During 1200 to 1800 h and from 1800 to 0000 h, shade cows had body temperatures of 39.0 and 39.2˚C, respectively. Body temperatures were significantly lower ($P < 0.05$) than no-shade cows during these times (39.3 and 39.4˚C, respectively). Furthermore, during the day and in between milking times, shade cows had lower ($P < 0.05$) body temperatures (38.9˚C) than no-shade cows (39.1˚C). Shade and no-shade cows had similar ($P > 0.10$) body temperatures at night between milkings and during milking. The results agree with Shütz et al. (2009) and Ammer et al. (2016) who found cow body temperatures to be greater with increased THI and ambient air temperatures. Tucker et al. (2007) found that shaded cows had lower minimum body temperatures than non-shaded cows, and that body temperatures of cows increased as daily solar radiation increased. However, in disagreement with the current study, Tucker et al. (2007) found no differences in body temperatures between shade cows and no-shade cows during the daytime between milkings quite possibly due to differing climates compared to the current study. Hourly body temperature results show that no-shade cows had higher ($P < 0.05$) body temperatures than shade cows during 1300 through 2300 h (Figure 6). On average, the difference in body temperature from 1300 to 2300h h between shade and no-shade cows was 0.5 °C. This follows daily trends of increased solar radiation and air temperatures between hours 1200 to 1600 in Minnesota (PVWatts, 2019). The reduced body temperature of the shade cows indicated a reduction in heat stress during the hottest times of the day. The results indicate that solar shade may be an effective method to reduce heat stress in pastured cows. Quite possibly, the difference in body temperature between the shade and no-shade cows would have increased further if the cows had been on the study for the entirety of the summer. More research is needed to determine body temperature thresholds in dairy cattle to determine if 0.5 °C may decrease reproductive performance, reduce milk production, decrease fat and protein content in milk, and increase SCC.

The activity recorded from the smaXtec Boluses was similar ($P > 0.10$) between both treatments between 1800 and 0600 h. However, from 0600 to 1200 h and from 1200 to 1800 h, shade cows had less ($P < 0.05$) activity (15.4 and 16.7, respectfully) than no-shade cows (18.2 and 19.5, respectfully). Hourly activity results from the smaXtec bolus (Figure 7) indicated shade cows had less ($P < 0.05$) activity during 0700, 0800, 0900, 1200, 1300, 1400, 1500, 1600, 1700, 1800, and 1900 h than no-shade cows. This may further indicate that shade cows preferred to remain under the shade during these hours rather than graze grass in the paddock.

Regression coefficients of cow body temperature and air temperature in the current study found that for every 1˚C increase in air temperature, body temperature of cows increased by 0.028˚C. For no-shade cows, this would have resulted in a 0.041˚C increase in body temperature ($P < 0.001$). For shade cows, a 1˚C increase in air temperature increased body temperature by 0.015˚C ($P < 0.001$), which is lower than the 0.041 for the no-shade cows. Furthermore, for every 1-unit increase in THI, no-shade cows increased 0.27˚C ($P < 0.001$) body temperature, and shade cows increased 0.011˚C ($P < 0.001$) body temperature. Lastly, for every 1 W/m^2 increase in solar radiation, no-shade cows increased body temperature by 0.00016˚C ($P < 0.001$). Interestingly, shade cows decreased 0.00001˚C ($P < 0.001$) in body temperature for every 1 W/m^2 increase in solar radiation, which indicates the shade cows were seeking protection from the sun. The findings of no-shade cows in the current study are similar to those of Tucker et at. (2008)

who found a positive relationship between solar radiation and mean cow body temperature.

CONCLUSIONS

Future research should be conducted on the impacts of climate change on heat stress in pastured dairy cows and heat abatement techniques especially within pasture-based systems and within different locations. The results of this study reported that cows sacrificed grazing time to stand in the protection of the shade. Therefore, more research should investigate whether shade use during the hottest hours of the day is more or less beneficial to the cow than grazing. Complete pasture coverage by PV systems may allow for simultaneous grazing and cooling of cows. Agrivoltaics may provide an acceptable method of heat abatement to pastured dairy cows, although more long term studies should be conducted to gain a clearer picture of the effects of solar shade on dairy cows. Future research on agrivoltaics in a pasture dairy system should explore the economic impacts of the agrivoltaic system as well as long term effects on milk production, reproductive performance, body weight, body condition, and fat plus protein.

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Table 1. Mean, high, and low temperature, humidity, THI, total precipitation, and solar irradiation during the summer of 2019 from the West Central Research and Outreach Center, Morris, Minnesota, weather station.

	Period 1[a]			Period 2			Period 3			Period 4		
Weather variable	Mean	Low	High	Mean	Low	High	Mean	Low	High	Mean	Low	High
Temperature (˚C)	21.0	10.0	33.9	21.5	13.9	28.9	20.1	12.2	27.2	21.6	11.7	30.6
Humidity (%)	64.0	22.5	96.9	83.6	50.5	102.2	86.0	48.2	102.4	82.4	35.8	102.8
Temperature humidity index (THI)	62.5	47.0	76.2	68.1	57.3	76.0	68.0	56.9	77.4	61.3	51.7	73.3
Total precipitation (mm)	33.8			11.7			45.0			34.8		
Solar irradiation (W/m^2)	288	0.0	983	267	0.0	960	245	0.0	884	164	0.0	747

[a] Period 1= June 3, 2019 to June 10, 2019, Period 2= July 8, 2019 to July 12, 2019, Period 3= August 12, 2019 to August 17, 2019, Period 4= September 16, 2019 to September 20, 2019

Table 2. Least squares means and standard errors of means for fly avoidance behaviors, number of stable, face, and horn flies, and respiration rates for shade and no shade cows during the morning and afternoon.

	Morning				Afternoon			
	Shade		No Shade		Shade		No Shade	
Measurement	LSM	SE	LSM	SE	LSM	SE	LSM	SE
Behaviors								
Tail swish (count/30 sec)	8.4	1.9	11.1	2.6	7.8	1.8	11.6	2.7
Foot stomp (count/30 sec)	3.6	0.5	3.9	0.6	4.6	0.7	5.2	0.8
Head toss (count/30 sec)	1.6	0.2	1.5	0.2	1.8	0.3	1.5	0.2
Skin twitch (count/30 sec)	15.2	1.7	9.7	1.1	14.3	1.6	9.2	1.0
Ear flick (count/30 sec)	13.2	1.1	11.5	1.0	11.4^{a}	1.0	8.6^{b}	0.7
Fly counts								
Stable flies (flies/leg)	11.4	0.04	10.9	0.03	12.2	0.04	12.9	0.04
Face fly (flies/face)	2.6	0.01	1.1	0.01	3.1	0.01	1.0	0.01
Horn fly(flies/side)	28.8	0.2	21.9	0.1	24.7	0.2	17.9	0.1
Total flies	62.9	0.2	52.9	0.2	61.7	0.2	53.1	0.2
Respiration rates (breaths/min)	50.9	3.5	52.5	3.4	66.4^{a}	3.4	78.3^{b}	3.3

^{a,b}Means within a row by time of day without common superscripts are different at $P < 0.05$.

Table 3. Least squares means and standard errors of means for hygiene, hock lesion, and locomotion scores, production, and fat and protein content of milk for shade and no shade cows.

	Shade		No Shade	
Measurement	LSM	SE	LSM	SE
Hygiene score				
Tail head	3.0	0.2	3.2	0.2
Upper leg	2.4	0.1	2.2	0.1
Belly	2.2^{a}	0.1	1.9^{b}	0.1
Udder	2.2	0.1	2.2	0.1
Lower leg	3.2^{a}	0.1	2.9^{b}	0.1
Hock score	1.0	0.04	1.03	0.04
Locomotion score	1.1	0.1	1.03	0.1
Milk production (kg)	13.9	1.5	15.5	1.5
Fat (%)	4.1	0.2	3.9	0.2
Protein (%)	3.1	0.1	3.1	0.1

[a,b]Means within a row without common superscripts are different at $P < 0.05$.

Table 4. Least squares means and standard errors of means for drinking bouts per day from smaXtec Bolus, and activity, eating, and ruminating behaviors from CowManager SensoOr, and lying and standing time from HOBO Loggers for shade and no shade cows.

	Shade		No Shade	
Measurement	LSM	SE	LSM	SE
Daily drinking bouts	4.4	0.4	3.7	0.4
High activity (min/hr)	6.7[a]	0.3	7.8[b]	0.3
Activity (min/hr)	5.6	0.8	7.5	0.8
Eating (min/hr)	21.3	0.8	19.7	0.9
Ruminating (min/hr)	17.3	0.7	17.6	0.7
No activity (min/hr)	9.4	0.5	7.5	0.5
Lying time (min/hr)	51.1	0.4	51.4	0.4
Standing time (min/hr)	8.9	0.4	8.6	0.4

[a,b]Means within a row without common superscripts are different at $P < 0.05$.

Table 5. Least squares means and standard errors of means of shade use for shade cows only per day.

	Use of shade		No use of shade	
Period	LSM	SE	LSM	SE
	---min---		---min---	
1	68.8[a]	6.8	111.2[b]	6.8
2	79.5	6.8	89.5	6.8
3	71.0[a]	6.8	107[b]	6.8
4	70.2[a]	6.8	109.8[b]	6.8

[a]Means within a row without common superscripts are different at $P < 0.05$.

Table 6. Least squares means and standard errors of means for body temperature and activity of cows from Smaxtec Bolus during specific periods during the day for shade and no shade cows.

	Shade		No Shade	
Time of day	LSM	SE	LSM	SE
Body temperature (˚C)				
0000 to 600 h	39.0	0.1	39.0	0.1
600 to 1200 h	38.7	0.1	38.7	0.1
1200 to 1800 h	39.0[a]	0.1	39.3[b]	0.1
1800 to 0000 h	39.2[a]	0.1	39.4[b]	0.1
Daylight between milkings[1]	38.9[a]	0.1	39.1[b]	0.1
Nighttime between milkings	39.1	0.1	39.2	0.1
During milkings	39.0	0.1	39.1	0.1
Activity				
0000 to 600 h	9.7	0.6	9.9	0.6
600 to 1200 h	15.4[a]	0.6	18.2[b]	0.6
1200 to 1800 h	16.7[a]	0.6	19.5[b]	0.6
1800 to 0000 h	16.2	0.6	17.1	0.6

[a,b] Means within a row by hourblock without common superscripts are different at $P < 0.05$.

[1] Daylight between milkings= 8:00-16:00, nighttime between milkings= 18:00-6:00, and during milkings= 6:00-8:00 and 16:00-18:00.

Figure 1. The 30 kilowatt solar photovoltaic ground-mounted system for solar shading at the University of Minnesota West Central Research and Outreach Center in Morris, Minnesota, USA.

Figure 2. Least squares means and standard errors of means for lying time by hour of day for shade cows (black) and no shade cows (yellow). *= Means within an hour of day for treatment groups are different at *P*<0.05.

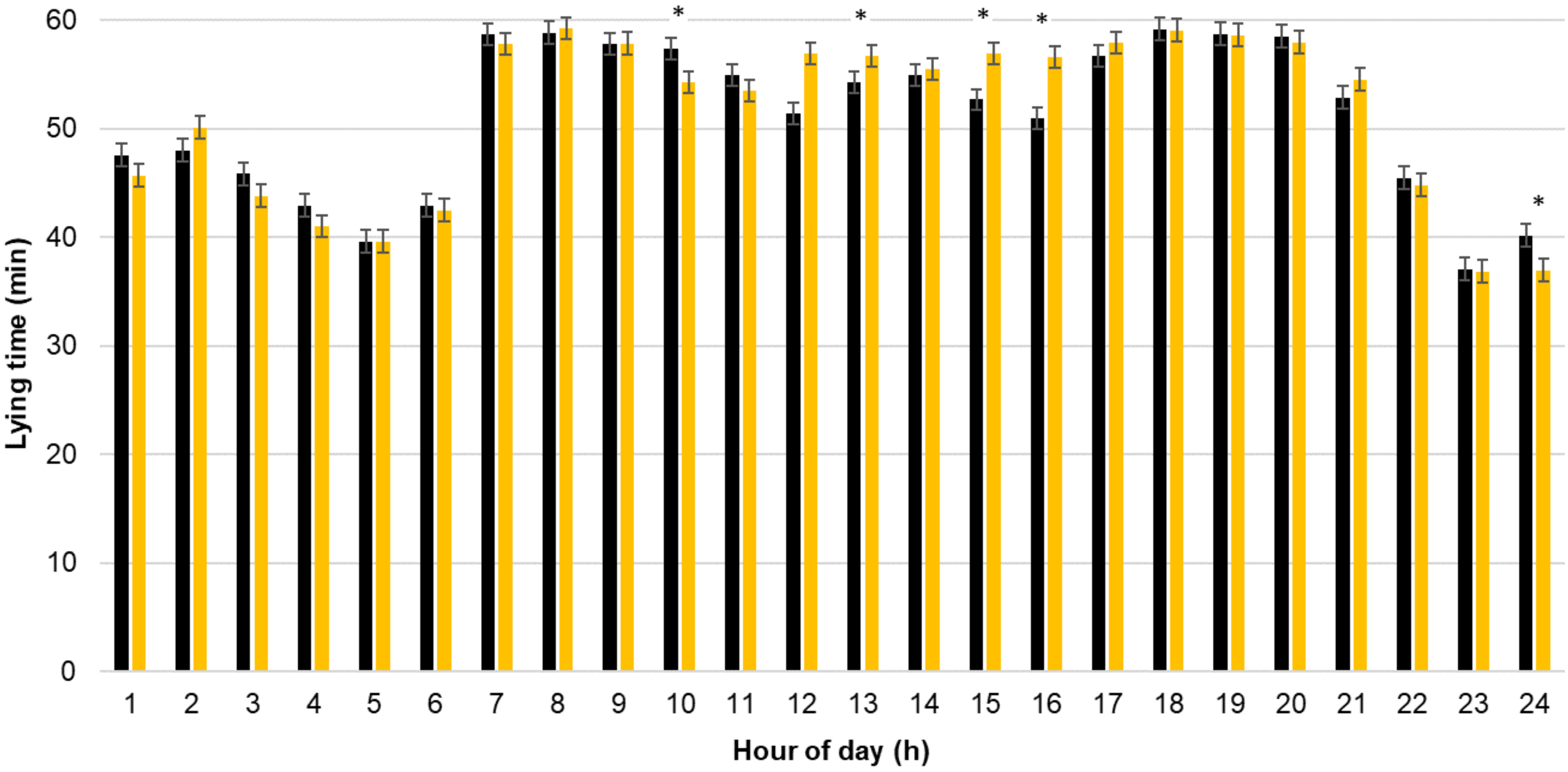


Figure 3. Least squares means and standard errors of means for rumination minutes per hour from CowManager sensor for shade (black) and no shade cows (yellow). *= Means within an hour of day for treatment groups are different at $P<0.05$.

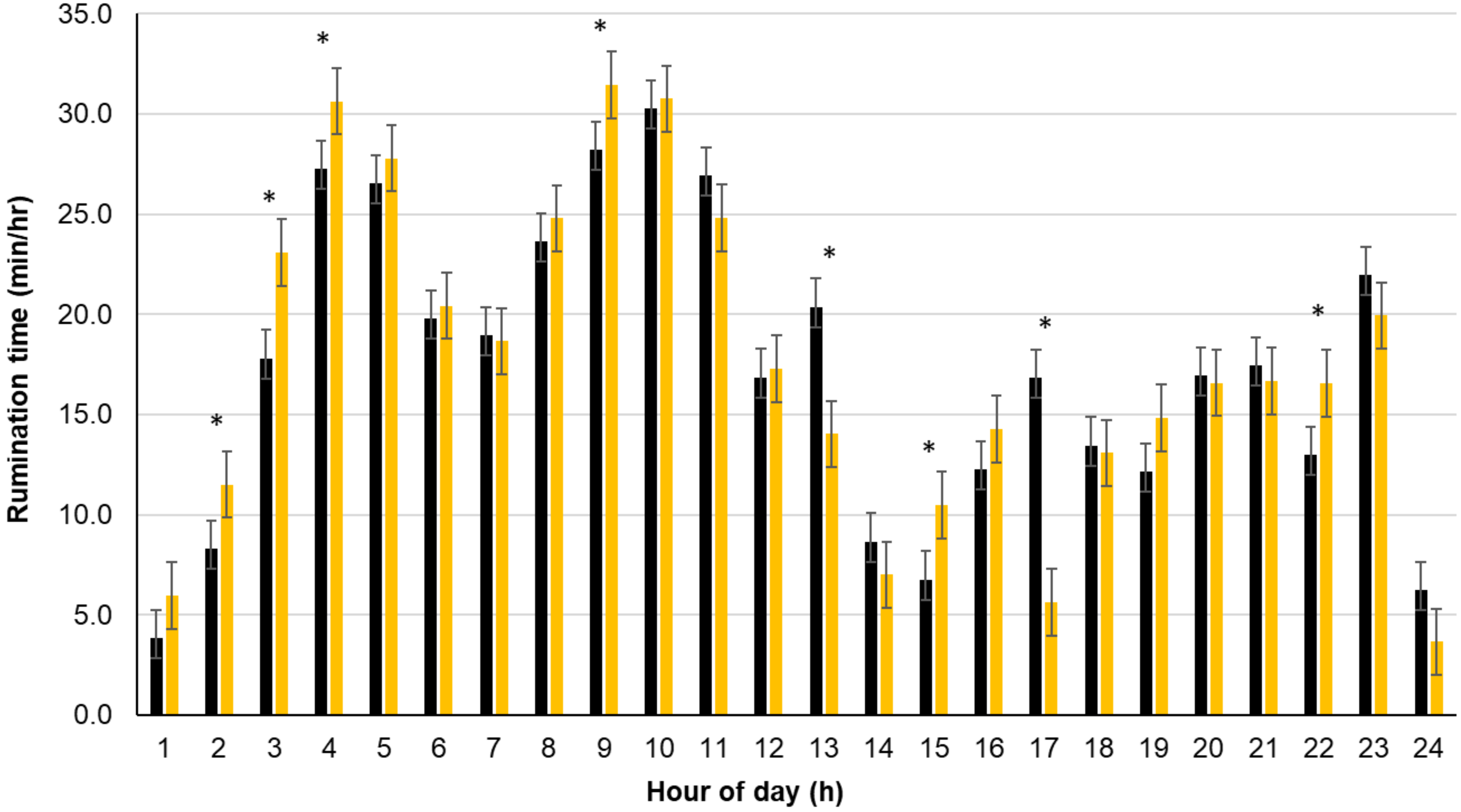


Figure 4. Least squares means and standard errors of means for eating minutes from CowManager sensor per hour for shade (black) and no shade cows (yellow). *= Means within an hour of day for treatment groups are different at $P<0.05$.

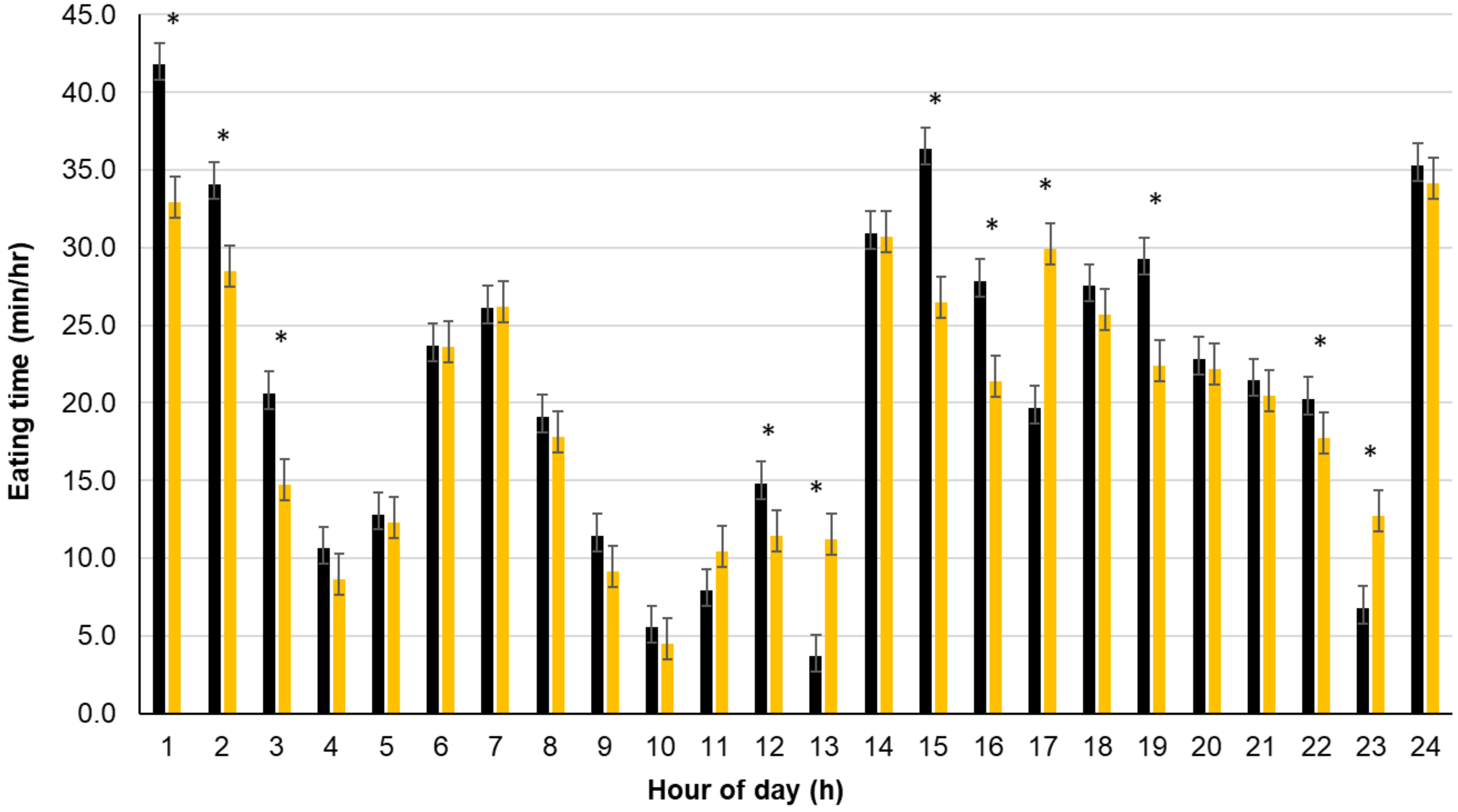


Figure 5. Least squares means and standard errors of means for active minutes from CowManager sensor per hour for shade (black) and no shade cows (yellow). *= Means within an hour of day for treatment groups are different at $P<0.05$.

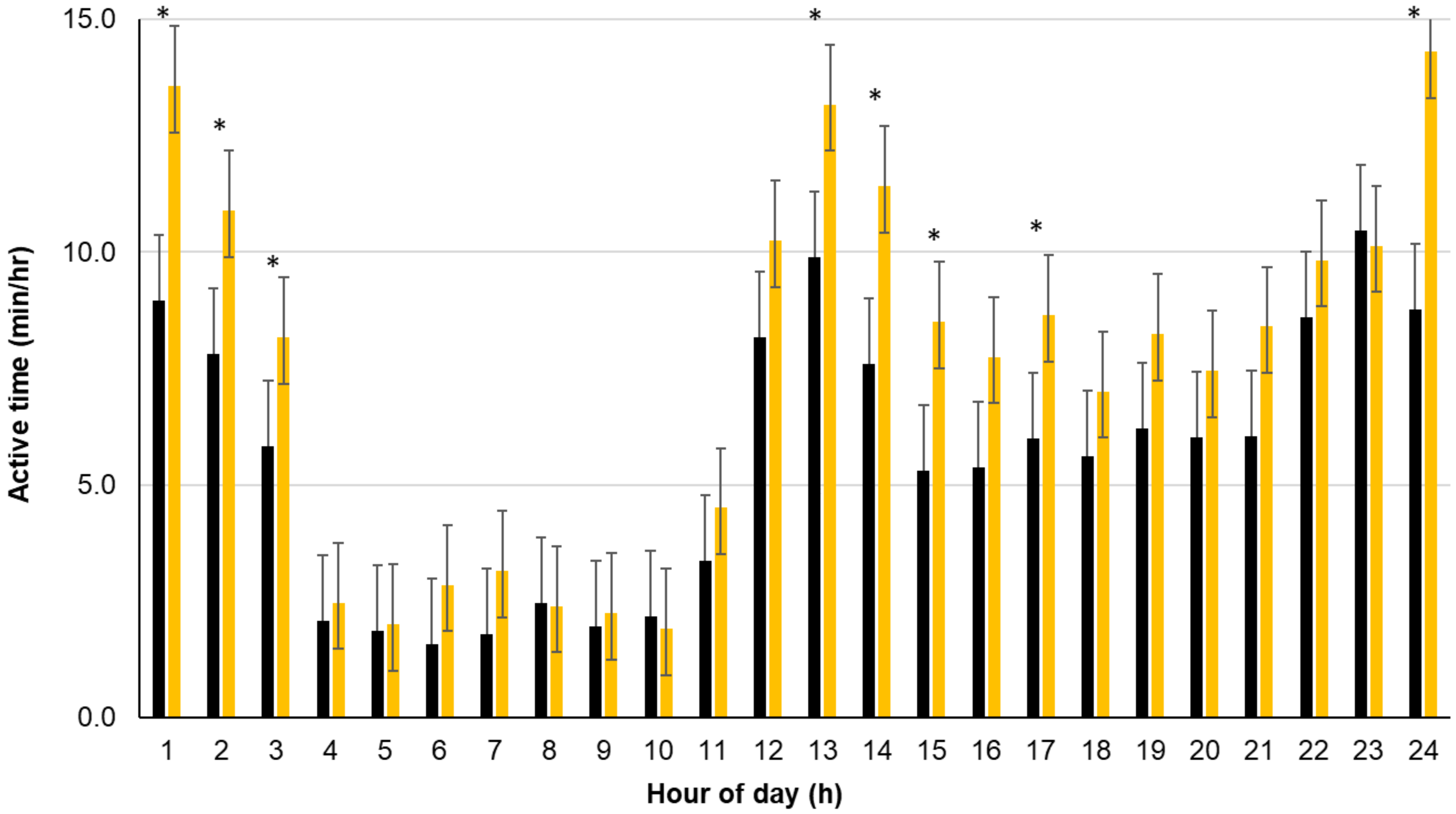


Figure 6. Least squares means and standard errors of means for body temperature from Smaxtec boluses by hour of day for shade cows (▲, black) and no shade cows (■, yellow). *= Means within an hour of day for treatment groups are different at *P*<0.05.

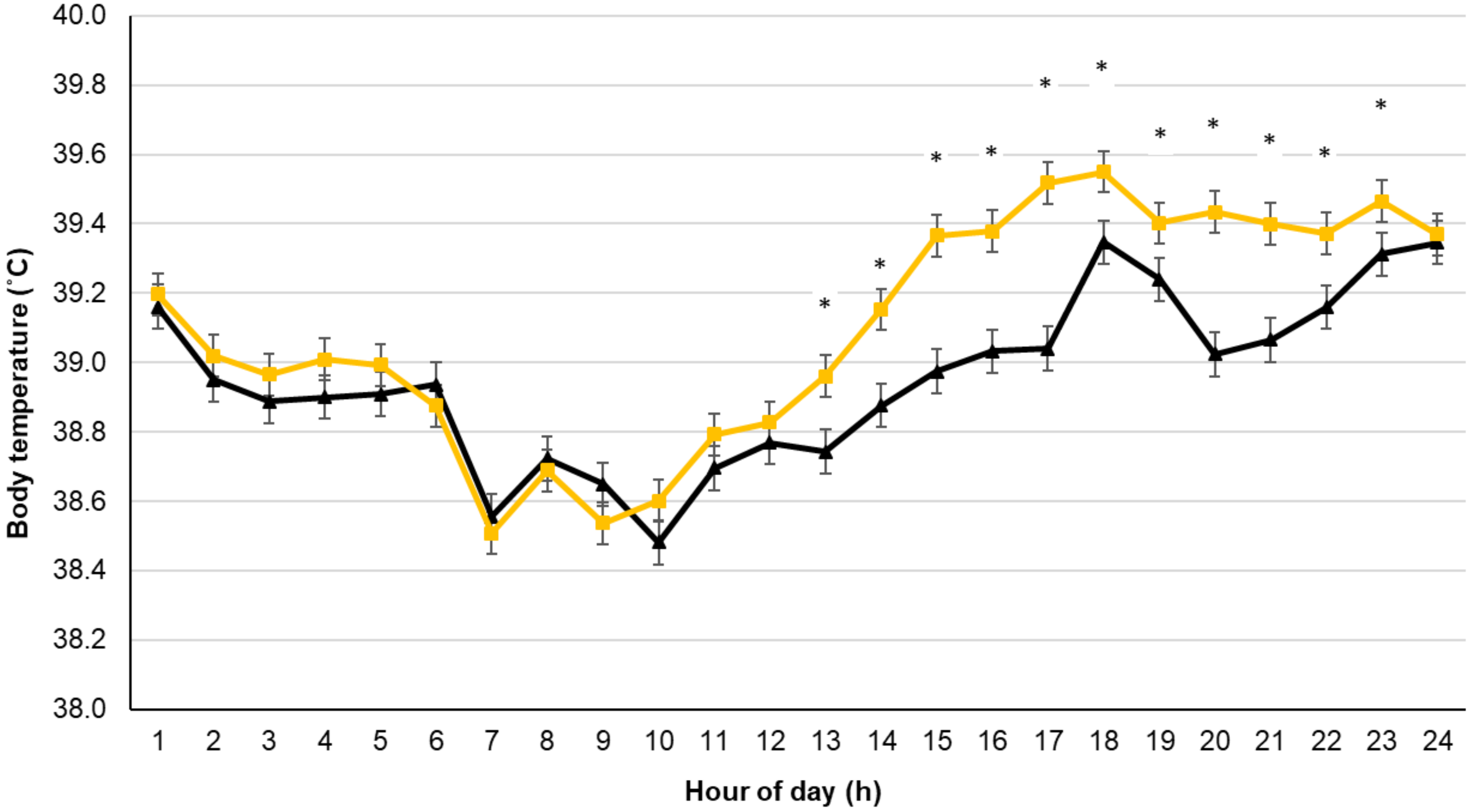
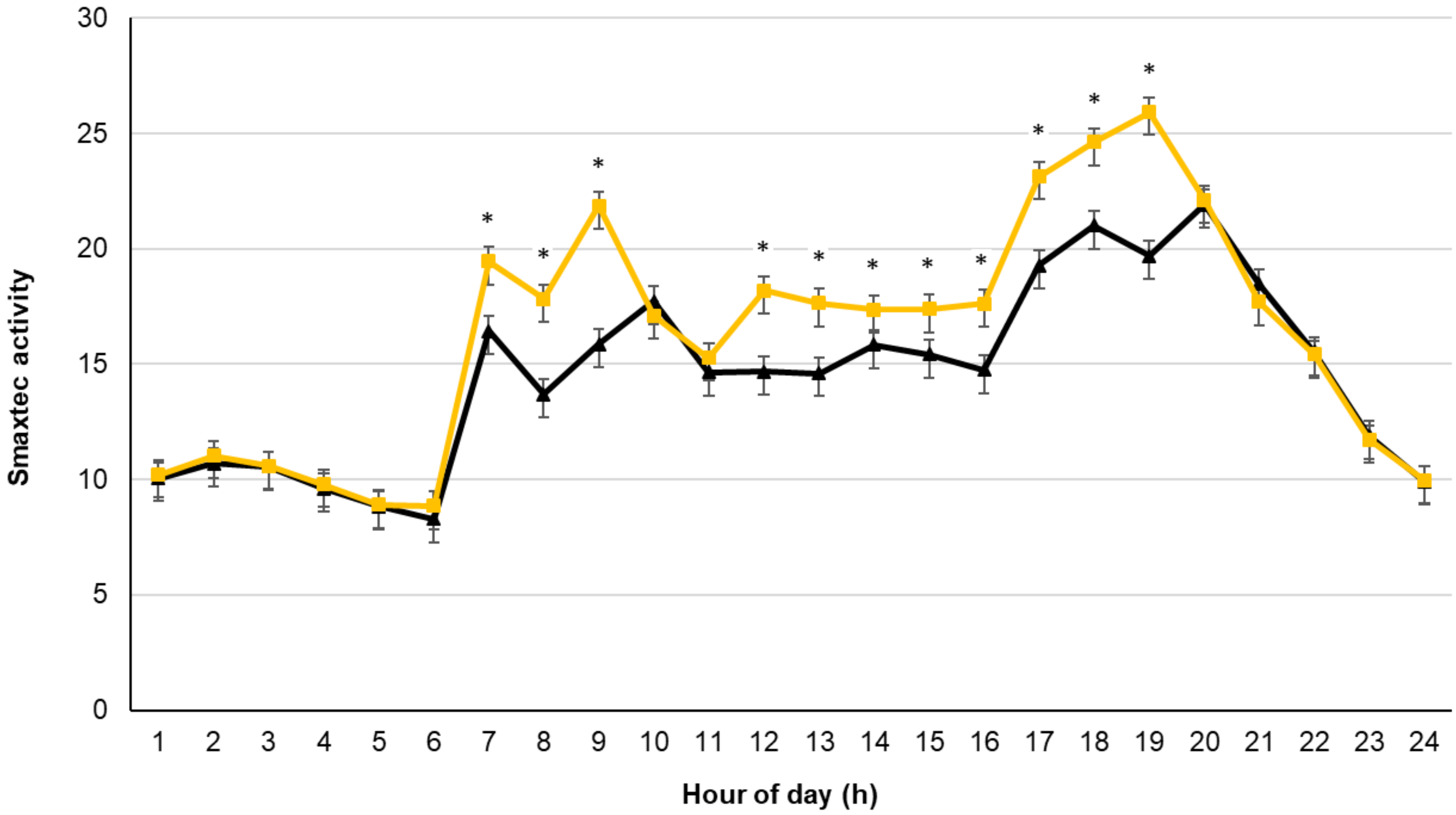


Figure 7. Least squares means and standard errors of means of activity from Smaxtec bolus by hour of day for shade cows (▲, black) and no shade cows (■, yellow). *= Means within an hour of day for treatment groups are different at $P<0.05$.



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