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Faculty of Veterinary Medicine and Animal Science

Light for dairy cows
– Methods to measure light in dairy barns

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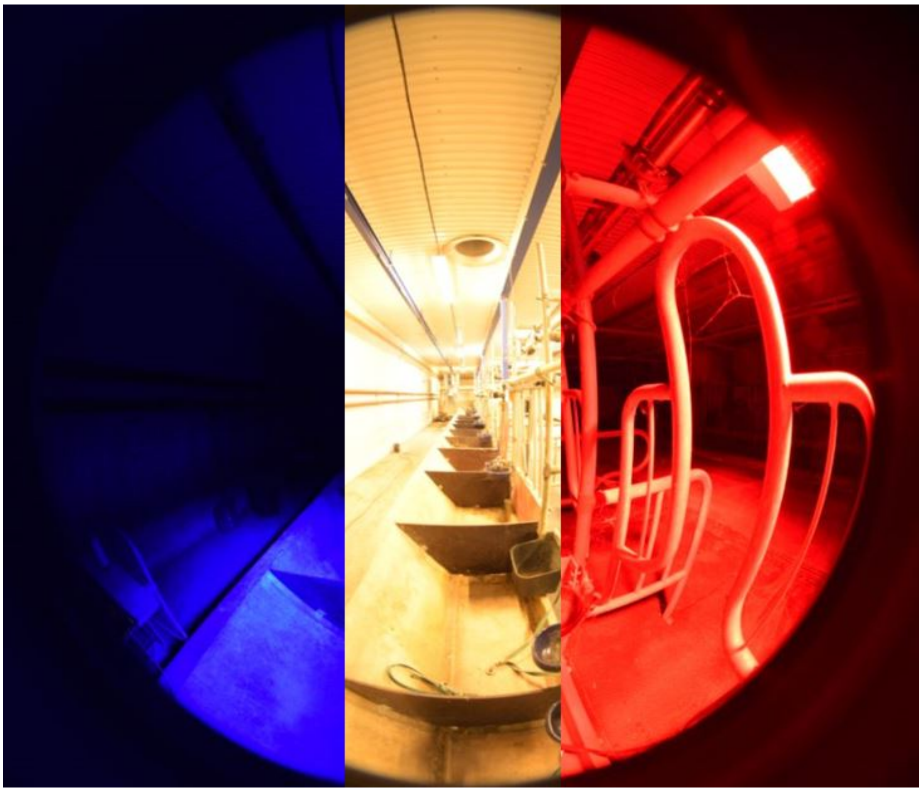

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Light for dairy cows – Methods to measure light in dairy barns

Ljus till mjölkkor – Metoder att mäta ljus i mjölkkostallar

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Abstract

Cows presumably perceive light differently from humans, due to physiological differences and the eyes' position. When designing light in dairy barns, a lux meter is the most commonly used instrument, and the design is often calculated without any daylight inlet. A lux meter has the same sensitivity spectrum of wavelengths as visible light for human's eye. Light to dairy cows is frequently discussed and it is known to affect both production and behaviour. The most commonly used method for quantifying light is lux meter but there are other options. The aim of this study was to investigate and compare a lux meter and other methods to measure light; a spectrophotometer and the ELF-method, with a cows' possibility to perceive light according to existing literature. The ELF-method is an innovation to quantify light that possibly reach an eye.

Several research studies have tested the effects of different light treatments on dairy cows production and welfare. However, the illuminance is often mentioned but not how the lux was measured. The results in this study showed that a lux meter is not optimal when measuring light for a dairy cow, since a lux meter does not show color occurrence nor the variation of photon flux over the wavelength spectrum. A spectrophotometer or the ELF-method would be recommended, due to the results that shows light intensities and the distribution of colors within a specific wavelength spectrum. The position of the instrument, vertical or horizontal, can affect the measured values and the reliability of the measurement. To measure a cow's field of vision, the ELF method is the best option. Also, the measurements showed significant differences in light intensity between different times during one day, in a barn with daylight inlets, and great differences in light intensity in one barn.

In conclusion, it is probably possible to measure light in a way that corresponds well with how light can reach the cow's eye. Measurements either with a spectrophotometer or with the ELF-method is recommended due to the results with light intensity and color occurrence. A lux meter is not the optimal choice since it does not have the same sensitivity for light as the cow's eye. The actual light intensity treatment is of great importance when measuring how the light affect dairy cows' production and welfare. One universal light unit when measuring light for dairy cows is requested.

Keywords: Light intensity, Dairy cow, Vision, Color, Lux meter, Spectrophotometer, ELF-method.

Sammanfattning

Kor uppfattar förmodligen ljus annorlunda än människan, på grund av fysiologiska skillnader och ögats placering. Vid planering av belysning i djurstallar är det vanligaste instrumentet för att mäta ljus en luxmätare och dimensioneringen är ofta beräknad utan påverkan av dagsljus. En luxmätare har samma känslighetsområde som synligt ljus för det mänskliga ögat. Eftersom belysning i ladugårdar ofta diskuteras och det är vedertaget att ljus påverkar mjölkkors produktion och beteende, behövs metoder att mäta ljus undersökas. Syftet med den här studien var att undersöka och jämföra en luxmätare med andra metoder att mäta ljus; en spektrofotometer och ELF-metoden, och att jämföra mätresultaten med kors möjlighet att uppfatta ljus enligt befintlig litteratur. ELF-metoden är en innovation för att kvantifiera det ljus som förmodligen når ett öga.

Flera studier har undersökt effekterna av olika ljusbehandlingar på mjölkkors produktion och djurhälsa. I studierna nämns den belysningsstyrka som korna har behandlats med men det saknas information om hur belysningsstyrkan är uppmätt. Resultaten i den här studien visar att en luxmätare inte är det bästa alternativet för att mäta ljus till mjölkkor eftersom luxmätaren inte visa färgfördelning eller variationen i fotonflöde över olika våglängder. Spektrofotometern eller ELF-metoden är att föredra, tack vare att analyserna visar ljusintensiteten och färgfördelning över olika våglängder. Instrumentets position, vertikalt eller horisontellt, vid mätning kan påverka det uppmätta värdet och trovärdigheten för mätningen. För att mäta synfältet för en ko är ELF-metoden det bästa valet. Mätningarna visade också signifikanta skillnader i fördelningen av ljusintensiteten i ett stall med dagsljusbelysning och ljusintensiteten under olika tidpunkter på dagen, i ett stall med dagsljusinsläpp.

Avslutningsvis, det är förmodligen möjligt att mäta det ljus som kan nå kons öga. Metoder att föredra är en spektrofotometer eller ELF-metoden eftersom resultaten visar ljusintensiteten och färgfördelning. En luxmätare är inte att föredra eftersom den inte har samma känslighet för ljus som kons öga. Den korrekta ljusintensiteten är viktig vid mätningar hur ljuset påverkar mjölkkors produktion och djurhälsa. En universal enhet att mäta ljus till mjölkkor är därför önskvärd.

Nyckelord: Ljusintensitet, mjölkkor, syn, färger, luxmätare, spektrofotometer, ELF-metoden, syn

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Abbreviations

Cd	Candela
ELF	Environmental Light Field method
NDPP	Natural day photoperiod
LED	Light emitting diode
Lm	Lumen
LDPP	Long day photoperiod
SDPP	Short day photoperiod

1 Introduction

Vision is one out of five senses and has a particularly important role in giving perception of the surroundings. The requirements of light are diverse and the eyes' function is well adapted for the animals' natural behavior and environment therefore, are the eyes' function various and different species perceive light on different wavelengths. For mammals, light contributes to biological diurnal rhythms and to generate a visual image of their environment (Freedman et al., 1999; Peirson and Foster, 2006). Today, indoor light in a dairy barns is standard equipment in Sweden however, a hundred years ago the available light was often from a small door or a small opening. It is mentioned in a text from the late 1800s, that light could be positive for milking hygiene (Israelsson, 2005). At present, it is commonly accepted that light and light intensity can affect a dairy cows' production and welfare positive (Dahl et al., 2011). Because of this, indoor light is frequently discussed in the dairy industry.

Expectations on barn lights include that the indoor light should create a light environment that corresponds with dairy cows' behavior, provide a comfortable work environment for barn staff, be cost-effective, have a low energy use and also a long lifetime. Light-emitting diode (LED) could be the answer to the demands mentioned above; with possibilities to set it up with wanted colors and light intensity, low energy use and a long lifetime (Starby, 2006).

Since the eyes' function is adapted for the cows' natural behavior and environment, it is of interest to know how light in a barn corresponds with outdoor light. According to Wickström (2016), outdoor light is different from light indoor both in color distribution, light intensity and the source of light. The light outdoor are brighter and have a significant difference in color distribution over and below the horizon compared to an indoor light environment (Wickström, 2016). An indoor light that resembles natural outdoor light could be more energy efficient and possibly affect biological functions; production, welfare and health, positive. How the differences in outdoor and indoor light affect cows, is not known since it is not investigated.

Light in buildings for dairy cows is regulated by the Swedish Board of Agriculture (SJVFS, 2017:24), the regulation controls indoor daytime lighting, inlets for natural daylight and the mandatory night-time dim-light. Additionally, the regulation says that the light should not create discomfort for the animals (SJVFS, 2017). What kind of light that can create discomfort for animals is not investigated.

When planning and designing indoor light, the light is often dimensioned in illuminance, which is one of many lighting metrics (Jeppsson et al., 2014). A lux meter is the most commonly used instrument when measuring illuminance (Jeppsson et al., 2014) and a lux meter is dimensioned after the human perception of light and most sensitive around white light (Hagner, 2018). It is not possible to detect color distribution with a lux meter and it is questionable if the measured illuminance with a lux meter is the same light intensity as a cow experience it. Another common tool for designing light is to use software where it is possible to visualize the planned light environment (Jeppsson et al., 2014). Most of the software's used to calculate light dimensioning cannot calculate for daylight inlet (Jeppsson et al., 2014), which is regulated in the law (SJVFS, 2017:24) and an excellent source of light in most modern dairy barns.

A project financed by the foundation Lantbruksforskning will investigate the effects of LED-light on milk production and activity in dairy cows and is a collaboration with Swedish University of Agricultural Science, Heliospectra AB and Arla Foods. To enable the study, a light lab will be created at the Swedish Livestock Research Centre and for the setup of LED-light, it is valuable to quantify the light with a suitable method. This paper is a part of the LED-project.

Fortunately, new methods have been developed for light calculations; methods specialized for humans and for plants. Methods that measure light differently from a lux meter and include both color distribution and light intensity have recently become available. These methods might be an opportunity to enable another approach when designing indoor light in a dairy barn.

The aim of this study was to investigate different methods to measure light and to compare the results with a cow's possibility to perceive light according to existing literature. There are several methods to measure light and there are possibilities to measure light intensity, color occurrence and the number of particles from a light source. The research question is, if it is possible to measure light and to analyze it understandably and comparably, additionally in a way that light reach the cow's eye.

2 Literature review

2.1 What is light?

Light is electromagnetic radiation and is often explained as wavelengths, a stream of particles or photons (Starby, 2006). The common definition of visible light is the spectrum of electromagnetic radiation, wavelengths, that the human eye can identify, which is between 400 nm to 700 nm (Hébert et al., 2014; Hjalmarsson et al., 2014; Kremers, 2016; Starby, 2006). Radiation from the sun that reaches earth is within the wavelengths spectral of 300 to 2500 nm (Hébert et al., 2014; Starby, 2006). An overview of different aspects of light that can be measured is given in table 1.

Table 1. Lighting metrics, modified from Palmer (2012) and Starby (2006)

Quantity	Unit	Factor
Luminous flux	Lumen	lm
Luminous intensity	Candela	cd
Luminance	Candela per square meter	cd/m^2
Illuminance	Lux	lm/m^2
Irradiance	Energy per square meter	W/m^2
Spectral irradiance	Photons per wavelength	$\mu mol * s^{-1} * m^{-2} * nm^{-1}$
Spectral photon radiance	LIT	$\log_{10} photons\ s^{-1} m^{-2}\ sr^{-1}\ nm^{-1}$

Luminous flux is the energy quantity of light emitted per second in all directions, for example, an artificial light source emits a specific luminous flux per time unit (Starby, 2006). The unit of luminous flux is lumen (lm) (Palmer, 2012). Luminous intensity from a light source within one unit of solid angle (one steradian) in a given direction is measured in the unit candela (cd) (Palmer, 2012). A solid angle is a three-dimension angle that can describe the range of specific luminous intensity in a certain direction (Starby, 2006).

Luminance is a unit that measures luminous intensity per area unit in a specific direction and is specified in candela per square meter (cd/m^2) (Palmer, 2012; Starby, 2006). In other words, luminance is a certain amount of particles, for example, photons, that reach the eye, or the amount of light on the surrounding area that reflects the eye (Starby, 2006).

Illuminance is the luminous flux towards a surface per area unit and is measured in lux (lm/m^2) (Starby, 2006). Lux is the most commonly used unit when measuring light and lux measures how the human's eye percept brightness (McCluney, 2014), which presumably differs from the perception of animals (Hjalmarsson et al., 2014) and it is further explained in section 2.2.1-2.2.4. The units of luminous flux is shown in figure 1.

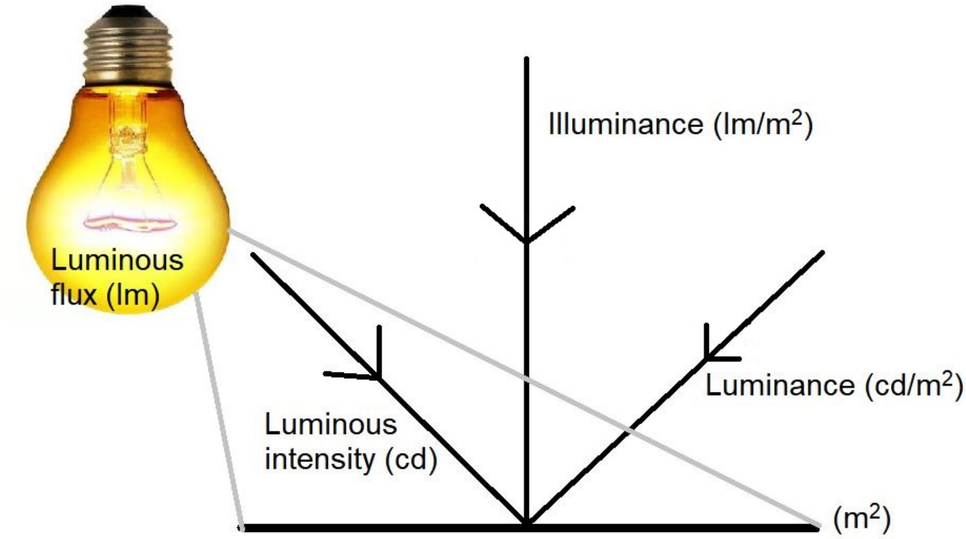

Figure 1. Units of luminous flux modified from Starby (2006).

Irradiance is the amount of energy at each wavelength emitted from a radiant sample (W/m^2) (Ocean Optics, 2018; Starby, 2006). When measuring irradiance, it is possible to calculate more specific values; moles of photons, lumens, lux, and candela (Ocean Optics, 2018). Additionally, it is possible to measure the amount of photons per wavelength, called spectral irradiance, it is measurement of light within numerous of wavelengths (Hébert et al., 2014).

Scientists at Lund University created a measurement unit that fits with their newly developed technique. This measurement unit is called Logarithmic intensity (LIT), and measure the spectral photon radiance. The measurement unit is Log photons, per second, per square meter, per steradian, per nanometer wavelength ($\log_{10} photons\ s^{-1} m^{-2}\ sr^{-1}\ nm^{-1}$). (Nilsson and Smolka, 2019).

2.1.1 How to measure light

When measuring light, it is important to differentiate closed environment measurements from in-field measurements (Starby, 2006). Closed environment measurements are a basis for the practical information about a product including luminaires, light distribution and luminaire efficiency (Starby, 2006). In-field measurements are influenced by several factors in the surroundings that is possible to avoid in closed environment measurements (Starby, 2006).

Different instruments are designed to measure light either horizontal or vertical or both angles (Hagner, 2018; Ocean Optics, 2018). When measuring illuminance indoor, the luminous flux is measured in a vertical angle (Starby, 2006). The instrument is directed towards the ceiling and by using a spirit-level the vertical level is ensured (McCluney, 2014). The horizontal angle is often used to measure illuminance on whiteboards or in sports arenas (Starby, 2006). Regardless of measurement angle a specific height should be used to enable comparison between measurements. Additionally, to get an precise measurement it is important not to cover the instrument when measuring (Starby, 2006).

2.1.2 Light sources in dairy barns

Light sources in dairy barns have historically not been of great focus, even though it is mentioned in a text from the late 1800s that spacious and bright barns could help prevent infectious diseases (Israelsson, 2005). Today the benefits of light on dairy cows is well known and the choice of light source is in focus. Additionally, 10% of the electricity use in barns is from the light sources (Hörndahl et al., 2012). Commonly used light sources when testing the impact of light is metal halide light source and fluorescent lights (Auchtung et al., 2004; Dahl et al., 1997; Hjalmarsson et al., 2014; Miller et al., 1999; Peters et al., 1978, 1980; Reksen et al., 1999; Rius et al., 2005; Rius and Dahl, 2006; Velasco et al., 2008). A metal halide light source is a development from the mercury light source, with a better color occurrence (Starby, 2006). The fluorescent light is energy efficient and recent models possible to dim to a lower light intensity (Starby, 2006). LED is different from the two light sources mentioned above; LED is several small diodes where every unit creates light with a certain color and it is possible to create blue, red and white light (Starby, 2006).

2.1.3 Influencing factors on light sources

The operation time of the light source can affect a light source’s photon flux (Starby, 2006). When measuring the luminous flux from a light source’, it is often measured at the optimal operation time, after 100 h in use (Starby, 2006). Maintenance can influence the light flow and light distribution, especially in areas where there is a high risk of contamination with dirt or dust (Starby, 2006). Light conditions over time, in a barn for dairy cows is primarily affected by the maintenance factor (Jeppsson et al., 2014). Another critical influence factor is daylight (Starby, 2006). There is regulation by law (SJVFS, 2017:24) for daylight inlet in animal housing and according to Starby (2006) the indoor light environment is profoundly affected by daylight. The recommendation to enable an accurate measurement of the indoor light, is to measure when there is no daylight inlet (Starby, 2006).

2.1.4 Light design in agricultural buildings

As mentioned, light in dairy barns is regulated by (SJVFS, 2017:24), and in general terms, it says that the indoor light environment should not create discomfort for the animals. Additionally, buildings for dairy cows must have dim-light during the night, and light that support diurnal rhythms and behavior(SJVFS, 2017:24). There are benchmarks for illuminance in agricultural buildings (SIS-TS, 2012) and according to Jeppsson et al. (2014) the guidelines are close to what is stated in the Swedish work environment authority and Swedish standards institutes (AFS, 2009; SIS-TS, 2012). However, there is no information available in the regulation or in scientific literature about threshold values for suitable light intensity at night or day.

When designing the dimension and type of light source in agricultural buildings in Sweden, the guidelines above are followed. Specialists often use a software to calculate the dimensions, three software with a wide spread is DiaLux, Relux and Radiance. When using one of those software's it is possible to visualize and to evaluate suitable light source according to the building´s area, material and furnish. The light sources are defined by both luminous flux and scattering angle to make the luminous flux as even as possible. Lux is the most common unit used in the software. (Jeppsson et al., 2014). However, there is variation in wavelength spectrum between the eyes of different animal species. The differences in light perception between the human eye and the cow eye is important to consider when designing illumination in cow barns.

2.2 Cows' perception of light

It is important to know the function of the eye to understand how cows perceive light. Furthermore, the effect of light on the cow's behavior and production, as described in the literature, adds to the understanding of the importance of exposure to light.

2.2.1 The eye – function and physiology

The organ of vision, the eye, consists of the globe (eyeball) and adnexal (accessory ocular) structures (Dyce et al., 2010). The eye is located in a bony cavity, the orbit, surrounded by generous quantities of adipose tissue (Dyce et al., 2010). Ruminants have a closed orbit a complete bone ring around the eyeball compared to, for example dogs that have an open orbit (Sjaastad et al., 2012). The form of the orbit and the position of the eyes is related to the animal´s method of feeding, habits, and environment (Dyce et al., 2010). Herbivores have, in general, their eyes more laterally than predatory species that have their eyes set well forward (Dyce et al., 2010). For herbivores, the right and left fields of vision barely overlap, but gives close to 360° panoramic vision with a binocular vision field of 25 - 50° depending on species and breed (Dyce et al., 2010; Grandin, 1980). Binocular vision is the field of vision that is overlapped by both eyes and gives depth perception, which cattle only have little capacity for (Dyce et al., 2010; Grandin, 1980).

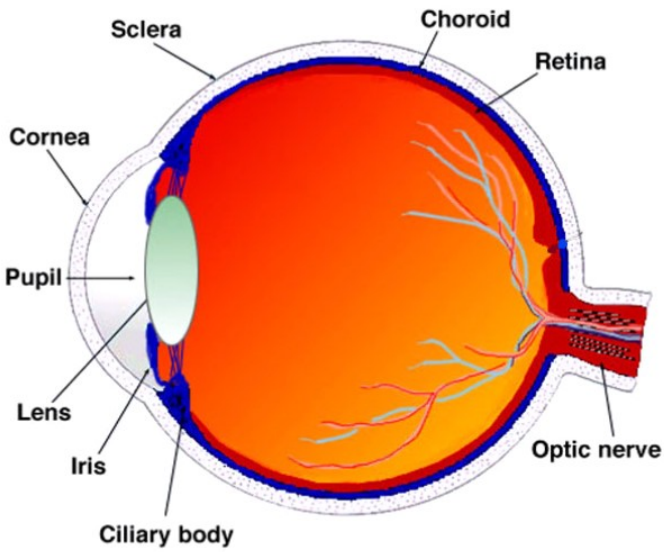

Figure 2. Schematic diagram of the eye in a diurnal mammal. Modified from Kolb.H. CC BY-NC.

Light enters through an opening in the middle of the eye, called the pupil (Sjaastad et al., 2012), see figure 2. Cattle and horses, like many other herbivores, have a pupil that changes to a horizontal crescent or a slit (Sjaastad et al., 2012), which is different to the round pupil in human eyes. The pupil changes in size to adjust the amount of light reaching the area of the eye that contains light-sensitive receptor cells, called the retina (Dyce et al., 2010).

2.2.2 Photosensitive cells

In the retina, there are two major types of light-sensitive receptor cells, rods and cones (Sjaastad et al., 2012). The visual response starts with the absorption of photons by rods or cones (Kremers, 2016). Cows, as well as human beings, have one type of rods. The rods are responsible for night vision where they provide monochromatic (greyscale) vision (Dyce et al., 2010; Kremers, 2016). However, there are two different types of cones in the retina of cattle; these different cones are sensitive to light at different wavelengths. It is the comparison of the signals from the different cones, in the brain, that provides the possibility to see colors (Kremers, 2016). Color vision requires a minimum of two different types of cones (Kremers, 2016).

2.2.3 Color vision

Humans have a trichromatic vision, where the color vision is based on three different types of cones (Sjaastad et al., 2012), long wavelength-sensitive (L), middle wavelength-sensitive (M), and short wavelength-sensitive (S) cones (Kremers, 2016). In primates, the L-cones' maximal sensitivity is around 560 nm, yellow-green color, M-cones around 530 nm, green color, and S-cones around 430 nm, blue color (Kremers, 2016). Most domestic animals, including cattle, are dichromatic with only two types of cones (Sjaastad et al., 2012). Cattle have S-cones with a maximal sensitivity of 451 nm and M/L-cones with a maximal sensitivity of 555 nm (Jacobs et al., 1998). Animals with dichromatic vision can separate light of shorter wavelengths from the light of longer wavelengths, however it is impossible to distinguish between red and green light (Kremers, 2016; Sjaastad et al., 2012).

2.2.4 Retinal ganglion cells

The outer layer of the retina host the rods and cones and neurons called ganglion cells are found in the inner layer (Sjaastad et al., 2012). Axons from the ganglion cells form the optic nerve (Sjaastad et al., 2012). A small fraction of the ganglion cells are, like rods and cones, photosensitive receptors containing melanopsin, these cells are called intrinsically photosensitive ganglion cells (ipsGCs) (Provencio et al., 1998). Melanopsin is a photopigment that is most sensitive to shorter wavelengths around 480 nm (Peirson and Foster, 2006). Additionally, the ipsRGCs receive input from the rods and cones, input used to pass information about the surrounding light (Graham and Wong, 2008). The ipsRGCs communicates directly with the suprachiasmatic nuclei (SCN), the part of the mammalian brain that controls the circadian rhythm (Welsh et al., 1995). According to Lucas et al. (1999) the role of the ipsGCs in vision is most likely minor, but importantly they provide the pineal gland with essential information about light intensity. The ipsGCs also contribute to pupil constriction (Lucas et al., 2001).

2.2.5 Circadian rhythm

The internal circadian rhythm in mammals correspond with the solar day by a light-induced resetting mechanism, which controls the endogenous body clock (Freedman et al., 1999). The endogenous body clock is located in the suprachiasmatic nuclei of the hypothalamus, and it normally follows a 24 h daily photoperiod induced by information from the environment (Evered and Clark, 2009). However, the 24 h photoperiod can differ to 25 or 26 h due to environmental changes (Evered and Clark, 2009). Changes in the environment is for example dusk and dawn along with seasonal changes (Evered and Clark, 2009). One of the most reliable markers of the periodicity of the endogenous body clock is the pineal hormone melatonin (Arendt, 1995). Compared to other indicators of circadian rhythms, such as body temperature or cortisol, melatonin is highly rhythmic and follows a characteristic pattern with high levels during nighttime and low levels during daytime (Lockley et al., 1997). Several authors highlight that the specialized retinal ganglion cells (ipRGCs) are of importance when studying how light in the environment affects the circadian rhythm (Lucas et al., 1999; Peirson and Foster, 2006). According to Piccione et al. (2011), mammals' circadian rhythm are associated with temperature, food supply and changes in light and darkness. The most consistent and reliable source of diurnal rhythms in mammals is changes in light intensity (Piccione et al., 2011).

2.2.6 Diurnal patterns

Even though dairy cows are kept in a different environment than their ancestors, their behavior when housed will show a diurnal rhythm (Kilgour, 2012). The main activities for cattle on pasture are grazing, ruminating or resting (Kilgour, 2012). A difference between day and night activity was detected in a review of 22 research articles by Kilgour (2012). During nighttime most of the time was spent resting and during the daytime most of the time was spent grazing. According to Phillips and Arab (1998), cows' activity rhythm on pasture is most likely related to a constant interruption by predators during the daytime. Behaviors like rumination, that can be performed lying down, are performed in the protection of darkness at nighttime (Phillips and Arab, 1998). During daylight, when cows are more exposed to predators, behaviors including moving around, feed and water intake were performed (Phillips and Arab, 1998). It has been found that cows housed indoors have a diurnal rhythm resembling that of cattle on pasture (Munksgaard et al., 2011).

2.2.7 Photoperiod

According to Dahl et al. (2011), the definition of photoperiod is the cycle and duration of light and dark that an organism experiences within a 24 h period. When influencing the photoperiod, it is shown to affect dairy cow's production and behavior (Dahl et al., 2011). Three different photoperiods are often mentioned in the literature when studying the effects of different light intensities; long day photoperiod (LDPP), short day photoperiod (SDPP) and natural day photoperiod (NDPP). How they differ is shown in table 2 (Dahl et al., 2011).

Table 2. Photoperiods; the cycle of light and darkness within 24 h (Auchtung et al., 2005, 2004; Dahl et al., 2011, 1997; Miller et al., 1999; Ponchon et al., 2017)

Photoperiod	Daytime (h)	Nighttime (h)
LDPP	16 to 18	6 to 8
SDPP	8	16
NDPP	9.5 to 14.5	9.5 to 14.5

2.2.8 Light affects behavior

Light intensity can affect cows' behavior indoor e.g. their walking behavior like gait and speed (Hjalmarsson et al., 2014; Phillips et al., 2000). Phillips et al. (2000) tested the correlation between floor friction and light intensity and it resulted in an increased number of steps per second with a lowered light intensity. In conclusion, to retain a natural walking behavior through passages during nighttime the light intensity should be between 32 lux to 119 lux (Phillips et al., 2000). Hjalmarsson et al. (2014) measured cow activity in the number of gate passages in Swedish AMS barns and showed that the cow activity was higher with 24 h of daylight. In comparison, when the cows were treated with a LDPP light program, their activity decreased (Hjalmarsson et al., 2014).

2.2.9 Light affects production

The length of the photoperiod has been shown to affect reproduction, growth, lactation and health in dairy cattle (Dahl et al., 2011). Focusing on lactation, studies have confirmed that milk yield increased during LDPP compared to SDPP in indoor light environment, probably due to a hormonal response to light intensity (reviewed by Dahl and Petitclerc, 2003). However, only a few studies in this field of research mention what kind of instrument they used when measuring the light intensity, as shown in Table 3. Most of the studies in Table 3 report the light source, lux at a specific height, the length of photoperiod, group of animals, and day in lactation. According to (Starby, 2006) it is possible to calculate the efficiency of one specific light source though, it is not reliable in large open places or places that are contaminated by dirt or dust (Starby, 2006).

Table 3. Instrument used when measured light treatment

References	Light source mentioned	Lux	Instrument	Photoperiod
Auchtung et al., 2003	N.A[1.]	N.A	N.A	LDPP & SDPP
Auchtung et al., 2004	Yes	450±10	N.A	LDPP & SDPP
Auchtung et al., 2005	N.A	N.A	N.A	LDPP & SDPP
Auchtung and Dahl, 2004	Yes	545±15	N.A	LDPP & SDPP
Bal et al., 2008	Yes	0-200	Light meter, Minolta	NDPP
Dahl et al., 1997	Yes	350	N.A	NDPP & LDPP
Hjalmarsson et al., 2014	Yes	11-158	Lux meter	LDPP & Continuous light
Miller et al., 1999	Yes	350	N.A	NDPP & LDPP
Muthuramalingam et al., 2006	Yes	200 + 0-50	Light meter, Minolta	LDPP
Peters et al., 1978	Yes	N.A	N.A	NDPP
Peters et al., 1980	Yes	104-116	N.A	NDPP, LDPP, Continuous light
Phillips et al., 2000	Yes	259	Spectroradiometer	N.A
Ponchon et al., 2017	N.A	N.A	N.A	LDPP & SDPP
Reksen et al., 1999	Yes	N.A	Lux meter	N.A
Rius et al., 2005	Yes	450	N.A	LDPP & SDPP
Rius and Dahl, 2006	Yes	350	N.A	LDPP & SDPP
Velasco et al., 2008	Yes	250±10	N.A	LDPP & SDPP

1. N.A abbreviation for not available

2.3 Methods to measure light

There are different methods to measure light. Four methods are specified and explained in this section.

2.3.1 Lux meter

A lux meter is the most commonly used method when doing a measurement of light in-field (Starby, 2006). There are many different lux meters available on the market; apps for smartphones, lux meters bought at a supermarket and very accurate precision instruments (Starby, 2006). The lux meter measures the illuminance in a horizontal or vertical plane (Starby, 2006). Lux meters have the same sensitivity for different wavelength's as visible light for the human eye (Hagner, 2018), which presumably is different from a cow's perception of light, see section 2.2.1-2.2.4. When measuring illuminance, with a lux meter, the level of error is ±10 % (Starby, 2006).

2.3.2 Luminance meter

A luminance meter is used to measure luminance at a certain position. The instrument is often used when designing road lighting (Hagner, 2018). Also, it is possible to use when measuring reflectance of different materials together with a reflectance reference (Jeppsson et al., 2014). According to (Hagner, 2018), a luminance meter is most sensitive within the wavelength spectrum for visible light for the human's eye, same as a lux meter.

2.3.3 The Environmental Field method

The Environment Light Field (ELF) method is a recent innovation, still in the development phase; this explanation is a direct quote from the developers:

The ELF method, developed by Nilsson and Smolka (2019), captures the essential aspects that form our perception of environmental light. By using a calibrated digital camera with a 180° fisheye lens, it is possible to record the full range of light intensities like the eye with a single press of a button (Nikon D3x camera with objective Sigma 8mm/3.5). The digital camera is calibrating with an image sensor, and the camera´s finder is not in use. To generate a high dynamic range (HDR) and guarantee that no pixels are saturated or completely dark the camera takes three exposures for each exposure in rapid succession with different shutter speeds. Before analyzing, the 180° circular image is remapping into a square image.

The ELF method measures with two different approaches, single scene and multiple scenes for general environment assessments. To test the effect of different lighting or comparing changes over time a single scene measurement is useful. However, to get an overview of the general light environment in a room or a building the multiple scenes is preferable. 20-40 individual exposures in a multiple scene measurement make general properties of the environment brought out, and any objects or structures from individual scenes are evened out. The analysis consists of an average image of the multiple scene measurement or the three exposure of the single scene measurement. From the average image the median intensity (in LIT) is calculated in every pixel and for all elevation angles. It results in a graph with a light grey area and a dark grey area. The light grey area shows 95% of the intensity variation at each elevation angle and the dark grey shows 50% of all intensity values. The graph also shows three spectral bands blue, green, red and black. It is the intensity curve as a function of each elevation angle independently calculated for the three spectral bands blue (400-500nm), green (500-600nm) red (600-700nm) and all colors together (black line 400-700nm).

2.3.4 Spectrophotometer

A spectrophotometer can be used in a wide variety of different areas, for example in chemistry, physics, and biochemistry (Corey, 2009). In light measurements, the spectrophotometer measures the ratio of two values of a photometric quantity at the same wavelength (McCluney, 2014). In other words, a spectrophotometer measures the intensity of light, it detects the amount of photons that is absorbed in the instrument within a spectra of wavelengths (Corey, 2009). The spectrophotometer can also be used for color measurements (Ocean Optics, 2018).

With a spectrophotometer it is possible to measure the spectral irradiance and it gives a comparable spectral of the amount of photons within specific wavelengths. Additionally, the spectrophotometer enables to measure the amount of photons over the spectral of visible light, between 400 – 700nm, or the amount of photons in the interval spectra of different colors (blue 400 – 500 nm, green 500-600 nm, red 600-700nm) (personal communication, Lindqvist. 2018).

3 Material and methods

The field study was conducted in two different dairy barns, at the Swedish Livestock Research centre in Uppland, Sweden, and a conventional dairy farm in Småland, Sweden (N65°;E15°), during September 2018 to October 2018.

3.1 Choice of instruments

Three methods were chosen for measuring light. Firstly, the most commonly used instrument when measuring light, a lux meter. In this trial a very accurate precision instrument was used (Hagner, 2018); a Hagner Screenmaster. The Hagner Screenmaster was used in Jeppsson et al. (2014). The lux meter measures illuminance in lux.

Secondly, a spectrophotometer called Jaz from Ocean Optics Inc (Ocean Optics, 2018) to enable light measurement within the wavelength spectra of visible light and color occurrence. The result from each measurement includes the photon flux at different wavelengths and the color occurrence. The chosen spectrophotometer is an instrument used by Heliospectra AB, who is a partner in the LED-project, when designing light spectra for plants in greenhouses. The instrument is sensitive to dust and dirt and needs to be handled with care. Jaz measures the spectral irradiance, which is the photon flux per wavelength.

Thirdly, the newly developed ELF method, a camera with an 180° fish-eye object (Nilsson and Smolka, 2019). It measures the photon flux within the wavelength spectra of visible light and color occurrence, the same as the spectrophotometer. However, the ELF method analyzes in spectral photon radiance, LIT. The analysis from the ELF method and the spectrophotometer will probably look different, but maybe either complement one another or give different results.

3.2 Experimental design

To enable a comparison between the methods the same measurement points were used for all three methods. When measuring light in a cow stable, it is both a possibility to measure the light that can reach the cows' foreheads or to measure the light that can reach the cows' eyes, described below in vertical and horizontal measurements. The chosen measurement angle followed the instruction for each method. This field study includes two different housing systems, tie barn at the Swedish Livestock Research centre and loose housing at the conventional farm. The approach of choosing measurement points differ therefore, depending on the cows' availability to move around or not in the barn. In addition, a reason for including measurements in the chosen tie barn was that the information would help in designing future light trials in that specific barn.

3.2.1 Measurements

Two measurement approaches were used, vertical and horizontal measurement. To measure the light that can reach the cows' forehead, vertical measurements were used. A vertical measurement measures the light that vertically reaches the instrument. Two out of three methods, the spectrophotometer and the lux meter are possible to use in a vertical angle. The other approach that was used to measure the light that possibly can reach a cows' eyes, was horizontal measurements. By turning the instrument 90° from vertical to horizontal, the instrument will collect the sample in

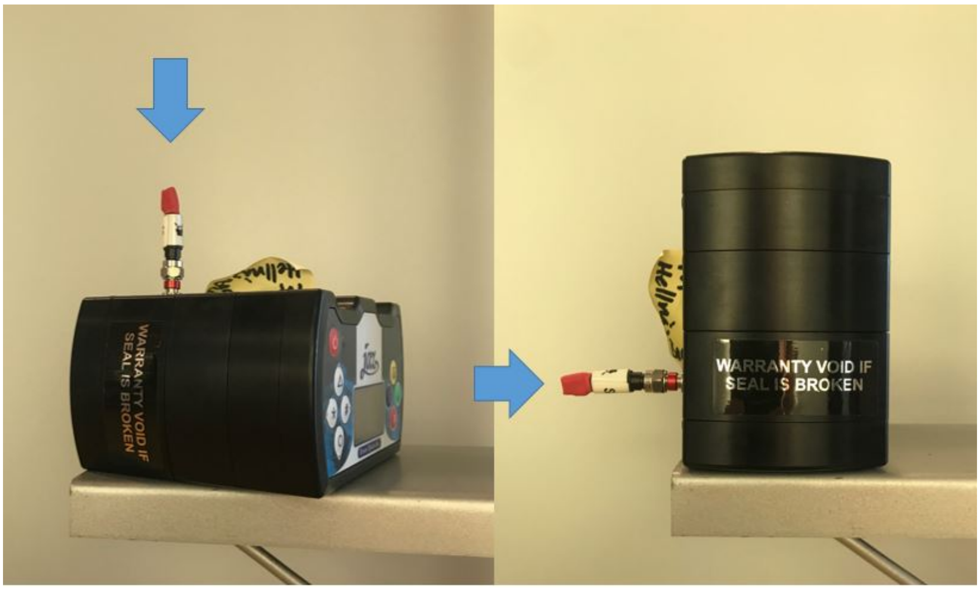

Figure 3. Vertical and horizontal measurement with a Jaz spectrophotometer

the same perspective as a cow's field of vision. One measurement in the same direction as each cow eye, the two measurements can be evaluated either singular or together. It is possible to measure horizontal with two out of three methods, the ELF method and the spectrophotometer. In figure 3 the difference between a vertical and a horizontal measurement is shown.

3.2.2 Lux meter

When a measurement point was chosen the Hagners Screenmaster was placed on a stand, 125 cm above the ground, with the lid open and the detector for illuminance facing the light vertically. The instrument went on when the lid was opened and the switch for illuminance/luminance was set on illuminance. A spirit level was used to ensure the instruments' vertical angle towards the light. At every measurement point, the values were noted for the lux meter and after every session, registrations were compiled in Microsoft Office Excel 2016.

3.2.3 Spectrophotometer

The Jaz spectrophotometer is very sensitive and need to be handled with care. When doing a measurement, the Jaz was placed at the measurement point on a stand, 125 cm above the ground. An Ethernet cable was connected between the Jaz and a router; additionally, another Ethernet cable was connected between the router and a laptop. The software JazLabTool was started on the laptop and a calibration file for this specific Jaz was chosen. The box electronic dark correction was highlighted and scans to average was set to 3 and the boxcar filter width to 5. The measurement procedure started with taking the lid off the instrument and the integration time search was started. If it was too dark for the software to set integrations time search, it was manually set to 4 seconds. Then the lid was put back on and dark reference was done. At last, the lid was taken off again and the sample was made. The file was saved and after each session the registrations were compiled in Microsoft Office Excel 2016.

3.2.4 ELF-method

A Nikon D810 camera was used together with a Sigma 8 mm F3.5 EX DG Circular Fisheye lens. The camera was used handheld when taking exposures, 125 cm above the ground. For each exposure, the camera takes three exposures in rapid succession with different shutter speeds. The exposure time used was 1/125. After each session the exposures where compiled into folders were each folder included one analyze. The registrations were sent to Lund University were analyzes was done.

3.2.5 The conventional dairy barn

The measurements at the conventional dairy barn occurred on September 27th, 2018, with three sessions; morning (AM), afternoon (PM) and evening. Due to the high risk of damage by dust and dirt, the Jaz spectrophotometer was not used. The conventional dairy barn is a barn with 450 dairy cows and cows in late gestation and newborn calves (design in figure 4). There are natural light inlets by the roof ridge and on the sides. At each session, the weather was noted before, during and after the measurements. Other factors such as where today's lighting is placed, the light source' approximate usage hours, colors indoors and the indoor maintenance factor was noted. This barn has a loose housing system with different groups of cows. To enable an overview of the light environment in the barn, measurements were done at the feed alley. Additionally, the feed alley were enclosed for cows therefore, the measurements were performed without disturbance.

Every session started with 31 randomly picked measurement points at the feed alley. Measurements were done from the feed alley, in vertical angle with the LUX meters and horizontal angle with the ELF method. Thereafter, to specify some specific places of interest out of a light point of view, six measurement points for a single scene was chosen. For example, the measurement point was chosen according to where the cows spend their time and where employees require sufficient lighting. The chosen places for a single scene were following: a walking alley for the cows from the milking parley to the cubicles, drinking place in the bottom of the barn, at the feed alley from a cows perspective, at a cow brush, cubicle and where the cows in late gestation are held.

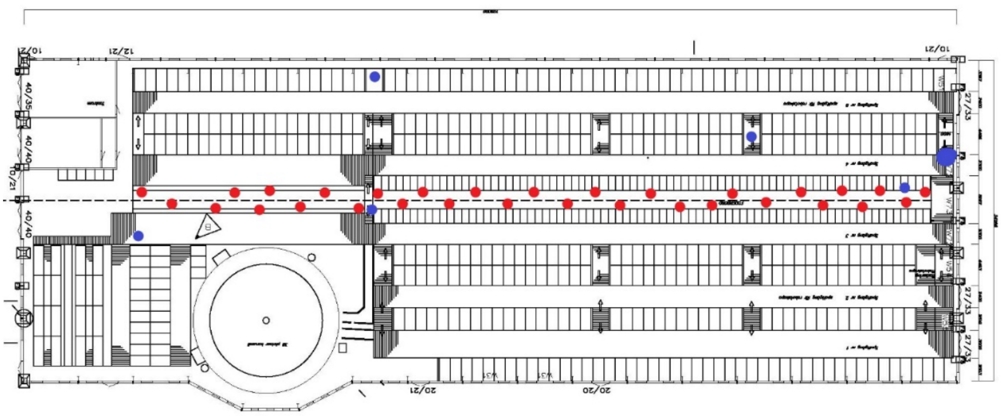

Figure 4. Design over the conventional dairy barn. Red dots indicates measurement points at the feed alley and the blue dots indicated specific measurement points for a single scene.

3.2.6 Swedish Livestock Research centre

At the Swedish Livestock Research centre, there is a stable without any natural day-light inlet that will be used in the future LED-project. The measurements occurred during two days, October 16th and 18th 2018 between 9.00am to 4.00pm. It is a tie barn with a place for twenty cows, ten per each side, as shown in figure 5. The ceiling is flat, and there are fourteen fluorescent lights placed evenly. In this stable, the measurements were done with the indoor light turned on; daytime lighting and night-time lighting. In daytime lighting the fourteen light sources are turned on and during the night-time lighting three out of fourteen light sources are turned on. Since

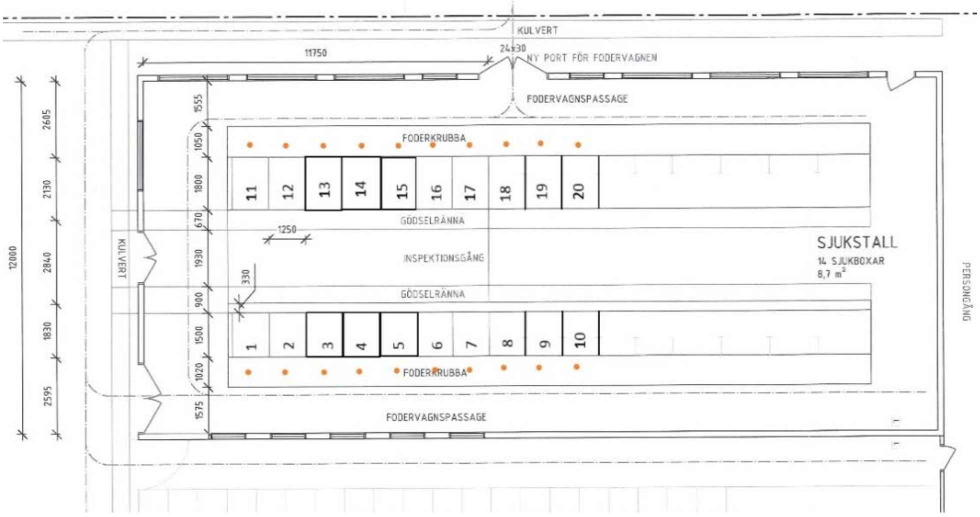

Figure 5. Design on the barn at the Swedish Livestock Research centre. 20 stalls are plotted and the orange dots mark the measurement points, one measurement point per stall, where one vertical and two horizontal measurements were done.

it is a tie barn were the cows stays at the same place, the measurements points were chosen at every cow place. Measurements were done in the feed alley where the cows' heads will be placed. The three different methods were tried; the ELF method (horizontally), Spectrometer (vertical and horizontal), LUX meter (vertical). In total 20 measurement points were chosen, one per cow place, with 10 measurement points per side, design in figure 5.

3.2.7 LED-light

Since LED-light is upcoming in the dairy industry and will be used in the LED-project, the methods were also tested in light from a single LED-light source. Only one LED-light was available at the time of measurement and the result may be different if multiple LED-lights were included. A LED-light was placed above one cow place in the stable at the Swedish Livestock Research Centre, at a height of 160 cm above the ground. Measurements were done at 125 cm with a stand. With the spectrophotometer and the LUX meter, the measurements were done in a vertical angle and with the ELF method and the spectrometer in a horizontal angle. Different light intensity was investigated, shown in table 4, first six measurements were done with either blue or red light, at different intensities. Thereafter, 20 % of white light was included to the blue or red light.

Table 4. List over the measurements with different light intensities with LED-light.

Measurement	Blue	Red
1	10	10
2	20	20
3	30	30
4	40	40
5	50	50
6	60	60
7	60 + 12 white	60 + 12 white
8	100 + 20 white	100 + 20 white
9	200 + 40 white	200 + 40 white
10	500 + 100 white	500 + 100 white

3.3 Analysis

The methods measure light in different units, illuminance, spectral irradiance and spectral photon radiance. Therefore, each method is evaluated alone, but compared statically, comparing the measurements at different sessions within each stable.

A Student's t-test was conducted in Microsoft Office Excel 2016 to test for general differences in means across the methods. The variables tested were: values measured with the lux meter for daytime and night-time lighting at the Swedish Livestock Research Centre; values measured with the Jaz spectrophotometer for daytime and night-time lighting at the Swedish Livestock Research Centre; values measured with the lux meter at morning and afternoon sessions at the conventional dairy barn; values measured with the lux meter at morning and evening sessions at the conventional dairy barn; values measured with the lux meter at afternoon and evening sessions at the conventional dairy barn; values measured with the lux meter for blue and red light at the Swedish Livestock Research Centre; values measured with the Jaz spectrophotometer for blue and red light at the Swedish Livestock Research Centre.

Correlation were tested between the lux meter and the Jaz spectrophotometer in daytime lighting measured at the Swedish Livestock Research Centre.

4 Results

In the following chapter, the results are presented. First, the measurements from the Swedish Livestock Research centre, followed by the measurements with a LED-light and at last the results from the conventional dairy barn is presented.

4.1 Swedish Livestock Research Centre

4.1.1 Lux meter

Registrations from the lux meter measured differences between daytime and night-time lighting (figure 6). In daytime lighting, the illuminance varied from 87 lux to 397 lux, and in the night-time lighting the illuminance varied from 2.4 lux to 139.4 lux. The illuminance varied within the barn in both daytime and night-time lighting, the highest measured values were found at measurement points straight below a light source.

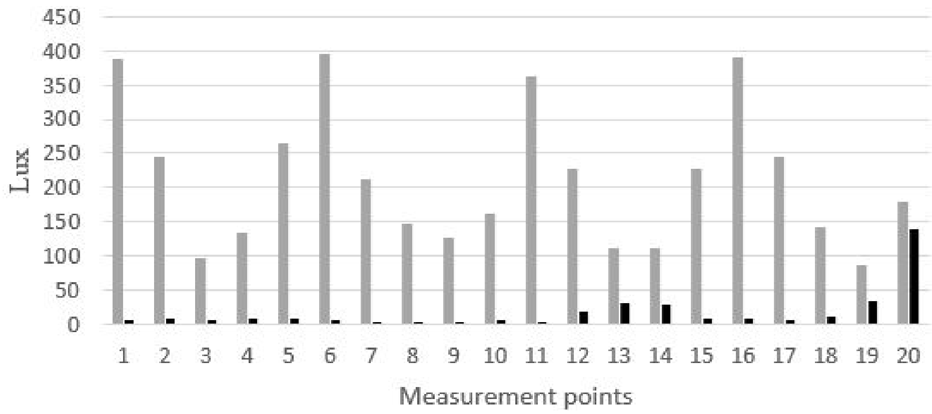

Figure 6. Registrations from the lux meter at Swedish Livestock Research centre, measured in lux, during daytime and night-time lighting.

4.1.2 Spectrophotometer

Registrations from the vertical measurements with the Jaz spectrophotometer in the daytime and night-time lighting (figure 7) were similar to the graph of the lux meter measured values. The values were measured in spectral irradiance, not illuminance. At four measurement points, during daytime lighting, the highest value of photon flux per wavelength was measured. Those four measurement points were straight below a fluorescent light source, and the same measurement points as mentioned for the lux meter. During daytime lighting, the measured values varied between 0.72 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$ to 4.93 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$, and during night-time lighting, the measured values were between 0.02 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$ to 1.47 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$.

Registrations from the horizontal measurements at every measurement point (figure 8 and 9) were different from the vertical measurements. Additionally, there were differences between the two horizontal measurements done at the same measurement point. The largest difference at one measurement point, during daytime lighting, was found at measurement point 15, where the measured value for horizontal one was 0.34 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$ and horizontal two 1.72 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$. During night-time, the largest difference was shown at measurement point 20, where the measured value for horizontal one is 0.06 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$, and horizontal two is 1.27 $\mu mol * s^{-1} * m^{-2} * nm^{-1}$.

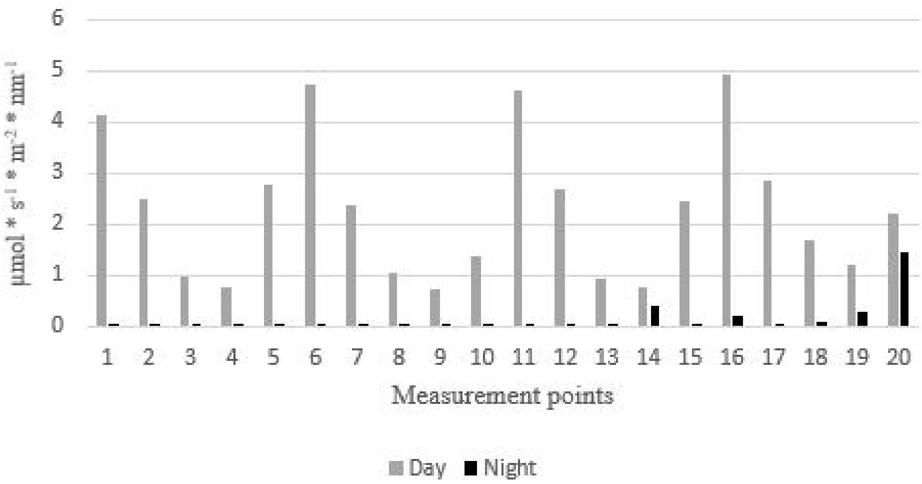

Figure 7. Registrations from Jaz spectrophotometer at the Swedish Livestock Research Centre, measured in $\mu mol * s^{-1} * m^{-2} * nm^{-1}$, vertically during daytime and night-time lighting.

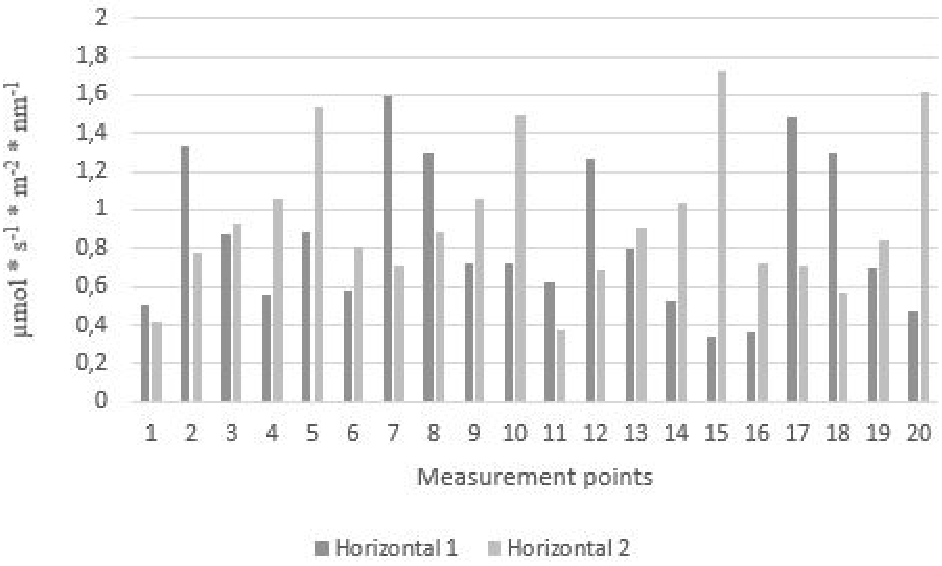

Figure 8. Registrations from Jaz spectrophotometer at the Swedish Livestock Research Centre, measured in µmol * s^{-1} * m^{-2} * nm^{-1}, horizontally during daytime lighting.

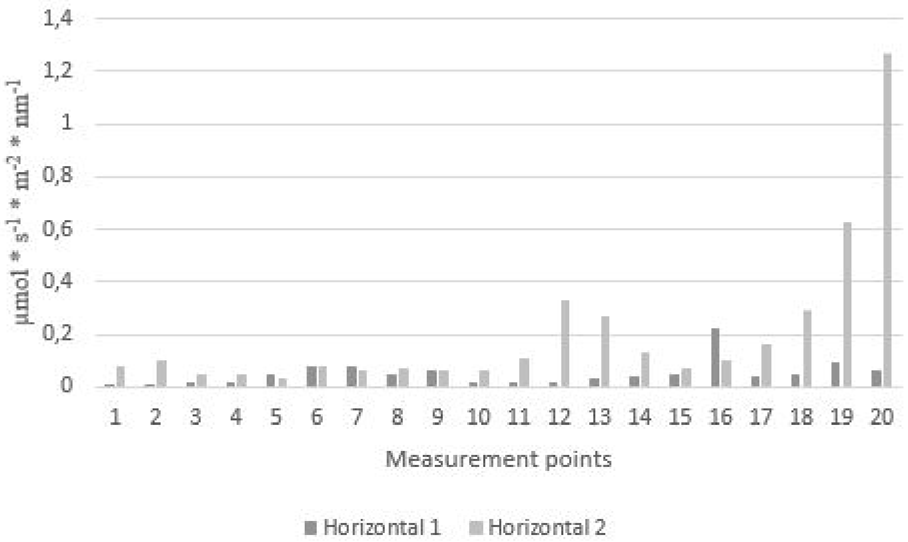

Figure 9. Registrations from Jaz spectrophotometer at the Swedish Livestock Research Centre, measured in µmol * s^{-1} * m^{-2} * nm^{-1}, horizontally during night-time lighting.

4.1.3 The ELF-method

The ELF-method measurements were analysed in two ways, firstly the light environment in the barn with a multiple scene analysis and secondly a single scene analyse. Registrations of the light environment from the ELF-method, horizontal measurements, measured a difference in the light intensity between daytime (figure 10) and night-time lighting (figure 11). In the daytime lighting the median spectral photon radiance varied from 13.8 LIT to 14.7 LIT, and in the night-time lighting, the median spectral photon radiance varied from 12.8 LIT to 14 LIT. The graphs show the median light intensity and peaks in the grey area show where the light intensity is higher e.g. a light source.

Registrations from the single scene analyse with the ELF-method indicated that there were differences between two horizontal measurements at the same measurement point. From the Jaz spectrophotometer analyse, two measurement points had the largest difference and the results from the ELF-method also indicates differences. Analyse from the measurement point 15 in daytime lighting (figure 12) show in the top graph the light intensity is lower than in the bottom graph. It results in two different light intensities for each angle, or for each eye of the cow. Similar results at measurement point 20 during night-time lighting (figure 13) where the difference in light intensity is greater.

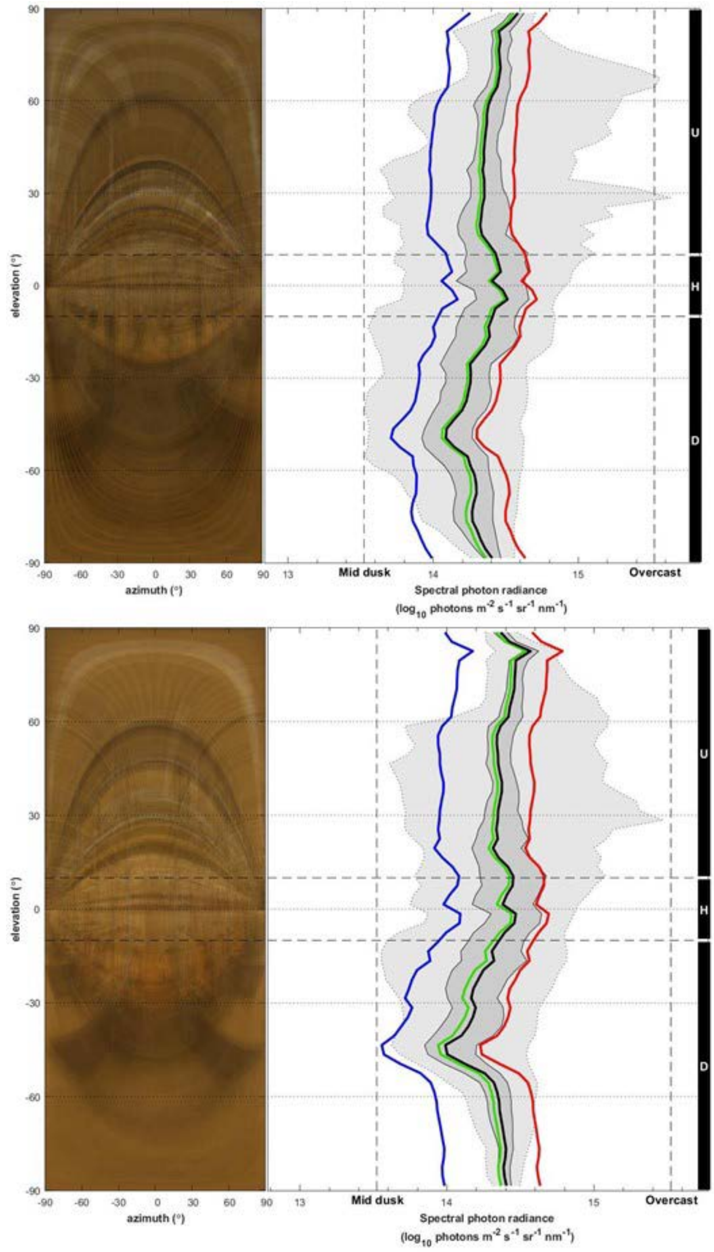

Figure 10. Registrations with the ELF-method, measured in LIT at Swedish Livestock Research centre. Multiple scene analysis including 24 individual exposures in daytime lighting side one and two.

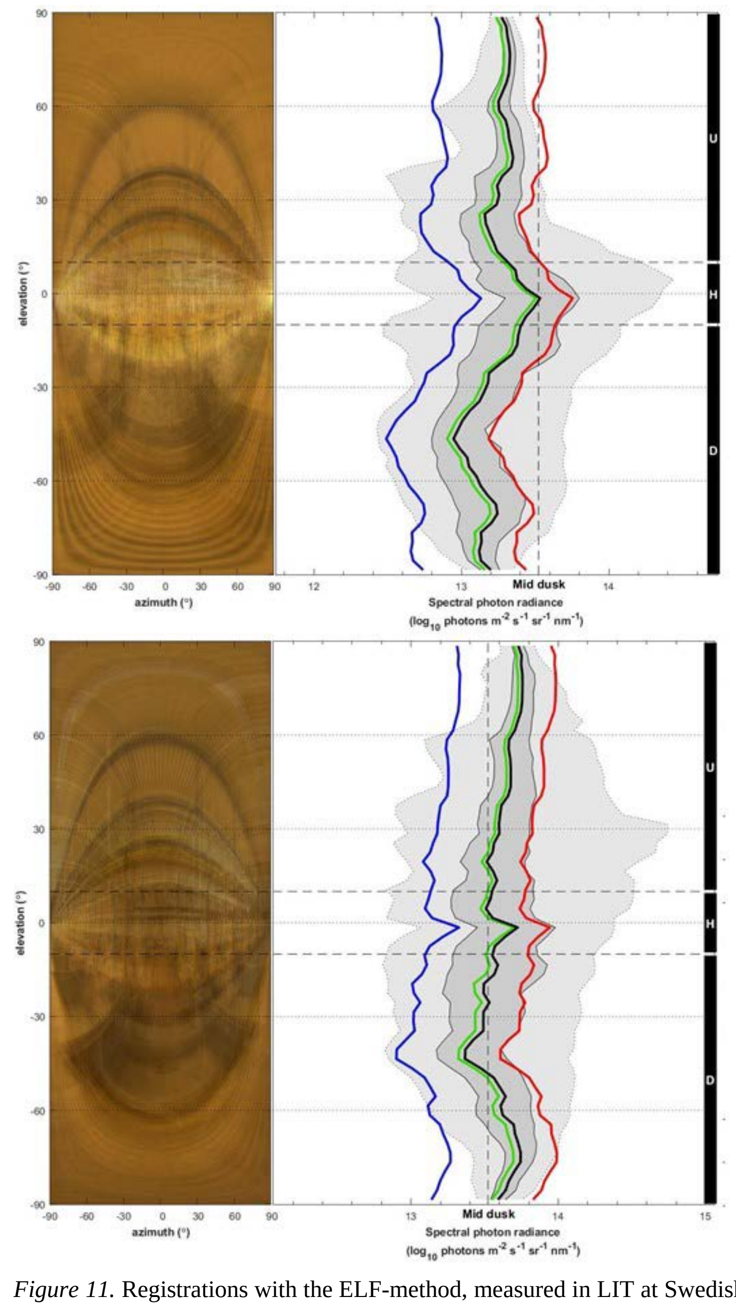

Figure 11. Registrations with the ELF-method, measured in LIT at Swedish Livestock Research centre. Multiple scene analysis including 24 individual exposures in night-time lighting side one and two.

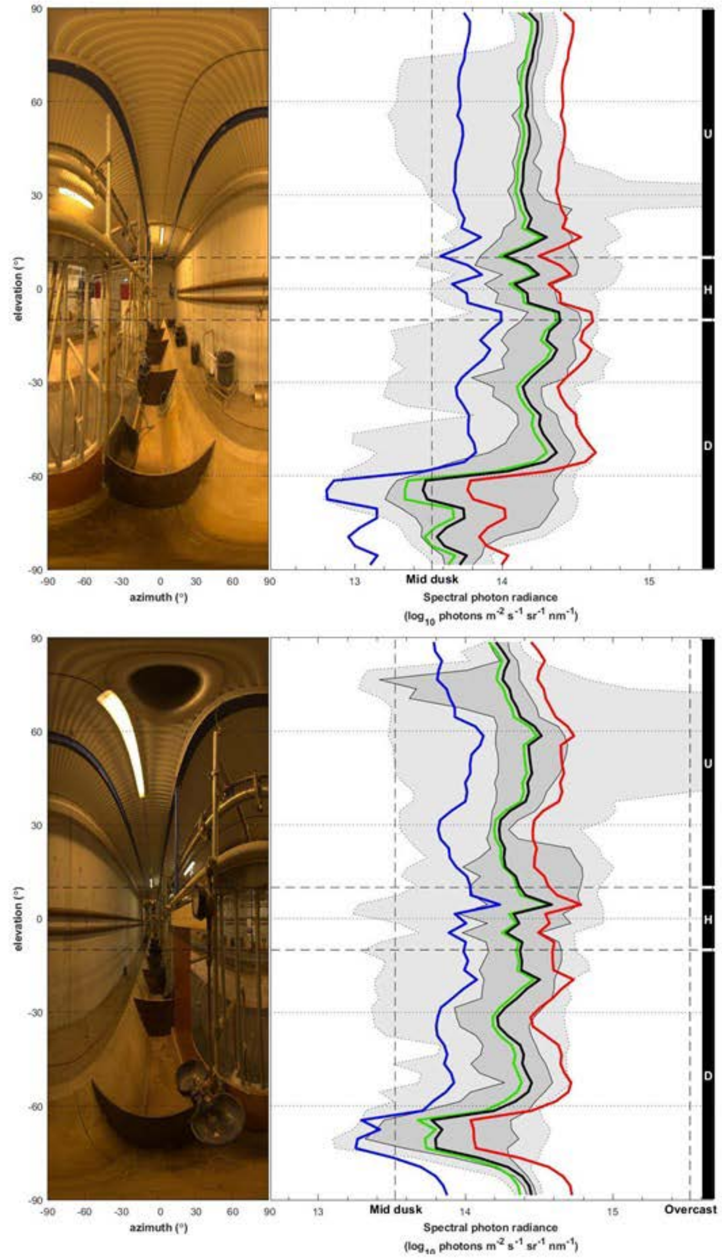

Figure 12. Registrations with the ELF-method, measured in LIT at Swedish Livestock Research centre. Single scene analyse during daytime lighting at measurement point 15.

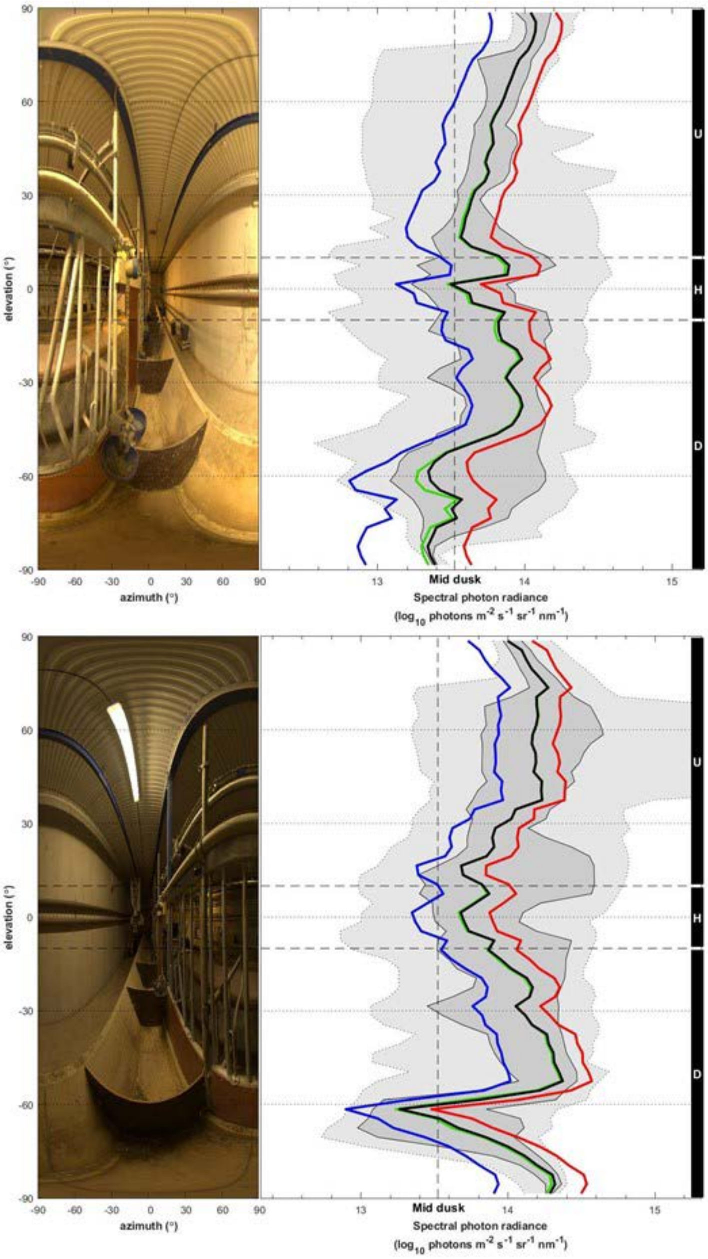

Figure 13. Registrations with the ELF-method, measured in LIT at Swedish Livestock Research centre. During night-time lighting, measurement point 20.

4.1.4 Analysis

The result of a Students t-test, between daytime and night-time lighting, with the lux meter and the vertical measurements with the Jaz spectrophotometer, with a P-value < 0.05, showed significant differences for both methods (table 5). In fluorescent light, both the lux meter and the Jaz spectrophotometer measured a significant difference between daytime and night-time lighting.

Table 5. Students t-test with registrations from daytime and night-time lighting. Both the lux meter and the spectrophotometer measured significant difference between daytime and night-time lighting.

	Lux	Jaz
Day and night	$1.409*10^{-7}$	$1.305*10^{-6}$

The result of a correlation between measurements in daytime lighting with the lux meter and the vertical measurements with the Jaz Spectrophotometer showed a very strong correlation, R^2= 0.8563 (figure 14), three outliers have been removed due to experimental errors.

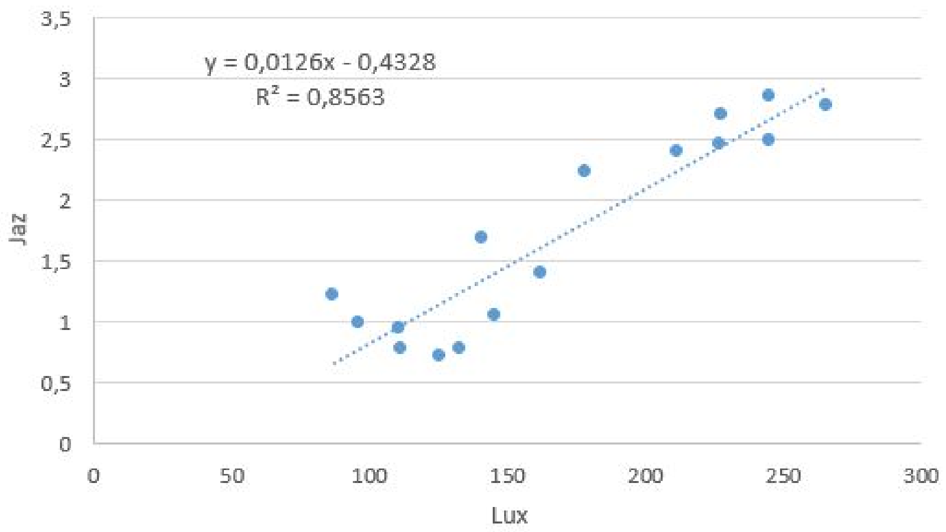

Figure 14. A very strong correlation in daytime lighting between lux meter and Jaz spectrophotometer.

4.2 LED-light

Registrations from the LED-light measurements with the lux meter showed some difference in lux between blue and red light (figure 15). Except, at measurement five and six, where the illuminance showed the similar values for the blue light as for the red light. The measured values with the Jaz spectrophotometer in with blue or red light were all different, also, at measurement five and six (figure 16).

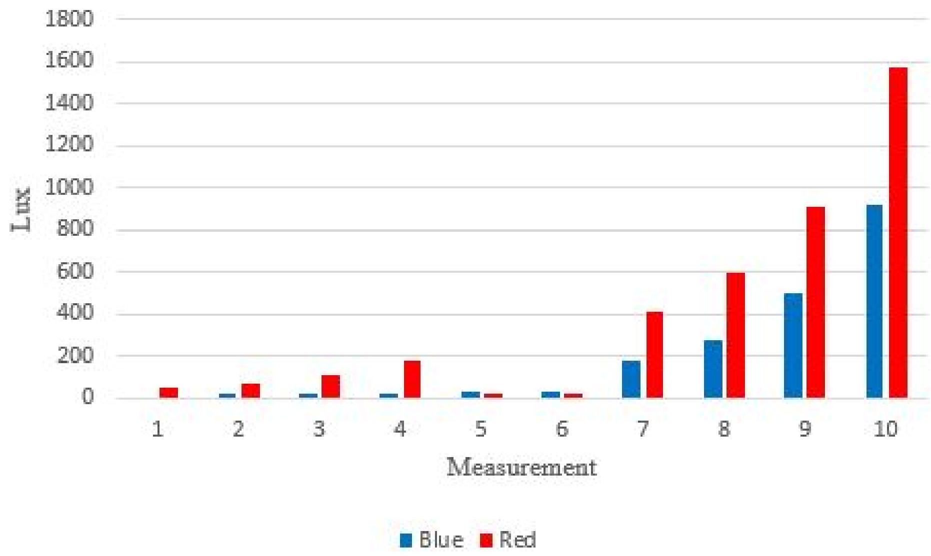

Figure 15. Registrations from the lux meter at Swedish Livestock Research centre, measured in lux, in LED-light with either blue or red light.

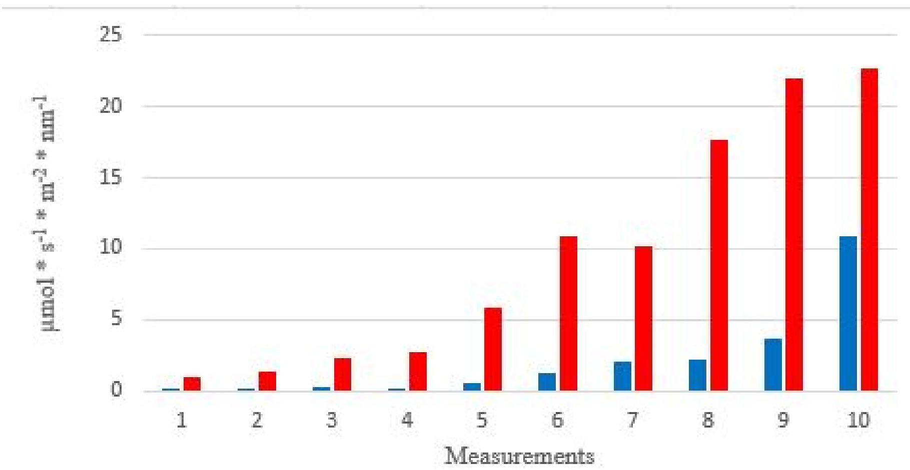

Figure 16. Registrations from Jaz spectrophotometer at Swedish Livestock Research centre, measured in lux, in LED-light with either blue or red light.

With the Jaz spectrophotometer the measured differences were also shown in graphs from measurement five (figure 17) and measurement six (figure 18), where the peaks are at the wavelengths for either blue (450 nm) or red (655 nm) light. The same measurements (five and six) where the lux meter did not measure any difference in illuminance.

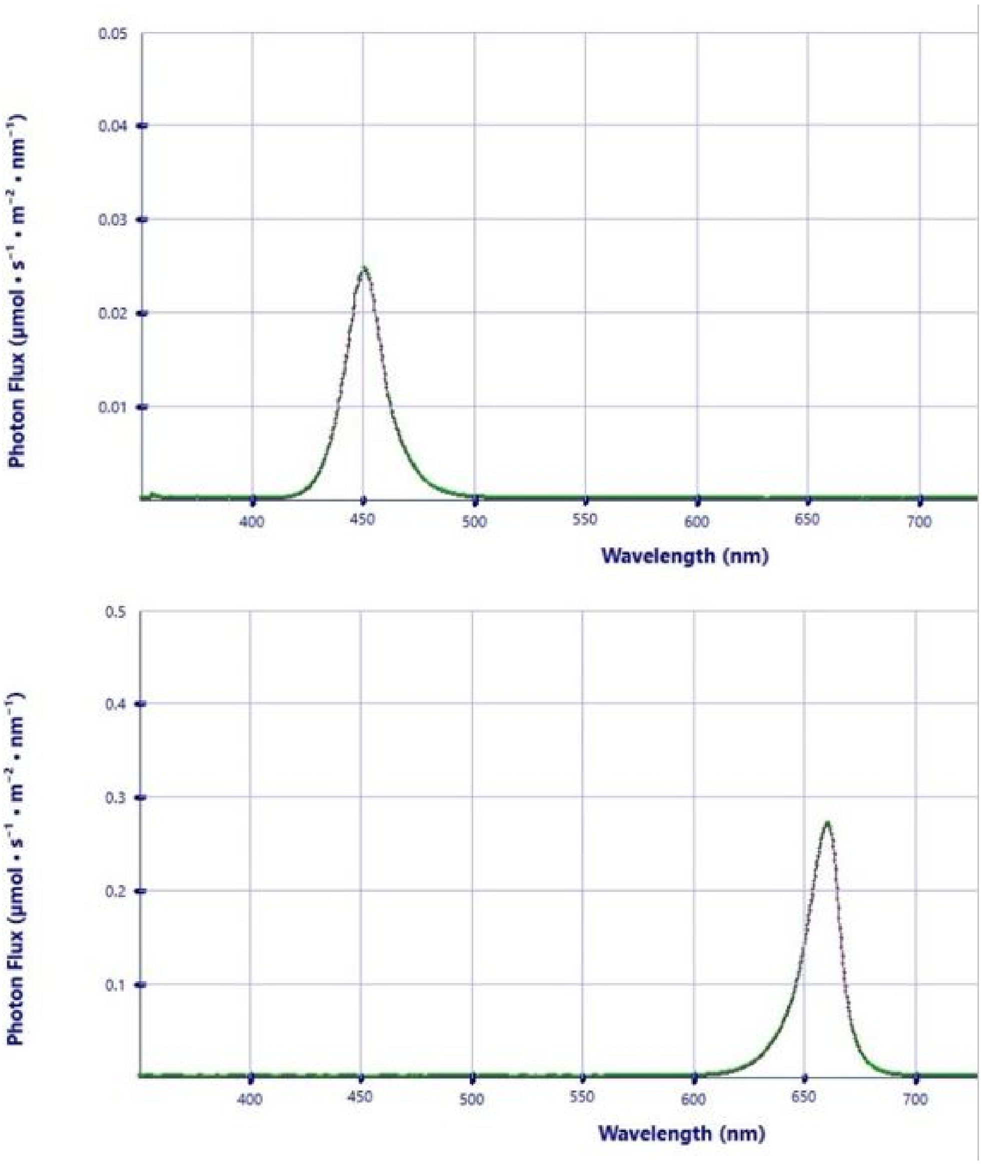

Figure 17. Registrations from Jaz spectrophotometer at Swedish Livestock Research centre, measured in µmol * s^{-1} * m^{-2} * nm^{-1}, in LED-light with either blue (top graph) or red light (bottom graph). Data from measurement five in LED-light.

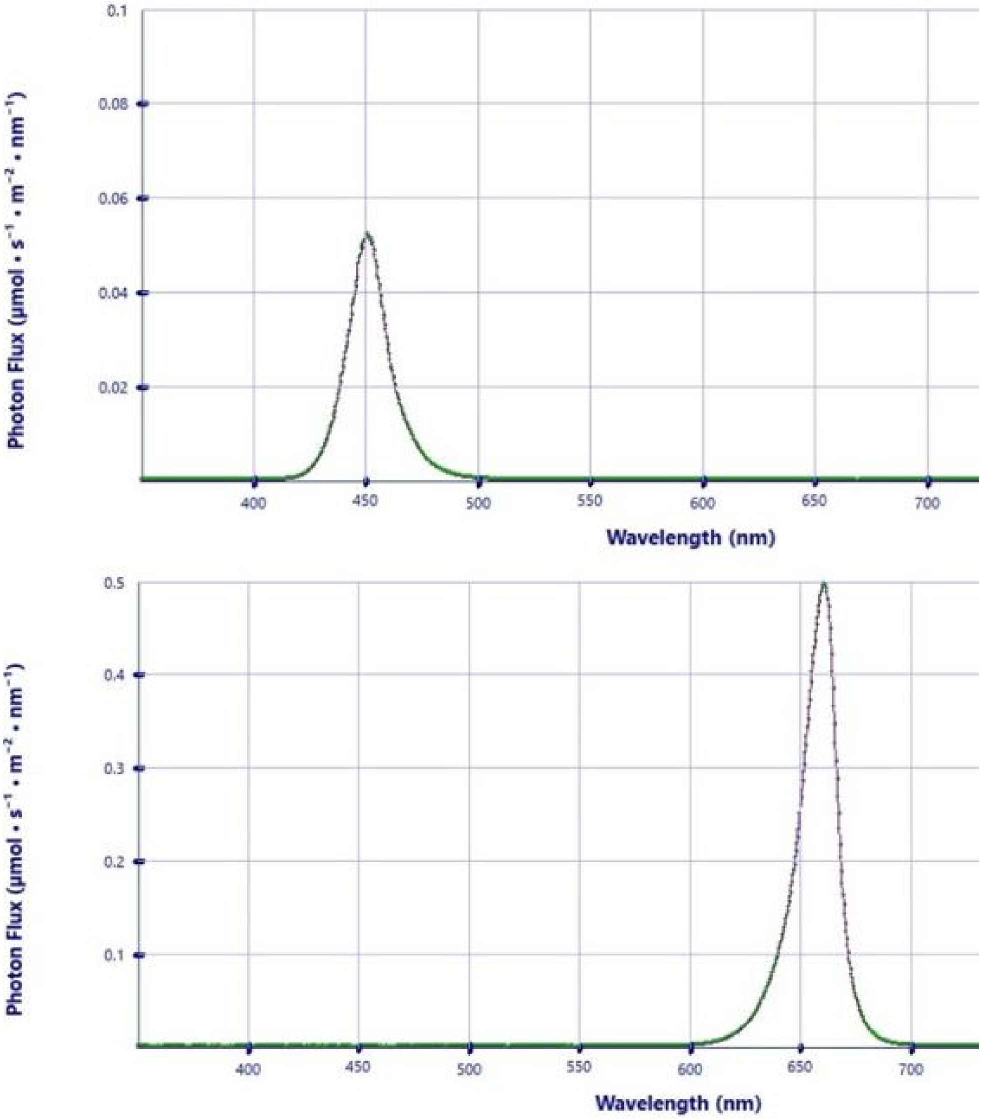

Figure 18. Registrations from Jaz spectrophotometer at Swedish Livestock Research centre, measured in µmol * s^{-1} * m^{-2} * nm^{-1}, in LED-light with either blue (top graph) or red light (bottom graph). Data from measurement six in LED-light.

Registrations from the LED-light measurements with the ELF-method showed the same kind of differences as the Jaz spectrophotometer. The measured differences in measurement five (figure 19) and measurement six (figure 20), show that it was either the blue or the red light that was dominant.

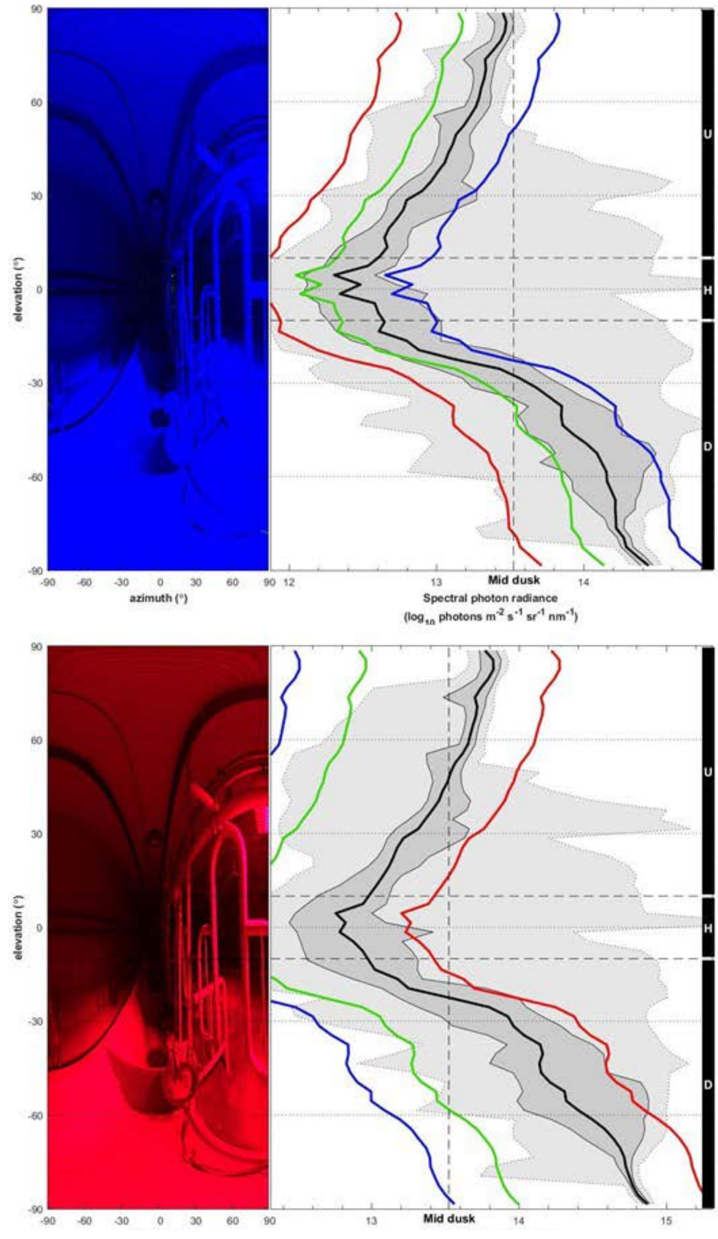

Figure 19. Registrations from the ELF-method at Swedish Livestock Research centre, measured in LIT, in LED-light with either blue (top graph) or red light (bottom graph). Single scene analysis from measurement five.

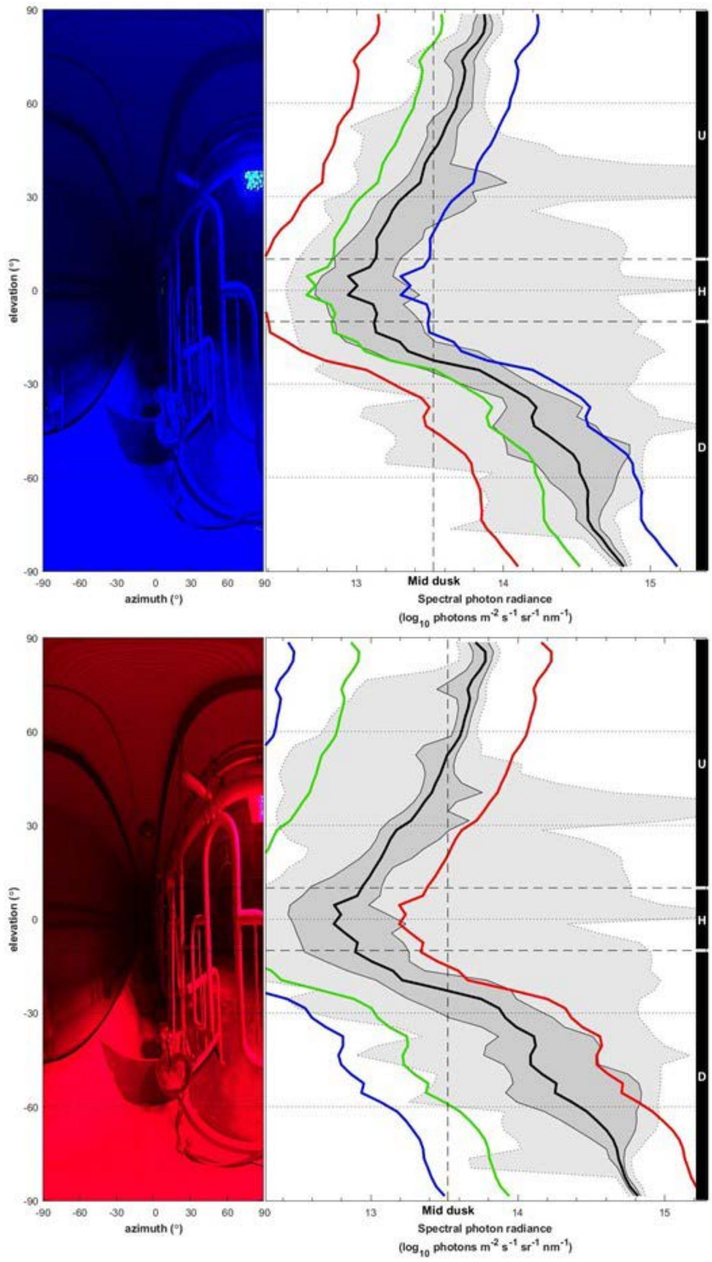

Figure 20. Registrations from the ELF-method at Swedish Livestock Research centre, measured in LIT, in LED-light with either blue (top graph) or red light (bottom graph). Single scene analysis from measurement six.

4.3 The conventional dairy barn

4.3.1 Light environment

Registrations from the lux meter shows differences between the three sessions, AM, PM, and evening (figure 21). During the first session, AM, the illuminance varied from 426 lux to 2020 lux, during the second session, PM, the illuminance varied from 131 lux to 1947 lux, and during the last session, evening, the illuminance varied from 4.2 lux to 121.7 lux. During the first and second session, the weather varied from cloudy to partly sunny.

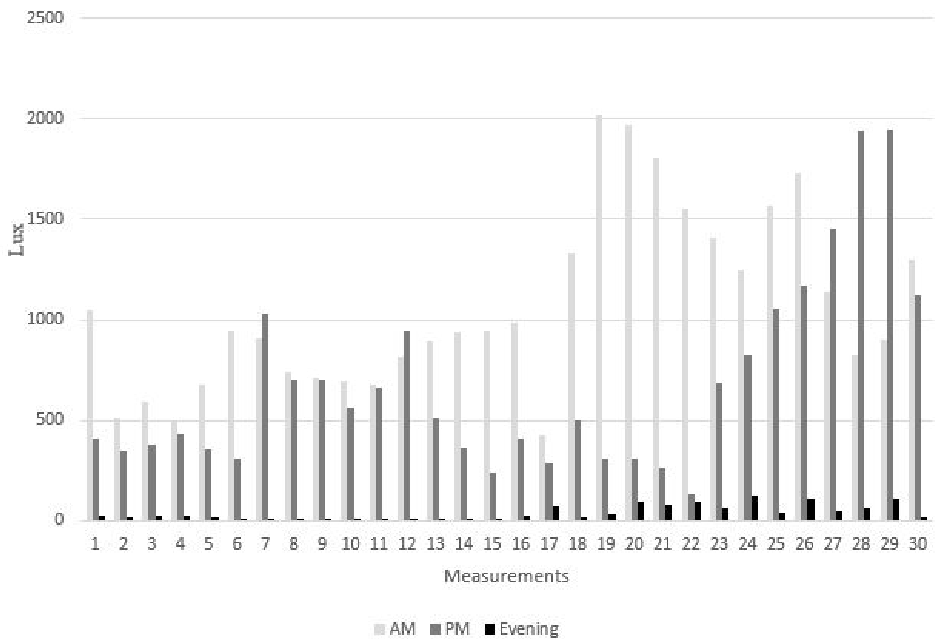

Figure 21. Registrations from the lux meter at the conventional dairy barn, measured in lux, during morning (AM), afternoon (PM), and evening, all sessions with daytime lighting.

Also, registrations from the ELF-method measured differences between the three sessions (figure 22). During the first session, AM, the median spectral photon radiance varied from 14.2 LIT to 15.7 LIT, during the second session, PM, the median spectral photon radiance varied from 13.8 LIT to 15.6 LIT, and during the last session, evening, the median spectral photon radiance varied from 12.6 LIT to 13.5 LIT.

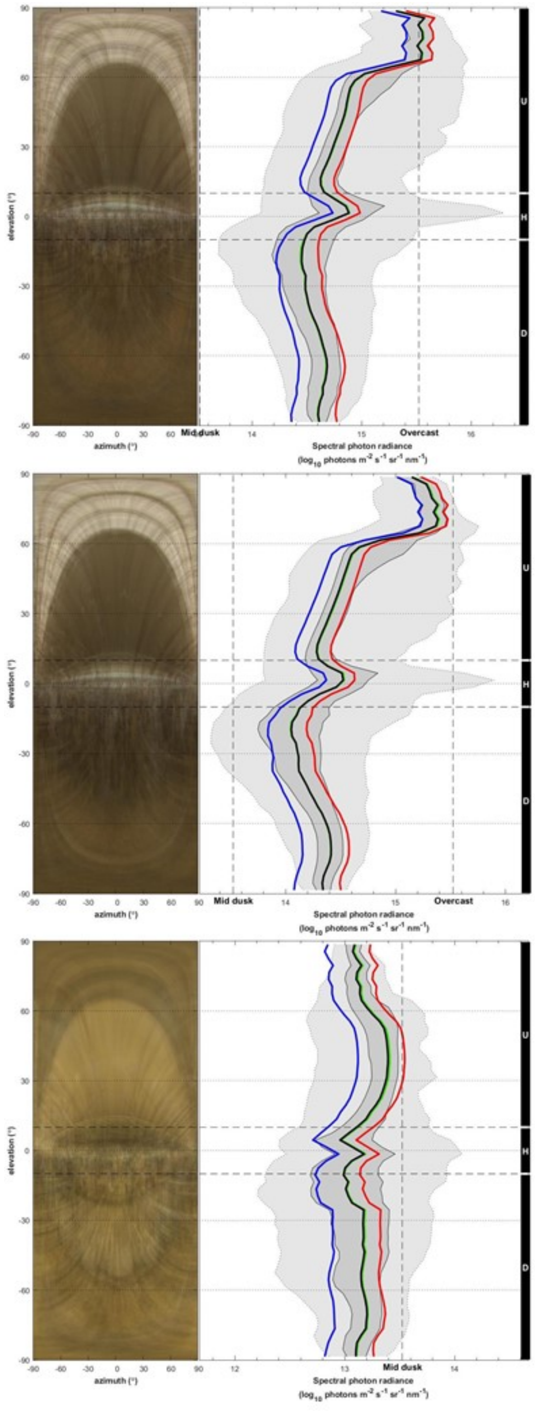

Figure 22. Registrations with the ELF-method, at the conventional dairy barn, measured in LIT, top left is during the morning (AM), top right is during the afternoon (PM), and at the bottom the evening, all sessions with daytime lighting. Multiple scene analysis.

4.3.2 Analysis

With a Students t-test it was shown that the lux meter measured significant differences between the different sessions (table 6), with a P-value < 0.05. The highest significance was shown between the AM and evening measurements.

Table 6. Students t-test with registrations from the conventional dairy barn with the highest significance between the AM and evening measurements.

	Lux
AM & PM	0.007
AM & Evening	$2{,}932 \cdot 10^{-13}$
PM & Evening	$2.417 \cdot 10^{-8}$

4.3.3 Single scene analysis

The single scene analysis with the ELF-method showed differences in light intensity during one day at one specific place in the barn. One single scene included the place of a cow brush and a water bowl, showed a light intensity of 14 – 15 LIT during AM and PM, compared to during the evening when the measured value was between 11.6 – 13 LIT (figure 23). Measured values with the lux meter was 1045 lux in the AM and 3 lux in the evening.

Another single scene showed the walking alley for cows from the milking parlor to the cubicles. The ELF-method measured light intensities between 14-17 LIT during AM and PM and 12.4-13.6 LIT in the evening (figure 24). Measured values with the lux meter was 1532 in the PM and 7.8 lux in the evening.

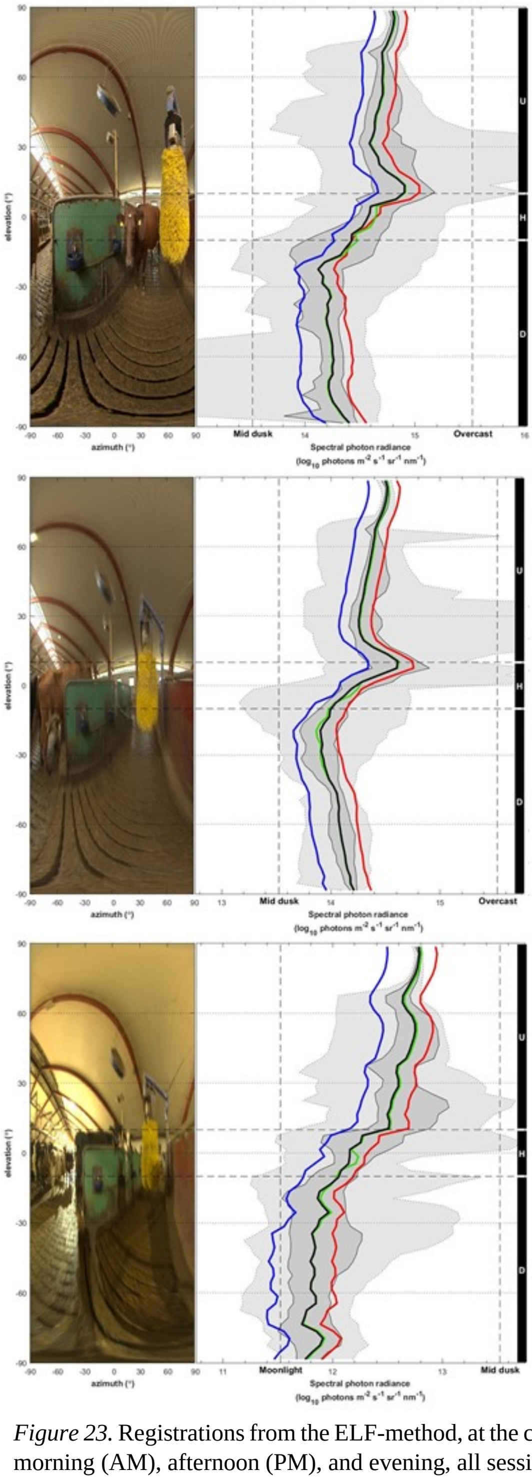

Figure 23. Registrations from the ELF-method, at the conventional dairy barn, measured in LIT, during morning (AM), afternoon (PM), and evening, all sessions with daytime lighting.

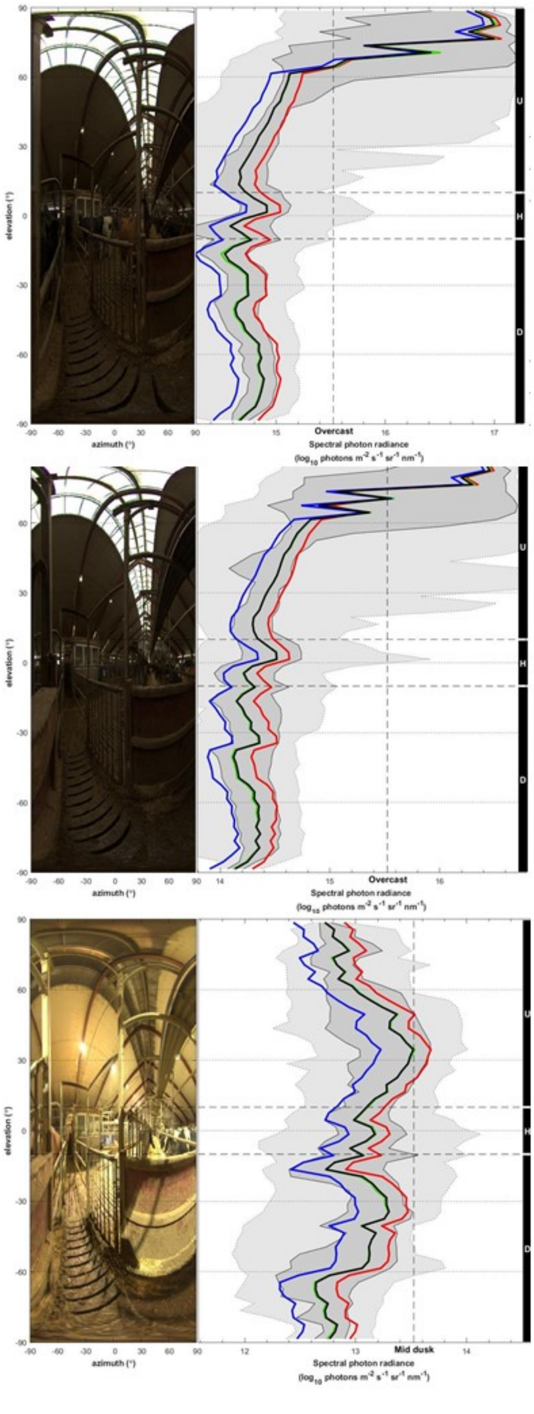

Figure 24. Registrations from the ELF-method, at the conventional dairy barn, measured in LIT, during morning (AM), afternoon (PM), and evening, all sessions with daytime lighting.

5 Discussion

5.1 Recent light studies

Only a few studies within this field of research (table 3) mention how they measured the light intensity in their field study, though the majority mentioned how many lux the animals were treated with. In this field study, the result from the Swedish Livestock Research Centre shows that there can be large variation within one barn in light intensities (figure 6, 7, 10 and 11). The differences were shown in lux, spectral irradiance and spectral photon radiance. The higher measured light intensities were discovered directly below a fluorescent light source. A barn with daylight inlets, the conventional dairy barn, also has significant differences in light intensity between different times of the day (figure 22, 23, 24, and table 6). For future light treatment studies each cows´ light intensity treatment when tied, or a complete light intensity drawing over the barn when loose housed, is essential to quantify the result of the actual treatment.

The three different methods included in this study measure light in different units. The different lighting metrics complicates the understanding of different light treatments. However, the different lighting metrics gives different information about the light environment that all can be useful in different situations. Both the lux meter and the Jaz spectrophotometer gives an average measurement from the area where the light is sampled, compared to the ELF-method where it is possible to distinguish in what elevation angle the photon flux is the most intense. The ELF-method resembles information that corresponds with the assumed field of vision and the method can be used when designing light in a barn or when evaluating a light environment. Also, the Jaz spectrophotometer gives a broader analyze than the lux meter about the light environment. This can be useful when designing a light environment, regarding the placement of light sources and when choosing the light frequency and intensity. Due to the visualized analysis from both the Jaz spectrophotometer and the ELF-method, these methods can give improved guidance when designing a light environment, compared to the lux meter that only gives a single value per measurement. This field of research would be enlightened from using one comparable lighting metrics. Additionally, one comparable lighting metric would simplify the results to a broader public. From the results in this paper, the suggestion would be to use photons per wavelength or LIT.

However, the reference base for measured values with a lux meter is large, which makes the correlation between the Jaz spectrophotometer and the lux meter interesting. The strong correlation in daytime lighting (figure 14) is probably due to the high occurrence of light within the sensitive spectra for the lux meter. It results in, that a lux meter is useful in light with high occurrence of green light, however, when adding more blue or red light the lux meter becomes unusable. Because, the peak of both blue and red light is not included within the sensitive spectrum of the lux meter.

5.2 Effects of light of different color

Measurements with a lux meter does not show color occurrence nor the variation of photon flux over the wavelengths spectra. This lack of information complicates when designing light in barns with LED-technology. Since the possibility to customize the LED-light at specific colors and light intensity after request. When designing light in a dairy barn with LED-light a spectrophotometer or the ELF-method is preferable. The effects of light on those specific wavelengths, on dairy cows' production and welfare is, today still unknown.

Melanopsin is most sensitive to shorter wavelengths (blue light) and therefore, blue light can be important for the diurnal rhythm. The ELF-method show clearly (figure 10, 11, 12, 13, 22, 23 and 24) that all measurements in the dairy barns include blue, red, and green light. All measurements with the ELF-method and the Jaz spectrophotometer had the highest occurrence of red light which corresponds with the findings of Wickström (2016). Since the color occurrence might influence the cow's behavior and welfare, a measurement method that includes color occurrence is preferable.

5.3 Vertical or horizontal measurement

According to Jeppsson et al. (2014) and Starby (2006), measurements when designing light, is done vertically. A vertical measurement gives the opportunity to get an overview of the light intensity in the barn (figure 6, 7 and 21). However, a dairy cow's eye is placed laterally (Sjaastad et al., 2012) and (figure 8, 9 10 and 11) a horizontal measurement gives another result compared to a vertical measurement. Also, a horizontal measurement gives a different result depending on what direction the instrument is faced, when doing the measurement. At the Swedish Livestock Research Centre with tied cows, one cow can have the light intensity of 0.06 photons per wavelength or 13.4 LIT from one side and on the other side the light intensity of 1.27 photons per wavelength or 14.6 LIT (figure 8, 9, 12 and 13), depending on which eye that is in focus for each measurement. At this specific measurement point it would be of interest to measure the cow's pupil size to get an idea of how many photons that can possibly reach the retina.

When measuring light, both vertical and horizontal, it is important not to cover the instruments measurement area (Starby, 2006). Vertical measurements are easy to, by mistake, cover by the person doing the measurement, and horizontal measurement can be affected by animals or other obstacles in front of the instrument. Furthermore, the variations in the horizontal measurement indicate the difficulties to use a horizontal measurement when designing indoor light in a barn, especially when it is a loose housing system. A vertical measurement might be better to get an overview of the light dimensions in the barn (figure 6, 7 and 21). Thereafter, to ensure that the light intensity is optimized for the cows' welfare, horizontal measurements could be an option at some specific places in the barn. For example, walking alleys, milking parley, feed ally, and cubicles. At the conventional dairy barn, some singles scenes were analyzed and showed differences in light intensity over a day (figure 23 and 24).

Cattle have a small field of binocular vision, but close to 360º panoramic vision (Dyce et al., 2010; Grandin, 1980). Therefore, to enable a measurement that resembles a cows' field of vision, two horizontal measurements in different directions summed together, is presumably be the best option. From the analyzes with the ELF-method it is possible to see where in the photo the light source is, and the occurrence of colors in every angle from the horizon. That enables to notify possible light disturbances and areas with high or low light intensities.

Additionally, a horizontal measurement gives the opportunity to measure the possible light intensity that reaches the eye. As mentioned above, it is difficult to know how many photons that reach the eye without measuring the size of the pupil. Since, it is the size of the pupil that regulates the amount of light that reaches the retina (Dyce et al., 2010). It would be of high interest to measure the size of the pupil and compare it with the measurements with the Jaz spectrophotometer and the ELF method. Maybe, the adjustment of the pupil's size corrects for the different light intensities in different directions.

5.4 Light programs

The significant results in light intensity between daytime and night-time lighting at the Swedish Livestock Research Centre (table 5) corresponds with previous reports about the important changes in light intensity within 24 hours to maintain diurnal rhythms. The significant difference is calculated from the mean measured values in the tie barn, which differs from the measured values when looking at one specific measurement point. At some measurement points there were no significant difference between daytime and night-time lighting (figure 6 and 7). This is important since lack of changes in light intensity could have a negative impact on the cows' well-being, production and behavior (Dahl et al., 2011; Dahl and Petitclerc, 2003; Hjalmarsson et al., 2014; Phillips et al., 2000). Additionally, changes in light intensity is important for the cow's diurnal rhythm (Piccione et al., 2011) and the results from some measurement points (figure 6 and 7) does not support any great changes in light intensity. The lack of changes in light intensity within 24 h highlights the difficulties when designing light in dairy barns. The source of light during night-time needs to be designed to a place where it does not disturb the cows.

The significantly brighter daylight in the conventional barn (table 6) highlights the impact of having daylight inlets in terms of energy savings and when designing a light program. A future development could be light sources that are programmed after sensors that follows the amount of daylight available. Maybe that could create a light environment that are both energy saving and corresponds with the daylight outside. Those sensors should measure the spectral irradiance or the spectral photon radiance to give information about both the light intensity and the color occurrence.

In a loose housing system, dark passages should be avoided (figure 23 and 24), since it affects cow's walking behavior (Hjalmarsson et al., 2014; Phillips et al., 2000). To avoid dark passages light sources could be strategically placed by walking passages and areas that are important for the work environment for the barn staff.

6 Conclusion

It is probably possible to measure light in a way that corresponds well with how light can reach the cow's eye, either with a spectrophotometer or with the ELF-method due to their advanced analysis. A lux meter is not the optimal choice, since it is most sensitive for a wavelength spectrum that is not the same as for cow's eye. When quantifying light for dairy cows, a spectrophotometer or the ELF-method is recommended to use and the ELF-method have the greatest potential since it is easy to handle in a cow barn environment. However, values measured with a lux meter are easy comparable with the large base of reference values since it is the most commonly used measurement.

The actual light intensity treatment is of great importance when measuring how the light affect dairy cows' production and welfare. Therefore, from the results of this study one universal light unit when measuring light for dairy cows is requested, preferably spectral irradiance or spectral photon radiance.

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