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# Research Opportunities in Environment Control of Confined Animal Housing Systems through Precision Livestock Farming

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**ABSTRACT** Environment control in confined animal housing systems is typically based on heat and moisture production rates at predetermined ambient temperature levels measured between 1950 and 1980 (ASABE and ASHRAE Standards). This traditional method can fall short in meeting the true thermal needs of the animals as it does not account for factors, such as humidity, drafts, radiation, physiological state, and social interactions, now acknowledged as affecting the animal's productive responses to surrounding conditions. Meanwhile, advancements in animal genetics, nutrition, and management practices have likely led to considerable changes in sensible and latent heat loads of modern livestock buildings. Therefore, there is a need to update heat and moisture production data for proper design of ventilation and heating systems and to develop multi-factor animal comfort indices for supporting rational environmental management decisions. In this context, precision livestock farming technologies (sensors, detectors, cameras, microphones, etc.), enabling a continuous, automatic monitoring of meteorological (temperature, relative humidity, and air speed at the animal level), physiological (body temperature or weight, respiration or heart rate, and milk or egg yield), and behavioral (activity, movement, and feed and water intake) variables, can be used to assess livestock performance and well-being.

**Keywords:** livestock, housing, environment control, smart farming, sensors.

**INTRODUCTION** The demographic growth along with rising incomes and urbanization in developing countries will increase the pressure on the world's livestock sector to meet the growing demand for animal products (Thornton, 2010). Since the number of farms is decreasing, the rise in livestock production will be achieved through intensification, resulting in larger farms. Furthermore, as consumers demand that animals be raised in a more humane way, animal welfare and health is putting additional pressure on livestock management practices. To ensure sufficient attention and care to animals and economically viable businesses, there is a need for modern livestock facilities to start monitoring animal behavior and health in addition to environmental conditions (Koenders et al., 2015).

Nowadays availability and accessibility to technological applications such as smart sensors, detectors, cameras, and microphones allow for the implementation of integrated management systems of animal husbandry. Such systems should be based on continuous, real-time monitoring of production, animal welfare and health, as well as environmental conditions. They enable farmers to instantaneously detect thermal stress, infection, or air quality problems and in response take immediate actions (Nääs et al., 2006; Groot Koerkamp et al., 2007; Banhazi et al., 2012; Berckmans, 2014). Such an approach has been referred to as precision livestock farming (PLF).

Animal comfort in confined livestock housing systems is typically based on heat and moisture production rates at predetermined ambient temperature levels measured between 1950 and 1980. This traditional method can fall short in meeting the true thermal needs of the animals since it does not always account for factors such as humidity, drafts, radiation, physiological state, and social interactions, now acknowledged as affecting the animal's productive responses to surrounding conditions. Meanwhile, advancements in animal genetics, nutrition, and management practices have likely led to considerable changes in sensible and latent heat loads of modern livestock buildings (Shao and Xin, 2008; DeShazer et al., 2009; Brown-Brandl et al., 2014). In this context, PLF could be the guiding concept for the development of an advanced control system based on automatic monitoring, at an appropriate frequency, of meteorological, physiological, and behavioral variables. It would also require, as illustrated in Figure 1: animal comfort indices to interpret measurements and an online controlling system to modify the animal microenvironment when critical thresholds are breached according to predetermined criteria and bioenergetic models (Wathes et al., 2008; Banhazi et al., 2012). The objective of this paper is to review these aspects and discuss research opportunities in precision environment control of livestock buildings.

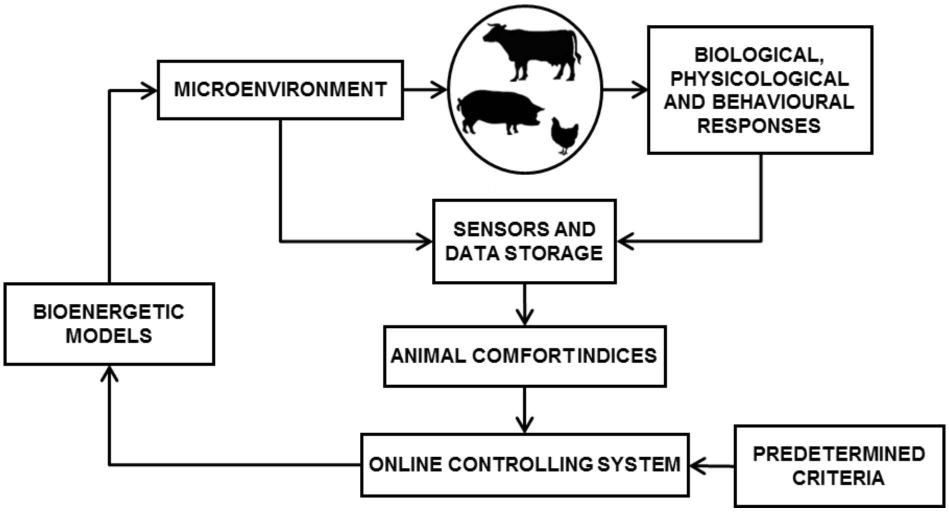

Figure 1. Schematic overview of the key components of environment control through precision livestock farming; adapted from Wathes et al. (2008).

**ANIMAL HEAT AND MOISTURE PRODUCTION** Intensive livestock production requires a proper building environmental control system to maximize animal well-being and productivity. Environmental modification is usually accomplished by ventilation (natural or mechanical), supplemental heaters for cold winter conditions, and cooling equipment for hot summer conditions. In order to effectively control environmental conditions within the facility, ventilation rates and heating or cooling needs are determined based on heat and moisture production values.

***Overview of bioenergetics models*** Assessment of heat losses from livestock buildings has been accomplished through numerous calorimetric and housing systems studies since the 1950s. Measurement of heat transfers between an animal and its environment has led to the development of livestock bioenergetic models. Mathematical modelling of animal heat production can be divided into three categories: empirical, mechanistic, and physiological (Wathes et al., 2008; Bridges and Gates, 2009).

Empirical models are essentially based on experimental observations or experience. They were mostly developed in the years 1945–1970 to predict the growth and thermal performance of animals as influenced by their environment (Bridges and Gates, 2009). Total (THP), sensible (SHP), and latent (LHP) heat production data of most significant empirical contributions can be found in published standards from the American Society of Agricultural and Biological Engineers (ASABE, 2012) and American Society of Heating, Refrigerating, Air Conditioning Engineers (ASHRAE, 2005). Although empirical methods have the advantage of a simple model structure with only few parameters, their application is often restricted to the conditions prevailing during the experimental tests from which the simulation results originated and may not be valid when conditions are beyond the range investigated (Bridges and Gates, 2009).

Mechanistic or deductive models are primarily based on theoretical analyses of the interaction of the system components, supplemented with empirical values if needed. They offer a means of predicting heat production under a broader range of conditions than do empirical models by integrating, for instance, nutrition, genetics, and carcass characteristics (Bridges and Gates, 2009). The approach was mainly developed in the 1970s and 1980 for cattle (Lofgreen and Garrett, 1968; Paine et al., 1974; Hellickson et al., 1978; Keener, 1979), swine (Teter et al., 1973; Holmes and Close, 1977; Close and Mount, 1978; Bruce and Clark, 1979; Black et al., 1986; DeShazer et al., 1988), and poultry (Emmans and Charles, 1976; Reece and Lott, 1982; Zulovich and DeShazer, 1990). Besides, the International Commission of Agricultural and Biosystems Engineering (CIGR) formed a working group on climate control of animal houses at the end of the 1970s to establish and update design standards for proper sizing and operation of ventilation, heating, and cooling equipment inside livestock buildings (Pedersen and Sällvik, 2002). The CIGR approach was founded on biological principles and the equations developed mainly depend on body mass, production (meat, milk, eggs, etc.), and energy concentration in feed as animals dissipate heat due to maintenance of their essential functions and productivity. The last CIGR procedure published in 2002 includes equations for total heat production at normal temperature, correction of temperature, and partition of heat production into sensible and latent components. Globally, mechanistic models sometimes include too many variables thus making them very complex (Bridges and Gates, 2009).

Physiological models are dynamic and aim at modeling the interactions of nutrient intake and digestion, degree of satisfaction of body maintenance demands, growth potential, tissue accretion, and the effects of ambient environment. Physiological models differ from mechanistic methods in that the body's interactions with the various components are used to simulate the animal's growth responses and heat production (Bridges and Gates, 2009). BABYBEEF (Loewer et al., 1983a; Loewer et al., 1983b) and NCPIG (Bridges et al., 1992a; Bridges et al., 1992b; Usry et al., 1992) are two examples for cattle and swine, respectively.

***Relevance of existing heat production standards and models*** Through the years, animal bioenergetic models have been developed to assess the quantity of energy produced by livestock, considering one or many factors. While the precision and complexity of physiological models may not be necessary for engineering calculations, empirical and some mechanistic approaches represent the standard approach to assess a priori total, sensible, and latent heat fluxes from livestock (e.g., ASABE and ASHRAE Standards). Although the collected data are extensive, they come from studies carried out between 1950 and 1980 and are often not continuous by weight or age. Advancements in animal genetics, nutrition, and management practices since then have led to significant changes in heat and moisture production rates of modern livestock housing systems (Brown-Brandl et al., 2014; Stinn and Xin, 2014).

Chepete and Xin (2001) conducted an extensive survey of heat and moisture data for poultry which clearly demonstrated increases in THP over the period 1953–2000. Chepete et al. (2004) also revealed that modern pullets have significantly higher (12% to 37%) THP than pullets of 20 to 50 years ago and that some layers at the initial stage of egg production showed 12% higher THP than that predicted by CIGR model (Pedersen and Sällvik, 2002).

Brown-Brandl et al. (2004) reviewed heat production data of pigs between 1936 and 2002. They noted that heat production under thermoneutrality was 17.4% higher during the period 1988 to 2002 than during the period prior to 1988. Later, Brown-Brandl et al. (2014) conducted a series of four indirect calorimetry studies (nursery, growing, finishing gilts, and finishing barrows), and six facility-level studies (nursery, growing, early finishing, late finishing, gestating gilts, and farrowing sows and litters). It was found that THP of modern pigs is 16% higher than the current standards indicate. Similarly, the values of Stinn and Xin (2014) for gestation sows in their early and late pregnancy stages showed increases of 35% and 12% in THP, 19% and 3% in SHP, and 72% and 34% in LHP, respectively, when compared with the standards (ASABE, 2012). Values for lactating sows and litters during the first week after parturition showed changes of 29% in THP, 6% in SHP, and 52% in LHP relative to the same standards. The reductions of THP from day to night for the three stages were 30% (early gestation), 27% (late gestation), and 6% (lactation).

Finally, the early research approaches to describe the interaction of a growing animal with its environment are not as applicable today as they once were. These studies indicated in the standards are currently underestimating heat and moisture production. This in turn causes ventilation designs to be undersized. Standard values and bioenergetic models should therefore be updated to reflect current animal genetics, nutrition, and housing characteristics in the manner of recent indirect calorimetry studies (Chepete et al., 2011; Hayes et al., 2013; Brown-Brandl et al., 2014; Stinn and Xin, 2014).

**THERMAL INDICES FOR ANIMALS** Conventionally, ventilation is designed to control indoor temperature based on outside hot weather conditions using total heat production and to manage relative humidity in cold weather conditions using moisture production. This traditional method can however fall short in meeting the true thermal needs of the animals because of limitations of these factors alone as control parameters of the livestock housing environment. Indeed, the method does not always account for factors such as drafts, radiation, physiological state, and social interactions, now acknowledged as affecting the animal's productive responses to its surrounding conditions (Shao and Xin, 2008; DeShazer et al., 2009). Consequently, many attempts to characterize the environmental aspects of farm buildings have led to the development of animal comfort indices (ACIs) as complementary tools for assessing the complex interactions between the physical and biological components of the environment (Nääs and Moura, 2006; Hahn et al., 2009; Brown-Brandl, 2013). Actually, farm ACIs (Appendix A) have been used to provide guides for environmental management and assessment of risk for losses through linkages with responses related to physiology or animal productivity. The linkage is based on observations of a selected performance criterion (e.g., body temperature, respiration rate, growth, milk or egg production) made concurrently with measures of the environment (temperature, relative humidity, radiation, and air speed). These serve as inputs for the ACI and an empirical relationship or biologic response function is developed to predict the response of animals to thermal load.

### *Overview of animal comfort indices*

The first indices were developed for evaluating the heat tolerance of cattle based on rectal temperature and respiration rate (Rhoad, 1944; Benezra, 1954; Bianca, 1963). Bianca (1962) then assessed rectal temperature of bull calves as a combination of dry- and wet-bulb temperatures. This work led to the temperature-humidity index (THI), which was first applied by Johnston et al. (1962) to determine the effects of both parameters on milk production and comfort of cows. Numerous studies further adjusted THI for different types of livestock (Ingram, 1965; Roller and Goldman, 1969; Johnson and Vanjonack, 1976; NOAA, 1976; Zulovich and DeShazer, 1990). In addition, THI has been used as the basis for the livestock weather safety index (LWSI) to describe categories of heat stress (normal = THI <74, alert = 74<THI<79, danger = 79<THI<84, and emergency = THI >84) for animals (LCI, 1970). The joint analysis of temperature and humidity has also served to develop other ACIs such as enthalpy, which indicates the quantity of thermal energy into the air surrounding the animal to be removed from the environment to enable thermal conditions of survival inside a building (Beckett, 1965; Moura et al., 1997; Rodrigues et al., 2011).

Generally, THI adequately represents the overall impact on animals since temperature and humidity influence much of the heat exchange impacts of warm and hot thermal environments. However, THI has recognized limitations related to radiation heat loads and air speed (Hahn et al., 2009; Gaughan et al., 2012; Sejian et al., 2015). In an attempt to account for solar load, Buffington et al. (1981) developed the black globe humidity index (BGHI), which replaces dry-bulb temperature by black globe temperature, to explain reductions in milk production for dairy cows exposed to hot conditions. Other minor indices called the equivalent temperature index (ETI) and apparent equivalent temperature (AET) respectively incorporating the impact of air speed for cows and vapor pressure for broilers were established (Baeta et al., 1987; Mitchell et al., 2001). Since respiration rate is the first visual symptom of heat stress, a respiration rate (RR) index based on ambient temperature, relative humidity, solar radiation, and wind speed was developed by Eigenberg et al. (2005) for unshaded cattle. A temperature-humidity-velocity index (THVI) for broilers was established by Tao and Xin (2003) based on body temperature rise of the birds during acute exposure to 18 thermally challenging combinations of three dry-bulb temperatures (35°C, 38°C, and 41°C), two dew-point temperatures (19.4°C and 26.1°C), and three air velocities (0.2, 0.7, and 1.2 m $s^{-1}$). The effective environmental temperature (EET) concept reported by Baker (2004) tries to define the true temperature experienced by a pig by increasing or decreasing the temperature measured by a thermometer based on other factors characterising the environment: heat loss by convection (air movement over the animal), conduction (heat transferred from the floor), and radiation (associated with the insulation value in the ceiling and walls of buildings). Using data from three cattle studies, Mader et al. (2006) developed wind speed and solar radiation adjustments for THI ($THI_{adj}$). The modifications were made on the basis of changes in panting score of feedlot cattle. Similarly, the heat load index (HLI) developed by Gaughan et al. (2008) for beef cattle accounts for biological differences (panting score, respiration rate, body temperature, and feed intake), breed differences, and management factors (e.g., access to shade). The HLI, acceptable within an ambient temperature range of 8°C to 45°C, combines the effects of relative humidity, wind speed, and black globe temperature on the panting score of feedlot cattle.

It has been recognized for some time that there is a need to assess heat load on the basis of diurnal variations in an animal's physiological responses (Pedersen and Sällvik, 2002; Gaughan et al., 2012; Sejian et al., 2015). To account for intensity and duration impacts, Hahn et al. (1999) derived a two-stage classification scheme ($THI_{hrs}$) that categorized heat stress based on the amount of time (hours) feedlot cattle were exposed to THI >79 or THI >84 and on the effects of night-time recovery (hours where THI <72). Gaughan et al. (2008) used the $THI_{hrs}$ concept to develop an accumulated heat load (AHL) model based on the HLI discussed previously. When an animal is exposed to a HLI above its threshold (adjusted according to animal characteristics and management), there is a rise in core body temperature. The greater the amount of hours an animal spends above the threshold, the greater the AHL, and the greater the stress on the animal.

None of the aforementioned ACIs incorporates major environmental components that are experienced over a range of both hot and cold conditions. The comprehensive climate index (CCI) developed by Mader et al. (2010) builds on the HLI by accounting for a much broader range of climatic conditions (-30°C to 45°C) and incorporates major environmental components that are experienced over a range of both hot and cold conditions. The purpose of the CCI was to provide a relative indicator of the environmental conditions surrounding an animal and to quantify how relative humidity, solar radiation, and wind speed interact with ambient temperature to produce an apparent temperature accounting for the effects of these specific environmental variables.

***Relevance of existing animal comfort indices*** It is well known that a multi-factor approach would be superior to a single factor index (temperature) for determining the true thermal needs of animals. As a result, ACIs have been developed to support rational environmental management decisions related to animal performance, health, and well-being. By integrating the effects of humidity, the THI captures much of the impact of warm to hot thermal environments on animals (Haeussermann et al., 2005; Shao and Xin, 2008; Hahn et al., 2009). The success of THI was such that it was established for almost all livestock and poultry species. However, modifications to THI became unavoidable considering limitations related to thermal radiation, airflow, heat intensity and duration, and cold conditions, especially for animals confined in unsheltered environments. The BGHI (Buffington et al., 1981), HLI/AHL (Gaughan et al., 2008), and CCI (Mader et al., 2010) appear to be useful in some applications. Other approaches for swine and poultry, such as the enthalpy (Rodrigues et al., 2011), AET (Mitchell et al., 2001), THVI (Tao and Xin, 2003), or EET (Baker, 2004), may also be appropriate.

However, the use of most of these ACIs for confined animals can be problematic because: (i) only weak correlations between some of the calculated indices (THI, BGHI, and RR) and measured physiological responses (skin temperature, respiration rate, and sweating rate) were found (Li et al., 2009); (ii) some were established 30-50 years ago (THI, EET, and BGHI); (iii) some do not account for humidity (EET) or air velocity (enthalpy, AET); and (iv) some were only developed for one species (EET, BGHI, AET, and THVI). In this context, ACIs should be updated, if needed, and adapted for other production systems.

**PRECISION LIVESTOCK FARMING DEVICES AND TECHNOLOGIES** Management decisions based on ACIs for precise environmental control require appropriate instrumentation and accurate monitoring of all parameters. Animals respond to their environment, which is characterized by temperature, humidity, radiation, and air speed, by physiological and behavioral means. Some of the responses measured can be body temperature, respiration and heart rates, body weight, feed and water intake, activity, and movement.

***Meteorological measurements*** Commonly measured meteorological parameters related to animal comfort include temperature, humidity, solar radiation, and air speed. These roughly characterize the animal environment and are measured in the zone where livestock is confined. Care must be taken to read a true measure and to protect the sensors from aggression (Eigenberg et al., 2009; Wheeler, 2012).

Devices which measure temperature rely on the change in some physical properties with temperature (Doebelin, 1990; ASHRAE, 2013), including volume at constant pressure (expansion of a gas or liquid), electrical resistance (thermistor or resistance temperature detector), semiconductor junction potential (semiconductor thermometer), resistivity of a pure metal or oxides of transition metals, and thermal voltage associated with dissimilar metals (thermocouples). Eigenberg et al. (2009) published a list of some pertinent characteristics of various temperature sensors. Livestock environmental temperatures can be successfully measured using thermocouples or thermistors. Thermocouples offer advantages of durability, relatively low cost, and versatility. Grids of thermocouples can easily be assembled. Thermistors offer a good solution where a small number of measurement points can be connected to a suitable datalogger located near the sample points.

The parameters for quantifying the amount of water vapor in a gas include the humidity ratio, specific humidity, saturation water vapor pressure, dew-point temperature, dry- and wet-bulb temperatures, percent saturation, and water activity, but relative humidity is likely the most used variable (Eigenberg et al., 2009). Although several methods are available to measure relative humidity, none of them are totally suitable because of range and accuracy (can reach 2% but is rarely better than 5%). Humidity devices must be protected from contaminants such as salt, hydrocarbons, and particulates with, for instance, a porous membrane filter that allows the passage of moist air while keeping out most impurities (Eigenberg et al., 2009; Wheeler, 2012). Condensation also damages humidity sensors, which might lose calibration and no longer read correctly (Doebelin, 1990; ASHRAE, 2013). Eigenberg et al. (2009) lists a variety of humidity sensors and their characteristics. Practical experience has shown that in harsh environments, such as livestock buildings, the thermal conductivity methods can be used with success. Accuracy is diminished at lower temperatures but the sensors can handle high temperatures, corrosive gases and dust. A combined thermistor (range of -40 to 60°C) and capacitive sensor (range of 0 to 100% relative humidity) protected by a sintered stainless-steel filter is typically installed in livestock buildings (Phillips et al., 1998; Haeussermann et al., 2005; Fournel et al., 2012).

Radiation can be grouped as shortwaves (0.3–4.0 μm) and longwaves (4.0–100 μm). Shortwave radiation refers to radiation that originates from the sun (temperature of 6000 K). Longwave radiation generally refers to radiation that originates from terrestrial sources (temperature of 290 K), such as soil surface and buildings. Radiant energy is commonly measured by detecting temperature changes of a surface exposed to radiation or by the response of a photoelectric cell. Pyranometers, which measure total, direct, and diffuse radiation, are the most common type of instrument used to quantify solar radiation for studies involving livestock. A pyranometer has a glass dome that allows the solar spectrum to heat white and black areas and corrects for cosine effects at various sun angles. Otherwise, the Vernon Globe Thermometer is the standard instrument for measuring the globe temperature and consists of a 15-cm hollow copper sphere with walls painted flat black on the outside and containing an unshielded dry-bulb thermometer in the center of the sphere. It integrates radiant heat exchange and convective heating or cooling into a single value that can be used to calculate the mean radiant temperature (Eigenberg et al., 2009).

Air speed is measured by anemometers (rotational, pressure, deflection, thermoelectric, and Doppler) in a number of ways based on mechanical methods, pressure relationships, thermal principles, and the Doppler effect. Some anemometers are non-directional and only provide the maximum speed, some use wind vanes to orient instruments and measure direction, and others combine multiple sensors to obtain both magnitude and direction of air velocity. Anemometers are actually delicate instruments and are easily affected by coatings of dust (Eigenberg et al., 2009; Wheeler, 2012). In livestock building applications, two types of anemometers are common, depending on the type of airflow being measured: hot-wire anemometers and propeller anemometers. A hot-wire anemometer is the instrument of choice for low air speed applications. The propeller anemometer is a more rugged instrument that is well-suited for streams that are at least as wide as the vane diameter (Kelly and Bond, 1971; Wheeler, 2012).

### *Physiological measurements*

Body temperature Up until the 1980s, most measurements of the deep body temperature of livestock were made using mercury rectal thermometers. After 1980, reliable and affordable electronic dataloggers became available and were used with thermocouples, infrared and thermistor sensors to replace short-term measurements using mercury thermometers. Continuous temperature measurements are now made using several techniques (Eigenberg et al., 2009). However, remote temperature measurement is not an easy thing. Some difficulties can be faced depending on the location of the measurement since physiological function of the body part or the level of invasiveness of the device can cause changes in temperature. There are mainly two categories of temperature sensors: those that are surgically implanted and those that are not (Sellier et al., 2014).

The instruments that are not surgically implanted may be placed in the rectum, vagina, or ear canal or ingested. Rectal, vaginal, and tympanic probes and ingestible telemetry are however short-term (no more than 10 d) techniques because of possible infection or passage through the digestive tract. Surgically-implanted sensors, which are used on fully or locally anaesthetized animals, are injected under the skin or placed in body cavities. These sensors can be dataloggers from which data are retrieved or radio transmitters which transmit data to a receiving unit. Concern is raised about the use of such sensors on animals intended for human consumption (Eigenberg et al., 2009; Sellier et al., 2014; McCafferty et al., 2015).

Besides deep body temperature, surface temperature can be measured. A commonly used and moderately non-invasive method involves fitting animals with an externally attached contact thermistor or thermocouple (Renaudeau et al., 2008). Other methods of measuring skin temperature include using dataloggers mounted to radio collars or glued securely with epoxy to the skin to track temperature over several days (McCafferty et al., 2015). Infrared thermography (IRT), which is a non-invasive technique based on the hypothesis that any variable that influences heat production is transmitted through blood vessels and are dissipated in infrared waves (Mitchell, 2013; Sellier et al., 2014; Sejian et al., 2015), may be employed as well to monitor surface body temperature responses through the use of cameras or thermometers (Yanagi et al., 2002; Mitchell, 2013). These methods only determine the surface temperature and, therefore, changes in internal temperature must be measured using other techniques. It is also why attempts have been made to correlate IRT surface temperature measurements with core body temperature (McCafferty et al., 2015).

Overall, all devices for monitoring body temperature have pros and cons. For long-term measurements, infrared thermography and implantable telemetry show some potential despite of their limitations (Brown-Brandl et al., 2003; Eigenberg et al., 2008).

Respiration rate Respiration rate is of particular interest as a physiological response because a large number of studies showed a correlation with dry-bulb temperature, solar radiation, and wind speed. As a result, respiration rate has been shown to be a good indicator of thermal stress. It also has the advantage of being readily observable and demonstrating little lag time relative to temperature (Eigenberg et al., 2009).

Respiration rate can be measured by counting flank movement over a certain period of time (Renaudeau et al., 2008). However, long-term studies that require frequent periodic measurements become labor intensive. Additionally, intrusions to observe animals may influence the measurements.

Existing automated respiration rate equipment is quite limited. A respiratory effort transducer for humans which incorporates a thin-film transducer into a silicone rubber strain assembly that changes resistance with changing thoracic circumference was successfully adapted for cattle

(Eigenberg et al., 2000). Since swine spend much of their time in the resting position and thus have less well-defined respiratory movements than cattle, Eigenberg et al. (2002) decided to record the audible component of the pig’s respiration. The sensor was a small microphone placed under the throat and held with standard elastic bandaging. The development of remote data acquisition methods allows building contact-free monitoring systems to measure respiration rate of dairy cows. Pastell et al. (2007) used a laser distance sensor pointing at the cow’s side when the animal is constrained to a milking robot, milking parlour, or tie-stall. The instrument measures the radial movement of the body surface and the results are recorded.

**Heart rate** Another physiological indicator of thermal stress is changes in heart rate. Measuring heart rate (HR) is based on electrocardiography or the count of the arterial pulse (Kovács et al., 2014). However, problems arise when using HR as a measure of stress because changes attributable to metabolic activity are difficult to distinguish from those attributable to emotional responses (Broom and Johnson, 1993). Therefore, measurement of heart rate variability (HRV) allows more detailed interpretation of cardiac activity and is thus a more accurate measure of stress in animals (Marchant-Forde et al., 2004).

HRV monitors do not record and store the whole electrocardiogram, but only the inter-beats intervals (IBIs). Consequently, an affordable option to investigate HRV is to use monitors that detect the peaks of the electrocardiogram during recording and then store IBI data in digital form. These devices use a belt containing two coated electrodes that fits around the thorax of the animal. Another approach to measure IBIs non-invasively is the use of implantable telemetric transmitters. However, complete anaesthesia of animals is necessary for the implantation of the transmitter and for the correct electrode positioning. Since there are some restrictions with the use of such implants in larger animals, recent developments include intracardiac bipolar electrodes (von Borell et al., 2007; Kovács et al., 2014).

**Body weight** The weight of an animal is an important indicator of its well-being. Actually, an unusual change in the weight of livestock can provide an early warning of health problems or simply problems with feeding or ventilation equipment (Frost et al., 1997).

Traditional weight measurements of swine, cattle, and poultry require to move the animal to ground or perch weighing devices (mechanical scale or electronic balance), which is physically stressful to both animal and worker. In order to reduce the stress, self-accessed scales, such as electronic weighing platforms placed in front of a single space feeder or walk-through scales, were developed for cattle and pigs. Automatic weighing systems have also been used for years to estimate the weight of poultry. The device consists in a strain gauge perch or platform. The instrument is monitored by a computer which determines the weight between each record, stores each reading, and provides a weight distribution of the flock to the farm manager (Frost et al., 1997; Stajnko et al., 2010; Li et al., 2014).

Indirect methods for live weight measurements which minimize harmful stress on animals are also available. The significant correlation between live weight and dimensions of an animal led many authors to study the possibility of estimating body weight from physical features. Another way to measure mass indirectly is to use the machine vision technique in cattle, pigs, and poultry. It has been found that there is a strong correlation between the weight of an animal and its plan view area. This has led to the development of systems in which images are processed automatically by a video camera connected to a computer equipped with the appropriate hardware and software. Computer algorithms then segment the bodies in the visual scene, extract the plan view area, and estimate the weight of the animal (Frost et al., 1997; Wang et al., 2008).

### *Behavioral measurements*

Feed and water intake Feed and water intake and feeding behavior have become useful indicators of the health status of animals (Banhazi et al., 2007; Brown-Brandl et al., 2013; Kashiha et al., 2013). Research also indicated that feed intake and feeding behavior changes can be related to thermal conditions. Systems that measure feed intake (total and rate of eating) in association with feeding behavior (meal length, meal interval, number of meals per day, and total time spent eating) have been tested in cattle, swine, and poultry.

Some of the systems are equipped with an antenna that detects the passive radio frequency transponder button located in the ear tag of the animal approaching the feed or water bin. For each visit, a computer records the data sent by the antenna, which include animal number, bin number, initial and final time, and weight, calculating afterwards the visit duration and intake. Other systems consist in electronic feeding stations with weighing feeder system. Several studies have been carried out on visits and water-meter measurements (Puma et al., 2001; Madsen and Kristensen, 2005; Meiszberg et al., 2009).

Animal presence, activity, or behavior The behavior of an animal can be a clear indicator of its physiological state: (i) a sick animal may be less active than a healthy one; (ii) animals in a cold environment may huddle together for warmth; and (iii) an animal's activity level may be linked to its stage in the reproductive cycle (Frost et al., 1997). Data on behavioral activity is most commonly collected by a human through direct observation or the analysis of video recordings. However, these methods are time consuming and labour intensive (Müller and Schrader, 2003).

The automatic recording of activity (lying, standing, and walking) can be achieved using a variety of sensor systems: ultrasonic proximity sensors (Hillman et al., 2000), mercury tilt switches (Champion et al., 1997; O'Driscoll et al., 2008), pedometers (Walker et al., 1985), accelerometers (Müller and Schrader, 2003; Diosdado et al., 2015), embedded sensor technologies (Darr and Epperson, 2009), and global or local position systems (Barbari et al., 2006; Gygax et al., 2007). However, animal behavior is much more complex than simply activity in an area. Actually, being able to electronically recognize a specific animal behavior (e.g., nuzzling, eating, fighting, biting) requires the development and training of a computer vision system. Information can be collected using digitized images by defining key components of the image using numerical equations. Images are produced by a variety of physical devices, including still and video cameras, X-ray devices, electron microscopes, radar, and ultrasound. The system is then calibrated by assigning behaviors based on visual observation and then determining the values of the parameters from the numerical equations. Then, in subsequent videos, the behaviors can be identified based solely on the values of the parameters (Leroy et al., 2006; Nääs et al., 2006; Xue and Henderson, 2006).

***Relevance of existing devices and technologies*** At the beginning of the century, the use of technological applications such as smart sensors, detectors, cameras, and microphones through PLF was expected to continuously gather information from animals to evaluate trends. Combined thermistor and capacitive sensors and anemometers can be satisfactory equipment to assess environmental conditions. Telemetric sensors for measuring heart rate, body temperature, and activity have been developed. Automatic weighing systems have been used for a number of years to estimate the average weight of animals. Systems that measure feed and water intake have been established for major livestock species. Low-cost cameras, in combination with image analysis techniques, can be used to quantify an animal's behavior, size, and shape. Sensors can also be attached directly to the animal, such as accelerometers, for monitoring behavior.

The above examples are not exhaustive, but demonstrate the present and future possibilities in feeding back signals from animals and environment as part of PLF. However, the availability of inexpensive, reliable, and robust sensors remains the main problem to be solved if PLF is to be applied in the field.

**CONCLUSION** Considering the expected demand for animal products, intensification of farms, and need for enhancing animal welfare, PLF could be the solution for livestock enterprises to at least maintain or even raise their levels of productivity and animal comfort. One of the key points on which PLF technologies could act upon is environment control.

In a complete PLF system (Figure 1), the first step is to use bioenergetic data to set ventilation stages among others. However, it has been clearly highlighted that the traditional method is outdated since heat and moisture production of animals has evolved through the years due to advances in genetics and nutrition. Studies have already been done in the Midwest of the United States to assess THP, SHP, and LHP of modern swine and poultry buildings. More similar calorimetric studies will be needed to extend the knowledge to other livestock species (e.g., beef and dairy cattle), types of housing systems, and locations. The new established values could then be used as a post-evaluation of ventilation, heating, and cooling needs of livestock farms for different times of the year.

Afterwards, ACIs as an integral part of a PLF strategy can provide a framework to assess whether or not a given livestock building offers the required environmental conditions with respect to outdoor conditions and expected animal productivity. The information provided by ACIs can actually serve as an early-warning system to producers so they can adapt their day-to-day operations in order to achieve expected performances. Similarly to bioenergetics data, the problem of ACIs is that most of them need to be updated. Recently, most of the research has focused on beef cattle since cows are raised in outside lots and the occurrence of thermal stress due to hot weather conditions is high. As reported, ACIs for confined animals do not always correlate well with physiological or performance variables, integrate measures of humidity and air velocity, and rely on recent experimental studies. Therefore, there is a need to develop new ACIs relating animal performance data to environmental conditions including air speed at animal level.

To be able to develop these ACIs, the last section described a wide variety of PLF technologies that can be used to measure meteorological, physiological, and behavioral variables. At this time, cost-efficient equipment for measuring, storing, and analysing variables such as body temperature, humidity, and behavior working well in harsh environments, that are not invasive, and capable of running automatically and continuously still need to be developed, improved, or validated.

The points developed in the last three paragraphs are the starting point for the development of an innovative strategy for the thermal control of animal environment that would include the analysis of: (i) heat production through most recent bioenergetics models; (ii) thermal comfort of animals through the use of ACIs based on some meteorological and physiological measurements; and (iii) behavior of animals as a response to the quality of their environment. This analysis could be done by an online controlling system based on all the information provided by the PLF system and the predetermined criteria or targets set by the producer. Indeed, a new generation of environmental control system, continuously recording data collected by electronic sensors and instruments, could be used to assess the effectiveness of certain controls on the modification of ambient conditions using ventilation, heating, and cooling systems. Such control system could be programmed to periodically derive and update an ACI using in situ data and to process animal behavior information enter manually by producers. Much like analytics is used operations research and management sciences, the recorded data could become the center piece of a controller-based warning system for follow-up and management of the livestock thermal environment. It is one thing to build a new confined animal housing system according to the most recent bioenergetics models; it is another to operate an existing system and PLF can certainly provide the relevant information to retrofit the latter. The idea is to recognize the indoor and outdoor environmental conditions that are damaging to animal production.

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## APPENDIX A

Table A1. Equations of some animal comfort indices.

| Index | Equation | Livestock | Reference |
|---|---|---|---|
| Iberian heat tolerance test (HTC) | $HTC = 100 - 18(RT - 38.3)$ | Cattle | Rhoad (1944) and Bianca (1963) |
| Heat tolerance index (HT) | $HT = \left(\frac{RT}{38.33}\right) + \left(\frac{RR}{23}\right)$ | Cattle | Benezra (1954) |
| Rectal temperature (RT) | $RT = 0.35T_{db} + 0.65T_{wb}$ | Cattle | Bianca (1962) |
| Temperature-humidity index (THI) | $THI = 0.72(T_{db} + T_{wb}) + 47$ | Cows | Johnston et al. (1962) |
| | $THI = 1.8(0.55T_{db} + 0.2T_{dp}) + 49.5$ | Cows | Johnson (1965) |
| | $THI = (1.8T_{db} + 32) - (0.55 - 0.0055RH)(1.8T_{db} - 26.8)$ | Cattle | Kelly and Bond (1971) |
| | $THI = T_{db} + 0.36T_{dp} + 41.2$ | Cows | Johnson and Vanjonack (1976) |
| | $THI = 0.8T_{db} + \frac{RH}{100}(T_{db} - 14.3) + 46.3$ | Cattle | NOAA (1976) |
| | $THI = 0.6T_{db} + 0.4T_{wb}$ | Hens | Zulovich and DeShazer (1990) |
| Wet- and dry-bulb temperature | $WD = 0.65T_{db} + 0.35T_{wb}$ | Pigs | Ingram (1965) |
| | $WD = 0.75T_{db} + 0.25T_{wb}$ | Pigs | Roller and Goldman |

| | | | |
|---|---|---|---|
| index (WD) | | | (1969) |
| Enthalpy (h) | $H = 1.006T_{db} + \frac{RH}{p_e} 10^{\left(\frac{7.5T_{db}}{237.3} + T_{db}\right)} (71.28 + 0.052T_{db})$ | Hens | Rodrigues et al. (2011) |
| Black globe humidity index (BGHI) | $BGHI = T_{bg} + 0.36T_{dp} + 41.5$ | Cows | Buffington et al. (1981) |
| Equivalent temperature index (ETI) | $ETI = 27.88 - 0.456T_{db} + 0.010754T_{db}^{2} - 0.4905RH + 0.00088RH^{2} + 1.15WS - 0.12644WS^{2} + 0.019876T_{db}RH - 0.046313T_{db}WS$ | Cows | Baeta et al. (1987) |
| Apparent equivalent temperature (AET) | $AET = T_{db} + \left(\frac{p_v}{\tilde{a}}\right)$ | Broilers | Mitchell et al. (2001) |
| Respiration rate index (RR) | $RR = -777 + 5HP + 26T_{db}$ | Broilers | Zhou and Yamamoto (1997) |
| | $RR = 5.1T_{db} + 0.58RH - 1.7WS + 0.039SR - 105.7$ | Cattle | Eigenberg et al. (2005) |
| | $RR = -183.6 + 4.22T_s + 3.89T_{db} - 0.07T_{dp} - 1.53WS + 0.03SR$ | Cattle | Brown-Brandl et al. (2005) |
| | $RR = 5.4T_{db} + 0.58RH - 0.63WS + 0.024SR - 110.9$ | Cattle | Eigenberg et al. (2008) |
| Temperature-humidity-velocity index (THVI) | $THVI = (0.85T_{db} + 0.15T_{wb})V_a^{-0.058}$ | Broilers | Tao et Xin (2003) |
| Adjusted THI ( $THI_{adj}$ ) | $THI_{adj} = 4.51 + THI - 1.992WS + 0.0068SR$<br>where THI is NOAA’s (1976) | Cattle | Mader et al. (2006) |
| THI-hours ( $THI_{hrs}$ ) | $THI_{hrs} = \sum_{h=1}^{24} (THI - base)$<br>where *base* = 79 or 84 | Cattle | Hahn et al. (1999) |
| Heat load index (HLI) | If $T_{bg} \geq 25°C$:<br>$HLI = 8.62 + 0.38RH + 1.55T_{bg} - 0.5WS + e^{(2.4 - WS)}$<br>If $T_{bg} < 25°C$:<br>$HLI = 10.66 + 0.28RH + 1.30T_{bg} - WS$ | Cattle | Gaughan et al. (2008) |
| Accumulated heat load model (AHL) | If $HLI_{ACC} < HLI_{LT}$ , $AHL = \frac{(HLI_{ACC} - HLI_{LT})}{D}$<br>If $HLI_{ACC} > HLI_{UT}$ , $AHL = \frac{(HLI_{ACC} - HLI_{UT})}{D}$<br>If $HLI_{LT} < HLI_{ACC} < HLI_{UT}$ , $AHL = 0$ | Cattle | Gaughan et al. (2008) |
| Comprehensive climate index (CCI) | $CCI = T_{db} + (RH + WS + SR)_{CorrectionFactors}$<br>where<br>$RH_{CorrectionFactor} = e^{(0.00182RH + 1.8T_{db} \times RH)} (0.000054T_{db}^{2} + 0.00192T_{db} - 0.0246)(RH - 30)$ | Cattle | Mader et al. (2010) |

$$WS_{CorrectionFactor} =$$

$$\frac{-6.56}{\frac{1}{e^{(2.26WS+0.23)^{0.45\left(2.9+1.14\times10^{-6}\times WS^{2.5}-\log_{0.3}(2.26WS+0.33)^{-2}\right)}}}}$$

$$-0.00566WS^{2}+3.33$$

$$SR_{CorrectionFactor} = 0.0076SR - 0.00002T_{db}SR +$$

$$0.00005T_{db}{}^{2}\sqrt{SR} + 0.1T_{db} - 2$$

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$\tilde{a}$ = corrected psychrometric constant (kPa °C$^{-1}$); $D$ = number of data collected per hour; $HLI_{ACC}$ = actual HLI value at a point in time; $HLI_{LT}$ = HLI threshold below which cattle in a particular class will dissipate heat; $HLI_{UT}$ = HLI threshold above which cattle in a particular class will gain heat; $HP$ = heat production (kJ kg$^{-0.75}$ h$^{-1}$); $p_e$ = barometric pressure (mm of Hg); $p_v$ = water vapor pressure (kPa); $RH$ = relative humidity (%);$SR$ = solar radiation (W m$^{-2}$); $T_{bg}$ = black globe temperature (°C);$T_{db}$ = dry-bulb temperature (°C); $T_{dp}$ = dew-point temperature (°C); $T_s$ = average afternoon hair coat surface temperature (°C); $T_{wb}$ = wet-bulb temperature (°C); $V_a$ = air velocity (m s$^{-1}$); $WS$ = wind speed (m s$^{-1}$).