Carbon dioxide concentrations, temperature, and broiler chicken performance in a Canadian Prairie climate

by

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Abstract

Carbon dioxide concentrations, indoor and outdoor temperature data were collected from 32 broiler barns and 15 observation sites across Southern Manitoba to better understand typical values observed during broiler production cycles. Individual dataset averages ranged from 421 to 4912 ppm of carbon dioxide. Monthly averages ranged from 1133 ppm to 3722 ppm. Monthly averages between November 2019 and March 2020 were all greater than 3000 ppm. 73 of 217 had averages greater than 3000 ppm, and 65 of these datasets occurred between November 2019 and March 2020. Of the 80 datasets collected between November 2019 and March 2020, 65 averaged over 3000 ppm. The data shows that carbon dioxide concentrations are closely related to outdoor temperatures on both an hourly and average level. This observation indicates that the fossil fuel combustion by the heating systems in the barns contribute significantly to the carbon dioxide concentrations in the barns. The observation was then proven using correlation and statistical analysis. Broiler performance parameters from two barns were obtained to relate the collected environmental data to broiler performance. The two broiler rooms were located on the same observation site and were of identical construction. Using JMP 16 analysis software (https://onthehub.com/), no statistically significant relationships at a 10% level between growth performance and environmental parameters were observed. Statistically significant relationships were observed when livability and condemnations were compared against the environmental data. Confounding variables were identified when relating performance parameters to carbon dioxide and the temperature difference between ambient conditions and the indoor barn temperature. The primary driver of the performance parameter trends cannot be made with this research.

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Dedication

This thesis is dedicated to my parents, Lorne and Karen Cruise. Without their unwavering support, technical input, and willingness to proofread my rough drafts several times, this thesis would not have been possible.

I would also like to dedicate this thesis to my wife, Gabrielle Carriere. Without her pushing me past my comfort zone and always being my number one fan, this thesis would also not have been possible.

I would also like to dedicate this thesis to my parents-in-law, Alain Carriere and Maxine Morin. Their firsthand experience in the industry has benefited my growth and understanding in the industry and has had a significant impact on this thesis.

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Chapter 1 Introduction

1.1 Overview

Managing the air quality and pollutants in broiler chicken barns is a challenging part of farm management, especially in regions that experience significant seasonal temperature fluctuations. Maintaining an appropriate temperature in the barn is imperative as broiler chicks are susceptible to temperatures above and below their acceptable temperature range (Deaton et al. 1986; Fairchild 2009). In cold climates, such as the Canadian Prairies winter months, when the differential between the ambient temperature and the required temperature for the broiler chicks is high, the temperature can be maintained cost-effectively by reducing the ventilation rates in the barn. For example, for several months of the year in Manitoba, the temperature differential can be as high as 60 ˚C, affecting broiler barn management practices. Lowering ventilation rates reduces the energy required to heat the barn by not replacing warm indoor air with cold fresh air from outside (Olanrewaju et al. 2008; Corkery et al. 2013). However, reducing ventilation rates can lead to higher carbon dioxide concentrations, ammonia concentrations, and elevated levels of other potentially harmful gases. In addition, depending on the litter quality in the barn, a reduction in the ventilation rates may cause the relative humidity to fluctuate outside of the acceptable range, which can cause other health and welfare concerns for the birds and the individuals working in the barns.

Little existing literature explores the effects of carbon dioxide on broiler chicken performance under field conditions. Past field studies on the impact of carbon dioxide on broiler chicks tend to focus on the growth parameters of the chicks and not as much on livability or condemnations (Reece and Lott 1980). It is also important to note that most of the literature on carbon dioxide and broiler performance comes from the USA. The climate between Canada and the USA are unique enough that the results obtained from a study in the USA are not always directly applicable to a Canadian environment.

Other controlled laboratory studies exposed broiler chicks to levels of carbon dioxide that would not be observed in a typical broiler production environment (Wilson and Edwards 1950). While these studies provide valuable insight into how carbon dioxide affects broiler chicks at various exposure levels and ages, more research is required to understand the effects of the carbon dioxide concentrations observed in the field.

Another critical area when considering the regulation of carbon dioxide in broiler barns or developing technologies to manage carbon dioxide is understanding the range of concentrations observed in the field. It is appropriate for a Canadian Prairie climate to separate the field observations by season because the heating and ventilation requirements significantly differ between the winter and summer months. In Manitoba, no long-term studies have been performed which evaluate the observed carbon dioxide concentrations in broiler barns over a broad geographical region. This thesis attempts to further the understanding of carbon dioxide concentrations observed in a Canadian prairie climate over an entire year in multiple barns. It will also attempt to advance the knowledge of how the observed carbon dioxide concentrations affect broiler chicken performance parameters.

1.2 Scope of Thesis

Thirty-two broiler barns across Manitoba at fifteen observation sites were fitted with Maximus® carbon dioxide sensors and temperature probes inside and outside the barn. Data were captured every 4 hours for six data points each day. In addition, data was received from each barn in a daily email sent to an account created for this project. This data was used to understand typical carbon dioxide concentrations observed over a year in Manitoba.

The barns at observation site 11 also included Maximus® sensors which measured relative humidity inside the barn, water consumption per bird, daily weight gain per bird, and average weight per bird. Although many of these sensors are standard or required in the industry, the Maximus® controller allows data logging of all parameters in one user-friendly program. At the end of the data collection period, end-of-cycle performance data was provided by the owner/operator of observation site 11. The processor reports from the slaughter/processing plants provided all of the end-of-cycle performance data. These end-of-cycle performance parameters were compared to the data collected during the production cycle to develop relationships between various air quality/temperature parameters and broiler performance.

Due to the scope of this study, end-of-cycle performance parameters were the only welfare/performance parameters used to determine the effects of carbon dioxide on the broiler chicks. Therefore, biological welfare parameters are not considered in this study. Further field studies with a narrower focus should be developed based on the findings of this thesis to gain further understanding of the effects of carbon dioxide on broiler chicken welfare.

1.3 Objectives

The first objective of this study was to develop a good understanding of the observed carbon dioxide concentrations over an entire year, from June 2019 to September 2020, in all the broiler barns monitored in this study.

The second objective of this study was to explore relationships between observed carbon dioxide and relative humidity from observation site 11 to the following broiler performance parameters:

- Livability

- Condemnations
- Feed Conversion Ratio (FCR)
- Live weight at the end of the production cycle
- Broiler Performance Index (BPI)

1.4 Outline of Thesis

This thesis consists of six chapters. Chapter 1 is an introduction to the thesis. Chapter 2 is an in-depth literature review on carbon dioxide in broiler barns, the effects of carbon dioxide on broiler performance and welfare, other air quality parameters that are critical to managing broiler production, a brief overview of the avian respiratory system, and a review of carbon dioxide emissions and sustainable livestock agriculture. Chapter 3 presents the data from the field study and details the "lay-of-the-land" concerning carbon dioxide concentrations in broiler barns in Manitoba. Chapter 3 also includes a more detailed description of the materials and methods used in the study. Chapter 4 presents the statistical analysis and discussion of the effects of carbon dioxide on broiler performance observed in this study. Chapter 5 summarizes the results of the study and provides conclusions. Finally, chapter 6 makes recommendations for future field studies based on the findings of this thesis research.

Chapter 2 Literature Review

The following section is a detailed literature review of carbon dioxide in the broiler industry and how broiler performance or welfare is affected by carbon dioxide concentrations. In addition, a brief overview of the avian respiratory system is provided to understand further how carbon dioxide affects mammals and avian species differently. A review of technologies and the potential benefits of managing carbon dioxide is also included in this section.

2.1 Carbon Dioxide in Broiler Barns

The primary sources of carbon dioxide in broiler barns come from the ambient conditions, the heating systems used in the barns, individual producer management practices, and the birds themselves (Olanrewaju et al. 2008; Cândido et al. 2018). The carbon dioxide concentration in barns often exceeds 3000 ppm due to either heating requirements in cold climates or reducing ventilation rates to consume less energy to heat the barn (Olanrewaju et al. 2008; Corkery et al. 2013). Sufficient ventilation or air exchange in barns leads to expelling potentially harmful pollutants such as carbon dioxide, ammonia, and particulate matter. In warm or hot climates, proper ventilation is also used to remove excess heat in the barns (Cândido et al. 2018).

Concerning individual producer management practices, one interesting note from a study on the litter types for cattle and swine found that deep litter contributed to higher carbon dioxide emissions than shallow litter (Jeppsson 2000). These findings were summarized and applied to the poultry industry in another study which concluded that deep litter contributed to higher carbon dioxide emissions due to microbial breakdown of the uric acids in poultry manure (Jeppsson 2000; Cândido et al. 2018). In their study, another critical discussion point and observation by Louton et al. (2018) was that carbon dioxide concentrations increased with bird age. This observation might indicate that carbon dioxide due to bird respiration contributes significantly to the overall concentration observed in the barns.

An article published by Huang and Guo (2019) looked at both the seasonal and diurnal greenhouse gas emissions from commercial broiler and layer barns. Although this study did not include bird performance in its scope, it came from Saskatchewan, Canada and the trends and conclusions from this study are likely applicable to Manitoba, Canada. Furthermore, the study by Huang and Guo (2019) addressed emissions from the barn and not the concentrations in the barn. Thus, due to the lowered ventilation rates observed in the winter to maintain appropriate temperatures and save energy, the carbon dioxide emissions from the broiler barn were relatively stable throughout the entire study period (Huang and Guo 2019). However, when reviewing the carbon dioxide concentration curves from the sensors located in the barns, it was observed that carbon dioxide concentrations ranged from approximately 1000 ppm in August and June of 2015 to just under 4500 ppm in January 2016 (Huang and Guo 2019). So, although the emissions were stable across the study period, the concentration of carbon dioxide in the barns fluctuated significantly from the cold to warm months.

The study by Huang Guo also demonstrated that the diurnal carbon dioxide emissions were consistent in the warm, mild, and cold seasons. However, they showed that the ventilation rates changed significantly throughout the day in the mild seasons, indicating a significant fluctuation of carbon dioxide concentrations inside the barn. It is also important to note that although the ventilation rates in the cold season were consistent, this does not mean carbon dioxide did not fluctuate diurnally in the barns. Many broiler producers ventilated based on heating requirements and ventilate at a lower rate in cold seasons to maintain an appropriate temperature inside the barn for the broiler chickens, while keeping heating costs down (Olanrewaju et al. 2008). One shortcoming of this publication is that external temperatures were not reported alongside carbon dioxide emissions or concentrations. External temperatures are critical to carbon dioxide emissions and concentrations, especially in cold climates (Huang and Guo 2019). The temperature range was provided by Huang and Guo (2019) for the study period, from -30℃ to +30℃. However, time-dependent data, especially for the diurnal emission assessment, would have helped develop a more direct relationship between the ambient temperature and carbon dioxide emissions or concentrations.

2.2 Conventional Heating Systems in Broiler Barns

When discussing the types of heating systems typically used in broiler barns, there are two main categories: radiant heating and space heating by forced air (University of Kentucky College of Agriculture and Kentucky Poultry Federation 2014). Radiant heat can be divided into open flame radiant brooders and radiant heat tubes. Although different, they both work using the same principle. Energy and heat that is emitted by the heater is absorbed by objects in the barn, then emitted by the objects as radiant heat or is absorbed by broilers. Forced air space heating works similarly to the heating system in a conventional home. Air is forced through a heating unit, and the combustion process is used to heat the air within the unit. The air is then forced into the barn with fans to heat the barn. Both radiant and forced-air heating methods usually burn fossil fuels and can contribute to carbon dioxide emissions.

Depending on the facilities, the byproducts of gas combustion directly contribute to the carbon dioxide concentrations in the barn, as Bokkers et al. (2010) documented in their study on heat exchangers. Some research shows that natural gas is the most cost-effective fuel to heat broiler barns. Unless natural gas prices rise significantly, it is unlikely that an alternative to natural gas will be widely adopted (Hope et al. 2015). Bokkers et al. (2010) also performed some calculations to quantify the energy required to heat the broiler barns in their study. They determined that it took 22 MJ/m^2 to 35 MJ/m^2 of energy from natural gas combustion to heat the barns over an entire production cycle without heat recovery technology.

2.3 Heat Recovery Technology in Literature

With respect to barn design, equipment and facilities, carbon dioxide in broiler barns is a compound issue concerning ventilation and fossil fuel combustion for heating. Heat recovery technology, or heat exchangers, are technologies that recovers heat from outgoing exhaust air in the ventilation of a broiler barn. The outgoing air is used to warm the incoming air, reducing the barn's heating requirement. This heat recovery allows producer to ventilate at a higher rate since heat is being recovered from exhaust air. Depending on the method by which the barn is heated, a heat exchanger can lower the carbon dioxide emissions from the barn (Bokkers et al. 2010).) Research by Bokkers et al. (2010) sought to determine the value of the heat exchanger in a broiler barn both qualitatively and quantitatively. This study analyzed broiler performance, feed intake, water intake, carbon dioxide emissions, and energy consumption. They also interviewed broiler producers about their opinion of the heat exchanger (Bokkers et al. 2010).

This study showed that broiler producers in the Netherlands could increase the litter quality and create a more uniform climate within the broiler barn, all by employing a heat exchange technology. They were unable to determine whether or not the heat exchange significantly affected the carbon dioxide emission from the farm when considering all activities from the transportation of feed, transportation of birds, and barn operation. However, it reduced the natural gas consumption required to heat the barns.

From a qualitative perspective, Bokkers et al. concluded that the broiler producers had increased job satisfaction and were satisfied with the heat exchange technology. However, it is essential to note where this study took place. A quick internet search will show that natural gas and electricity prices are considerably higher in the regions where the study by Bokkers et al. (2010) took place when compared to energy costs in Manitoba, Canada. Therefore, energy prices are essential to keep in mind when considering both the broiler producers' satisfaction and the economic value of the heat exchange technology.

The study by Bokkers et al. (2010) studied carbon dioxide emissions and not the concentration of carbon dioxide in the barn, so it is impossible to conclude from this study alone that the heat exchanger reduced the concentrations within the barn. One of the contributors to carbon dioxide is the birds themselves, and the heat exchanger would not affect the carbon dioxide produced by the broilers through respiration. Furthermore, this study had a much broader scope than just barn operations. Direct energy use only accounts for 25% of carbon dioxide emissions from broiler production, whereas 70% comes from in-direct activities such as bird transportation, feed mill operations, and other poultry industry areas (Spedding et al. 1983; Bokkers et al. 2010).

The study by Bokkers et al. (2010) has a different scope concerning carbon dioxide than what this literature review intends to address, so although they were unable to conclude that a heat exchanger affected the carbon dioxide emissions from broiler production, the study did conclude that the heat exchanger was able to reduce the energy consumption for heating the barn. This claim of gas reduction may indicate that the heat exchanger could lower the carbon dioxide concentration in the barns simply by burning less fuel to heat the barn. In addition, all of the barns in the study used direct heating, where emissions from the heating system are released into the barn (Bokkers et al. 2010). Therefore, this reduction in gas consumption means that less gas used in the barn could result in a lower carbon dioxide emission, thus lowering the concentration in the barn, assuming that the emissions from the heating system contributed significantly to the concentrations in the barn. The researchers in this study also concluded that using the heat exchanger did not affect the specific broiler performance parameters measured by (Bokkers et al. 2010).

A publication by Shah et al. (2011) looks at heat exchangers coupled with a biofilter to reduce heating costs and ammonia emissions from a broiler barn. Although the scope and intent of this study are not related to broiler performance or carbon dioxide, meaningful conclusions concerning the function and value of the heat exchanger can still be drawn from this publication and are consistent with those drawn by Bokkers et al. (2010). Using a biofilter in livestock barns can reduce ammonia emissions and other potentially harmful gases by forcing exhaust air through a system of compost, wood chips or other organic material. However, a biofilter increases the cost of the production (Shah et al. 2011). Shah et al. (2011) concluded that a heat exchanger reduced the biofilter's operational cost by lowering the barn's heat requirement. The barn in this study used propane combustion to heat the barns, and the by-productions of propane combustion are water, carbon monoxide, energy in the form of heat, and carbon dioxide. Therefore, by reducing the heating requirement, Shah et al. (2011) also reduced the carbon dioxide emissions and possibly the carbon dioxide concentration in the barns by employing a heat exchanger.

Shah et al. (2011) and Bokkers et al. (2010) explore more traditional heat recovery technologies, with a counter flow of exhaust air and incoming fresh air to exchange heat between the two flows. A publication by Morshed et al. (2018) explores the function and efficiency of a ground-coupled heat exchanger for cooling broiler barns in Iraq. A ground-coupled heat exchanger works by pumping fresh air through pipes buried in the ground to warm or cool the fresh air, depending on ambient conditions and the desired conditions in the barn, Morshed et al. (2018) claim that soil can be used as both a heat source and a heat sink the cold and warm months respectively. It was shown that pumping fresh air through both wetted and dried soil could lower the temperature of the air (Morshed et al. 2018).

The climate difference between Iraq and the Canadian Prairies is substantial. However, a heat exchanger between air and the ground relies on the temperature difference between the two media. If the pipe were buried deep enough, this heat exchange method might apply to a Canadian Prairie environment in both the summer and winter. Further research on this heat exchange method is required to assess efficacy and efficiency for broiler production in cold climates.

2.4 Carbon Dioxide vs. Broiler Performance & Health

Unfortunately, there is little literature pertaining to broiler health and performance that considers carbon dioxide exposure over an entire production cycle in a field study. One study performed by Reece and Lott (1980) sought to identify if long-term exposure to carbon dioxide affected the growth parameters of broiler birds. Through a 4-week exposure to 3000 ppm, 6000 ppm, and 12000 ppm, they were able to determine that there was not a statistically significant difference in the feed conversion nor the weight of the birds between the control group, the 3000 ppm exposure group, and the 6000 ppm exposure group (Reece and Lott 1980). The carbon dioxide concentrations for the control group did not exceed 1000 ppm during the exposure period. However, there was a statistical difference between the 12000 ppm group and the other exposure groups (Reece and Lott 1980). This statistically significant difference indicates a threshold for carbon dioxide exposure levels over a 4-week period where growth rates are affected. However, 12000 ppm is likely a higher concentration of carbon dioxide than what is observed under normal production levels. This study by Reece and Lott (1980) did not address other broiler health parameters, and there was no mention of mortality or condemnations in the article.

Another study by Wilson and Edwards (1950) exposed one-day-old broiler chicks to various temperatures and carbon dioxide concentrations. This study's carbon dioxide exposures were quite extreme, ranging from 2000 ppm to 174000 ppm (Wilson and Edwards 1950). Although this study does not do much to answer the questions surrounding long-term exposure of broiler chickens to the carbon dioxide levels observed in a Canadian Prairie climate, it does indicate that mortality was observed at 174000 ppm with short-term exposure (Wilson and Edwards 1950). The exact time the broiler chicks were exposed to the extreme concentration was not documented. However, it is relevant to note that human fatality can occur at 100,000 ppm of short-term exposure (Permentier et al. 2017). This difference between short-term exposure mortality levels indicates that the respiratory systems of humans and broiler chicks are unique and distinct from each other, especially when the exposure limit per body weight is considered.

Fairchild and Czarick (2012) proposed that carbon dioxide concentrations should be kept below 5,000 ppm in their publications. However, they suggest that the ideal carbon dioxide concentration should be below 3500 ppm (Czarick and Fairchild 2012). The justification for the 3500 ppm limit is not substantiated in this article, and it is not clear whether this suggested limit is based on human or avian exposure limits. It is also important to note that this article originates from the University of Georgia, which has a winter temperature of around +10 to +15 degrees Celsius.

A study by Cândido et al. (2018) assessed the effect of carbon dioxide on turkey poults. This literature review is focused on carbon dioxide as it pertains to broiler chicks; however, this study on turkey poults provides some insight and direction on the effects of carbon dioxide on avian livestock species. Throughout the study, 552 turkey poults were exposed to 2000 ppm, 4000 ppm, or 6000 ppm of carbon dioxide until 21 days of age. Growth parameters of the birds and bird activity were compared between carbon dioxide exposure groups. After the study was complete, the birds were grown to 19 weeks of age at a commercial growing facility. At the end of the cycle, 64 turkeys from the trial were randomly selected to have their hearts assessed for evidence of spontaneous turkey cardiomyopathy (STC) (Cândido et al. 2018).

Contrary to the study performed by Reece and Lott (1980), Cândido et al. (2018) demonstrate that the turkey poults in the 4000 ppm and 6000 ppm exposure groups had inhibited growth when compared to the 2000 ppm exposure group. However, turkey poults and broiler chicks are different species, and it is noted that this difference between the turkey and broiler growth response to carbon dioxide exposure could be due to the physiological difference between the two species (Cândido et al. 2018). The study also concluded that the exposure levels did not significantly affect the mortality or STC prevalence amongst the turkey poults. Though, it is essential to note that the exposure study only lasted three weeks, and after these exposure studies, the birds were all raised in the same commercial growing facility for 16 more weeks. Therefore, it is unclear whether or not more prolonged exposure would affect the mortality rates or instances of STC between the exposure groups (Cândido et al. 2018). Although there was an effect on growth performance, Cândido et al. (2018) conclude that exposure up to 6,000 ppm was not a strong factor in reducing the performance of the birds.

2.5 Other Indoor Environmental Parameters of Interest

2.5.1 Ammonia and Relative Humidity

Although this literature review is primarily concerned with carbon dioxide in broiler production barns, it is impossible to ignore other environmental or air quality parameters that affect broiler performance. For example, some literature shows that relative humidity, carbon dioxide, and ammonia concentrations are closely related and that the best environmental parameter to control the ventilation rates might be relative humidity. A study by Czarick and Fairchild (2019) claims the ventilation rates required to maintain appropriate relative humidity levels are greater than what is required to manage other air quality parameters. Czarick and Fairchild (2009) also ascertain that monitoring relative humidity is much more reliable and economically viable than monitoring carbon dioxide, ammonia, or some combination of all three. This is because instrumentation to measure relative humidity is less expensive and more reliable than other air quality measuring equipment. It is again important to note the location of this study as the climate experienced in Georgia, USA, is different enough from the Canadian Prairies that it cannot be assumed that only monitoring relative humidity is an acceptable management practice in the Canadian Prairies.

However, a study conducted in Germany contradicts Czarick and Fairchild's (2009) claim that measuring only one parameter is an acceptable barn management practice. Louton et al. (2018) could not correlate carbon dioxide and ammonia concentrations in both an open and closed barn design and claim that each noxious gas must be measured and managed individually.

One study performed in Ireland states that broiler producers often use relative humidity as an indicator for ammonia since they appear to be directly proportional to each other, and the results from the study substantiate this practice (Corkery et al. 2013). Another study states that the ventilation rates required to manage moisture levels in the barn will be greater than those needed to handle the carbon dioxide (Purswell et al. 2011) which is consistent with the claims made by Czarick and Fairchild (2019). This claim further clarifies that relative humidity might be the best air quality parameter to control ventilation in broiler barns if only one parameter is used to manage the air quality.

There is disagreement amongst the scientific community about the most efficient way to monitor air quality in broiler barns. However, regardless of how the parameters are measured, poor management of relative humidity and ammonia concentrations can lead to welfare concerns in the broiler barns.

The primary reason relative humidity is so critical in a broiler barn is that if the air is too dry, below 50%, dry particulate matter can become airborne, which may cause respiratory concerns for the birds and workers in the broiler barn (Fairchild 2009). A barn with a relative humidity greater than 70% provides conditions suitable for microbial growth in the barn litter (Fairchild 2009). One potential risk of microbial growth in the litter is cellulitis, which the presence of E.coli may cause during specific periods of broiler growth (Schrader et al. 2004). Louton et al. (2018) were able to show that higher concentrations of ammonia were related to incidences of hock burn amongst broiler chickens.

2.5.2 Indoor Temperature

Indoor temperature is vitally important during the first two weeks of brooding as the broiler chicks cannot regulate their temperatures. Extreme temperatures at young ages can cause bird death. However, even minor cooling or overheating of broiler chicks can impact the immune and digestive systems of the birds (Fairchild 2009). It has also been well documented that as broiler chicks age, the optimal temperature to optimize their growth performances decreases

(Charles 1986). Due to the observed temperature sensitivity and potential lack of growth performance effects by carbon dioxide concentrations observed under standard conditions (Reece and Lott 1980; Deaton et al. 1986; Olanrewaju et al. 2008; Fairchild 2009), greater importance might be given to maintaining appropriate temperatures in the barn, at the expense of carbon dioxide concentrations, to a certain degree. This claim is an inference based on current literature, and further research would need to be done to substantiate the claim.

A study by May and Lott (2001) demonstrated the sensitivity of the growth performance of broilers to varying temperatures. In this study, male and female chicks were reared for 21 days under normal temperature conditions for their age. Afterward, the chicks were split into groups by sex and further divided into four groups to study the effect of temperature on the growth of birds. This study demonstrated that a temperature of 12-19 degrees Celsius was optimal for both male and female chicks when considering the genetics of the chicks used within this study (May and Lott 2001). It is important to note that in Manitoba, broilers are raised for approximately 30 days, give or take a few days depending on the desired weight of the birds. Any results that May and Lott (2001) obtained after 30 days of age might not apply to the management practices and schedules observed in Manitoba

2.6 Avian Respiratory System

Previous sections of this literature review indicate that elevated levels of carbon dioxide do not have a significant effect on broiler growth performance and a brief discussion on the avian respiratory system is provided to further the understanding of these previous studies. The avian respiratory system is starkly different from that of humans. One of the most significant differences concerning gas exchange between birds and mammals is the one-way flow of air instead of the two-way flow observed in the human (Maina 2017b). The avian respiratory system consists of multiple air sacs and a tubular network of parabronchi. The parabronchi are where the gas exchange occurs, not in the air sacs. Through inhalation, the air is moved from the posterior air sac through the parabronchi, where gas exchange occurs, to an anterior air sac. From the anterior air sac, the air is ultimately exhaled. Some research indicates that the avian respiratory system operates on a counter-current principle. In contrast, other research suggests that a cross-current flow of deoxygenated blood and oxygenated air is used to accomplish gas exchange (Maina 2017a). Regardless of which gas exchange method is used to oxygenate the blood, the respiratory system of birds is more efficient than that of humans (Maina 2017a).

The avian respiratory system was evolved to allow for flight, a considerably more aerobic activity than walking or running. Therefore, flight requires a more efficient gas exchange method to be an efficient form of travel. Furthermore, at higher altitudes, the oxygen concentration in the air is much lower than at sea level. The avian respiratory system must extract sufficient oxygen levels to maintain the flight (Maina 2017a). Analyzing and comparing the respiratory system of avian species to mammalian species is outside the scope of this study however this brief literature review of the avian respiratory system in this thesis demonstrates that the two systems function differently.

2.7 Efficient Farming, Precision Farming, and Animal Welfare

Dawkins (2017) opines that animal welfare and efficient farming are often thought to be conflicting schools of thought regarding animal husbandry practices. Efficient farming maximizes production output and does not necessarily consider animal welfare (Dawkins 2017). Examples of efficient farming include increasing stocking density, strategically managing certain functions of the facility that might negatively affect animal welfare to save on overhead costs and strategic selection for genetic traits that increase output but may negatively affect animal welfare (Dawkins 2017).

This publication argues that there are economic benefits to having animal welfare as a top consideration for livestock producers (Dawkins 2017). Some of the economic factors discussed are that when animal welfare is considered, the product is usually of higher quality, there is reduced disease amongst livestock, and the animals are generally healthier (Dawkins 2017). Further, it is discussed that when animal welfare is made a top priority, it reduces the chances of zoonoses and animal-borne diseases (Dawkins 2017). Under the current global circumstances surrounding COVID-19, this argument for reducing the chances of zoonoses and animal-borne diseases is particularly fundamental. One final item discussed is an increasing market for ethically or sustainably sourced animal products. Ensuring a high quality of life for livestock may make consumers willing to pay a premium price for the product. However, this research concedes that not all efforts to improve animal welfare will result in an economic advantage for the livestock producer.

Another key discussion point in the publication is to not make assumptions about what is good welfare for the animal without science-based evidence (Dawkins 2017). The example cited in the article is that it is often assumed that giving animals "free-range" mobility increases the animal’s welfare. In reality, it is possible that through genetic selection and evolution, certain animals are no longer suited to outdoor environments due to sensitivity to weather fluctuations or risks of predation (Dawkins 2017). Although this point is not specific to carbon dioxide concentrations in broiler barns, it does highlight the importance of basing any decision about animal welfare on the species being considered.

Precision livestock farming uses high precision technology to measure different environmental and biological parameters. These measurements allow livestock producers to make management decisions to use resources more efficiently and minimize inputs while maximizing outputs (Monteiro et al. 2021). The definition of precision livestock farming is different from the efficient farming definition described earlier; however, precision livestock farming is a broader definition that can encompass topics such as environmental sustainability and animal welfare (Dawkins 2017; Monteiro et al. 2021).

The concept of efficient farming and precision livestock farming have the potential for considerable crossover, and this potential was highlighted by the article by Bokkers et al. (2010). This article used heat exchangers in broiler barns and determined that the inputs required to heat the barn were reduced, thus reducing overhead costs of the production facility. The researchers took it a step further to try and determine if the heat exchanger technology had any effect on the growth performance of the broilers but concluded that the heat exchangers did not affect the measured performance parameters (Bokkers et al. 2010). However, if the definition of animal welfare provided by Dawkins (2017) is considered, whether the heat exchangers in Bokkers et al.'s (2010) study influenced the welfare of the broilers, not just the growth performance parameters can be raised. Suppose it could be shown that heat recovery technology directly benefits the animals' welfare and the barns' operational costs. It is more likely that this technology will be widely adopted in the industry despite the extra labour associated with maintaining the heat exchangers (Bokkers et al. 2010).

2.8 Carbon Dioxide and Other Greenhouse Gas Emissions

Although the primary focus of this literature review is to review and discuss carbon dioxide or other indoor air pollutants within the context of broiler performance, health, and welfare, many studies address greenhouse gas emissions from broiler barns and not just the concentration of the gases in the barn. Animal production agriculture has been under scrutiny concerning greenhouse gas emissions globally. It is estimated that broiler production accounts for 54% of the carbon dioxide and other greenhouse gas emissions in the Canadian poultry industry (Vergé et al. 2009). However, the same publication by Vergé et al. (2009) also states that the greenhouse gas emissions from poultry are 47% of the pork industry and only 10% of the beef industry per live weight. It is also important to note that carbon dioxide resulting from animal respiration and the decomposition of crop residue and manure were not considered in these figures as they are considered a net-zero process (Vergé et al. 2009).

Due to the lower emissions, nonruminant animal protein sources are being looked at with ever-increasing favour. Consequently, the Canadian poultry industry has experienced more than 50% growth between 1981 and 2006 (Vergé et al. 2009). Of course, not all the growth is related to the lower greenhouse gas emissions of the industry when compared to other livestock industries; however, it certainly is a contributing factor.

Nitrous oxide was the highest greenhouse gas contributor to the broiler industry at 57%, followed by carbon dioxide at 38% (Vergé et al. 2009). This study identified nitrous oxide sources as nitrogen fertilizer applications for crop growth and manure storage systems (Vergé et al. 2009). The carbon dioxide sources came from transportation, heavy machinery operation to produce feed and barn facilities. It is important to note that this study addressed all poultry production operations, not just on-farm processes.

Over the study period, from 1985 to 2006, the carbon dioxide emissions from broiler-specific activities increased from 0.34 Tg to 0.61 Tg. Although there was an increase in the overall emissions, Vergé et al. (2009) state that the greenhouse gas intensity decreased over the study period. Greenhouse gas intensity is a ratio or measure of greenhouse gas emissions of a particular sector to the sector's economic value (Perch-Nielsen et al. 2010). The decrease in the greenhouse gas intensity might indicate that although there was an increase in the emissions, it might be related to the industry's growth and that greenhouse gas emitting activities within the industry have improved or become more environmentally friendly from 1981 to 2006.

It is important to note that this analysis looks at all farm activities related to broiler production. Although nitrous oxide was the primary greenhouse gas contributor, this contribution comes from the production and application of fertilizer to grow crops, which becomes feed for the livestock (Vergé et al. 2009). Carbon dioxide emissions in the publication came from fossil fuel burning for equipment used for crop production, equipment and facilities in the barns, and the transportation of birds to and from barns. Considering all these activities when discussing climate change or greenhouse gas emissions is essential. However, taking too broad of an approach can often dilute the importance of addressing one area of emissions. Bokkers et al.'s (2010) and Huang and Guo’s (2019) publications took a more barn-specific approach and although these publications have been previously discussed, it is worth briefly revisiting them under the context of greenhouse gas emissions rather than concentrations,

As previously mentioned, Bokkers et al. (2010) could not significantly reduce carbon dioxide emissions from a broiler production facility when considering a similar scope to the publication of Vergé et al. (2019). However, suppose the scope of the study was narrowed, and the emissions from a barn with a heat exchanger were compared to a control barn without a heat exchanger. In that case, the survey results might paint a different picture of the value of the heat exchanger concerning greenhouse gas emissions. The study by Huang and Guo identified that average carbon dioxide emissions were 433 ± 21mg/s/AU in the mild season, 437 ± 25mg/s/AU in the warm season, and 410 ± 25 mg/s/AU in the cold season. It would be interesting and valuable to repeat their experiment and compare a barn using heat recovery technology to a barn not using heat recovery technology. The study by Huang and Guo (2019) took place in Saskatchewan, so it paints a good picture of what might be observed in a typical Manitoba broiler barn.

Through a literature review alone, it is impossible to conclusively state the effect of carbon dioxide on the performance of broiler chickens in Manitoba. However, even if growth performance is not affected, similar to the observations of Reece and Lott (1980) and no other performance parameters are affected, the work by Bokkers et al. (2010), Vergé et al. (2019) and Dawkins (2017) indicates that there might be economical and environmental value in reducing carbon dioxide concentrations in broiler barns.

Chapter 3 Environmental Variables Compared to Indoor Carbon Dioxide Concentrations

Abstract

Carbon dioxide concentrations and indoor and outdoor temperature data were collected from 32 broiler barns and 15 observation sites across Southern Manitoba to understand better typical carbon dioxide concentrations observed in the field during production cycles. The data were collected using Maximus® controllers and Maximus® sensors. Data were collected every four hours for each production cycle for 217 datasets. Analysis and observations between days 2 to 29 were only considered to eliminate management practices interfering with the observations. Individual dataset averages ranged from 421 to 4912 ppm of carbon dioxide. When the data was broken down by month, the monthly averages ranged from 1133 ppm to 3722 ppm. The monthly averages between November 2019 and March 2020 were greater than 3000 ppm. Of the 217 datasets collected, 73 had averages greater than 3000 ppm, and 65 of these datasets occurred between November 2019 and March 2020. Of the 80 datasets collected between November 2019 and March 2020, 65 averaged over 3000 ppm. The data collected shows that average carbon dioxide concentrations are closely related to average outdoor temperatures, or the difference between indoor and outdoor temperatures. The data also show that the carbon dioxide concentrations are related to the outdoor temperature. A shift in outside temperature was accompanied by a change in the carbon dioxide concentration. This observation indicates that the fossil fuel combustion by the heating systems in the barns contribute significantly to the carbon dioxide concentrations in the barns. The observation was then proven using correlation and probability statistics.

3.1 Introduction

This chapter details the carbon dioxide concentration results from the 32 barns and the 15 observation sites that were a part of this study. A critical part of this study was that each participant was given instructions not to alter their management practices during this study period. These instructions were provided to ensure the collected data represents the most accurate picture concerning observed carbon dioxide concentrations in broiler barns in Manitoba, Canada.

One consideration in regulating carbon dioxide in broiler barns or developing technologies to manage carbon dioxide is understanding the range of concentrations observed in the field. It is appropriate for a Canadian Prairie climate to break down the field observations by season as the heating and ventilation requirements will be significantly different between the winter and summer months. In Manitoba, prior to this thesis, no long-term studies had been performed which evaluate the observed carbon dioxide concentrations in broiler barns over a broad geographical region.

This chapter will also look at an entire production cycle for the datasets with the highest and lowest maximum observed carbon dioxide concentration, average carbon dioxide concentration, and median carbon dioxide concentration. This will be done to gain insight into the sustained maximums, minimums, trends over the production cycle, and outdoor temperatures where these maximums occurred.

3.2 Materials and Methods

The following subsection details the materials and methods used to collect carbon dioxide, indoor temperature, and outdoor temperature data. This subsection also includes descriptions of how the data were managed and analyzed.

3.2.1 Observation sites

Manitoba Chicken Producers (MCP) selected observation sites for this study based on the following criteria.

- All observation sites used the same feed program.
- All barns were fitted with Maximus® controllers before the study period.
- All producers agreed to share their data for this study.

If an observation site was not fitted with the Maximus® Carbon Dioxide sensor, the sensor was purchased for this study and the cost was shared by MCP and Chicken Farmers of Canada (CFC). The author of this thesis did not participate in the site selection or any of the financial decisions. This thesis was only approved at the University of Manitoba after MCP had selected all observation sites.

Detailed barn design and facilities were not provided as the scope of the study was to develop and understanding of typical carbon dioxide concentrations in broiler barns in a Canadian prairie climate, rather than compare different barn designs and equipment. However, a high-level description of some key aspects of the barn design is provided below in Table 3-1 below. Not all the producers involved in this study provided information on their operations.

Table 3-1 High-level overview of typical barn construction and facilities

Number of Barns	Heat Source	Fuel Source	Exhaust	Stocking Density
2	space heater/forced air	natural gas	internal	regular
2	space heater/forced air	natural gas	internal	regular
2	space heater/forced air	natural gas	internal	regular
2	space heater/forced air	natural gas	internal	regular
2	boiler	natural gas	external	high density
1	space heater/forced air	propane	internal	regular
3	space heater/forced air	natural gas	internal	regular
2	space heater/forced air	natural gas	internal	regular
1	radiant	natural gas	internal	high density
4	space heater/forced air	natural gas	internal	high density
1	space heater/forced air	natural gas	internal	regular
2	space heater/forced air	natural gas	internal	high density

A few key points from Table 3-1 are that of the information that was provided, only one barn had external exhaust from the heating systems and only one barn used propane as a fuel source for heating. Regular stocking density is considered less than 31 kg/m^2 at the time of shipping the broilers to the processors. High density stocking occurs between 31 – 38 kg/m^2 at the time of shipping. Although barn and facility comparisons are outside the scope of this study, Table 3-1 demonstrates that a diverse cross section of typical barn construction was included in this study

3.2.2 Carbon Dioxide Sensor Installation

Nathan Martens installed each sensor that required installation throughout the spring and summer of 2019 so that the data collection could begin in June of 2019. Each Maximus® carbon dioxide sensor was installed near the door in each barn at the height of three feet above the ground.

3.2.3 Data Collection and Management

Per the ethics arrangement of this study, the author of this study had no contact with the individual participants, except for producer 11. There was no contact with any animals during the study period, and there were no visits to the observation sites.

The following data were captured every 4-hours, for a total of 6 data points each day, and sent by email to an account created specifically for this project.

- Date and time
- Bird age
- Indoor temperature
- Outdoor temperature
- Indoor carbon dioxide concentration

The data was sent in an .XML format, and all the data columns and information were set up and formatted by Vanessa Doerksen of Summit Technologies. Each email was received at approximately midnight daily, and a set of email rules was used to organize each email by observation site and barn. After each dataset was received, it was converted to an .XLSX format for analysis.

Each day, six new lines were appended to the .XML file received by email the previous day. The data was provided this way in case there was a malfunction with the Maximus® controller or internet in the barn. The data would not be lost as it would appear in all subsequent .XML files until the end of the production cycle. At the end of each production cycle, the producer would select an "end of cycle" option, which would stop the daily email from being sent until the controller was reset. At the beginning of each production cycle, the producer would select a “new flock” option on the Maximus® controller, which would reset the bird age column and trigger the controller to send daily emails.

One error that occurred during the data collection was that the Maximus® controller only captured one data point each day for the first production cycle for many participants. Since this portion of the thesis is to understand the observed field concentration of carbon dioxide, the production cycles with only one data point per day will be treated the same as those with six data points per day. Although the accuracy will be reduced for these production cycles with only one data point, the overall trends are unlikely to be affected. Furthermore, the data were collected at midnight for all production cycles that contained only one data point per day. The relevance of this and why it will not significantly affect the observations of this study will be discussed later in this section.

Since the producers who participated in this study were explicitly told not to change their management practices during the period, some producers used the “end-of-flock” function differently. Occasionally it was used at the end of the flock, and other times “end-of-flock” and “new flock” were selected on the same day, and several weeks' worth of empty barn data was provided. However, it was a straightforward process to filter through all the data and pull out what was necessary, and this practice did not affect the observed results.

3.2.4 Data representation

The tables and figures in the following sections are organized by observation sites involved in the study. For the sake of anonymity, each producer was randomly assigned a number at the beginning of the study. If a producer utilized more than one Maximus® controller on an observation site, a letter designation was used to differentiate each barn. The barns were further differentiated using roman numerals when a producer used a single Maximus® controller for two broiler rooms. For example, say producer 99 has three barns; the first barn is on its own controller. The second and third barns share one controller. The designations are as follows:

- Site 1. 99a
- Site 2: 99bi
- Site 3: 99bii

The rationale for this representation is that many barns that shared controllers were two-story barns with only one outdoor temperature probe. Therefore, demonstrating that these data sets were not entirely independent ensures a proper understanding of the observation site.

Only the bird ages between 2 and 29 were considered during this study. Only these days were evaluated for several reasons: The first is that the broilers' grow-out period in Manitoba, Canada, can range from 30 to 33 days depending on the contract between the broiler producer and the processor. Therefore, since consistent dataset sizes were desired for this study, day 29 was selected as the final observation day.

Another reason only days 2 to 29 were considered is because this study intended to remove as much variation in carbon dioxide concentrations due to the producer's management practices as possible. For example, if the producer used heavy equipment in the barn one or two days before the broiler chicks were placed, day 0 or 1 may have had an artificially higher carbon dioxide concentration which may skew the results of this study. The final reason only days 2 to 29 were considered was that not all producers used the “end-of-flock” function on the day the birds were shipped. Therefore, to ensure no data from an empty barn was used in further analysis, datasets were truncated after day 29.

In the following subsection, some of the data is represented monthly. The month the producer’s 29th day of production fell into was the month where the data were attributed. Although this is not the most accurate way to present the data, it is appropriate to gain a high-level understanding of what was observed in the field. No detailed statistics were performed when data was represented this way. It was only used to understand the monthly data before more detailed analysis.

3.2.5 Data Analysis

JMP 16 statistical analysis software (https://onthehub.com/) was used to develop correlation statistics between observed carbon dioxide concentrations, temperature differential between ambient temperatures and indoor temperatures and, bird age. A P-value of 0.10 was used for all statistical analyses to establish significance. The null hypothesis for the statistical tests is that there is no correlation between the parameters being considered.

The reasons that a 10% significance level was used in this research is the broiler production is a complicated system to analyze. Many of the variables considered within this research are difficult to separate and discuss independently. Further to this complication, since this is a field study, there are many other things that were not controlled during this study that could happen during a broiler production cycle that could have an impact on the results. This can include, but is not limited to power failures, disease outbreak or genetic concerns with the broilers. In order develop meaningful relationships, the significance level was relaxed to 10% to account for as much of the uncontrolled situations and variables as possible.

3.3 Observed Carbon Dioxide Levels

The following subsection details the observed levels of carbon dioxide and associated outdoor temperatures in Manitoba over the study period.

3.3.1 Overall Data

Figure 3-1 located below, shows all collected carbon dioxide and outdoor temperature data for the entire study period. Figure 3-1 is comprised of 34,052 data points for both carbon dioxide concentrations and temperature data. As the chart shows, carbon dioxide and outdoor temperature appear to be negatively correlated, meaning that as the temperature decreases, the average carbon dioxide concentration increases.

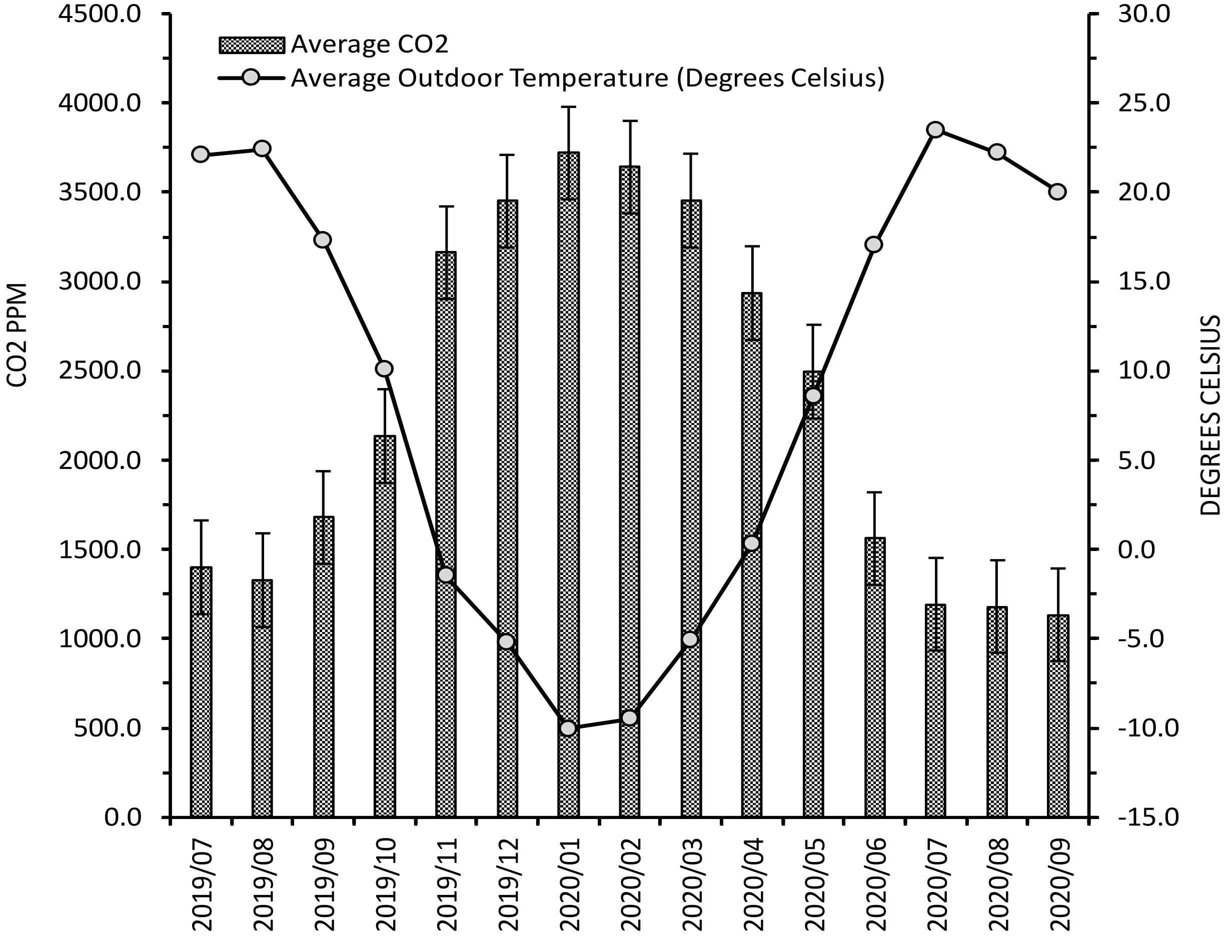

Figure 3-1: Overall visualization of all collected carbon dioxide and temperature data

Table 3-2 below shows the same data used to create Figure 1 but helps to more clearly identify the average temperature range and carbon dioxide concentration range observed throughout the study period. It is clear from Table 3-2 that the 2019/2020 winter months were unseasonably warm, with the coldest average monthly only coming in at -10.1 ̊C. The average carbon dioxide concentrations ranged from 1113 ppm and 3722 ppm, while the median ranged from 1046 ppm to 3700 ppm. It was worth noting that the maximum mean and median did not occur in the same month. The previous observation also holds true when considering the minimum mean and median values. These observations may indicate multiple drivers behind the observed carbon dioxide concentrations.

Table 3-2: Tabular format of all collected carbon dioxide and temperature data

Year – Month	Average CO_2 (ppm)	Median CO_2 (ppm)	Sample Standard Deviation (ppm)	Average Outdoor Temperature (°C)	Sample Standard Deviation (°C)	Observations Sites (#)
2019 – Jul	1399	1315	536.6	22.1	2.4	2
2019 – Aug	1327	1320	343.0	22.4	2.7	12
2019 – Sep	1681	1773	343.2	17.3	3.5	16
2019 – Oct	2136	2108	480.1	10.1	5.5	21
2019 – No	3163	3118	620.9	-1.5	5.7	17
2019 – Dec	3453	3398	575.4	-5.2	6.5	13
2020 – Jan	3722	3666	636.3	-10.1	6.7	24
2020 – Feb	3642	3700	631.4	-9.5	6.9	16
2020 – Mar	3455	3542	461.2	-5.1	6.4	10
2020 – Apr	2935	2881	573.9	0.3	6.3	20
2020 – May	2496	2384	673.1	8.6	7.5	21
2020 – Jun	1561	1601	630.4	17.1	7.3	16
2020 – Jul	1191	1045	475.8	23.5	5.4	16
2020 – Aug	1179	1046	475.8	22.2	5.5	12
2020 – Sep	1133	1056	397.0	20.0	5.2	2

3.3.2 Highest and Lowest Maximum Observed Carbon Dioxide Concentration

Figure 3-2 below shows the dataset's time-dependent data with the highest observed maximum carbon dioxide concentrations at 8905 ppm. The x-axis of the figure is the time at which each datum was collected. The figure can be considered a running log of the entire production cycle. The observed concentration for this dataset occurred at 4:00 am on the second day of the production cycle and falls sharply to levels somewhat more consistent with other observations in this study. This dataset's mean and median levels were 3773 ppm and 3665 ppm, with a sample standard deviation of 793 ppm. If day two is discarded from the dataset, the maximum observed concentration becomes 4869 ppm. The mean and median become 3643 ppm and 3464 ppm, respectively, with a standard deviation of 332 ppm. This sharp decrease observed on day two and subsequent stabilization of the carbon dioxide concentrations on day three might indicate that the individual management practices during and before this production cycle significantly affected the observed concentrations. The average temperature through the production cycle was -9.6°C, and the observation date range was 2019/12/1 to 2019/12/28.

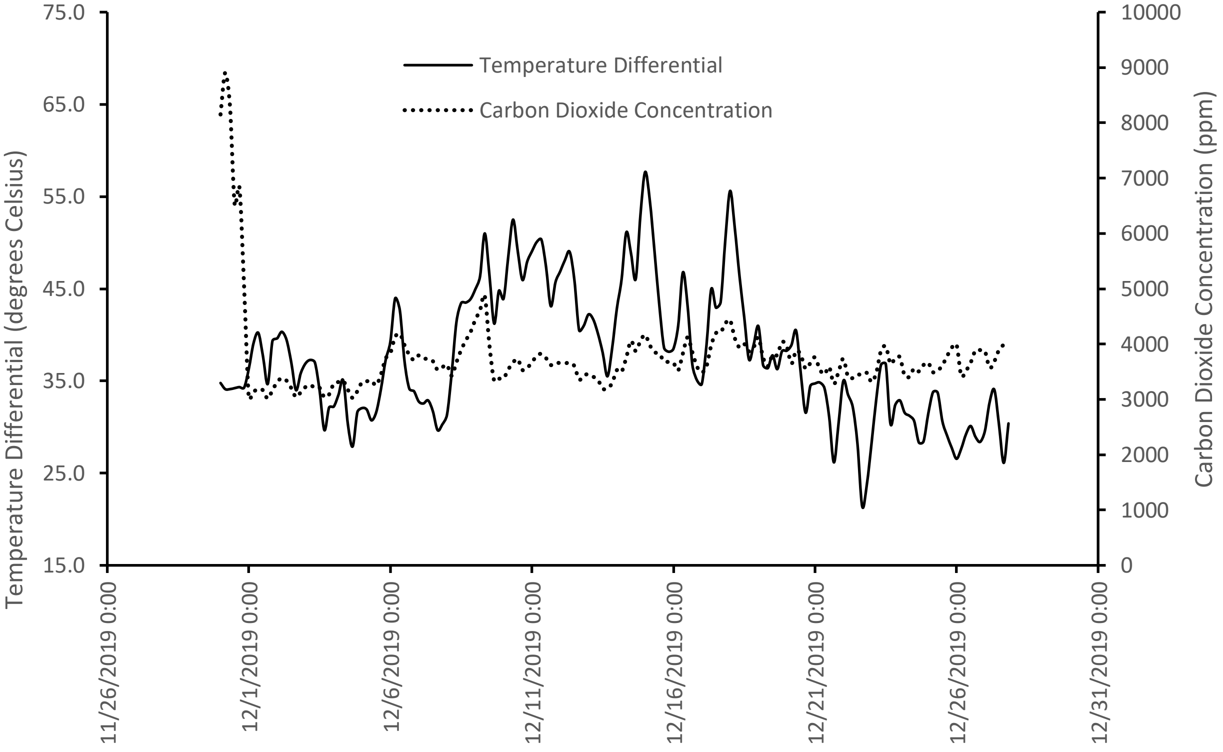

Figure 3-2: Individual production cycle with the highest observed maximum carbon dioxide concentration

Table 3-3 below shows the correlation statistics for carbon dioxide concentration, temperature differential and bird age for the production cycle with the highest observed single maximum carbon dioxide concentration.

Table 3-3: Individual production cycle with the highest observed maximum carbon dioxide concentration correlation statistics

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	1.0000	0.0955	-0.1422
Temperature Differential	0.0955	1.0000	-0.2308
Bird Age	-0.1422	-0.2308	1.0000

Table 3-4 below shows the p-values associated with the correlation statistics in Table 3-3.

Table 3-4: Individual production cycle with the highest observed maximum carbon dioxide concentration p-values

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	<0.0001	0.2183	0.0659
Temperature Differential	0.2183	<0.0001	0.0026
Bird Age	0.0659	0.0026	<0.0001

Figure 3-3 demonstrates that there are statistically significant relationships between average carbon dioxide concentration and bird age, and temperature differential and bird age. It shows that there is not a statistically significant relationship between average carbon dioxide concentration and the temperature differential. However, since there are clear outliers in Figure 3-2, day two data points were removed from the dataset to obtain the following correlation statistics and p-values.

Table 3-5: Individual production cycle with the highest observed maximum carbon dioxide concentration correlation statistics with day two data removed

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	1.0000	0.4279	0.3425
Temperature Differential	0.4279	1.0000	-0.2765
Bird Age	0.3425	-0.2765	1.0000

Table 3-6: Individual production cycle with the highest observed maximum carbon dioxide concentration p-values with day two data removed

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	<0.0001	<0.0001	<0.0001
Temperature Differential	<0.0001	<0.0001	0.0004
Bird Age	<0.0001	0.0004	<0.0001

When the outliers are removed from the dataset, the probability statistics demonstrate that there is a strong relationship between all the parameters considered. Possible reasons for this are addressed in the discussion section of chapter 3.

Figure 3-3, located below, is the dataset that contains the lowest maximum carbon dioxide concentration of all the datasets included in this study, at 1352 ppm. The mean and median of this dataset are 1019 ppm and 1072 ppm, respectively, with a sample standard deviation of 229 ppm. The average temperature throughout the production cycle for Figure 3-3 was 22.4°C, and the observation date range was 2019/7/18 to 2019/8/14.

As previously mentioned, the dataset used to create Figure 3-3 comprises significantly fewer data points than the dataset used to create Figure 3-2. This can be observed by the appearance of smoother lines in Figure 3-3.

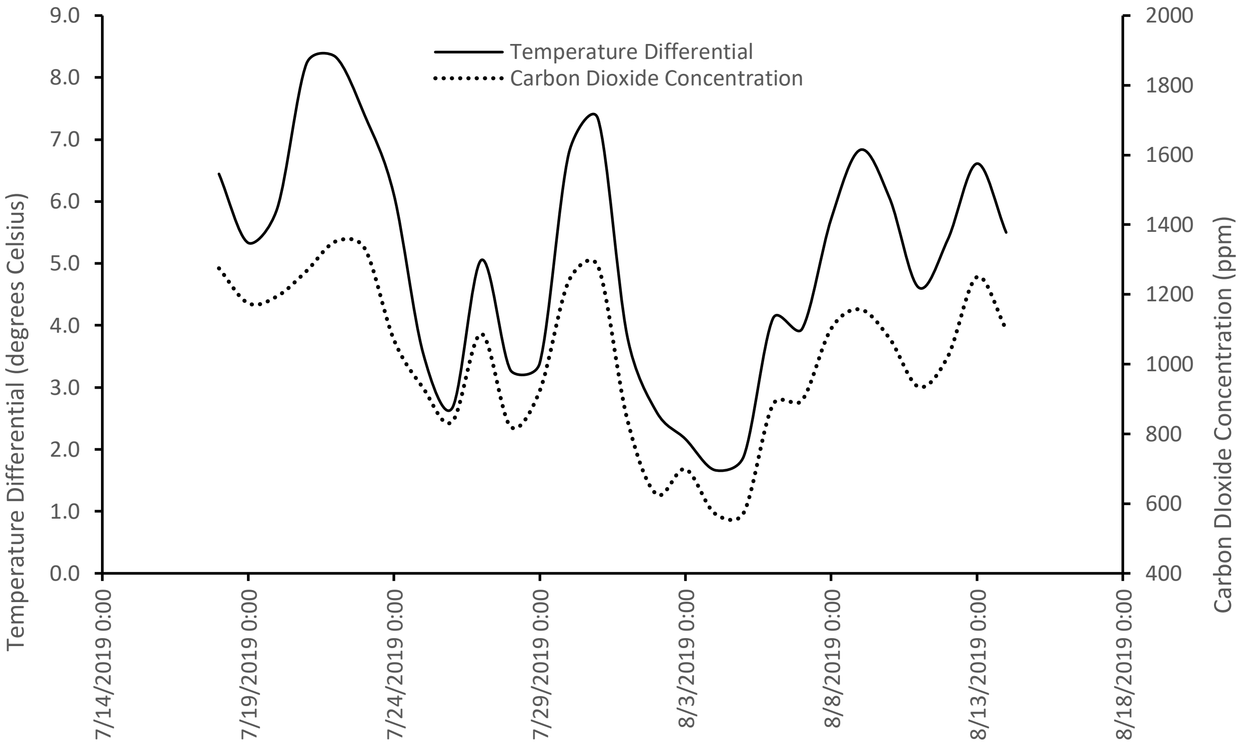

Figure 3-3: Individual production cycle with the lowest observed maximum carbon dioxide concentration

Figure 3-7 below shows the correlation statistics for carbon dioxide concentration, temperature differential and bird age for the production cycle with the lowest observed single maximum carbon dioxide concentration.

Table 3-7: Individual production cycle with the lowest observed maximum carbon dioxide concentration correlation statistics

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	1.0000	0.9542	-0.3069
Temperature Differential	0.9542	1.0000	-0.4382
Bird Age	-0.3069	-0.4382	1.0000

Table 3-8 below shows the p-values associated with the correlation statistics in Table 3-7.

Table 3-8: Individual production cycle with the highest observed maximum carbon dioxide concentration p-values

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	<0.0001	<0.0001	0.1121
Temperature Differential	<0.0001	<0.0001	0.0197
Bird Age	0.1121	0.0197	<0.0001

3.3.3 Highest and Lowest Mean and Median Carbon Dioxide Concentration

Similar to the above figures, Figure 3-4 below is the dataset that contains the highest maximum observed mean and median concentration of carbon dioxide. The maximum median and mean occurred in the same dataset for this observation. The observation dates for the dataset used to create Figure 3-4 were between 2019/12/29 and 2020/1/25. The average and median carbon dioxide concentration was 4912 ppm and 4866 ppm, with a sample standard deviation of 931 ppm. The maximum observed value in this dataset was 6813 ppm. The average temperature that was recorded for this dataset was -10.2°C. Since the mean is higher than the median in this dataset, it might suggest that the data is skewed towards higher carbon dioxide concentrations.

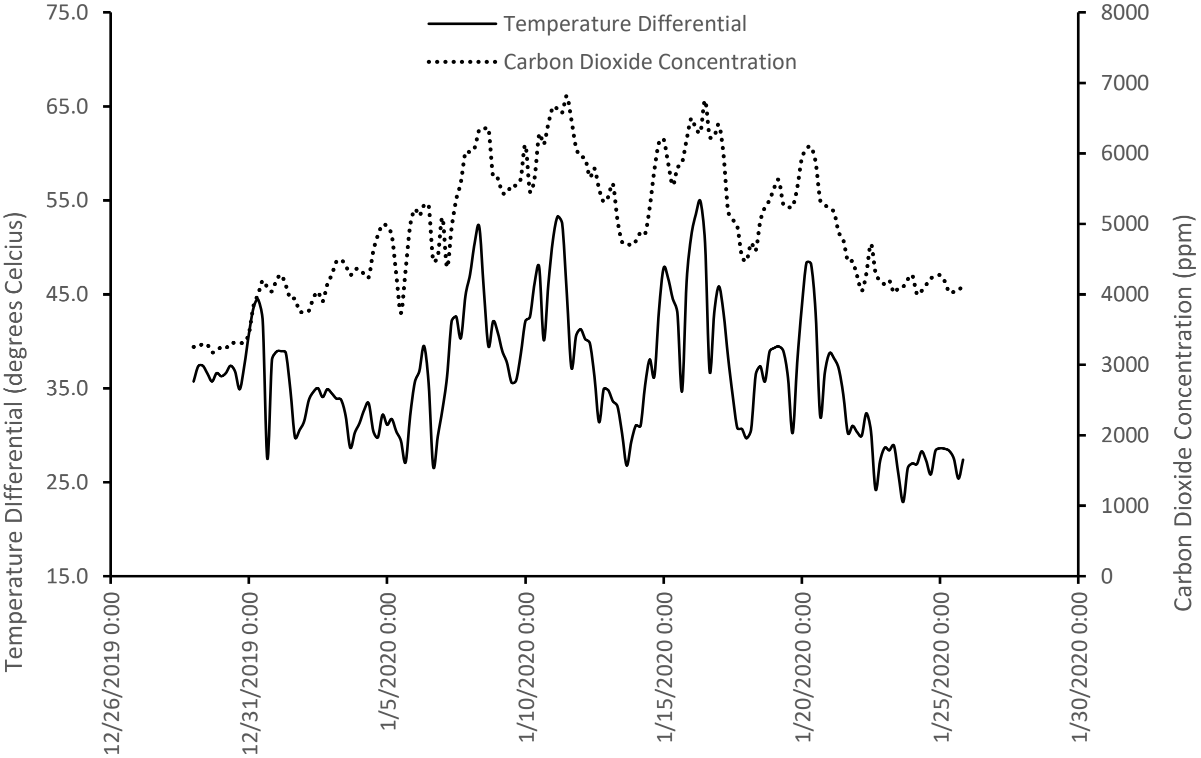

Figure 3-4: Individual production cycle with the highest observed mean and median carbon dioxide

Table 3-9 below shows the correlation statistics for carbon dioxide concentration, temperature differential and bird age for the production cycle with the highest mean and median carbon dioxide concentration.

Table 3-9: Individual production cycle with the highest observed mean and median carbon dioxide concentration correlation statistics

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	1.0000	0.6566	0.2866
Temperature Differential	0.6566	1.0000	-0.181
Bird Age	0.2866	-0.181	1.0000

Table 3-10 below shows the p-values associated with the correlation statistics in Table 3-9.

Table 3-10: Individual production cycle with the highest observed mean and median carbon dioxide concentration p-values

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	<0.0001	<0.0001	0.0002
Temperature Differential	<0.0001	<0.0001	0.0208
Bird Age	0.0002	0.0208	<0.0001

Figure 3-5 below represents the dataset that contains the lowest observed carbon dioxide mean and median. Similar to Figure 3-4 above, the lowest observed mean and median carbon dioxide concentrations occurred in the same production cycle. The mean and median values were 421 and 367 ppm, respectively, with a sample standard deviation of 164 ppm. The maximum observed carbon dioxide concentration was 1467 ppm, and the average temperature throughout the production cycle was 19.4°C. The observation dates of this production cycle were between 2020/5/29 and 2020/6/27. The trend and relationship observed in Figure 3-5 are unique from the other charts in this section, and potential reasons for this difference are discussed in section 3.4.3.

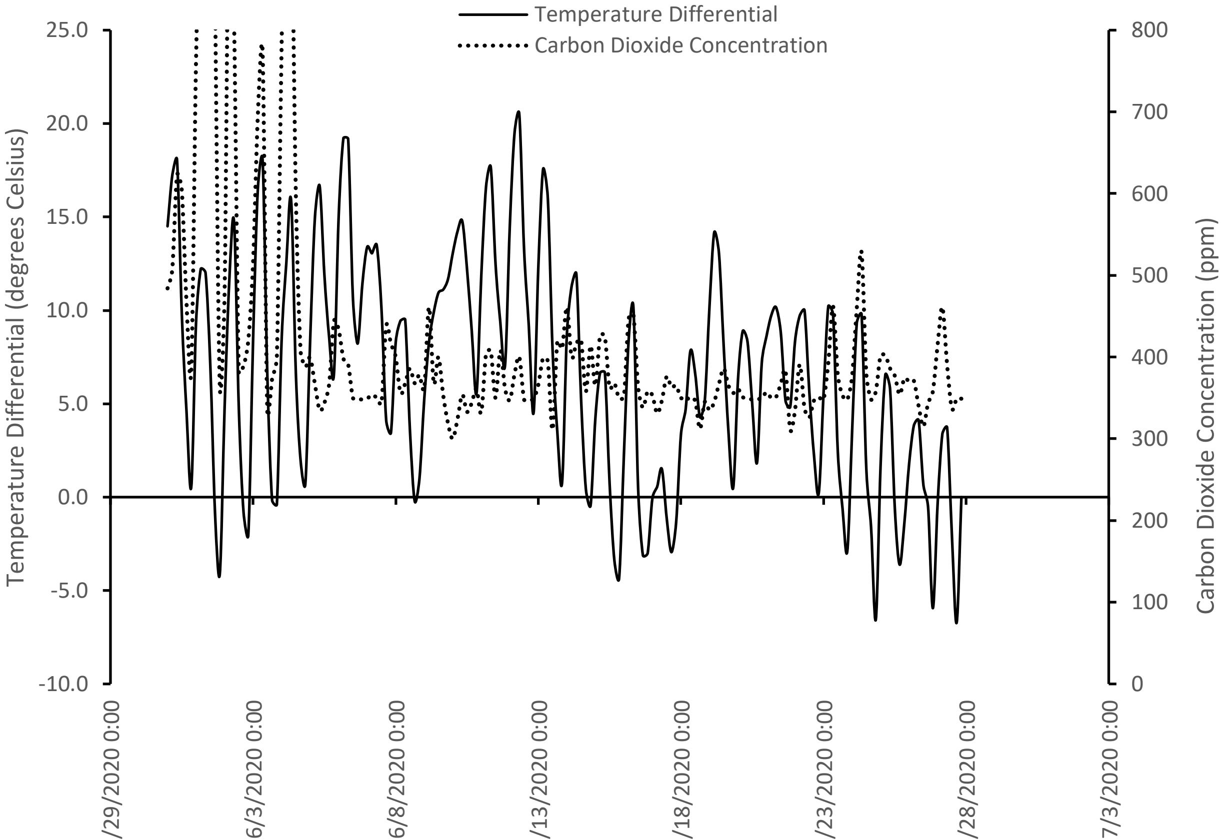

Figure 3-5: Individual production cycle with the lowest observed mean and median carbon dioxide

Table 3-11 below shows the correlation statistics for carbon dioxide concentration, temperature differential and bird age for the production cycle with the highest mean and median carbon dioxide concentration.

Table 3-11: Individual production cycle with the lowest observed mean and median carbon dioxide concentration correlation statistics

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	1.0000	0.2028	-0.4371
Temperature Differential	0.2028	1.0000	-0.1949
Bird Age	-0.4371	-0.1949	1.0000

Table 3-12 below shows the p-values associated with the correlation statistics in Table 3-11.

Table 3-12: Individual production cycle with the lowest observed mean and median carbon dioxide concentration p-values

	Average CO_2 Concentration	Temperature Differential	Bird Age
Average CO_2 Concentration	<0.0001	0.0084	<0.0001
Temperature Differential	0.0084	<0.0001	0.0114
Bird Age	<0.0001	0.0114	<0.0001

3.4 Discussion

3.4.1 Overall Data

3.4.1.1 Average Carbon Dioxide Concentrations and Temperature Differential

The average carbon dioxide concentrations in this study were between 421 ppm and 4912 ppm, and the monthly averages ranged from 1133 ppm to 3722 ppm. Between November 2019 and March 2020, the average monthly carbon dioxide concentrations exceeded 3000 ppm. Of the 217 datasets collected for this thesis, 73 had average concentrations over 3000 ppm for a total of 33%. Of these 73 datasets with average carbon dioxide concentrations greater than 3000 ppm, 65 were between November 2019 and March 2020, for 89%. Out of the 80 production cycles between November 2019 and March 2020, 65 of them had average concentrations of carbon dioxide greater than 3000 ppm, for a percentage of 81%.

The most evident trend that can be observed in Figure 3-1 is that carbon dioxide concentrations appear to be inversely related to the outside temperature. This finding is consistent with many of the publications considered in the literature review of this thesis (Olanrewaju et al. 2008; Corkery et al. 2013; Cândido et al. 2018). It is worth noting that the 2019/2020 winter season was mild compared to what is typically observed in Manitoba. Some climate data puts the mean January temperature in Manitoba at -14°C, whereas the data in this thesis shows that the mean January temperature was -10.1°C. This is an important observation since this thesis attempts to understand typical field carbon dioxide concentrations in a Canadian Prairie climate, and the carbon dioxide concentrations are very closely related to the outdoor temperature. When a simple linear regression model is used to fit a relationship between average carbon dioxide concentration and average outdoor temperature, the R^2 coefficient is 0.8597, as shown in Figure 3-6. This R^2 coefficient indicates a strong relationship between average outdoor temperature and average indoor carbon dioxide concentrations using linear regression to fit the data.

There is undoubtedly variation within Figure 3-6, possibly due to the diversity of barn age and technologies used in participating barns. Some of the variability within Figure 3-6 may be due to individual management practices of producers. For example, some producers may choose to ventilate based on a carbon dioxide concentration parameter, a relative humidity parameter, or something different altogether. These differences in management practices would likely lead to variability of carbon dioxide concentration from barn to barn, even with an identical barn design.

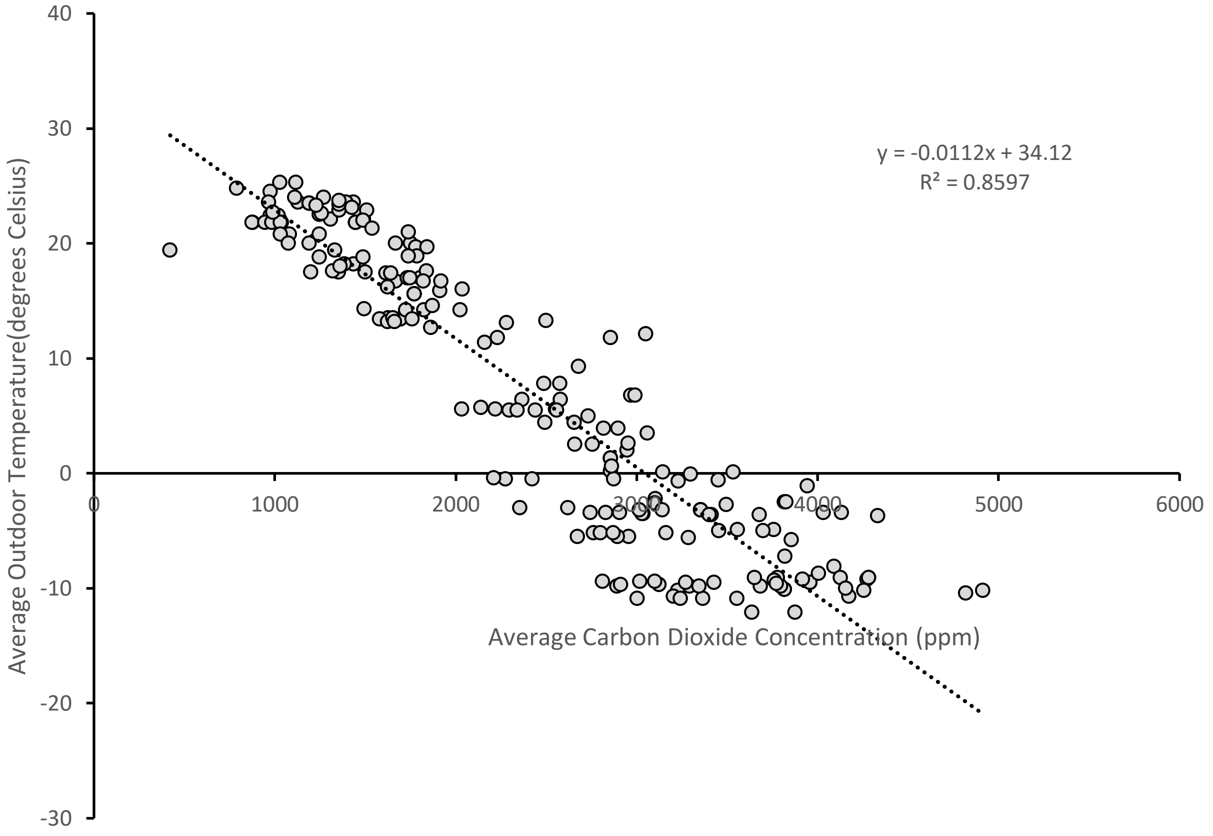

Figure 3-6: Average Outdoor Temperature plotted against Average Carbon Dioxide Concentration for all production cycles

3.4.1.2 Carbon Dioxide Concentration and Outdoor Temperature Below -20̊C

So far, the difference between indoor and outdoor temperature has been discussed. However, analyzing the trends using outdoor temperature only also provides valuable information. Figure 3-7 plots the carbon dioxide concentrations against the outdoor temperature for all instances where the outdoor temperature was equal to or less than -20̊C at observation site 11. Observation site 11 consists of 3 barns and four broiler grow-out rooms. Observation site 11 will be discussed in greater detail in Chapter4.

The average carbon dioxide concentration in Figure 3-7 is 4105 ppm, and the sample standard deviation is 427.0 ppm. The maximum and minimum 4-hour carbon dioxide concentrations were 5197 ppm and 2966 ppm, respectively. The maximum 4-hour carbon dioxide concentration occurred at 14 days of age and with an outdoor temperature recording of -21.2℃. The minimum 4-hour carbon dioxide concentration occurred at eight days of age and with an outdoor temperature recording of -21.3C. The minimum and maximum occurred in the same barn and production cycle and were recorded on 2020/1/16 at 8:00 am and 20202/1/10 at noon, respectively.

An explanation for why the minimum and maximum were recorded only six days apart, with similar outdoor temperatures, is that the three recordings before the maximum observed carbon dioxide concentration were -28.5℃, -30.0℃, and -28.4℃. Therefore, since the temperature differential in the 12 hours leading up to the maximum observed carbon dioxide concentration was high, more fuel was being combusted to maintain appropriate temperatures, resulting in higher carbon dioxide concentrations in the broiler room.

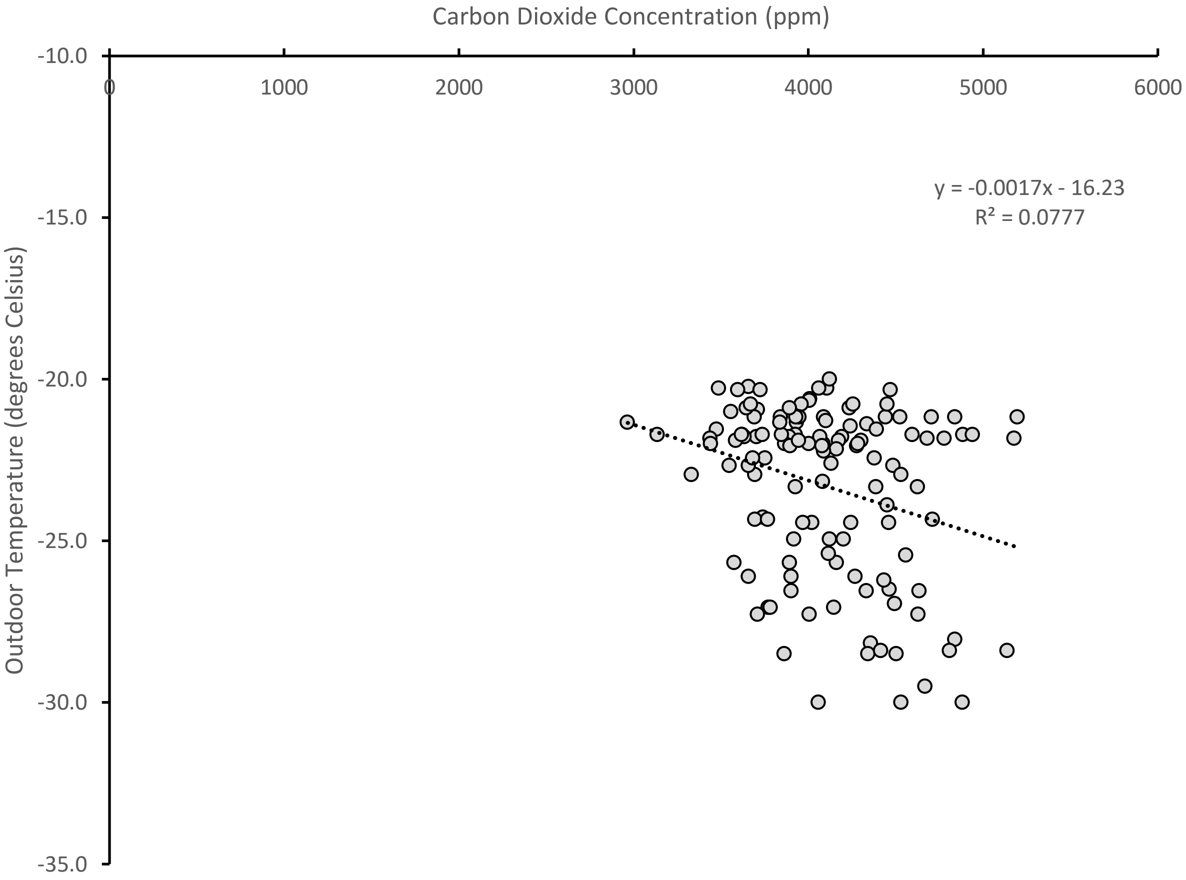

Figure 3-7: Carbon dioxide concentrations where the outdoor temperature is below -20̊C from observation site 11

Although temperature differential might be the more accurate metric to use when considering carbon dioxide concentration, outdoor temperature alone still demonstrates that at temperatures below -20̊C, carbon dioxide concentrations can exceed 3000 ppm, as shown in Figure 3-7 above.

Another key idea that can be taken away from considering the 4-hourly data is that when the resolution is increased, it becomes more challenging to predict carbon dioxide concentrations using outdoor temperature as there is a latency effect between the observed temperature and observed carbon dioxide concentrations. This conclusion that prediction is more difficult at higher resolutions is further strengthened by the low R^2 value used to fit the data in Figure 3-7.

When considering the R^2 shown in Figure 3-6, there is a higher degree of accuracy and certainty when predicting average carbon dioxide concentrations using average outdoor temperature than predicting 4-hourly carbon dioxide concentrations using 4-hourly temperature data.

3.4.2 Highest and Lowest Maximum Observed Carbon Dioxide Concentration

The highest maximum observed 4-hour concentration of carbon dioxide in the study was 8905 ppm and occurred on 2019/11/30 at 4:00 am, or day 2 of the production cycle. However, suppose the curve of carbon dioxide concentrations is considered in Figure 3-2, it is observed that the concentrations decrease sharply and stabilize on day 3, at a level more consistent with other datasets in this thesis. This observation might suggest that the concentration of 8905 ppm is due to individual producer management practices and not strictly environmental conditions. One possible explanation for this observation is that this producer may have been rapidly heating their barn back up to an appropriate temperature right before the placement of chicks. If the heating system was running at a high capacity, this could explain the observed high level of carbon dioxide. The sharp drop-off could be explained by the producer increasing the ventilation to reduce the concentrations once the temperature had stabilized. The effects that this practice may have on broiler chicks are not known at this time. This data further demonstrates that producer management practices can have a significant effect on carbon dioxide concentrations, and the observed carbon dioxide data is not solely due to outdoor temperature.

When the day two from this dataset is not considered in the correlation and p-value statistics, as shown in and Table 3-6, we reject the null hypothesis that the there is no correlation between the parameters considered. This analysis demonstrates that the temperature differential between the ambient temperature and indoor temperature was negatively correlated with the observed carbon dioxide concentration.

Table 3-6 also shows that there is a statistically significant relationship between bird age and observed carbon dioxide concentration. This is an important observation as it indicates there is more than one driver behind the observed carbon dioxide concentrations. Table 3-4

The next highest concentration of carbon dioxide observed in this study was 7493 ppm and will be discussed to eliminate management practices from the analysis. The production cycle containing the second-highest maximum of 7495 ppm is shown in Figure 3-8. The maximum was observed at 8:00 am on 2019/12/17, or day 5 of the production cycle. The maximum occurred early in the production cycle, just as it did with the 8905. However, it is not accompanied by a sharp drop-off, as observed in Figure 3-2, and does happen three days later in the cycle than the maximum observed in Figure 3-8. This observation indicates that the maximum of 7493 ppm might be related to the environmental conditions and not individual management practices. However, comparing these two charts, Figure 3-8 and Figure 3-2, it might be concluded that individual management practices between and during production cycles can significantly affect the observed carbon dioxide concentrations.

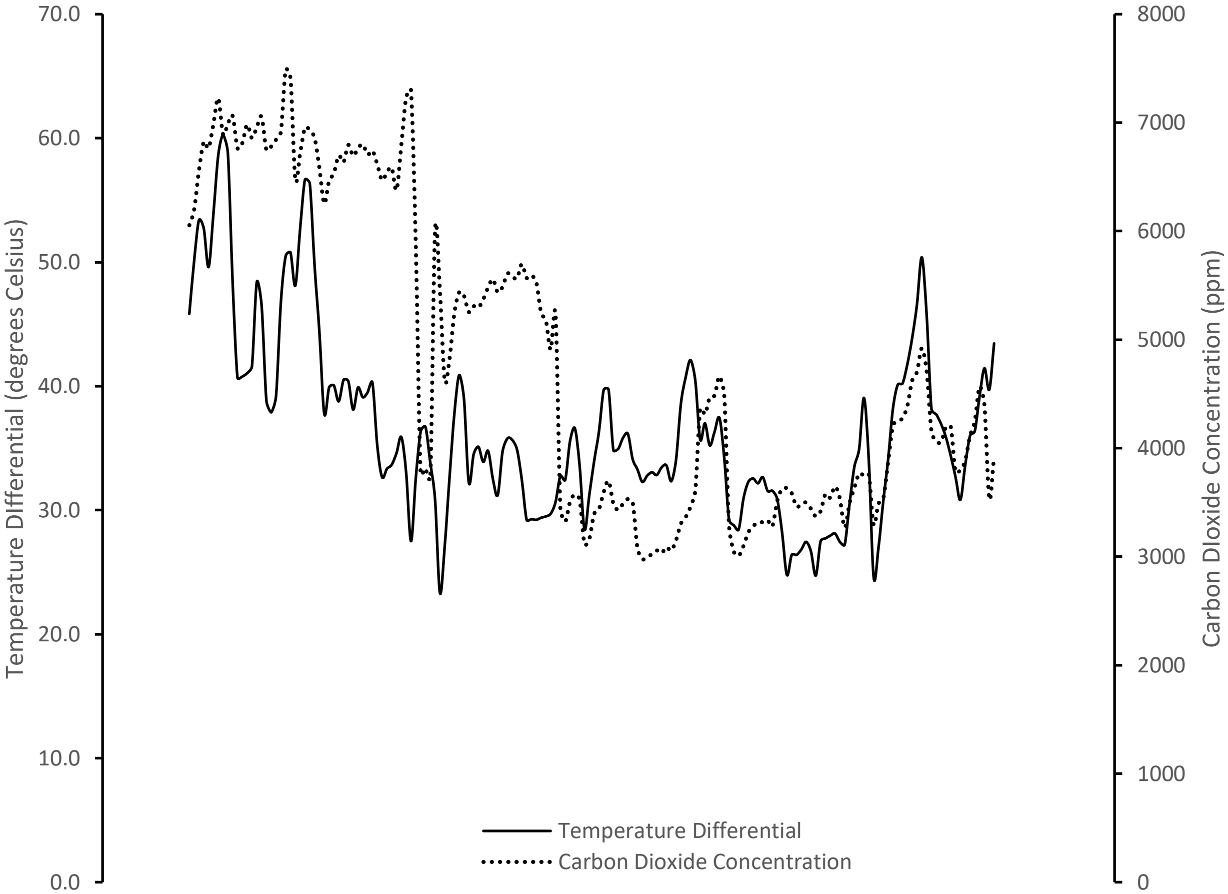

Figure 3-8: Individual production cycle with the second-highest observed maximum carbon dioxide concentration

The lowest maximum value observed during this study was 1352 ppm and occurred on 2019/7/22 at midnight. The heating requirement or temperature differential at data capture is one key difference between the highest and lowest observed maximum values. The temperature differential at the lowest observed maximum was only 10.6℃, whereas the temperature differential during the second highest observed maximum was 50.5℃. Both carbon dioxide concentrations occurred early in the cycle, where the ideal temperature for the broilers is around 30℃. The indoor temperature was 30.8℃ and 28.9℃ for the lowest and highest observed maximum carbon dioxide concentrations, respectively. This observation further shows that the carbon dioxide concentrations in the barns are closely linked to the indoor and outdoor temperature difference or the heating requirement.

When the correlation statistics from the production cycle with the lowest observed maximum carbon dioxide concentration are considered, the results tell a different story from the statistics from the highest observed maximum carbon dioxide concentration. Table 3-8 demonstrates that we reject the null hypothesis that the true correlation between carbon dioxide and outdoor temperature is equal to but fail to reject the null hypothesis that there is no correlation between the considered parameters.

One explanation for why the results is different between the highest and lowest observed maximum is that the observations take place in opposite seasons. The cycle with the highest observed maximum occurs in the winter of 2019 and the cycle with the lowest observed maximum occurs in the summer of 2019. In the summer months, producers ventilate at a higher rate in order to remove excess heat from the barns. In the winter months, producers ventilate at a lower rate to retain heat in the barns. In summer, it is hypothesized that the producer was ventilating at a high enough rate that carbon dioxide produced through bird respiration is removed from the barn as fast, or faster than it is produced and therefore does not affect the recorded results. In the winter months, it is the opposite story where carbon dioxide produced through respiration accumulates faster than it is ventilated. As the birds grow, they produce more carbon dioxide through respiration and this is why there is a statistically significant relationship between bird age and carbon dioxide concentrations in the winter months, but not in the summer months.

3.4.3 Highest and Lowest Mean and Median Carbon Dioxide Concentration

The highest and lowest average and median occurred in the same barn and during the same production cycle. This observation shows that although the outdoor temperature considerably affects carbon dioxide concentrations, the barn's facilities and design also play into the carbon dioxide concentration. The literature review in this thesis supports this observation that both barn design and the climate affect carbon dioxide concentrations. In addition, the timeframe in which these minimums and maximums occur is consistent with previous observations in this study, with the highest values observed in the cold months and the lowest values observed in the warm months.

Figure 3-4 also displays another important observation of carbon dioxide in broiler barns. Despite the average concentration being 4912 ppm, the levels fluctuate considerably in the barn. This observation is supported by the standard deviation of 931 ppm and the observed minimum and maximum of 3177 ppm and 6813 ppm, respectively. This fluctuation of carbon dioxide concentrations can also be observed in the other figures tracking temperature differential and carbon dioxide concentration over an entire production cycle.

One of the most important observations that can be made from Figure 3-4 and most of the other similar figures, is how closely the temperature differential and carbon dioxide concentration curves follow each other. A sudden change in temperature differential is often followed by a sudden change in carbon dioxide concentration. This is important as previous observations show that average carbon dioxide and average outdoor temperature are closely related; however, no information on how the two parameters relate to each other with respect to time can be gathered by only looking at averages. This time-dependent data cannot conclude precisely how quickly a change in temperature differential results in a change in carbon dioxide due to data only being captured every 4 hours. However, a rapid change in temperature differential was accompanied by a rapid change in carbon dioxide at the subsequent data capture, or 4 hours later. This trend shows that the carbon dioxide response to outdoor temperature changes might be less than 4 hours and that outdoor temperature, even hourly, is related to carbon dioxide concentrations in the barns in the cold months. This observation is further validated by the correlation and probability statistics relating temperature differential to observed carbon dioxide concentration.

At first, Figure 3-5 might look like there were issues with some of the barn sensors, though discussing the barn's design may lead to alternate conclusions. It is known that the barn associated with Figure 3-5 is the second story of a two-story barn. It is well known that heat rises, and carbon dioxide is a much heavier gas than oxygen. The molar masses of carbon dioxide and oxygen gas are 44.01 g/mol and 32.00 g/mol, respectively. Therefore, it can be hypothesized that the second story of this barn was receiving some heat from the first story, thus reducing the heating requirement or even causing overheating since this production cycle occurred in summer.

It can also be hypothesized that carbon dioxide may have been sinking from the second story to the first story, lowering the second story's concentration. Producers will ventilate at higher rates in warm months to keep the barns cool. Suppose the second story in this barn was ventilating at a high rate due to heat from the barn below and hot summer conditions. In that case, it is reasonable to assume that the carbon dioxide levels would be much closer to ambient conditions, especially if the carbon dioxide concentration in the barn were lower due to the sinking of the gas to the first floor. Although, at high enough ventilation rates, the hypothesis of the carbon dioxide leaching to the floor below may not be valid.

This is a hypothesis; however, at this point, the observed average of 421 ppm is assumed to be a valid data point and not an error due to sensor malfunction. Anecdotally, most broiler producers with two-story barns will state that they consistently have better air quality in the second story compared to the first story. This anecdote further supports the hypothesis stated above, but more research is needed to substantiate the claim.

When observing Figure 3-5 it may appear the trend where a sudden shift in temperature results in a sudden shift in carbon dioxide concentration is not applicable. However, Table 3-10 and Table 3-12 show that the carbon dioxide concentrations were statistically correlated to bird age and outdoor temperature in both the production cycle with the highest and lowest mean and median carbon dioxide concentrations. These results further demonstrate that outdoor temperature and carbon dioxide are closely linked in all seasons. In the case of the highest and lowest mean carbon dioxide concentration, bird age and carbon dioxide concentrations were statistically correlated in both instances with p-values of 0.0002 and <0.0001, respectively when outliers were removed from the dataset.

The conclusion that bird age and carbon dioxide are statistically correlated differs from the conclusions that were made when considering the highest and lowest maximum carbon dioxide concentration, where bird age and carbon dioxide concentration were only statistically correlated in the winter. The p-values relating bird age to carbon dioxide concentration in the cycles with the highest and lowest carbon dioxide concentration are <0.0001 and 0.1121, respectively.

3.5 Summary

This section of the thesis shows that indoor carbon dioxide concentrations are closely linked to the outdoor temperature or the temperature differential inside and outside the barn.

Using a linear regression model, it was shown that the R^2 value relating to average carbon dioxide concentrations and average outdoor temperature was 0.8597. When monthly averages are considered, there also appears to be a strong relationship between the sample standard deviation of carbon dioxide concentrations and the sample standard deviation of outdoor temperatures. This observation suggests that the more the temperature fluctuates, the more the carbon dioxide concentrations fluctuate.

This study's average carbon dioxide concentrations were 421 ppm to 4912 ppm, with the maximum average occurring in January 2020 and the minimum average occurring in June 2020. These observations further indicate that as temperatures decrease, carbon dioxide increases. This increase in carbon dioxide is most likely due to the increased heating requirement to maintain appropriate temperatures in the barns. When the data was broken down by month, the averages ranged between 1133 ppm and 3722 ppm.

It was also demonstrated that at observation site 11, the average carbon dioxide concentration for all outdoor temperatures equal to or below -20℃ was 4105 ppm. Since the indoor temperature is not constant over a broiler grow-out, using the temperature difference is likely the more accurate parameter to consider. However, by only considering outdoor temperature, valuable information can still be obtained. It was shown that below -20℃, carbon dioxide concentrations can easily exceed 3000 ppm. Although observation site 11 was the only site considered for this analysis, it is assumed that the trends seen at observation site 11 would be seen at other observation sites.

The highest 4-hour maximum carbon dioxide concentration in a production cycle was 8905 ppm. The curve presented in Figure 3-2 suggests that this maximum is likely due to a combination of management practices and the temperature differential. This observation occurred in December 2019, so the environmental conditions can not be discounted entirely. The lowest 4-hour maximum recorded was 1352 ppm and occurred in August 2019, again showing that temperature plays a critical role in the observed carbon dioxide concentrations.

The section also shows that temperature and carbon dioxide levels are linked hourly, not just on average. The two curves in Figure 3-4, temperature differential and carbon dioxide, closely follow each other, showing that a rapid change in temperature differential is accompanied by a rapid change in carbon dioxide concentrations at the subsequent data capture or 4-hours later. This claim is further substantiated by the correlation and probability statistics relating carbon dioxide concentration to temperature differentials. Bird age and carbon dioxide concentrations were statistically correlated in all instances but one. This discrepancy may be due to different barn designs, or different producer practices regarding ventilation.

One area of further research that this section identifies is the difference in air quality between the first and second levels in a two-story barn. The lowest carbon dioxide average observed was 421 ppm and occurred in June 2020; however, it also happened in the second story of a two-story barn. A possible explanation of why the lowest average was observed in the second story, using the rising heat from the first story and the fact that carbon dioxide is heavier than oxygen gas, has been presented.

Chapter 4 Broiler Performance Analysis

Abstract

Carbon dioxide, room temperature, relative humidity, and outdoor temperature data were collected from two broiler rooms for an entire year. In total, data from eight complete production cycles were collected. Broiler performance parameters were obtained from the processor reports to relate the collected environmental data to broiler performance. The two broiler rooms were located on the same observation site and were of identical construction. Using JMP 16 analysis software (https://onthehub.com/), no statistically significant relationships between growth performance and environmental parameters were observed at a 10% significance level. However, statistically significant relationships were observed when livability and condemnations were compared against the environmental data. Livability and condemnations were statistically correlated to average carbon dioxide concentrations and outdoor temperature. However, it does create a confounding effect in this analysis. An argument has been presented for the outdoor temperature being the primary reason for the observed trends in livability and condemnations. Further research is required to reach a meaningful conclusion.

4.1 Introduction

There is sparse literature that explores the effects of carbon dioxide on broiler chicken performance under field conditions. Past field studies on the impact of carbon dioxide concentration on broilers tend to focus on the growth parameters and not on livability or condemnations (Reece and Lott 1980). Many of these studies conclude that carbon dioxide concentrations typically observed in the field do not affect the growth performance parameters of broilers (Reece and Lott 1980; Bokkers et al. 2010). However, not all literature regarding avian species points to this conclusion (Cândido et al. 2018).

Other controlled laboratory studies exposed broiler chicks to levels of carbon dioxide that would not be observed in a typical broiler production environment (Wilson and Edwards 1950). While these studies provide valuable insight into how carbon dioxide affects broiler chicks at various exposure levels and ages, more research is required to understand the effects of the carbon dioxide concentrations observed in the field. It is also important to note that the study by Wilson and Edwards (1950) was used to develop ethical euthanasia processes and not to determine the effect of long-term exposure under field conditions.

Understanding how carbon dioxide affects performance parameters is essential when the conclusions of Chapter 3 of this thesis are considered. Chapter 3 concluded that carbon dioxide levels are directly linked to the difference between indoor and outdoor temperatures. Carbon dioxide concentrations were also shown to fluctuate considerably between the warm and cold months. It has also been shown that carbon dioxide concentrations vary throughout a single production cycle. Developing relationships between broiler performance parameters and carbon dioxide concentrations will be essential for management practices, decision-making, and future regulation within the industry.

This thesis chapter follows observation site 11 more closely and attempts to relate broiler performance parameters to carbon dioxide concentrations and other environmental parameters.

4.2 Materials and Methods

This section details the materials and methods that were used to analyze performance data from observation site 11 and how the data were obtained

4.2.1 Observation Site 11 Description

Observation site 11 consisted of 3 barns where each barn used its own Maximus® controller. There were four broiler rooms on the observation site as one of the barns had two floors and was identified as 11ci for the ground floor and 11cii for the second floor. Barns 11a and 11b were of identical construction with specifications as follows:

- Forced air heat systems
- Five heaters at 73 kW (250000 BTU) in each barn
- The floor area of 1532 m^2
- 3m ceiling height

For detailed statistical analysis, only barns 11a and 11b were considered as the construction and age of each barn were similar.

4.2.2 Data Collection from Barn

The following data were collected from barn 11a, 11b, 11ci, and 11cii using the Maximus® controller system, as detailed in Chapter 3. The following data were collected from all four rooms:

- Bird age (days)

- Indoor temperature (F)
- Outdoor temperature (F)
- Carbon dioxide concentration (ppm)
- Relative Humidity (%)
- Water consumption per bird (mL)
- Average mixed weight (g)
- Daily weight gain (g)

One error that occurred during data collection was that the feed program in the barns was switched. Initially, 11a was fed an antibiotic-free diet (RWA), and 11b was fed a non-RWA (NRWA) diet. In the second production cycle, 11b was fed an RWA diet, and 11a was fed an NRWA diet. The feed program switched again between barns on production cycle 5 and then again on production cycle 8. This switch was only identified after the data collection period was complete

Although there was a change in diet between the barns, individual production cycles did not switch from an NRWA feed program to an RWA or vice versa. Since the barns had identical construction and each production cycle is effectively a reset, the barns were analyzed as 11-RWA and 11-NRWA, rather than 11a and 11b.

4.2.3 Performance Data

The following information was obtained from the processor's reports at the end of each production cycle:

- Birds placed per cycle (#)
- Weight shipped (kg)

- Time to market (days)
- Livability (%)
- Condemnations (%)
- Feed Conversion Ratio
- Broiler Performance Index

Livability is the percentage of placed chicks shipped at the end of each production cycle. Condemnations are an aggregated score of health issues identified at the processing facility. Condemnations could include cellulitis, ascites, lameness, and lacerations, to name a few.

The feed conversion ratio (FCR) is calculated as the feed mass in kilograms required for the birds to gain 1 kilogram of mass. The feed conversion ratio is a direct profitability metric and provides insight into broiler welfare. A stressed bird will use energy to maintain homeostasis, not for weight gain. In isolation, the feed conversion ratio is not a good metric for animal welfare as feed quality is also important for bird weight gain. However, used in conjunction with other performance parameters, it can be used as an indicator of broiler health and welfare.

The Broiler Performance Index (BPI) is a culmination of the bullet points above BPI in the list above and is calculated by Equation 4.1, found below. The BPI is a tool that producers use to evaluate the performance of their flock and can be used to measure the profitability of the flock. Therefore, a higher BPI indicates a higher-performing flock. The Broiler Performance Index (BPI) is calculated by using Equation 4.1.

$$BPI = \frac{(Livability\%)\big(Average\ live\ weight\ at\ end\ of\ production\ cycle\ (kg)\big)}{(Feed\ Coversion\ Ratio)(Days\ to\ market)} * 100 \tag{4.1}$$

Suppose a flock had livability of 97%, an average weight of 2.1 kg, an FCR of 1.4, and the broilers were grown for 30 days. The BPI calculation would be as follows in Equation 4.2:

$$BPI = \frac{(0.97*100)(2.1\ kg)}{(1.4\frac{kg}{kg})(30\ days)} * 100 = 485\ \frac{kg}{day} \tag{4.2}$$

Table 4-1 below is the performance data from the processor reports from the 11-RWA rooms at observation site 11. Table 4-1 also includes the average carbon dioxide concentration and average outdoor temperature observed for each of the eight production cycles.

Table 4-1: Raw performance data from 11-RWA

29th Day	CO_2 (ppm)	Outdoor Temp (°C)	RH (%)	Days to Market	Weight (kg)	Livability (%)	Cond (%)	FCR (kg/kg)	BPI (kg/day)
2019/09/05	1500	17.5	58.2	32	2.14	97.81	1.34	1.498	437.0
2019/10/24	2138	5.7	64.6	33	2.22	98.62	1.59	1.546	429.9
2019/12/12	2871	-5.2	64.4	33	2.06	95.85	1.97	1.600	374.0
2020/01/29	3204	-10.7	63.7	34	2.14	95.76	1.47	1.635	367.8
2020/03/19	3285	-5.6	54.3	33	2.18	96.83	1.98	1.554	411.0
2020/05/07	2557	5.5	53.8	33	2.24	97.89	1.32	1.543	437.9
2020/06/25	1212	18.8	58.6	33	2.06	97.85	1.01	1.572	388.7
2020/08/13	946	21.8	75.2	33	2.11	98.72	0.83	1.562	403.0

Table 4-2 below is the performance data from the processor reports from the 11-RWA rooms at observation site 11. Table 4-2 also includes the average carbon dioxide concentration and average outdoor temperature observed for each eight production cycles.

Table 4-2: Raw performance data from 11-NRWA

29th Day	CO_2 (ppm)	Outdoor Temp (°C)	RH (%)	Days to Market	Weight (kg)	Livability (%)	Cond (%)	FCR (kg/kg)	BPI (kg/day)
2019/09/05	1321	17.6	67.2	33	2.08	98.10	1.25	1.545	399.6
2019/10/24	2551	5.6	55.2	32	2.10	97.31	1.23	1.473	433.8
2019/12/12	3161	-5.2	52.8	32	2.21	97.64	1.86	1.497	450.6
2020/01/29	3555	-10.9	54.3	33	2.15	96.23	1.42	1.610	388.0
2020/03/19	2674	-5.5	62.0	32	2.04	96.76	1.39	1.457	423.0
2020/05/07	2340	5.5	63.8	33	2.20	96.19	1.63	1.522	421.0
2020/06/25	1245	18.8	68.2	33	2.07	98.08	1.05	1.505	422.6
2020/08/13	1030	21.8	62.4	33	2.21	98.67	1.05	1.507	437.9

4.3 Analysis

All data for the 11-RWA and 11-NRWA rooms were collected using Maximus® controllers and sensors described in Chapter 3. Average values for each data type were calculated for all eight production cycles from each room. Summary tables were created for each room and were imported into JMP 16 for further statistical analysis.

Using the multivariate analysis tool in JMP 16, the average carbon dioxide concentrations were compared to all the performance parameters. In addition, relative humidity is compared to all the performance parameters to identify significant relationships. A P-value of 0.10 was used for all statistical analyses to establish significance. The null hypothesis for the statistical tests is that there is no correlation between the parameters being considered. The alternate hypothesis is that the actual correlation between the parameters is not equal to zero. For a p-value greater than 0.10, the null hypothesis is not rejected. For any p-value less than 0.10, we reject the null hypothesis.

4.3.1 Growth Performance Analysis

For the following section, the null hypothesis is that average carbon dioxide concentration and the growth performance parameters are not correlated or have a correlation coefficient of zero. The alternative hypothesis is that, at a 10% significance level, the average carbon dioxide concentration has either a positive or negative correlation with the growth performance parameters.

4.3.1.1 11-RWA Rooms

Table 4-3 is a matrix showing all the correlation coefficients for the multivariate analysis comparing average carbon dioxide and the relative humidity against the growth parameters obtained from processor reports for 11-RWA. All eight production cycles from the study period were used to develop this matrix.

Table 4-3: Correlation coefficient for growth performance parameters for 11-RWA

	Average CO_2 Concentration	Relative Humidity	End of Cycle Weight	FCR	BPI
Average CO_2 Concentration	1.0000	-0.4189	0.3198	0.4583	-0.2571
Relative Humidity	-0.4189	1.0000	-0.3764	0.3037	-0.3521
End of Cycle Weight	0.3198	-0.3764	1.0000	-0.4003	0.7274
FCR	0.4583	0.3037	0.7274	1.0000	-0.9106
BPI	-0.2571	-0.3521	0.7274	-0.9106	1.0000

Table 4-4 is a matrix showing all the p-values for the multi-variate correlation analysis comparing average carbon dioxide and the relative humidity against the growth parameters obtained from processor reports for 11-RWA. All eight production cycles from the study period were used to develop this matrix.

Table 4-4: P-value from Table 4-3 correlation coefficient analysis

	Average CO_2 Concentration	Relative Humidity	End of Cycle Weight	FCR	BPI
Average CO_2 Concentration	<0.0001	0.3020	0.4400	0.2534	0.5388
Relative Humidity	0.3020	<0.0001	0.3581	0.4647	0.3923
End of Cycle Weight	0.4400	0.3581	<0.0001	0.3257	0.0408
FCR	0.2534	0.4647	0.3257	<0.0001	0.0017
BPI	0.5388	0.3923	0.0408	0.0017	<0.0001

Table 4-4In Table 4-4, the BPI - End of Cycle Weight and BPI – FCR comparisons are the only comparison where the null hypothesis is rejected. For all comparisons between carbon dioxide and growth parameters, the null hypothesis is not rejected at a 10% significance level and there is statistically significant correlation between the parameters considered.

4.3.1.2 11-NRWA Rooms

Table 4-5 is a matrix showing all the correlation coefficients for the multivariate analysis comparing average carbon dioxide and the relative humidity against the growth parameters obtained from processor reports for 11-RWA. All eight production cycles from the study period were used to develop this matrix.

Table 4-5: Correlation coefficient for growth performance parameters for 11-NRWA

	Average CO_2 Concentration	Relative Humidity	End of Cycle Weight	FCR	BPI
Average CO_2 Concentration	1.0000	-0.8218	0.1485	0.2025	-0.1021
Relative Humidity	-0.8218	1.0000	-0.3964	-0.0956	-0.2235
End of Cycle Weight	0.1485	-0.3964	1.0000	0.2519	0.3611
FCR	0.2025	-0.0956	0.2519	1.0000	-0.764
BPI	-0.1021	-0.2235	0.3611	-0.764	1.0000

Table 4-6 is a matrix showing all the p-values for the multi-variate correlation analysis comparing average carbon dioxide and the relative humidity against the growth parameters obtained from processor reports for 11-RWA. All eight production cycles from the study period were used to develop this matrix.

Table 4-6 Correlation coefficient for growth performance parameters for 11-RWA

	Average CO_2 Concentration	Relative Humidity	End of Cycle Weight	FCR	BPI
Average CO_2 Concentration	<0.0001	0.0123	0.7256	0.6306	0.8099
Relative Humidity	0.0123	<0.0001	0.3309	0.8219	0.5947
End of Cycle Weight	0.7256	0.3309	<0.0001	0.5473	0.3795
FCR	0.6306	0.8219	0.5473	<0.0001	0.0273
BPI	0.8099	0.5947	0.3795	0.0273	<0.0001

From Table 4-6, the only relationships where the null hypothesis is rejected are the comparisons between BPI – FCR and Average CO_2 Concentration – Relative Humidity. The null hypothesis is not rejected at a 10% significance level for all comparisons between carbon dioxide and growth parameters.

Indoor and outdoor temperature parameters were not shown in the above tables as no statistically significant relationship between growth parameters and the indoor or outdoor temperature were identified.

4.3.2 Livability and Condemnation Analysis

4.3.1.2 11-RWA Rooms

The following analysis did not include the relative humidity as no statistically significant trends between relative humidity and livability, or condemnations were identified. Table 4-7 shows the correlation coefficients relating average carbon dioxide concentrations to the average outdoor temperature, livability, and condemnations for all eight production cycles from the 11-RWA rooms. The livability and condemnation parameters were obtained from processors' reports, whereas the outdoor temperature and carbon dioxide data were collected using the Maximus® controllers. The reason outdoor temperature was considered in this analysis, but not the analysis in section 4.3.1, will be addressed in discussion section 4.5.2.

Table 4-7: Correlation coefficient for livability & condemnations for 11-RWA

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	1.0000	-0.9773	-0.5150	-0.7633	0.8338
Average Outdoor Temperature	-0.9773	1.0000	0.5156	0.8186	-0.8104
Average Indoor Temperature	-0.5150	0.5156	1.0000	0.4814	-0.6650
Livability	-0.7633	0.8186	0.4814	1.0000	-0.6343
Condemnations	0.8338	-0.8104	-0.6650	-0.6343	1.0000

Table 4-8 is a matrix showing all the p-values for the multi-variate correlation analysis comparing average carbon dioxide, outdoor temperature, livability, and condemnations for the 11-RWA rooms.

Table 4-8: P-values from Table 4-7 correlation coefficient analysis

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	<0.0001	<0.0001	0.1915	0.0275	0.0101
Average Outdoor Temperature	<0.0001	<0.0001	0.1909	0.0130	0.0147
Average Indoor Temperature	0.1915	0.1909	<0.0001	0.2272	0.0720
Livability	0.0275	0.0130	0.2272	<0.0001	0.0912
Condemnations	0.0101	0.0147	0.0720	0.0912	<0.0001

At a 10% significance level, the only relationships in Table 4-8 that are not significant are the relationships between average indoor temperature and, average carbon dioxide, average outdoor temperature, and livability. In all other relationships, the null hypothesis is rejected, and the table demonstrates that there is statistically significant correlation between all parameters with a p-value less than 0.10.

4.3.1.2 11-NRWA Rooms

Table 4-7 below shows the correlation coefficients relating average carbon dioxide concentrations to the average outdoor temperature, livability, and condemnations for all eight production cycles from the 11-NRWA rooms. The livability and condemnation parameters were obtained from processors' reports, whereas the outdoor temperature and carbon dioxide data were collected using the Maximus® controllers

Table 4-9: Correlation coefficient for livability & condemnations for 11-NRWA

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	1.0000	-0.9773	-0.9604	-0.7646	0.7198
Average Outdoor Temperature	-0.9773	1.0000	0.9066	0.7735	-0.7023
Average Indoor Temperature	-0.9604	0.9066	1.0000	0.6354	-0.6409
Livability	-0.7646	0.7735	0.6354	1.0000	-0.5403
Condemnations	0.7198	-0.7023	-0.6409	-0.5403	1.0000

Table 4-8 is a matrix showing all the p-values for the multi-variate correlation analysis comparing average carbon dioxide, outdoor temperature, livability, and condemnations for the 11-NRWA rooms.

Table 4-10: P-values from Table 4-9 correlation coefficient analysis

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	<0.0001	<0.0001	0.0002	0.0271	0.0441
Average Outdoor Temperature	<0.0001	<0.0001	0.0019	0.0243	0.0521
Average Indoor Temperature	0.0002	0.0019	<0.0001	0.0905	0.0868
Livability	0.0271	0.0243	0.0905	<0.0001	0.1668
Condemnations	0.0441	0.0521	0.0868	0.1668	<0.0001

At a 10% significance level, the only null hypothesis that is not rejected comes from the relationship between livability and condemnations. For all other relationships in Table 4-10, the null hypothesis is rejected.

4.4 Discussion

The following subsections contain discussions surrounding the growth performance, livability, and condemnation analysis performed in section 4.3.

4.4.1 Growth Performance Discussion

From the tables shown in section 4.3.1, the observed level of carbon dioxide did not influence the observed growth performance parameters, at a 10% significance level. However, the range of observed carbon dioxide concentrations must be considered when discussing this conclusion. The 11-RWA average carbon dioxide concentration ranged from 946 ppm to 3285 ppm. The 11-NRWA average carbon dioxide concentration ranged from 1030 ppm to 3555 ppm. These results do not necessarily show that carbon dioxide and growth performance parameters are not related; they show that no effect on the growth parameters was observed within the range of carbon dioxide concentrations in the study.

It is safe to assume that an effect on growth parameters will be observed at some level of carbon dioxide concentration, as demonstrated by Reece and Lott (1980) and Cândido et al. (2018). However, the average carbon dioxide concentration that affects growth performance parameters was not reached in this field study for the 11-RWA and 11-NRWA rooms. Therefore, the results of this field study are consistent with the results of studies performed by Reece and Lott (1980) that sustained or average concentrations under 6,000 ppm do not significantly affect the growth parameters of broiler chickens.

For the 11-RWA and 11-NRWA rooms, statistically, significant correlations were observed between the BPI and FCR. This relationship is understandable as FCR is one component of the equation used to calculate BPI. The End of Cycle Weight in the 11-NRWA rooms was not significantly correlated with the corresponding BPI despite this correlation being statistically significant in the 11-RWA rooms. Revisiting Equation 4.1, the End of Cycle Weight is also used to calculate BPI; therefore, the two parameters must be related. One explanation for why these parameters were correlated in one room and not the other is that BPI is made of several unique performance parameters and the fluctuation of End of Cycle Weight, relative to another variable, such as Livability or FCR, for the 11-NRWA room had a lesser effect on the BPI calculation. This explanation does not preclude a statistically significant relationship between the parameters, simply that the observed changes in End of Cycle Weight were not the primary reason for observed changes in BPI across the observation period.

It was also shown that the relative humidity levels observed in this study did not influence the growth performance parameters at a significance level of 10%. Average relative humidity ranged between 53.8% and 75.2% for the 11-RWA rooms and 52.8% to 67.2% for the 11-NRWA rooms. Similar to the conclusions about carbon dioxide and growth parameters, the relative humidity range must be considered. As discussed in this thesis's literature review, poorly managed humidity levels can cause health and performance concerns for broiler chickens. The humidity levels in rooms 11-RWA and 11-NRWA were well managed, and thus no effect on broiler performance parameters was observed.

One interesting difference between the 11-RWA and 11-NRWA rooms was how relative humidity correlated to the average carbon dioxide concentrations. Relative humidity and average carbon dioxide were statistically correlated in the 11-NRWA rooms but not in the 11-RWA rooms. Comparing feed types is outside the scope of this study. However, the type of feed influences the waste composition of the birds. It may account for why relative humidity and carbon dioxide were correlated in the 11-NRWA room and not the 11-RWA room.

4.5.2 Livability and Condemnation Discussion

The tables in section 4.3.2 show a significant correlation between condemnations, outdoor temperature and carbon dioxide concentration. The tables also show that with a significance level of 10%, there is a correlation between livability, carbon dioxide concentrations, and outdoor temperature. These relationships are valid for both the 11-RWA rooms and the 11-NRWA rooms. It is worth noting that in the 11-RWA rooms, livability and condemnations are statistically correlated. This relationship might indicate that the driver of the seasonal livability trend is related to the driver of the seasonal condemnation trend.

By looking at these relationships between the environmental parameters and performance parameters, it is clear that there are some confounding variables. Partial correlation values and the associated p-values were calculated to deal with the confounding variables. The following tables detail the results from the partial correlation analysis for the 11-RWA rooms.

Table 4-11: Partial correlation Coefficient for livability & condemnations for 11-RWA

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	.	-0.9077	0.0774	0.2736	0.3203
Average Outdoor Temperature	-0.9077	.	0.0005	0.5237	0.0358
Average Indoor Temperature	0.0774	0.0005	.	0.1592	-0.5049
Livability	0.2736	0.5237	0.1592	.	0.0662
Condemnations	0.3203	0.0358	-0.5049	0.0662	.

Table 4-12: P-values from Table 4-11 partial correlation coefficient analysis

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	.	0.0332	0.9016	0.6561	0.5992
Average Outdoor Temperature	0.0332	.	0.9993	0.3650	0.9544
Average Indoor Temperature	0.9016	0.9993	.	0.7981	0.3856
Livability	0.6561	0.3650	0.7981	.	0.9158
Condemnations	0.5992	0.9544	0.3856	0.9158	.

The following tables detail the results from the partial correlation analysis for the 11-NRWA rooms.

Table 4-13: Partial correlation coefficient for livability & condemnations for 11-NRWA

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	.	-0.8425	-0.8961	-0.5429	0.4390
Average Outdoor Temperature	-0.8425	.	-0.5629	-0.1960	0.2211
Average Indoor Temperature	-0.8961	-0.5629	.	-0.5784	0.3883
Livability	-0.5429	-0.1960	-0.5784	.	0.2407
Condemnations	0.4390	0.2211	0.3883	0.2407	.

Table 4-14: P-values from Table 4-13 partial correlation coefficient analysis

	Average CO_2 Concentration	Average Outdoor Temperature	Average Indoor Temperature	Livability	Condemnations
Average CO_2 Concentration	.	0.0732	0.0396	0.3444	0.4596
Average Outdoor Temperature	0.0732	.	0.3231	0.752	0.7208
Average Indoor Temperature	0.0396	0.3231	.	0.3070	0.5183
Livability	0.3444	0.7520	0.3070	.	0.6965
Condemnations	0.4596	0.7208	0.5183	0.6965	.

The results from the partial correlation analysis are opposite to those obtained in the correlation analysis when considering the relationship between the livability or condemnations and environmental parameters. The only statistically significant relationship in the partial correlation analysis is the correlation between average carbon dioxide concentration and average outdoor temperature. This relationship further confirms the conclusions from chapter 3.

Since the relationships between performance and environmental parameters are the exact opposite when using partial correlation and correlation statistics, the partial correlation analysis does not help identify whether carbon dioxide or outdoor temperature is the driver of the trends observed in section 4.3.2. However, when the broiler catching and shipping processes at the end of each production cycle are considered, an argument can be made that the outdoor temperature is the cause for the trend in livability and condemnations, not the average carbon dioxide levels.

The first argument that outdoor temperatures cause the trends observed in the livability is that no growth performance trends were observed over the study period. Excess carbon dioxide can cause lethargy and decreased energy levels. If carbon dioxide were the driver behind the livability trend observed in this study, a trend at the End of Cycle Weight parameter would likely also be observed. Furthermore, a stressed animal will use energy to maintain homeostasis. If the increase in carbon dioxide in the winter months in this study caused stress in the animals, a trend in the feed conversion ratio would likely have been observed between the winter and summer months.

A second argument for outdoor temperature driving the trends observed in livability is that broilers are exposed to extreme cold outdoor temperatures during the chicken placement/delivery and may be exposed to freezing temperatures with the opening and closing of doors to access the barn. It is known that extreme cold temperatures can be fatal to broiler chickens, and the trailers used to ship broilers from the barn to the processors exposed the birds to the outdoor weather.

A similar argument for using outdoor temperature to explain the livability trends can also be used to explain the condemnation trends. The condemnation score is an aggregate of many problems identified at the processing plant. Condemnations include but are not limited to ascites, hock burn, and cellulitis but also include bruising, lacerations, and lameness. Of course, the latter three categories can be biological; however, they can also be mechanical and occur during the catching and shipping processes. The catching process requires a team of workers to enter the barn with equipment and cages. The broilers are systematically loaded into the cages and then onto the truck. It is possible that condemnation trends in this study are related to bird and human behaviour in cold temperatures and not necessarily the carbon dioxide concentrations observed during the production cycle.

A third confounding variable is introduced when the average indoor temperature correlated with livability and condemnations. When considering the RWA rooms, indoor temperature was statistically correlated to condemnation, but not livability. For the NRWA rooms, the indoor temperature was statistically correlated to both livability and condemnations. This confounding variable is further complicated when average carbon dioxide is compared against average indoor temperature. Average indoor temperatures were not statistically correlated to the average carbon dioxide concentrations or the average outdoor temperature for the RWA rooms but were statistically correlated in the NRWA rooms. As analyzing broiler diet is outside the scope of this study, no conclusion can be drawn regarding the pertaining to the RWA and NRWA diets.

The effect of temperatures on broilers has already been discussed in detail however, no conclusions as to which parameter is the primary driver of the trends in livability and condemnations can be made in this thesis due to the three confounding variables. Although no conclusions can be made, the confounding variables highlight the complex nature of a broiler production system and how a more controlled experimental design is required to determine the driver of the trends in livability and condemnations that were observed in this study.

The condemnation parameter used in this study was obtained from the processor reports, and DOAs (dead on arrivals) are included in this report. The broilers are also exposed to extreme outdoor temperatures during the catching and shipping process. A more detailed report on the breakdown of condemnations would be required to differentiate the potential effects of the outdoor temperatures on the broiler during the placement and shipping procedures.

It is important to note that correlation statistics have been used in this study and that correlation does not imply causation. This thesis is a field or observational study where instructions were given to all participants not to change their management practices and processes. Considering these instructions and the nature of this study creates the possibility of encountering all sorts of confounding variables as broiler production can be a complicated system to analyze. To fully understand whether carbon dioxide concentrations affect condemnations, a standardized process for catching must be implemented to ensure no variability in the equipment or processes used to catch the broilers. Furthermore, the condemnation score needs to be broken into further categories to ensure that meaningful relationships can be developed. Finally, to fully understand whether livability is affected by typical carbon dioxide levels in broiler barns, mortality data should be collected daily to analyze the catching and shipping processes independently from the production cycle.

Another management practice that may have influenced these results is how condemnations are calculated at the processing plant. When a whole bird is condemned at the processing plant, the plant uses the average end-of-cycle weight to calculate the condemned weight and not the weight of the condemned bird. This directly impacts farm profitability as it is likely that the average end-of-cycle weight is higher than the weight of an unhealthy bird. This calculation means that a condemned whole bird costs the farm more than if the bird were culled before shipping, thus making it difficult to differentiate between condemnations and the livability score if the producer properly culled the barns before shipping. It is unknown if producer 11 followed this practice in the barn the day before shipping. However, culling broilers is a required management practice to ensure a healthy flock. This management practice further indicates that daily mortality information and the reason for the mortality are needed to properly assess whether typical carbon dioxide concentrations affect the liability and condemnations of broiler chickens.

Although this thesis cannot conclude whether carbon dioxide concentrations, outdoor temperatures, or the shipping and catching processes were responsible for the observed trends, statistically significant trends were observed. Additionally, the seasonal trends observed in both the livability and condemnations identify a future area of research. This future research topic can increase the farm's profitability and the welfare of the broilers.

4.5 Summary

With the carbon dioxide, indoor temperature, outdoor temperature, and relative humidity data observed in this study, no relationship between growth performance parameters and environmental data was identified at a significance level of 10%. The null hypothesis for this analysis was that there was no correlation between environmental and growth performance parameters. All the p-values for this analysis were less than 0.10. Therefore, the null hypothesis is not rejected. The lack of relationship between growth parameters and environmental parameters was observed in the 11-RWA rooms and the 11-NRWA rooms. These findings are consistent with the observations of Reece et al. (2018) and Bokkers et al. (2010) concerning broiler performance growth parameters.

Statistically significant relationships were observed when livability and condemnations were considered against the average carbon dioxide concentration and outdoor temperature. Chapter 3 demonstrates that average carbon dioxide concentrations and outdoor temperatures are closely linked, and the analysis in this chapter confirms this relationship statistically. However, the relationship between carbon dioxide and outdoor temperature introduces a confounding effect when considering livability and condemnations.

A third confounding variables was introduced when average indoor temperature was considered in the statistical analysis. Average indoor temperature was statistically correlated to condemnation, but not livability in the RWA rooms. Average indoor temperature was statistically correlated to both livability and condemnations in the NRWA rooms. Average indoor temperatures were not statistically correlated to the average carbon dioxide concentrations or the average outdoor temperature for the RWA rooms but were statistically correlated in the NRWA rooms

An argument was made in the discussion section of this chapter for the average outdoor or indoor temperature driving the observed trends in livability and condemnations. This argument is based on the known responses of broiler chickens to outdoor temperatures, catching processes, and shipping processes. Although the indoor temperatures are not as extreme as outdoor temperatures, prolonged exposure to suboptimal temperatures may result in performance or welfare related issues (Fairchild 2009). Another cause for uncertainty in this analysis is how the performance data was collected. Data from processor reports are calculated at the processing plant, and no daily mortality or condemnation information can be obtained from these reports.

Although this study cannot conclude the primary driver behind these trends, statistically significant correlations were observed when the data was considered seasonally. Further research into this trend is recommended to reach a meaningful conclusion.

Chapter 5 Conclusions

This thesis was divided into two major sections: developing a baseline for typically observed carbon dioxide concentrations in broiler barns under a Canadian Prairie climate and relating carbon dioxide concentrations to broiler performance parameters.

5.1 Environmental Variables

Chapter 3 of this thesis concludes that when average carbon dioxide concentrations and outdoor temperatures are considered, a linear regression model can be used to relate the two parameters with a high degree of accuracy. The R^2 value for the linear regression model was shown to be 0.86. Furthermore, chapter 3 determined a strong relationship between the outdoor temperature on a 4-hour basis, not just on an average level. Modelling the 4-hourly carbon dioxide concertation as a function of outdoor temperature does not result in a high R^2 value as when the averages are considered. However, the correlation between the two parameters is still statistically significant. The relationship is also demonstrated by the running log of the temperature differential and carbon dioxide concentrations shown in sections 3.2.2 and 3.2.3. The two curves in Figure 3-4, temperature differential and carbon dioxide, closely follow each other, indicating that a rapid change in temperature differential is accompanied by a rapid change in carbon dioxide concentrations at the subsequent data capture or 4-hours later.

When considering the 217 production cycles or datasets collected for this thesis, 73 of them had average concentrations over 3000 ppm for a total of 33%. Of these 73 datasets with average carbon dioxide concentrations greater than 3000 ppm, 65 were between November 2019 and March 2020, for a total of 89%. Out of the 80 production cycles between November 2019 and March 2020, 65 of them had average concentrations of carbon dioxide greater than 3000 ppm, for a percentage of 81%.

Chapter 3 demonstrates that maintaining carbon dioxide below 3000 ppm is not feasible with current technology in Manitoba, Canada. Manitoba's 2019/2020 winter season was unseasonably warm, and between November 2019 and March 2020, all the month averages were greater than 3000 ppm. It has been shown that temperature and carbon dioxide concentrations are closely linked. It is then assumed that carbon dioxide concentrations in a colder Manitoba winter would be higher than what was observed in this study,

5. 2 Relationship to Broiler Performance

Chapter 4 looked more closely at two broiler rooms involved in the carbon dioxide study and attempted to relate observed indoor air quality parameters to broiler performance. No relationship between growth performance parameters and indoor environmental data was observed at a 10% significance level. The results of this chapter are consistent with many existing publications on carbon dioxide and broiler growth performance. The lack of statistically significant difference does not imply there is no impact from the environmental variables. Therefore, it is important to remember that this thesis does not claim that carbon dioxide and relative humidity do not affect the growth performance of broilers at any level.

This thesis only concludes that no effect on growth performance was observed at the observed levels of carbon dioxide and humidity. It is safe to assume that humidity levels and carbon dioxide concentrations affect broiler growth, although those levels were not attained in this study.

Statistically significant relationships were observed when livability and condemnations were considered against the average carbon dioxide concentration and outdoor temperature. Chapter 3 demonstrates that average carbon dioxide concentrations and outdoor temperatures are closely linked, and the analysis in this chapter confirms this relationship statistically significant. However, the relationship between carbon dioxide and outdoor temperature introduces a confounding effect when considering livability and condemnations.

The statistical analysis introduced a third confounding variable when the average indoor temperature was considered. Average indoor temperature was statistically correlated to condemnation but not livability in the RWA rooms. Average indoor temperature was statistically correlated to both livability and condemnations in the NRWA rooms. Average indoor temperatures were not statistically correlated to the average carbon dioxide concentrations or the average outdoor temperature for the RWA rooms but were statistically correlated in the NRWA rooms

An argument was made in the discussion section of this chapter for the average outdoor or indoor temperature driving the observed trends in livability and condemnations. This argument is based on the known responses of broiler chickens to outdoor temperatures, catching processes, and shipping processes. Although the indoor temperatures are not as extreme as outdoor temperatures, prolonged exposure to suboptimal temperatures may result in performance or welfare-related issues (Fairchild 2009). Another cause for uncertainty in this analysis is how the performance data was collected. Data from processor reports are calculated at the processing plant, and no daily mortality or condemnation information can be obtained from these reports. Although this study cannot conclude the primary driver behind these trends, statistically significant correlations were observed when the data was considered seasonally.

Chapter 6 Recommendations

Several thought-provoking questions that have future research potential were discussed in this thesis. This chapter outlines possible future research opportunities that will help better understand barn design and facilities, broiler performance and how these areas relate to indoor and outdoor environmental conditions.

6.1 Recommendations on Environmental Variables

Chapter 3 presents a hypothesis regarding the carbon dioxide concentrations between the first and second story in a two-story barn. The lowest average carbon dioxide concentration for a single production cycle was 421 ppm, observed in June 2020; however, it was also observed in the second story of a two-story barn. Further research into comparing the air quality between the first and second stories is needed. A possible explanation for why the lowest average was observed in the second story was provided in section 3.4.3. Further research into this question is required and recommended to understand the observed phenomena better. Although two-story barns are not a common design for new construction in Manitoba, the principles of future research in this area may apply to a floor heating system where the fuel source is not burned in the boiler room.

It was shown that the winter season of 2019/2020 was unseasonably mild. It is recommended that monitoring carbon dioxide concentrations relative to outdoor temperatures is continued to develop a more robust model. Obtaining data from typical winter seasons and cold winter seasons will allow for an even greater understanding of typically observed carbon dioxide concentrations in broiler barns in a Canadian prairie climate.

6.2 Recommendations on Performance Parameters

Further research into the trends between environmental data such as carbon dioxide, outdoor temperature, indoor temperature and performance parameters such as livability and condemnations are required to develop meaningful relationships. Furthermore, it is recommended that the experimental design of future studies allow for daily mortality and mortality causes during catching and shipping to be analyzed independently of each other. It is also recommended that in future studies, a standardized catching and shipping process is developed to remove as much variability from the field study as possible.

6.3 Environment Control Technology

Heat recovery technology or heat exchangers have briefly been discussed in the literature review of this thesis regarding their ability to reduce the energy required to maintain appropriate temperatures in broiler barns. In its basic format, a heat exchanger works by recovering heat from exhaust air through a counter flow to warm incoming fresh air. Recovering heat from exhaust air reduces the heating requirement as the incoming fresh air enters the barn at a higher temperature than if no heat exchanger were used. Since this is a passive process, a heat exchanger can cool incoming air if the air temperature outside is warmer than the air inside the barn. The incoming fresh air warms the exhaust air in this process. However, since a broiler barn is not air-conditioned and relies on convective cooling from the ventilation fans, the heat exchanger function will not be addressed further in this thesis.

Conveniently, observation site 11 used heat exchangers in both barns considered in the previous section several years ago. Raymond Funk with Summit Technologies provided information on capital investment costs and cost savings for observation site 11. The producer who owns and operates observation site 11 provided information on their experience with heat exchangers.

6.3.1 Advantages of Heat Exchangers in Broiler Operations

As Bokkers et al. (2010) demonstrated, the producers involved in their study of heat exchangers in broiler barns could maintain consistent air quality and litter in the barn and reduce the energy required to heat the barns. The same conclusions of energy reduction to heat the barns by Bokkers et al. (2010) were reached by Shah et al. (2011). Furthermore, the heat exchangers used at observation site 11 in the past could warm incoming air to approximately 16 ̊C when the ambient temperatures were around 0 ̊C. Summit Technologies calculated the efficiency of the heat exchanger to be about 65%.

At this time, no research on reducing indoor carbon dioxide concentrations of broiler barns has been completed. However, the conclusions and content of the literature review, in conjunction with the results from Chapter 3 of this thesis, demonstrate that heat recovery technology can reduce indoor concentrations of carbon dioxide. In addition, it was shown in Chapter 4 of this thesis that carbon dioxide did not affect the growth parameters of broilers. However, heat exchangers still have some advantages when considering the overhead costs of broiler production.

The capital investment required to install heat exchangers in both barns at the observation site was provided by Summit Technologies and was approximately $40,000 CAD. Although this is a high initial cost, the payback period for this system was calculated to be three years when considering the price of natural gas in Manitoba at the time of the analysis. A 3-year return on investment when considering the life cycle of a broiler barn is a good return on investment and, afterward, can increase the profitability of the barn. An increase in farm profitability is significant when considering farm succession as the quota price in Manitoba is high, $67.40 per kg in 2017. Increasing barn profitability can help new or young broiler producers amortize their loans over a shorter period and start seeing profits earlier in their careers.

6.3.2 Disadvantages of Heat Exchangers in Broiler Operations

Although heat recovery technology has clear benefits in the poultry livestock industry, several significant shortcomings preclude widespread adoption in Manitoba or other areas that experience frigid temperatures. The heat exchangers' main issue is condensation build-up due to the mixing of fresh air outdoor air and warm indoor air.

The primary issue surrounding moisture accumulation is functional. At colder temperatures, the condensation buildup can cause the system to freeze. Freezing results in the system not being operational in the conditions that provide the most value. Anecdotally, it has been observed in Manitoba that below -10 ̊C, the designs are not functional as they freeze up. Further analysis is needed to determine the exact operational temperature range. However, several producers in Manitoba have had similar experiences where the systems freeze and no longer operate at cold temperatures.

For now, suppose -10 ̊C is the lower threshold of heat exchanger operation. When consulting Table 3-2 in Chapter 3 of this thesis, two months have average temperatures below -10 ̊C. It has also been noted that the winter months during the data collection period of this study had above-average temperatures for the region. The mean temperatures for December 2021 to March 2022 were below -10 ̊C. The advantage of using heat exchangers is drastically reduced if the system can not operate in the months where they would provide the most significant economic and air quality advantages.

Intelligent design and construction techniques for new barn construction can likely manage moisture build-up in the heat exchangers. However, the current heat exchanger technology that has been trialed in Manitoba is not conducive to broiler operations in Manitoba for the retrofit market.

6.3.4 Recommendations

It is recommended that before regulation of carbon dioxide is considered in broiler barns, technologies should exist on the market that can keep the carbon dioxide concentrations at or below the regulated level without causing a financial burden for producers. This technology needs to apply to both new construction and the retrofit markets.

It is recommended that the efficacy of heat exchangers concerning the energy required to heat barns and the ability to manage carbon dioxide levels is researched further with input from broiler producers with current technology experience. This should be done to facilitate the development of new technology that helps manage the energy requirement and carbon dioxide concentrations in the barn.

It is also recommended that alternate heat recovery methods be explored and considered concerning broiler operations. Many parts of the world use innovative and creative ways to warm incoming fresh air, and these methods have not been considered and explored in a Canadian Prairie climate. For example, a ground-coupled heat exchanger was shown to cool incoming air in a poultry barn under sweltering conditions in Iraq (Morshed et al. 2018). The efficiency and efficacy of alternate heat exchange technologies and processes like this should be explored in the Canadian Prairie climate. This research may facilitate the development of heat recovery or exchange technologies and have economic and environmental value in the Canadian Prairies.

From the literature review and in discussions with industry professionals, it is evident that heat recovery technology can potentially reduce broiler barns' heating requirements in the winter. Since most barns in Manitoba are heated using propane or natural gas, reducing the heating requirement can reduce carbon dioxide concentrations in broiler barns. However, current heat exchange technology is not conducive to a broiler production environment, and generally, the average winter temperature in Manitoba is below the operational temperature of the heat exchanger. At the time of writing this thesis, there is promising new technology on the market, though it has not yet been proven during a Manitoba winter.

It is also recommended that alternate heat recovery methods be explored and considered concerning broiler operations. Many parts of the world use innovative and creative ways to warm incoming fresh air, and these methods have not been considered and explored in a Canadian Prairie climate. This research may facilitate the development of heat recovery or exchange technologies that generate economic and environmental value in the Canadian Prairies.

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