THESIS

EFFECT OF PULMONARY ARTERIAL PRESSURE AND PRECIPITATION ON REPRODUCTIVE PERFORMANCE IN ANGUS HEIFERS IN SOUTH CENTRAL WYOMING

Submitted by

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ABSTRACT

EFFECT OF PULMONARY ARTERIAL PRESSURE AND PRECIPITATION ON REPRODUCTIVE PERFORMANCE IN ANGUS HEIFERS IN SOUTH CENTRAL WYOMING

Reproductive success is important for profitability of the commercial beef operation. However, fertility is affected by many physiological and environmental factors. Age and weight directly influence puberty in cattle, which is also influenced by nutrition. Many areas in the western United States where beef cattle are produced are arid rangelands that rely on natural precipitation. In addition, irrigation systems are often contingent on snowmelt. This variable water availability effects forage production and nutrient availability for developing heifers relying on forage resources. Due to this, precipitation amount is of concern to beef producers. Furthermore, in areas of the mountain west above 1,500 meters, producers have to contend with high altitude disease (HAD) as a result of reduced atmospheric oxygen. This can be a fatal disease in cattle that is a consequence of right sided heart failure. Pulmonary arterial pressure (PAP) scores are indicator traits of HAD, and can be used to diagnose cattle at risk for the disease, or animals in the early stages of pulmonary hypertension and (or) heart failure. There is concern that the physiological stress of elevated PAP score could compound environmental stressors, such as variable precipitation. Thus, the objective of this study was to investigate the effects of precipitation and PAP score on beef heifer fertility.

Data used for this study were sourced from the Colorado State University Beef Improvement Center (CSU-BIC; 1993-2019; n = 3,834; 2,150 to 2,411 m elevation) near

Saratoga, Wyoming where an Angus cow herd of 420 mother cows are managed for research purposes. Records included identification, birth year, yearling year, yearling weight (YW), PAP, first service conception (FSC), overall heifer pregnancy (HPG) and sire. Precipitation data were sourced from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cag/county/time-series, March 3, 2021). From these data, three classifications were created: cumulative precipitation from birth to breeding, precipitation from heifer birth to weaning, and precipitation from heifer weaning to breeding. Mean FSC was 47% (± 10%) while average HPG was 85% (± 8%). Average PAP score was 41.09 mmHg (± 7.52 mmHg) and average YW was 308.52 kg (± 47.85 kg). Cumulative precipitation averaged 56.01 cm (± 8.74 cm), birth to weaning precipitation averaged 26.97 cm (± 5.94 cm) and weaning to breeding precipitation averaged 29.06 cm (± 5.89 cm). Initial models contained sources of variation of precipitation classification, PAP, and YW for the response of HPG and FSC. Logistical regression was executed and analysis of variance (ANOVA) revealed that regardless of classification, precipitation was a significant source of variation for HPG (P<0.01). Yearling weight was an important predictor for FSC (P<0.01) and PAP was an important indicator of both HPG and FSC (P<0.05). A favorable, positive relationship was detected between precipitation and HPG (β_i= 0.06 to 0.07; P<0.01). A favorable, positive relationship also existed between YW and FSC (β_i= 0.00120 to 0.00124; P<0.01). The favorable, negative relationship between PAP and reproductive success suggested that lower PAP scores were advantageous for heifer reproductive success (β_i=-0.0091 to -0.0168; P<0.01).

Following the execution of the initial models, the heifer's sire was included in the models as a random effect to assess potential genetic effects in the analyses of FSC and HPG. Precipitation was still an important source of variation for HPG (P<0.01) and similar results were found with YW (*P*<0.01) in these models. However, PAP was an important source of variation for HPG (*P*<0.01), and a tendency was observed for FSC (*P*<0.10). These results suggested a moderate to strong genetic effect exist in prediction of heifer fertility traits. Relationships between precipitation and HPG were favorable and positive (β_i= 0.05 to 0.07; *P*<0.01) and YW relationships were also favorable and positive for FSC (β_i= 0.00128 to 0.00134; *P*<0.01). Pulmonary arterial pressure was a favorable, negative relationship with HPG (β_i= -0.0180 to -0.0185; *P*<0.05). The results suggested that sire, PAP score and precipitation directly affect heifer fertility. Thus, we conclude that low PAP scores and higher precipitation are advantageous for breeding success of purebred Angus heifers.

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CHAPTER 1

INTRODUCTION

Female fertility is of major economic importance for beef producers. Most *Bos taurus* heifers conceive by 15 months of age in order to have their first calf at 2 years of age (Patterson et al., 1992; Toghiani et al., 2017). Furthermore, females that conceive at first service (FSC) will often produce a higher quality calf if serviced via artificial insemination (AI) versus a natural mating. Heifers that conceive earlier in the breeding season will also calve earlier, allowing them a longer post-partum interval to recycle and rebreed and calve as three-year-olds. Due to this, FSC is considered a valuable measure of fertility (Bormann et al., 2006; Foxworthy et al., 2019).

Data collection is historically limited for FSC making the trait difficult to evaluate (Eler et al., 2002; Gutierrez et al., 2002). There are also numerous factors, both physiological and environmental that affect the trait itself.

Fertility, and specifically puberty are important to physiological development. Body functions key to survival are given priority in energy allotment, and only once those key functions are developed is energy partitioned for the development of the reproductive system (Perry, 2016). Fat stores must be adequate to support the reproductive system; thus, weight and nutrition are key factors for the development of the reproductive system (Senger, 2012).

An environmental factor that likely impacts heifer development due to its impact on forage production is precipitation. Producers in the western United States often develop heifers on dry rangeland or on pastures irrigated from water sources that are considered variable since they are sourced from snow pack. Drought conditions have a negative impact on forage communities with drought potentially reducing forage production by up to 50% compared to average precipitation (Bai et al., 2019). Drought can also alter what plants dominate the landscape and if those plants are less palatable to livestock. Weaning weights and average daily gain are negatively impacted when cattle are grazing rangeland experiencing drought conditions and therefore there is concern that the lack of adequate nutrition in drought situations may negatively affect fertility in females (Scasta et al., 2015).

In addition to previous factors mentioned, pulmonary hypertension (PH) is a concern for beef production systems located at or above 1,500 meters due to the reduced atmospheric oxygen at these altitudes. The resulting high altitude disease (HAD) is a fatal condition that is caused by the hypoxic environment and the inefficient utilization of oxygen by the bovine cardiopulmonary system. Some beef herds have experienced up to 20% death loss due to HAD (Williams et al., 2012). Briefly, alveolar-hypoxia and pulmonary arterial vasoconstriction occurs, causing significant development of PH. Right ventricular hypertrophy then occurs, progressing into right ventricular dilation and eventually right side heart failure. Therefore, pulmonary arterial pressure is considered to be an indicator trait for HAD. Based on PAP scores, management decisions can be made to cull animals that are identified as being susceptible to HAD, or are suffering from elevated PAP scores (Holt and Callan, 2007).

Currently, limited information is available regarding both the independent and combined effects of PAP score and precipitation on heifer fertility. Due to the stress caused by both drought conditions and/or elevated PAP score, there is concern that these factors may have a negative effect on female fertility. Thus, the objective of this study was to evaluate the effect of PAP score and variable precipitation on fertility of Angus heifers located in south central Wyoming.

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CHAPTER 2

REVIEW OF LITERATURE

INTRODUCTION

Female fertility an economically relevant trait for beef production (Gutierrez et al., 2002). Due to this, female fertility must be optimized. However, there are numerous complicated intrinsic and extrinsic factors that influence pregnancy success rates in beef cattle (Kelly et al., 2020). Beyond the genetics of the individual female, the environment affects cattle performance. The environment can be defined as the physical place and conditions in which the female is surviving, as well as the biological factors such as mothering ability of her dam that develop into physiological effects displayed by the female. These environmental and physiological effects can negatively impact other production traits and may influence female fertility itself. An understanding of these influences could potentially allow producers to better understand how fertility and allow them to optimize conditions and genetics to improve fertility rates within their herd.

Weather is an unavoidable factor that all beef producers must contend with. However, it can be particularly important to rangeland operations that rely on storms to provide moisture for feed production. Seasons of drought cause significant economic loss resulting in reduction of feed, poor animal gains and performance. However, study of the relationship of drought in the Rocky Mountain region with fertility has had limited investigation.

In addition to the challenges facing all U.S. beef producers, operations located above 1,500 meters have to contend with the effects of altitude-induced pulmonary hypertension (Neary et al., 2013; Bailey et al., 2016; Speidel et al., 2020). This pulmonary hypertension leads to high altitude disease (HAD), a potentially fatal disease. However, by utilizing pulmonary arterial pressure (PAP) as an indicator trait, producers can select to improve this genetically inherited trait for climate adapted cattle (Speidel et al., 2020). Therefore, the understanding of this hypoxic condition, the genetics behind HAD and how to use PAP score as an indicator trait, allows production of high elevation tolerant livestock.

Overall, it is known that HAD and weather influence female performance and fertility separately. However, the relationship of the combination of the two traits has not been explored. Because these influences on fertility, an economically relevant trait, exploring the relationship could be of value to commercial beef production systems in the Western U.S.

SECTION 1: GENETICS AND FERTILITY

Fertility is an economically relevant trait in beef production systems. However, selection based solely on production traits has led to a decrease in fertility across the beef industry (Toghiani et al., 2017). A variety of issues in improving fertility exist, such as the lack of uniformity in fertility traits, the nature of the binary trait relating to analysis and the relatively low heritability of fertility traits (Cammack et al., 2009; Peters et al., 2013; Toghiani et al., 2017; Sanchez-Castro, 2021).

1.1 Heritability of fertility traits

Heritability (h^2) is the measure of strength of the relationship between performance (phenotypic values) and breeding values for a trait in a population (Bourdon, 2000). An understanding of heritability is key to genetic improvement due to the fact that selection occurs based on phenotypic observation. If a trait is highly heritable, selection based on that trait typically yield progeny resembling the performance of their parents. However, if it is a lowly heritable trait, then the progeny may or may not resemble the parents, due to the fact that performance is not a strong indicator of breeding value. For lowly heritable traits, environment plays a large role in dictating the expression of the trait. Thus, any strong relationship displayed for a lowly heritable trait is much more so the relationship between environment and performance, rather than the relationship between performance and breeding values (Bourdon, 2000).

Heritability is expressed as a value from 0 to 1. Some highly heritable traits in beef cattle are mature weight (0.65) and scrotal circumference (0.50). A moderately heritable trait would be weaning weight at 0.30 (Bourdon, 2000). However, lowly heritable traits (0-0.20) tend to be related to fertility. This is due to the extreme pressure that the environment plays in the expression of these traits (Gwazdauskas, 1985). Table 2.1 Illustrates some known heritabilities of fertility traits.

Table 2.1. Summary of heritability estimates of fertility traits in literature.

Trait	h^2	Reference
First Service Conception	0.03	Sanchez-Castro, 2021
	0.03	Borman et al., 2006
	0.06	Foxworthy et al, 2019
	0.18	Peters, et al., 2013
	0.22	Dearborn et al., 1973
Overall Pregnancy	0.04	Sanchez-Castro, 2021
	0.09	Dearborn et al., 1973
	0.10	Peters, et al., 2013
	0.12	Boldt, et al., 2018
	0.13	Borman et al., 2006
	0.15	Toghiani et al., 2017
	0.21-0.27	Doyle, et al., 2000
	0.57*	Eler, et al., 2001
Age at First Calving	0.03	Toghiani et al., 2017
Age of Puberty	0.20	Toghiani et al., 2017
Calving Interval	0.05	Bourdon, 2000
First Cycle Calving	0.015	Foxworthy et al, 2019
Subsequent Rebreeding	0.12-0.19	Doyle, et al., 2000

* *Bos indicus cattle*

1.2 Heifer pregnancy and first service conception

Heifer pregnancy (HPG) was defined by Doyle and colleagues (2000) as the observation of a heifer conceiving and remaining pregnant to palpation at 120 days post AI. An alternate definition is the prediction of a female's ability to become pregnant during her first breeding season (Boldt et al., 2018). It has been reported that fertility traits have the ability to greatly improve profitability of cow calf enterprises and suggested that the relative economic importance of fertility traits can be upwards of four times more economically important than end product traits (Evans et al., 1999). Due to this, heifer pregnancy is imperative to maximize. However, fertility traits pose some difficulties in quantifying. Overall heifer pregnancy is a binary trait and is expressed as a 1 for pregnant heifers, and a 0 for non-pregnant females (Eler et al., 2002). Unfortunately, fertility traits can be difficult to collect, because of long gestation lengths and generation intervals; thus causing collection of a significant amount of data points to be drawn out over many years (Gutierrez et al., 2002). Of fertility traits, overall pregnancy status expressed as heifer pregnancy, is commonly used to examine fertility status. Recently, first service conception has become a method of measuring fertility (Cammack et al., 2009).

First service conception (FSC) is an important trait and important measure of fertility for a variety of reasons. First service conception often describes the outcome of the first service of artificial insemination (Foxworthy et al., 2019). Since FSC conception deals directly with first exposure to AI, it details the reproductive development of the female at breeding. This trait separates early cycling females from those that take multiple exposures to breed later in the breeding season. This gives FSC an advantage compared to overall heifer pregnancy due to the separating of early and late cycling females (Bormann et al., 2006). Heifers that breed earlier in the season will subsequently calve earlier in the calving season which allows them an increased postpartum interval before rebreeding compared to their later cycling counter parts. In addition, FSC is economically relevant for a number of reasons. There are added costs with multiple AI services, such as semen cost and labor associated with heat checking and servicing the females. Calves conceived from AI matings are often of higher quality than natural service calves conceived from a clean-up natural service sire. Calves conceived at FSC will be older, and heavier, at weaning providing added pounds of profit compared to counter parts that are born later in the calving season because of later matings (Bormann et al., 2006; Foxworthy et al., 2019). Unfortunately, as shown in table 1.1., FSC traits tend to be lowly heritable, yet of higher heritability than most reproductive traits. However, due to the economic relevance and physiological knowledge associated with the trait, it is still valuable to assess in fertility models (Dearborn et al., 1973; Cammack et al., 2009).

1.3 Statistical analysis of fertility traits

Regression analyses are utilized in genetic evaluations in order to determine change in one variable that can be expected for a given amount of change in another variable (Bourdon, 2000). Regression is very useful when analyzing observational research that does not allow for random assignment to treatment groups. Linear regression is a common regression method used to examine associations between an outcome and several independent variables in order to determine how well an outcome is predicted by the set of independent variables. However, linear regressions can only be used to analyze continuous outcomes and assumes that the relationship between the outcome and independent variables follows a straight line (Stolzfus, 2011). Due to this, it is not an appropriate statistical method to examine binary responses. In order to examine models containing binary responses, logistical regression is the most fit statistical analysis method (Ott and Longnecker, 2016).

Fertility traits such as heifer pregnancy and first service conception are binary in nature and are expressed as 0 for non-pregnant, and 1 for pregnant (Eler et al., 2002). Models assessing fertility often are binary responses. In order to assess this binary response, logistical regression must be utilized instead of linear regression. Logistical analyses utilize the natural logarithm of the odds ratio, relating to the explanatory variables by a linear model. By utilizing this logit scale transformation, it will produce an explanatory variable that has a probability that varies between 0 and 1 (Stolzfus, 2011; Ott and Longnecker, 2016). This makes logistical regression the proper method to use when analyzing fertility traits.

SECTION 2: BIOLOGICAL EFFECTS ON FEMALE DEVELOPMENT AND PUBERTY

Early puberty in beef females is of paramount importance to ensure a timely and efficient calving season, and to maintain fertility throughout the female's lifespan (Kelly, et al., 2020). In order to be successful in restrictive breeding systems, females need to calve by 24 months of age, and thus conceive at 15 months in order to maximize lifetime productivity (Patterson et al., 1992). Ultimately, heifers that reach early age of puberty will cycle sooner, breed sooner in the breeding season, and will calve earlier in the calving season. This early time frame is advantageous as early calving females tend to be retained for a longer period of time in the herd, and will often wean more pounds of calf than females that calf in the latter two thirds of the breeding season (Perry, 2016). However, for this to be successful, puberty and age of puberty must occur quickly, and this is a complex biological process.

2.1 Female development: physiology and hormonal development

Puberty in beef females has been defined as when ovulation is accompanied by visual signs of estrus followed by normal luteal function and lifespan (Perry, 2016). Puberty itself is a complex process involving the maturing of the hypothalamic-pituitary-ovarian (HPO) axis. This process gradually occurs and is regulated by a complex network of biochemical processes that include many key metabolic, neuroendocrine and reproductive tissues in order to achieve HPO maturation (Kelly, 2020).

Reproductive development and the process of puberty begins as early as during gestation. During the prenatal development stage, primordial follicles were observed as early as 74 days of gestational age in a Tanaka and colleagues' study (2001). Follicular stimulating hormone (FSH) along with estradiol were detected mid-gestation and continued to increase. From here, follicular development continues after birth and occurs in waves as follicle growth increases in follicle numbers and size (Gasser, 2013). As follicles develop, neuroendocrine activity occurs simultaneously. During the first few months, gonadotropin concentrations, particularly luteinizing hormone (LH) are episodic. Around 3-4 months of age an increase in LH followed by an increase in estradiol concentrations aid in developing the HPO axis. However, it has been shown that pulses of LH concentrations tend to plateau and do not change from 22-34 weeks (Hansen et al., 1983). Then the low frequency gonadotropin releasing hormone (GnRH) pulses that are released into the hypothalamic-pituitary portal system shift to high frequency pulses during sexual maturation. This stimulates the acceleration of LH secretions from pituitary gonadotropins, allowing the final maturation of ovarian follicles (Cardoso et al., 2020; Figure 2.2.). In addition, these increased LH surges subsequently stimulate the ovary to produce more and more estradiol. Once estradiol levels reach a certain threshold, a massive discharge of GnRH occurs from the surge center, located in the hypothalamus. This discharge of GnRH is important for the first ovulation to occur; which is considered puberty (Garverick and Smith, 1993; Senger, 2012).

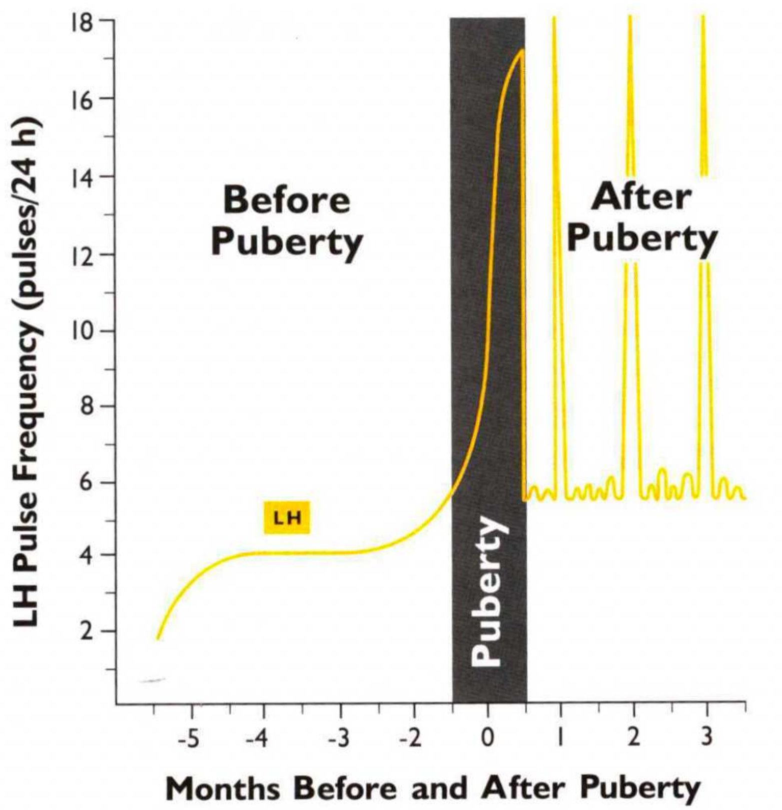

Figure 2.1. Frequency of luteinizing hormone pulses in pre-pubertal heifers (Senger, 2012).

2.2 Effects of weight and nutrition on puberty and subsequent fertility

Puberty is controlled by many factors. Arguably some of the most pivotal factors are nutrition and body weight. Age and genetics are also known regulators of age of puberty due to being regulators of the endocrine maturation that needs to occur for sustained estrous cycling to occur (Perry, 2016). There is a predisposed target weight that must be reached for puberty to occur in most cattle and it is believed that this has to do with energy partitioning. As the neonate grows, energy is utilized for maturation and maintenance of vital physiological functions. Any extraneous use of energy for developing non-essential functions is a low priority, and reproduction is one of these non-essential functions. However, as the animal develops, the ratio of body mass to surface area decreases, which requires less energy to maintain body temperature.

In addition, essential body functions complete the developmental process thus allowing for nonessential body functions to develop. The overall metabolic rate also decreases at this point, allowing for more energy to become available for other functions than maintenance. As this energy becomes available, fat stores are developed and reproductive development of endocrine systems can begin and puberty occurs shortly after (Senger, 2012; Cardosa et al., 2021).

Calf nutrition is key to puberty, as is dam nutrition. In a study conducted by Martin and colleagues, it was found that dam nutrition subsequently effected heifer offspring fertility. A greater portion of heifers born from dams supplemented to meet nutritional requirements in the Sandhill range of Nebraska calved earlier in the first 21 days of the calving season, and had greater pregnancy rates than heifers reared by dams that were not supplemented crude protein during late gestation. However, not supplementing dams during early lactation showed no difference in pregnancy rate, nor did supplementation effect age of puberty (Martin, et al., 2007).

Post-puberty, weight and nutrition continue to play a role in female fertility. However, from the onset of puberty, excess nutrition or too much body weight appear to have a negative effect on fertility. Due to previous findings of negative correlations between cow weight and fertility and stayability, Snelling and colleagues investigated the genetic correlations between weight and cumulative productivity of crossbred cows (2018). They utilized data from the Germplasm Evaluation (GPE) project to execute random regression models on records from 13,707 females. They examined weights at pregnancy testing and calf production from each exposure to breeding in the univariate and bivariate random regression analysis. Their results agree with previous findings, showing a general negative correlation with cow weights and fertility. They also suggested that this could be due to having a diverse set of cows. When comparing body condition scores, that were provided at pregnancy diagnosis, it was found that nutrition was more than adequate for heavy weight cows. In addition, it was stated that more cows were classified as fat to very fat than near average cows. Due to this, they proposed a decrease in fertility could be observed in heavy weight females (Snelling, et al., 2018)

SECTION 3: ENVIRONMENTAL AND PHYSIOLOGICAL EFFECTS ON PERFORMANCE

Extrinsic factors can cause a notable change in performance in cattle. Some of these factors are environmental, such as weather. Ambient temperature has effects on performance. Drought conditions can affect forage production and quality, thus effecting cattle performance (Nardone et al., 2006; Holecheck et al., 2011). Other factors such as high altitude can induce physiological responses such as pulmonary hypertension that result in reduced performance and in severe cases, death (Holt and Callan, 2007). An understanding of these outside forces can allow producers to alter management strategies in order to address these concerns.

3.1 Environmental effects on development

Physical environment plays a key role in development in all aspects of the life cycle of cattle. Most notably, these effects are temperature stress and drought stress (Nardone et al., 2006; Scasta et al., 2015).These stressors can effect cattle directly, or effect the forage cattle consume, which subsequently affects performance (Thomas et al., 2007; McCuistion et al., 2014).

3.1.1 Known effects of temperature on performance

Every organism has a comfort zone in which minimal energy is used to maintain homeothermy. Once the animal is outside this comfort zone, maintenance of homeothermy induces stress. The difference between normal and lethal body temperatures is 5° to 25° C in the cold, while it is 3°to 6° C in the heat. Due to this, cold is less of an issue than heat and there is notably less research on the effect of cold stress than there is on heat stress because cold stress is less of an issue (Nardone et al., 2006). Briefly, heat stress has been shown to increase disease incidence, decrease weight gain and pregnancy rates, delay puberty in heifers, cause anestrus in cows, depress estrous activity, induce abortions and increase perinatal mortality (Amundson et al., 2006; Nardone et al., 2006). This is due to energy reserves diverting to thermoregulatory processes, leaving reduced energy for other body processes. Limited research indicates energy reserve diversion is seen in cold stress as well as heat stress. (Howard et al., 2013).

In the limited cold stress studies that have been conducted, Mercier and Salisbury (1947) found conception rates of dairy cows in Eastern Canada were lowest in cold winter months and highest in the warm summer months. Specifically, lowest in February and highest in July. However, the authors note that the difference in fertility may be due to number of daylight hours rather than cold temperatures, or a combination of the two. Amundson and colleagues (2006) agreed that when considering other environmental effects in combination with minimum temperature, a potential exists for reduction in fertility early in the breeding season if minimum temperature is too low. In a review by Hemsworth and colleagues (1995), it was stated that calves are relatively cold sensitive at birth due to their larger surface area compared to adult cows and lack of rumen fermentation. In addition, the cold can affect immunoglobulin transfer in the colostrum. Newborn calves do however have a well-adapted thermogenic mechanisms to combat cold stress, including shivering thermogenesis in muscle tissue and non-shivering thermogenesis in brown adipose tissue (BAT). These mechanisms help support thermal balance during the neonatal period. Specifically, BAT is a specialized organ that generates heat by uncoupling oxidative phosphorylation from mitochondrial respiration. This process is aids in thermoregulation, allowing the neonate to adapt to cold conditions (Carstens et al., 1997).

Cows can be effected by the cold due to forage availability and grazing behavior (Kartchner, 1981; Adams et al., 1986). In confinement it has been shown that feed consumption increases to meet added maintenance requirements due to the cold. However, loss of body condition in range cattle is associated with harsh winters where a positive relationship between temperature and intake existed (Adams et al., 1986). Kartchner (1981) reported that consumption during harsh winters decreases for range cattle. Adams and colleagues agreed, showing that intake was reduced with colder minimum daily temperature. Grazing time was positively correlated with daily temperature, and reducing minimum daily temperature from 0° to -40° C reduced grazing time by 50%. This would explain loss of body condition due to cold weather (1986).

3.1.2 Effects of drought on the environment and performance

Drought has been proven to have an impact on agriculture, which includes beef production (Scasta et al., 2015). Drought can be defined as receiving 75% or less of annual precipitation. Climate records indicate that drought is expected about every 3 years out of 10 on western rangelands (Holecheck et al., 2011). Furthermore, it can be characterized three different ways: (1) persistence, (2) intensity or deficit severity, and (3) the interval between events (Scasta et al., 2015). Most often, the effect of drought is a reduction of forage quality and carrying capacity which can lead to herd reduction or even de-stocking. Drought can reduce forage production by more than 50% compared to annual average precipitation. It can also alter which plants dominate the landscape, altering forage quality for grazing if the species that dominates is of lower quality or palatability to grazing livestock. Because of this reduction of forage production and potential quality, limiting stocking rate has been effective drought management strategy. By limiting stocking rate, recovery following the drought occurs quicker and damage to the range itself does not occur from overgrazing (Holecheck et al., 2011).

A decrease in forage quality has been shown to have an effect on cattle performance. Scasta and colleagues (2015) explored how drought affected weaning weight (WW) and average daily gain (ADG) from 2011-2014 in south eastern Wyoming at two different ranches. The locations were the McGuire Ranch, north of Laramie, Wyoming at an elevation of 7,165 feet, and the second location was at the Sustainable Agriculture Research and Extension Center (SAREC) located northwest of Lingle, Wyoming at 4,104 feet. They reported that WW and ADG were lowest in the worst drought year during the study, 2012, while WW and ADG was highest in the wettest year during the study, 2014. A linear relationship predicting a decrease in WW along the drought gradient was significant and highly correlated. In addition, they reported that with every one-inch decrease in precipitation amounts there was a 0.06 to 0.07 lbs of ADG decrease at the McGuire Ranch. There was a 0.03 to 0.04 decrease in lbs of ADG with every one-inch decrease in precipitation at SAREC. They suggested that the differences in change in ADG was due to the difference in forage communities at each location, and how these forage communities responded to drought. They stated that forage variation may affect genetic potential for growth and optimization at the different peaks of precipitation. This was supported by the fact that WW and ADG were similar across locations in the wettest years, but maximum precipitation levels were different in those wettest years between the two locations (Scasta et al., 2015).

In areas of low precipitation, management strategies have been adopted to account for low annual rainfall. This can be observed in the Chihuahuan Desert production system in New Mexico where they have altered stocking rates in response to the desert climate. Winder and colleagues (2000) reported that calf crop percentages were higher in conservatively stocked pastures than moderately stocked. In addition, cows that grazed conservative stocked pastures produced more actual and 205-day adjusted weaning weight per cow per year than cows grazing moderately stocked pastures. There was a year by stocking rate interaction observed, which would explain why in drought years conservative stocked pastures had greater calf yields; however, in adequate rainfall years, the yields were similar. This explained how cows were able to regain lost body condition that were grazing moderately stocked pastures in non-drought years, allowing them to conceive and wean calves of equal merit to those from conservatively stocked pastures.

Another study located in the Chihuahuan Desert looked at body condition score (BCS), cow weight, calf weight and pregnancy rates. Weaning weights did not differ between light (25% to 30% use) and conservatively grazed pastures (35 to 40% use). However, in 2001, weaning weights were lower than other years due to drought. Pregnancy rates tended ($P < 0.10$) to be greater in conservatively stocked pastures relative to lightly grazed pastures; however, pregnancy rates for stocking rates were considered acceptable. Cow body weights tended to be heavier in lighter grazed pastures than conservative, but were still acceptable. Body condition scores were similar in theses grazing systems (Thomas et al., 2007).

Drought has been proven to be a major factor to consider for western U.S. beef production organizations. Unfortunately, it is a factor that is un-preventable, and requires adaptive management (Winder et al. 2000). These management factors can be reduced stocking rates or reducing cow numbers (Holechek et al., 2011). This reduction of herd numbers along with decreased calf weights and cow productivity cause monetary loss, making the consequences of drought more sever to the producer than just reduction of system productivity (Thomas et al., 2007; Scasta et al., 2015).

3.2 Effects of pulmonary hypertension and high-altitude disease on beef cattle

In locations above 1,500 meters, beef producers have to contend with hypoxic conditions due to altitude that can induce HAD (Neary et al., 2013; Bailey, et al., 2016; Speidel, et al., 2020). The condition is known as HMD, brisket disease, dropsy or big brisket in beef cattle. It is due to fluid edema that occurs in the brisket due to pulmonary hypertension (Holt and Callan, 2007). High altitude disease was first documented in 1915 by Glover and Newsom, and it is speculated that this disease emerged at this time period because cattle had not resided at elevation in the continental United States prior to this (Holt and Callan, 2007; Neary et al, 2013). It was this time that cattle were moved to elevation in the Rocky Mountain region and replaced the sheep that had grazed there prior. The breeds that were used to populate the high elevation of the western United States were *Bos taurus* breeds that originated at low altitudes. Therefore, these cattle did not have the necessary evolutionary time to adapt to these altitudes, unlike the Indian cattle that tolerate the high-altitude regions of the Himalayas and Ethiopia with little consequence (Neary et al., 2013).

High altitude disease can be fatal for cattle, and can result in up to twenty percent death loss in herds when moved to these elevations (Holt and Callan, 2007; Williams et al., 2012). However, PAP scores can be used as an indicator for an animal’s susceptibility to the disease.

For this reason, PAP testing has been accepted as a tool to select high altitude adapted cattle (Holt and Callan, 2007).

3.2.1 Physiology of pulmonary hypertension

Locations of high altitude are characterized by reduced atmospheric oxygen, which is known to cause pulmonary vascular shunting (Holt and Callan, 2007; Neary et al, 2013). Shunting of pulmonary blood flow has been observed in cattle at a greater degree than other species, compounded by the fact that even the healthy bovine cardiopulmonary system does not efficiently utilize oxygen (Holt and Callan 2007; Pauling, et al., 2018). Shunting occurs to distribute pulmonary blood flow away from poorly oxygenated lung tissue and to more oxygen rich areas. This shunting, along with the anatomy of the bovine lobulated lung and small lung size to body weight ratio, yield to severely reduce pulmonary capacity in cattle. As this alveolar-hypoxia induces pulmonary vaso-constriction, vascular wall remodeling occurs (Pauling, et al., 2018). Pulmonary arterial hypertension results in cor pulmonale and right ventricular hypertrophy (Holt and Callan, 2007). Cor pulmonale is an overarching term to describe pulmonary hypertension that occurs due to a disease, such as HAD, affecting the structure and function of the lungs (Weitzenblum and Chaouat, 2009). As the damage due to HAD progresses, right ventricular dilation occurs, inducing right sided congestive heart failure (Hot and Callan, 2007). See figure 2.2.

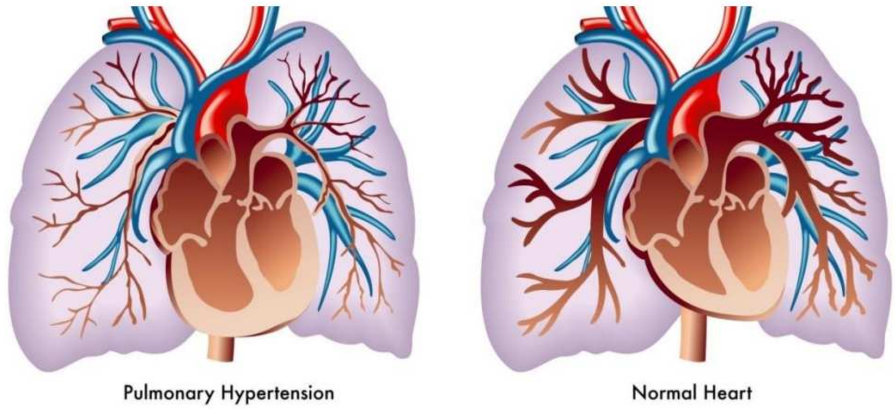

Figure 2.2. Visual description of the cardiovascular changes induced by pulmonary hypertension (Briggs, 2020).

Physically, cattle suffering from pulmonary hypertension can be identified by pitting edema observed primarily in the brisket region. This pitting edema is due to increased hydrostatic pressure resulting from right ventricular heart failure and venous hypertension. Limb, intermandibular and ventral abdominal edema can also occur; however, they are much less common than brisket edema. Cattle also tend to be lethargic, and as the disease progresses, they lose their appetite and muscle tone, leading to anorexia during the terminal stage. Breathing and heart rate increases, but fever is not a symptom. It is also common for the liver to become enlarged, and the right side of the heart becomes enlarged and flaccid as heart failure occurs (Holt and Callan, 2007).

3.2.2 Pulmonary arterial pressure as an indicator of high-altitude disease: genetics, testing, and management

Due to pulmonary hypertension causing HAD, PAP testing can act as an indicator for the presence of pulmonary hypertension and susceptibility to HAD. It was reported that with elevated PAP scores have a greater probability of developing HAD than animals with low PAP scores (Speidel, et al., 2020). In addition, PAP score has been reported to be genetically influenced, and Pauling and colleagues (2018) reported that PAP scores collected at both high altitude and moderate altitude are moderately heritable, with a strong genetic relationship existing between altitudes. Due to the genetic aspect of PAP scores and HAD, a PAP score estimated progeny difference (EPD) was developed by the American Angus Association (AAA) and publicly reported in May of 2020. With the availability of PAP EPD, producers can now select breeding animals at low altitudes, and they will be genetically predisposed to withstanding the stress of high altitude.

Holt and Callan (2007) detailed the procedure of collecting PAP scores. These scores need to be collected by a registered veterinarian and done so in working facilities equipped with a cattle squeeze chute. Once the animal is caught in the chute, the jugular furrow must be exposed by restraining the head, ideally with a well-fitted halter. The proximal lateral jugular furrow must be disinfected prior to being occulated to cause jugular distension. Following the distension, the jugular vein is punctured with a 12- or 13-gauge needle until blood flows from the needle. The needle is threaded into the jugular vein so a polyethylene catheter can be passed through the needle and into the jugular vein. A sterile isotonic saline (0.9% sodium chloride) flush is utilized before placing the needle and while the catheter is being threaded into the jugular vein. The external end of the catheter is connected to a pressure transducer. The catheter is then advanced to the distal jugular vein and the jugular pressure is evaluated. It should be noted that jugular pressure at 1,500 meters or above should be 6 to 12 mmHg. The catheter is then passed into the right cardiac atrium through the right atrioventricular valve and into the right ventricle of the heart. Another pressure reading is collected at this location, and is normally 18 to 30 mmHg. It should be noted that an atrial spike may occur but is difficult to evaluate. Finally, the catheter is fed through the right cardiac ventricle through the pulmonary valve and into the pulmonary artery. The catheter is held constant until the pressure regulates and a mean PAP measurement is obtained. Subsequently the catheter is removed (Holt and Callan, 2007).

Properly interpreting PAP scores is key to making management decisions regarding culling or retaining cattle based on their chances of contracting HAD. One must be aware of the elevation in which the PAP test took place and how the scores relate to where the cattle will be utilized. It should also be noted that PAP score has been shown to increase with age (Neary et al., 2015). However, it is recognized that PAP scores collected at a year of age are appropriate to use for culling decisions (Pauling, et al. 2018). The following guidelines for PAP scores and predisposition to HAD based on the test elevation were published by the Beef Improvement Federation (BIF) in 2021 (https://guidelines.beefimprovement.org/index.php/Pulmonary_arterial_pressure_(PAP); Table 2.2.). The BIF guidelines note that PAP measurements taken between 900 to 1,200 meter elevation should be considered a screening measurement only.

Table 2.2. PAP test measurement evaluation and risk of use by elevation based on where PAP test occurred.

PAP test conducted at elevation <1,200 meters				
PAP	**Use at Low Elev.**	**Use at Moderate Elev.**	**Use at High Elev.**	**Use at Extreme**
Score	*< 1,200 meters*	*1,200 to 1,500 meters*	*1,500 to 2,200 meters*	*>2,200 meters*
34-39	Low Risk	Low Risk	Moderate Risk	Moderate Risk
40-45	Low Risk	Moderate Risk	High Risk	High Risk
46-49	Moderate Risk	High Risk	Do Not Use	Do Not Use
>=50	Moderate Risk	High Risk	Do Not Use	Do Not Use
PAP test conducted at elevation 1,200 to 1,600 meters				
PAP	**Use at Low Elev.**	**Use at Moderate Elev.**	**Use at High Elev.**	**Use at Extreme**
Score	*< 1,200 meters*	*1,200 to 1,500 meters*	*1,500 to 2,200 meters*	*>2,200 meters*
34-39	Low Risk	Low Risk	Low Risk	Low Risk
40-45	Low Risk	Low Risk	Moderate Risk	Moderate Risk
46-49	Moderate Risk	High Risk	Do Not Use	Do Not Use
>=50	Moderate Risk	High Risk	Do Not Use	Do Not Use
PAP test conducted at elevation 1,600 to 2,100 meters				
PAP	**Use at Low Elev.**	**Use at Moderate Elev.**	**Use at High Elev.**	**Use at Extreme**
Score	*< 1,200 meters*	*1,200 to 1,500 meters*	*1,500 to 2,200 meters*	*>2,200 meters*
34-39	Low Risk	Low Risk	Low Risk	Low Risk
40-45	Low Risk	Low Risk	Low/Moderate Risk	Low/Moderate Risk
46-49	Moderate Risk	Moderate Risk	Moderate Risk	High Risk
>=50	Moderate Risk	Moderate Risk	High Risk	High Risk

SECTION 4: CLIMATE PATTERNS AND IRRIGATION IN THE ROCKY MOUNTAIN WEST

The Rocky Mountain region of the United States is home to many commercial cattle operations with many crossing state lines (Thomas, 2020). An understanding of the terrain and climate patterns of the region aid in management decisions for producers.

4.1 Colorado topographic features and climate patterns

Colorado is an incredibly ecologically diverse state and is the highest contiguous state in elevation in the United States. The average elevation is 2,000 meters and rises to higher than

4,200 meters in the mountains. In Colorado, the Rocky Mountains divide the state with 40 percent of the state considered high eastern plains. The plains gradually slope upward for 320 kilometers from the eastern border of the state to the base of the foothills of the Rocky Mountains. Colorado is considered a headwater state, all rivers rise within the borders and flow outward with the exception of the Green River. Four major rivers source in Colorado, and include Arkansas, Colorado, North Platte and South Platte (Doesken et al., 2003).

The combination of high elevation, mid latitude interior continent geography, and dramatic changes in elevation lead to an extremely variable climate. Average precipitation for the state is 43 centimeters, with a low of only 17 centimeters in the San Luis Valley in south central Colorado to a high of over 152 centimeters in some mountain locations. Summer is hot and dry in the plains with afternoon thunderstorms while the mountains are cool with variable storms. Humidity is low and days are generally sunny with high intensity sunlight due to the elevation and thinner atmosphere. Climate is affected by elevation and orientation of mountain ranges and valleys with respect to general air movements. Temperature generally decreases with elevation while precipitation increases. These patterns are modified by the orientation of mountain slopes with respect to prevailing winds and by the influence of topographical features in creating local air movements. Colorado's distance from ocean precipitation leads to light precipitation in lower elevations. Prevailing air currents reach Colorado from the west while eastward moving storms from the Pacific Ocean generally lose much of their moisture on the mountains and westward facing slopes. Eastern slopes receive relatively small amounts of precipitation from these storms. Storms from the north usually carry little moisture and occur mainly in the fall and winter. They can bring outbreaks of polar air and when these outbreaks occur there are strong northerly winds. When these winds come into contact with moist air from the south, the interaction can cause heavy snowfall or even blizzards. The cold air is usually too shallow to cross the mountains so the plains may experience severe storm while the mountains and western valleys may be mild. Warm moist air from the south can move into Colorado infrequently in the spring, summer and early fall. As the air is carried northward and westward to higher elevations, the heaviest rainfalls and wet snows occur over eastern Colorado from April through early September. Southern and western Colorado experience moist air from mid-July into September associated with the wind pattern called the Southwest Monsoon, causing frequent showers and thunderstorms. At other times, the wind shifts to the southwest bringing hot, dry air from the Southwest causing periods of high ambient temperature (Doesken et al., 2003).

Severe storms are often observed as thunderstorms in the eastern plains and eastern slopes of the mountains in the spring and summer. Accompanying hail storms make some counties of eastern Colorado among the most hail prone areas in the Unites States. Tornadoes are also a threat to eastern Colorado but are rare in the mountains and western valleys. Lightning is one of the greatest weather threats throughout the state, causing several fatalities and injuries each year. Blizzards occur on the eastern high plains from fall to spring. Heavy snow in high mountains can cause avalanches leading to the loss of life. Spring floods occur due to snow melt at high elevations. However, the greatest threat of flooding is from flash flooding due to localized intense thunderstorms. The most flash-flood prone regions of Colorado are at the base of the lower eastern foothills. Flash floods occur on the western slope at lower frequency and intensity due to reduced supply of moisture in these storms (Doesken et al., 2003).

4.2 Wyoming topographic features and climate patterns

Much like Colorado, Wyoming is a mountainous state with varying topography. The mean elevation is 2,000 meters in elevation, with the lowest elevation being 950 meters at the north east corner and the highest elevation being 4,200 meters at the peak of Gannett Peak in the Wind River Range. The mountain ranges generally run north to south, providing an effective barrier to prevailing air currents moving from the Pacific Ocean. This forces storms to drop most of their moisture along the western slopes, causing the rest of the state to be considered semiarid east of the mountains. The topography and variations in elevation make it difficult to divide the state into homogenous, climatological areas. The Continental Divide splits the state from the northwest corner to the center of the southern border, leaving the drainage areas to the east. Run off drains into three major river systems, the Columbia, the Colorado and the Missouri. The south-central portion of the state contains the Great Divide Basin. Part of this area is referred to as the Red Desert. No drainage from the basin occurs. Precipitation here only averages 17 to 25 centimeters and any precipitation either evaporates or percolates into the ground. Snow accumulates in the high mountains, providing water for irrigation and electric power (Water Resources Data System & State Climate Office).

Wyoming has a relatively cool climate due to elevation. Temperatures rarely exceed 37°C above 1,800 meters in elevation. For most of the state the mean maximum temperatures range between 30° to 35°C. Few places above 2,700 meters in elevation have maximum July temperatures close to 21°C. Summer nights are cool. In the high mountains and valleys, temperatures can occasionally drop below freezing in the summer. Wintertime has rapid and frequent changes between mild and cold spells. The majority of cold waves move southward on the east side of the Divide. In the coldest month, January, the average minimum temperatures range from -26° to -24°C. The western valleys average -28°C. Valleys can collect cold air drainage at night, causing colder air to settle and will be colder than the mountain sides that experience stirring of air due to wind. Due to cold temperature, the growing season is relatively short with early freezes in the fall and late freezes in the spring. The average growing season in principle agriculture areas is approximately 125 days with some areas such as Farson seeing an average growing season of 42 days (Water Resources Data System & State Climate Office).

Precipitation varies greatly with drought being an issue in Wyoming (Water Resources Data System & State Climate Office; Micheli and Ostermann, 2003). Precipitation events occur mainly in the spring and early summer. It occurs at greater amounts in the mountains and high elevations, however, there are exceptions (Water Resources Data System & State Climate Office). Basin areas can receive as little as 10 to 15 centimeters while mountain areas can receive in excess of 152 to 203 centimeters (Micheli and Ostermann, 2003). Mountain ranges often block the flow of wet air from the east as well as from the west. During the summer, showers are common but rarely bring more than a few hundredths of an inch of rain. Occasionally isolated thunderstorms will bring 2 to 5 centimeters of rain in a 24-hour period. Average humidity is relatively low state wide (Water Resources Data System & State Climate Office).

Severe storms occur in the form of hailstorms, tornadoes, and windstorms. Hailstorms are the most destructive type of local storm and can cause severe damage. Tornadoes do occur but they are much less frequent and destructive than those that occur in the Midwest. They are also smaller in size and duration. However, Wyoming is very windy. In the winter winds can reach 48 to 64 kilometers per hour with gust of 80 to 96 (Water Resources Data System & State Climate Office).

Snowfall occurs frequently from November through May but accumulations above 25 to 38 centimeters for a single storm are rare outside the mountains. Wind accompanies snow storms causing drifting snow that can create drifts several meters deep. Total annual snowfall varies considerably. At dry, lower elevations in the southwest, totals can range from 114 to 140 centimeters. The Big Horn Basin can see as little as 38 to 50 centimeters over the lower portions of the Basin. However, the mountains can receive upwards of 500 centimeters. Beckler River Ranger Station in the southwest corner of Yellowstone Park averages 665 centimeters. Weather patterns that are most favorable for precipitation are ones with a low-pressure center slightly south of the state. This will allow for cool air at the surface to be overrun by warmer moist air. It is shown that wind flows that cover the state are mostly from the Pacific. A small percentage of the time cold air masses will move down from Canada (Water Resources Data System & State Climate Office).

4.3 Irrigation in the Western United States

When the United States was first being developed for agricultural land east of the Mississippi, riparian usage was the system in which water rights were allocated. Land owners owned the water rights of the water that flowed through their land and could use that water as they saw fit. However, as the semi-arid and arid west was developed, it was clear that a different allocation system was needed to address water rights in areas prone to drought. Due to this, most of the Western United States follows prior appropriation for allocation of water rights. Under prior appropriation, water rights are distributed based on the timing of the initial water diversion claim. Construction of irrigation infrastructure such as a ditch to divert a specific amount of water from a given location in a timely manner for irrigation was sufficient to establish a claim and satisfy beneficial use requirements. During times of drought, water is first diverted to the oldest, or senior water rights, and then following the senior water rights usage, junior water rights receive their allocation of water. In 1876 prior appropriation was established in Colorado; Wyoming followed in 1890. Colorado developed ten distinct water districts in order to enforce proper allocation of water. The Department of Commerce declared Colorado's water right system as the most well defined of the western states, and this became the guide for other prior appropriation states to follow (Leonard and Libecap, 2019).

Irrigation in the west relies on ground water and surface water. Ground water is sourced directly from aquifers and underground water that lies less than 600 meters below the surface. Surface water is sourced from reservoirs, streams, rivers and lakes. Snowpack serves as a natural reservoir for surface water, feeding water bodies as the snow melts throughout the summer months (Anderson and Woosley, 2005). However, drought conditions can occur if significant snowpack is not built up (Niswonger et al., 2017). Due to this irrigation usage in the United States has been more efficient to deal with reduced water sources. According to the United States Department of Agriculture, Economic Research Service, irrigation usage has decreased from 1.5 meters per hectare to 1.13 meters per hectare from 1969 to 2017 (2022).

Methods of irrigations vary, but typically in southern Wyoming, flood irrigation is utilized to irrigate hay meadows. This method of irrigation is more inefficient due to seepage from drainage ditches, however, this seepage is responsible for creating wetlands. These wetlands serve to be valuable habitat for endangered species such as the Wyoming Toad. They also serve as valuable breeding grounds for migrating waterfowl. While it may be beneficial from an efficiency standpoint to update the system, profitability is too low from hay production to justify upgrades. Therefore the wetlands will continue to exist in this unique ecosystem (Peck and Lovvorn, 2001).

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CHAPTER 3

EFFECTS OF PULMONARY HYPERTENSION AND PRECIPITATION ON REPRODUCTIVE PERFORMANCE IN ANGUS HEIFERS

SUMMARY

Reproductive success of beef females is economically relevant to production systems. However, fertility is controlled by a variety of physiological factors and can be influenced by the environment. It is also known that timing of puberty is influenced by nutrition, weight and management practices, while conception and maintenance of pregnancy can further be influenced by management practices. Due to this, there is concern that physical environment could influence fertility in beef heifers. Specifically, precipitation amounts and timing is of concern in dryland range operations in the western United States that rely on precipitation for forage production. Furthermore, dry rangeland operations in the mountain west can manage their cattle at locations above 1,500 meters also puts the cattle at risk for high altitude disease (HAD) due to the effects of pulmonary hypertension (PH). The hypoxic environment can lead to high pulmonary arterial pressure (PAP), leading to cardio-pulmonary stress as the heart undergoes right side remodeling. As the condition progresses and remodeling continues, the heart will eventually fail. Because of this, it is a concern that animals may experience negative effects on fertility as PAP scores increase and the chance of PH occurs. Therefore, the objective of this study was to evaluate the effects of PAP and precipitation amounts on reproductive performance of Angus heifers located at the Colorado State University Beef Improvement Center (CSU-BIC) in Saratoga, Wyoming. These heifers were managed at altitude on a mix of arid dryland in the

spring and snow-pack fed irrigated pastures in the fall and winter. Due to snowfall heifers were fed hay in the pastures in the winter. Results of this study may provide insight into influences on heifer performance in similar management settings, aiding producers in management decisions.

Three rainfall and developmental periods were assessed: birth to weaning, weaning to breeding, and cumulative precipitation from birth to breeding. Heifer data contained records from 3,834 Angus heifers. Determined through logistical regression, PAP score was an important source of variation in prediction of FSC and HPG during all developmental periods ($P<0.05$). Yearling weight also affected FSC across all developmental periods ($P<0.01$) Finally, precipitation levels affected HPG across all developmental periods ($P<0.01$). Results showed a favorable, negative relationship between PAP and fertility measures, suggesting that a low PAP score was the most advantageous to heifer breeding success (β_i=-0.0091 to -0.0168; $P<0.01$). A favorable, positive relationship existed between YW and FSC, suggesting that heavier females may have become pubertal and were more likely to conceive (β_i= 0.00120 to 0.00124; $P<0.01$). Finally, a favorable, positive relationship was observed between precipitation and HPG suggesting heavier precipitation years were most desirable for HPG (β_i= 0.06 to 0.07; $P<0.01$). Coefficient of determination values ranged from 0.014 to 0.017 in all these analyses.

The influence of sire on HPG and FSC was then assessed. Fixed effects included precipitation, YW and PAP with a random sire effect. Logistical regression was executed for each of the three developmental periods. Results mimicked prior analysis. PAP affected HPG ($P<0.01$) and demonstrated a tendency for effecting FSC ($P<0.10$); yearling weight also affected FSC ($P<0.01$) and all precipitation classifications significantly affected HPG ($P<0.05$). PAP had a favorable, negative relationship with HPG and FSC (β_i= -0.0180 to -0.0185; $P<0.05$), while YW had a favorable, positive relationship with FSC (β_i= 0.00128 to 0.00134; $P<0.01$) and precipitation had a favorable, positive relationship with HPG (β_i= 0.05 to 0.07; P<0.01). Inclusion of sire in these statistical models increased the overall coefficient of determination values to a range of 0.029 to 0.034 for the full model. Fixed effect coefficient of determination values ranged from 0.004 to 0.007 and random effect values ranged from 0.025 to 0.027.

Results suggested that physiological and environmental stressors, such as high PAP scores and drought conditions influence heifer breeding success. These results have the ability to provide beef producers with further knowledge upon which to base heifer selection decisions. While both effects are out of producers control, selecting low PAP females and managing rangelands to account for drought conditions through lower stocking rates could potentially prevent depression in fertility rates.

INTRODUCTION

The beef cattle producer must be aware of and consider physical and physiological factors in the management of heifer reproductive success in order to maximize profitability. Replacement heifer fertility is directly influenced by puberty. Heifers must become pubertal and conceive by 15 months of age in order to maximize pregnancy rates (Buskirk et al., 1995; Eborn et al., 2013). For puberty to occur, maturation of the hypothalamic-pituitary-ovarian (HPO) axis, recruitment of ovarian follicles, induction of ovulation, and initiation of estrous cycles must occur. These events are directly controlled by nutrition and growth (Eborn et al., 2013). Puberty can only occur once a certain level of development and weight has been reached. Proper nutrition must be available during all developmental periods in order for proper development to occur (Wiltbank, et al., 1966).

Proper nutrition is potentially a concern in the arid western United States. This is due to the variability in precipitation on dry rangelands. With continuing drought conditions and warming trends, drought is becoming an increasing concern for rangeland producers (Scasta et al, 2015a). While rangelands are mainly affected by drought, areas that use irrigation water from natural sources fed by snow melt also suffer the effects of drought. This can directly affect forage production of irrigated pastures similar to how rangeland forage is affected by drought (Doughty et al., 2018). In drought conditions, nutrient availability in forage is reduced along with forage availability. Due to these reductions in nutrients, reduced gains and pregnancy rates have been observed. (Thomas et al., 2007; Scasta et al., 2015b).

Beef production systems in the mountain west above 1,500 meters also have to manage for the repercussions from the hypoxic environment. Reduced oxygen amounts at these altitudes lead to PH in beef cattle, known as high altitude disease (HAD), which can result in up to 20% death loss in some herds. The hypoxic environment, in combination with inefficient oxygen utilization by the bovine cardiopulmonary system, causes alveolar-hypoxia and pulmonary arterial vasoconstriction. As the arterial vasoconstriction progresses so does right heart ventricular hypertrophy ultimately leading to ventricular dilation and potential heart failure (Ahola et al., 2006; Holt and Callan, 2007).

Pulmonary arterial pressure score is an industry-utilized predictor trait of HAD (Holt and Callan, 2007). When conducted at altitudes above 1,220 meters, PAP scores can be used as a culling measure to select for altitude tolerant cattle. Generally, a PAP score below 40 mmHg is considered low risk, 40-45 mmHg are at moderate risk and scores above 46 mmHg are at high risk of HAD. Pulmonary arterial pressure scores also have been used to evaluate performance of those animals in early stages of HAD, where the only observable phenotype was elevated PAP score (Beef Improvement Federation, 2021). Weaning weights and growth have been observed at reduced rates in animals suffering from high PAP scores (Shirley et al., 2008).

The objective of this study was to investigate the effect of high altitude on reproductive performance of Angus heifers and determine how environmental effects such as precipitation interact(s) with these effects. Subsequently, we hypothesized that PAP and environmental stress, such as drought, would have a negative effect on reproductive success genetic influences on heifer fertility traits and PAP also contribute.

MATERIALS AND METHODS

Data were collected using protocol (#KP1526) approved by the instructional animal care and use committee at Colorado State University.

Animals

The Colorado State University John E. Rouse Beef Improvement Center manages approximately 420 mother cows of Angus lineage utilizing typical beef industry practices while facilitating research. The cow herd was originally established from registered Angus genetics. Registered Angus bulls are utilized as artificial insemination (AI) sires and natural service bulls are sourced from within the herd as are the replacement females.

Historically, heifers were artificially inseminated during the third week of May at an average of 421.65 (± 20.95) days of age after using a CIDR-progesterone based estrus synchronization protocol. Females received an injection of gonadotropin releasing hormone (GnRH) and a progesterone based controlled internal drug release (CIDR) was inserted at day 0. Seven days later the CIDR was removed and females received a prostaglandin ($PGF_{2\alpha}$) injection.

Females were typically bred 12 hours after expression of estrus, or in a mass mate group on day 10 if standing heat was not expressed (i.e., 66 hours post CIDR removal). Ten to 14 days after AI, heifers were exposed to bulls for 60 days. Mature cows followed the same protocol as heifers 21 days after AI of heifers. This was the protocol followed unless experimental estrous synchronization protocols were being tested for research purposes.

After AI, heifers were managed on irrigated breeding pastures where they graze for the summer months. They were also pastured hroughout the duration of the winter months where they were fed hay once the ambient temperature decreased and snow accumulated. During calving, heifers were pastured close to the headquarters and fed hay in the afternoons to promote calving during the daylight hours. Indoor calving facilities were available but rarely used for mature cows due to absence of dystocia in mature females.

To maintain the herd size, heifer retention selections followed pregnancy diagnosis each fall. Criteria for replacement heifers include pregnancy status, performance, pedigree of AI sire and PAP score. Typically, heifers that conceived earlier in the season and AI progeny were retained. Heifers and mature cows that were non-pregnant or had poor feet and legs and udders were culled. Pulmonary arterial pressure score was also considered when choosing replacement heifers. These criteria yielded multiple pregnancy evaluations paired with PAP scores, allowing for fertility research to be conducted.

Location and Precipitation

The Colorado State University John E. Rouse Beef Improvement Center is located in Carbon County, Wyoming. Ranch headquarters are approximately 17.7 km northeast of Encampment, Wyoming and approximately 35.4 km southeast of Saratoga, Wyoming. Elevation ranges from 2,150 to 2,411 m. The North Platte River flows through the ranch property, so water from the North Platte is used to irrigate alfalfa fields. Irrigation for meadows is sourced from Brush Creek. Senior water rights allow for three months of irrigation water. Flood irrigation is utilized on the meadows. Dominant grass species in meadow pastures were *Alopecurus arundinaceus* and *Bromus biebersteinii*. Dry rangelands dominated by grass-shrub lands seeded with *Agropyron cristatum* and *Agropyron desertorum* exist at higher elevation of the ranch (University of Wyoming Extension, 2022).

Rainfall predominantly occurs during the spring months, with May being the wettest month. Occasional summer storms occur; however, accumulation is minimal. Snowfall occurs mainly during the winter but snow has been known to fall during every month of the year. Greatest accumulation of snow occurs November through March.

Data Collection

Fertility, PAP Data and Yearling Weight

Data were collected from 1993 to 2019. Individual records were from 3,834 yearling Angus heifers. Data collected included individual information (identification, sire, dam, birth year), birth weight, weaning weight, YW, mating year, AI technician, AI sire, mating age, first service conception (FSC), overall heifer pregnancy (HPG), age at first calving, PAP score and PAP collection date. In the present study, FSC was defined as the ability to conceive in response to her first exposure to AI, and maintain the pregnancy until the end of the breeding season. First service conception was determined by fetal age obtained through pregnancy evaluation utilizing ultrasonography via rectal palpation of females at 40 and 130 days post AI. Overall heifer pregnancy was defined as the heifer’s ability to conceive and maintain a pregnancy until the end of the breeding season. Overall pregnancy was determined at 130 days post AI and represented conception at some point during the breeding season. If a female failed to conceive during the breeding season, she was determined to be open (i.e., non-pregnant) and culled. Both observations, FSC and HPG were recorded as 1 = successful and 0 = unsuccessful.

The PAP score was collected when heifers were yearlings (i.e. ~365 days of age), generally in the spring between February and April. However, heifers bred in 1995 had their PAP scores collected in November of 1994. The PAP data collection was performed by the same Colorado/Wyoming licensed veterinarian every year using procedures described by Holt and Callan (2007). Briefly, a polyethylene catheter was inserted in the jugular vein and passed through the right atrium, into the right ventricle through the pulmonary valve and into the pulmonary artery. Mean logarithm of systolic and diastolic pulmonary artery pressure was collected via a pressure transducer connected to the catheter. Based off knowledge regarding acceptable scores and risk factors associated with PAP, generally at this elevation a PAP score of 41 and below was considered the cut off for females to be considered good candidates for replacement females in the CSU-BIC herd. However, all heifers were exposed irrespective of PAP score throughout the duration of the breeding season. Females that conceived with high PAP scores were then marketed and sold as bred heifers in the fall to producers located at low altitude. Yearling weight was recorded at a year of age, generally at the same time as PAP scores (i.e. between February and April).

Precipitation Data

Climate data was necessary for this thesis. Ideally, a weather station located on the same land that the cattle resided would be utilized to obtain the necessary climate data. However, a nearby weather station was not available, so alternate data source was sought

The ranch manager uses data from Natural Resource Conservation Service Snow Telemetry (NRCS SNOTEL) service in order to predict irrigation amounts for the next growing season. However, the nearest SNOTEL locations were located in the mountains above the ranch at substantially higher elevations (2,572 to 3,088 meters in elevation) than the ranch location (2,150 to 2,411 meters). Due to this, precipitation amounts recorded by SNOTEL were substantially higher than the recorded average for where the ranch resides. SNOTEL averages ranged from 70.0 to 109.80 centimeters while the average precipitation of Saratoga, Wyoming, 35 kilometers from where the ranch is located was 24.63 centimeters (Western Regional Climate Center). Therefore, another source of information was sought.

Through the assistance of the local county University of Wyoming Extension agent, Abby Perry, a Weather Variability Specialist and Regional Extension Program Coordinator of the USDA Northern Plains Climate Hub, Windy Kelley, was contacted to obtain climate data. There were a variety of sources available, such as the Agriculture Applied Climate Information System (AgACIS), the PRISM Climate Group and the High Plains Regional Climate Center (HPRCC). Ultimately, data from the National Oceanic and Atmospheric Administration (NOAA) was utilized. It was chosen due the historical nature of the data available and that the average annual precipitation recorded was 40.59 centimeters. Monthly average minimum and maximum temperature, along with precipitation amounts, were available on a county basis dating back to 1895. Data from the ranch county was selected from the time frame of heifer data. Precipitation data was downloaded and appropriately sorted for the time periods of the study.

From the monthly precipitation data, time periods were constructed. Due to the nature of evaluating cumulative precipitation, along with developmental periods, three classifications for each year of heifers were created (Figure 3.1). Cumulative precipitation from birth to AI exposure, i.e. breeding, was created for each year class of heifers. This consisted of 16 months ranging from February to the following May when heifers were first exposed. Two separate divisions were created from the cumulative precipitation. The first spanned from February to October, encompassing the time that the heifers were calves nursing at their dam's side until weaning. The second spanned from October to May, aligning with weaning until breeding. This was done to assess how precipitation had an effect on fertility based on when the precipitation fell during heifer development.

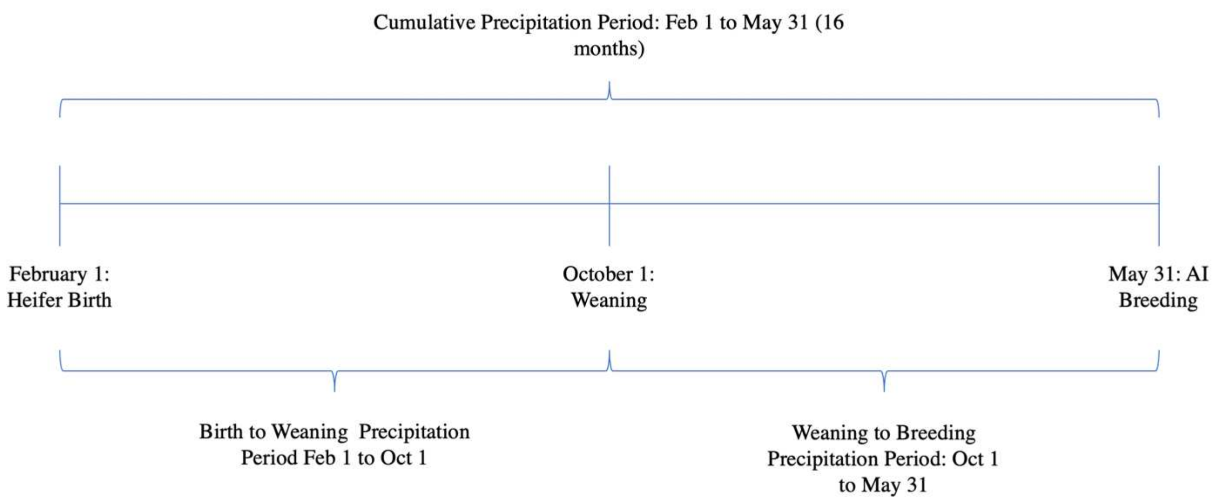

Figure 3.1. Precipitation classifications based on heifer development periods of Angus heifers raised in a seedstock operation located at altitude in the Rocky Mountain region.

Statistical Analysis

The initial relationship between PAP, fertility, precipitation and YW was assessed using three statistical models, one for each precipitation classification. All models were executed in logistical regression analysis due to fertility measures being binary traits. The model equation is presented below:

$$y_i = \mu + B_1x_1 + B_2x_2 + B_3x_3 + e_i$$

Where y_i was the vector of observed phenotypes for the trait of interest, which included FSC and HPG, μ was the overall mean of the observations, B_1 was the slope of the regression line of precipitation, x_1 was the vector of predictor variables for the fixed effect of the continuous variable precipitation, B_2 was the parameter for the slope of the regression line of PAP, x_2 was the vector of predictor variables for the continuous fixed effect of PAP, B_3 was the parameter of the population regression line of the continuous fixed effect of YW, x_3 was the vector of predictor variables for the continuous fixed effect of YW, and e_i was the vector of random residuals.

Type III sums of squares were calculated for each model and used to assess important ($P < 0.05$) sources of variation. Tendencies were determined as $0.05<P<0.10$. Data were analyzed using the R statistical software package (R Core Team, 2020). Model structures were as follows.

1. **FSC/HPG = cumulative precipitation + PAP + YW**
2. **FSC/HPG = birth to weaning + PAP + YW**
3. **FSC/HPG = weaning to breeding + PAP + YW**

Following execution of the initial three models, sire was added to the models to assess genetic variation. Sire ID was included in the model as a random term where the fixed effects were precipitation classification, PAP and YW. Models were executed as logistical regressions and Type III sums of squares were calculated for each model to determine important ($P < 0.05$) sources of variation. Tendencies also were determined as $0.05<P<0.10$. Data were analyzed using the R statistical software package (R Core Team, 2020). Model structure was as follows.

1. **FSC/HPG = cumulative precipitation + PAP + YW + sire**
2. **FSC/HPG = birth to weaning + PAP + YW + sire**
3. **FSC/HPG = weaning to breeding + PAP + YW + sire**

PAP data was noted as being non-normally distributed with a skewed right tail distribution; however, the non-normality did not alter results based on additional analysis. A Box-Cox analysis was performed, suggesting PAP data should be raised to the power of -1.6. When analysis was executed, a right tail remained; however, it was lessened. When data analyses were executed with transformed PAP data, significance of results were not altered, and P-values differed less than 15% for test analysis of precipitation, and less than 25% for PAP values. These differences did not affect the significance level of the P-values or the interpretation of results. This could be due to the distribution of the data. While there is a tail, 3,749 observations, or 97.78% of the values, fall under the bell curve. The right sided tail accounts for only 85 observations (Figure 3.2). While this does create distribution of non-normality, the variation likely accounted within the bell curve and allows for use of PAP values recognized by the Western U.S. Beef Industry. It has also been reported in literature that raw PAP data and power transformed data yield similar statistical results (Zeng, 2016). Raw PAP data is preferable to power transformed PAP data for genetic analysis due to its similar genetic heritability to power transformed data, higher accuracy and easier interpretation by livestock producers (Zeng, 2016; Speidel, 2020).

A contemporary group was not included in the model due to precipitation classification acting as a contemporary group within each year. Yearling weight and precipitation was found to be lowly correlated indicating collinearity was not a concern (r=0.0009 to 0.1318). Models containing a PAP by YW interaction were tested and found to have no significance. Due to this, the interaction was removed from the models. A final interaction between PAP and precipitation was evaluated. In general, the PAP by precipitation interaction was not detected. However, PAP by weaning to breeding precipitation tended to predict HPG *(P*=0.0636*)*. Due to no significance found, and a single tendency detected, the interaction was omitted from this thesis. However, there is evidence to suggest that PAP and weaning to breeding precipitation may influence breeding success.

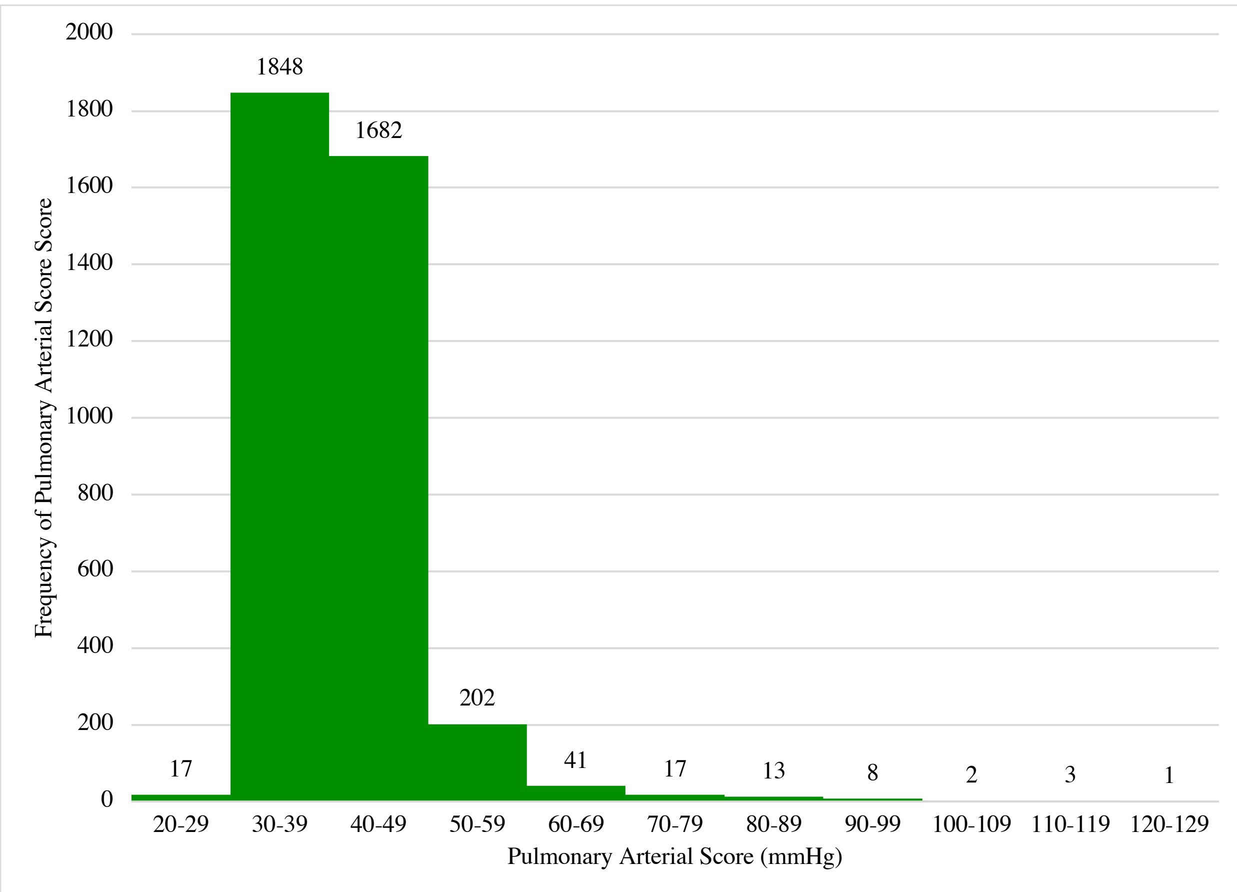

Figure 3.2. Pulmonary arterial pressure (PAP) score frequency in yearling Angus heifers (n = 3,834) raised at altitude (2,150–2,411 m).

.

RESULTS AND DISCUSSION

Data Description and Summary Statistics

Overall, FSC rates averaged 47% while HPG averaged 85% (Table 3.1; Figure 3.3). Average precipitation for cumulative precipitation was 56.01 cm (± 8.74 cm), birth to weaning was 26.97 cm (± 5.94 cm) and weaning to breeding was 29.06 (± 5.89 cm). Yearly precipitation averages were 40.59 cm and displayed below (Figure 3.4). Yearly precipitation revealed a slight trend when compared to fertility percentages, visually. From here, precipitation was manipulated into biological classification of cumulative precipitation, birth to breeding precipitation and weaning to breeding (Figures 3.5, 3.6, 3.7).

Pulmonary arterial pressure scores averaged 41.09 with a low score of 21 to a high score of 129. The heifer with a 129 mmHg score was exposed to breeding but did not conceive. The female with the low PAP score of 21 conceived at first service. Average YW was 308.52 kg with a lowest weight of 180.53 kg and a highest weight of 526.17 kg (Table 3.1).

Table 3.1 Descriptive statistics of precipitation amounts relating to heifer development and phenotypic observations of yearling Angus heifers (n = 3,834) raised at altitude (2,150–2,411 m).

Object	Mean	SD	Minimum	Maximum
Yearling weight (kg)	308.52	47.85	180.53	526.17
Pulmonary Arterial Pressure (mmHg)	41.09	7.52	21	129
First Service Conception (%)	47%	10%	27%	68%
Overall Heifer Pregnancy (%)	85%	8%	64%	96%
Cumulative Precipitation (cm)	56.01	8.74	38.74	74.09
Birth to Weaning Precipitation (cm)	26.97	5.94	15.98	42.65
Weaning to Breeding Precipitation (cm)	29.06	5.89	18.90	42.09

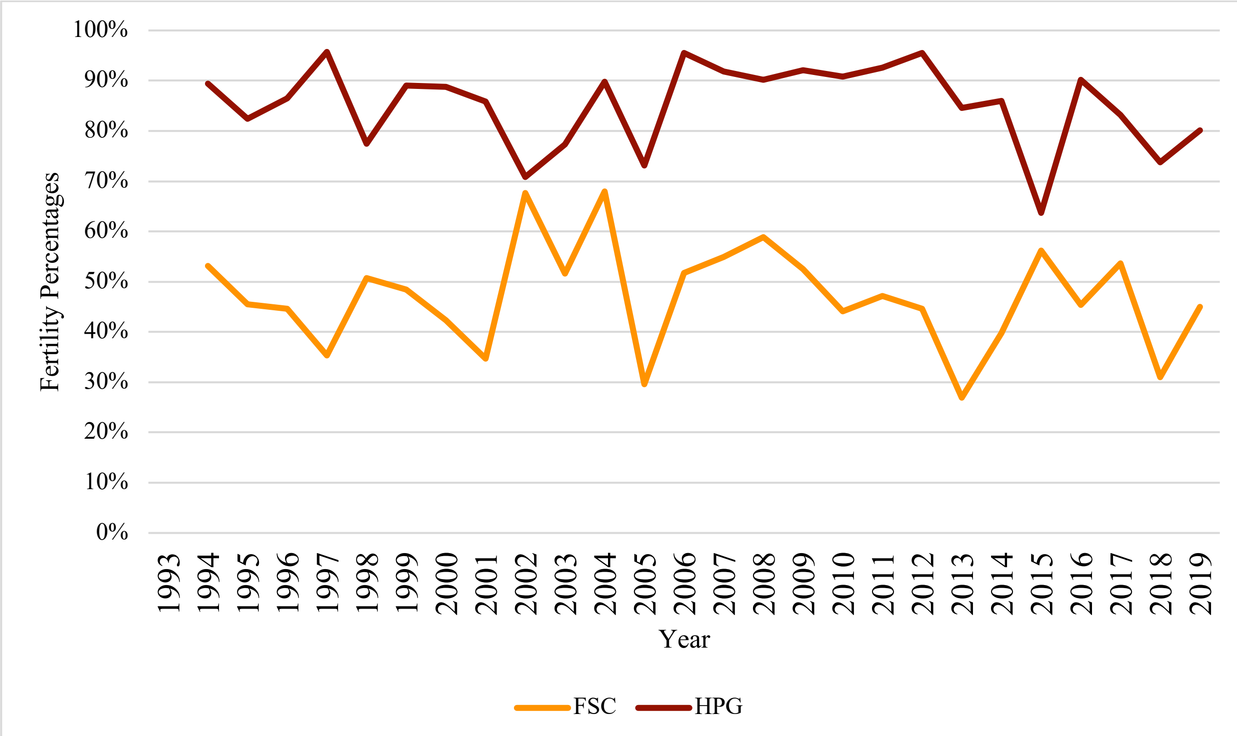

Figure 3.3. First service conception and overall pregnancy rates from 1994-2019 of yearling Angus heifers (n = 3,834) raised at altitude (2,150–2,411 m).

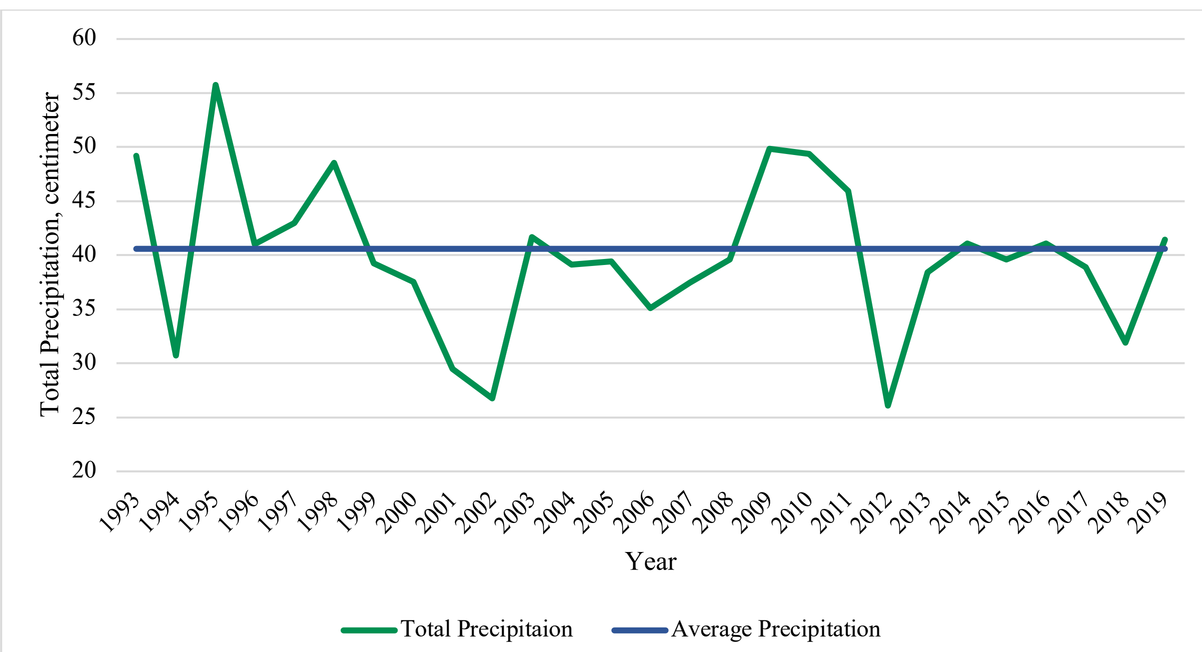

Figure 3.4. Total precipitation and average precipitation of Carbon County, Wyoming by calendar year from 1993 to 2019.

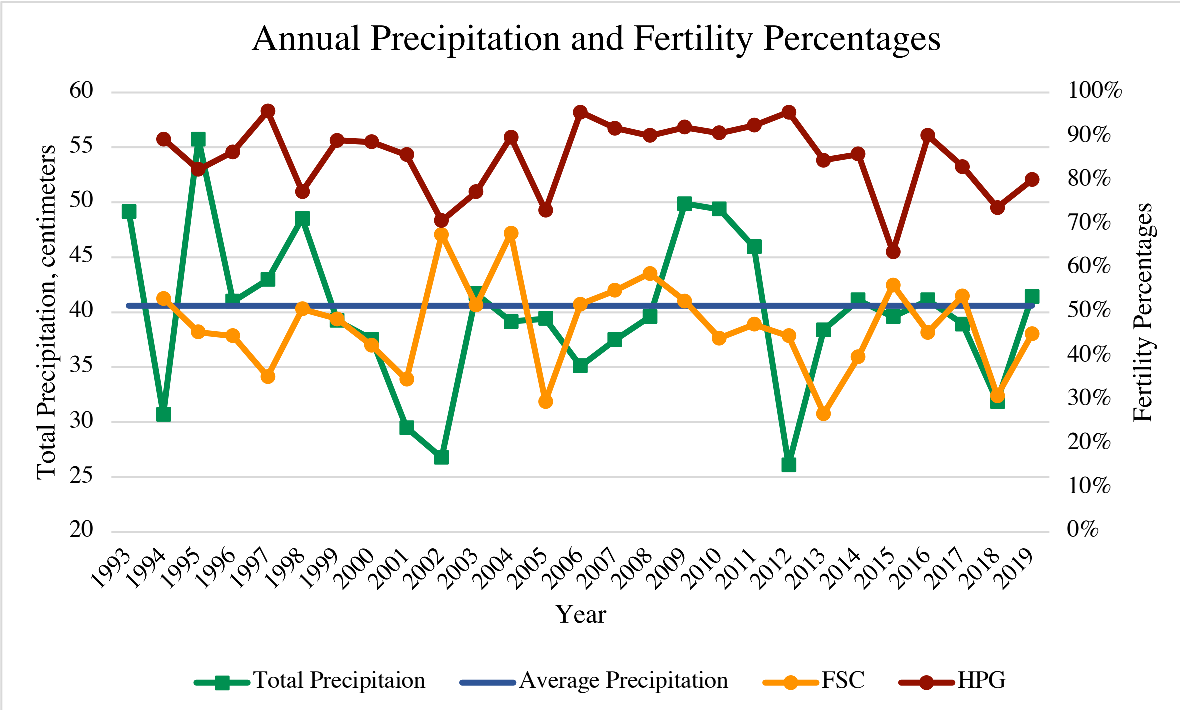

Figure 3.5. Total precipitation and average precipitation of Carbon County, Wyoming by calendar year from 1993 to 2019 presented with first service conception and overall pregnancy rates from 1994-2019 of yearling Angus heifers (n = 3,834) raised at altitude (2,150–2,411 m).

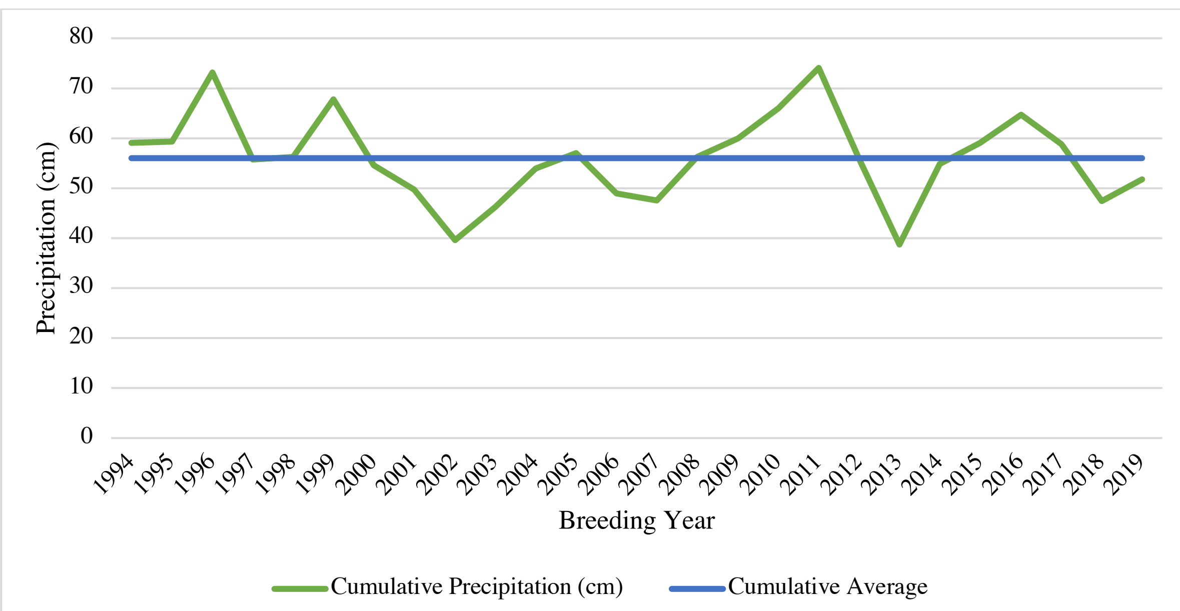

Figure 3.6. Cumulative precipitation in Carbon County, Wyoming presented from yearling heifer heifers' birth to breeding (16 months from February 1 to May 31). Presented by breeding year.

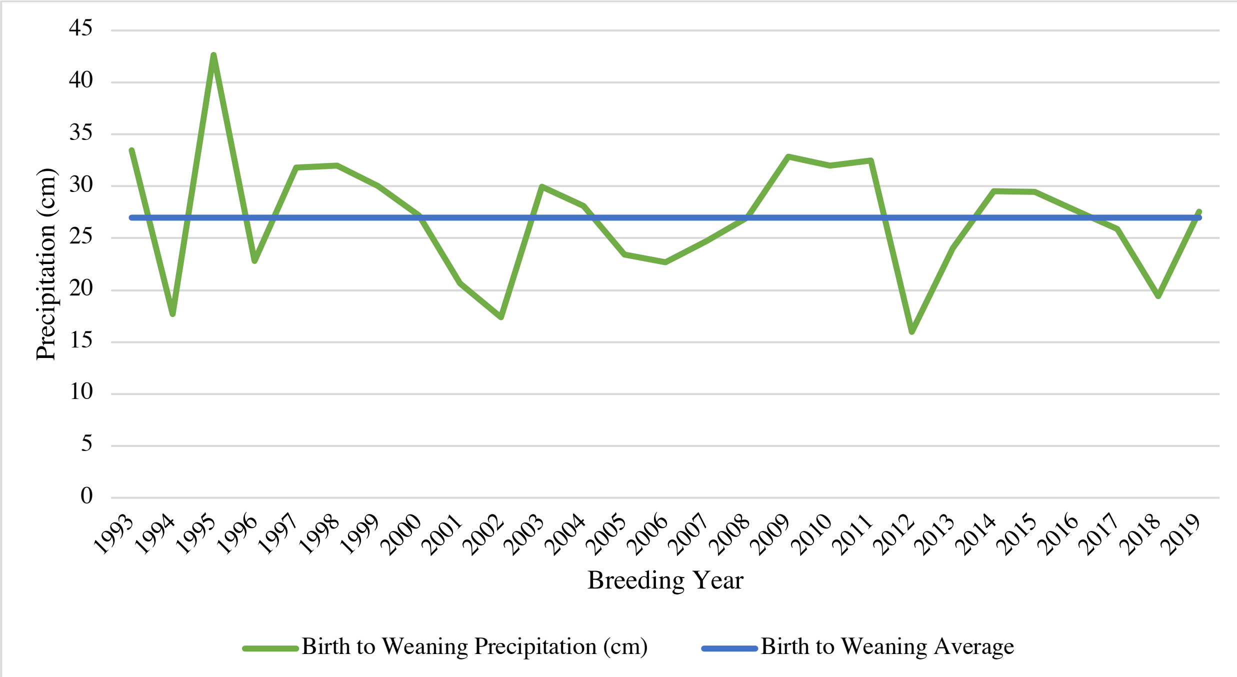

Figure 3.7. Precipitation in Carbon County, Wyoming presented from yearling heifer heifers' birth to weaning (February 1 to October 1). Presented by following breeding year.

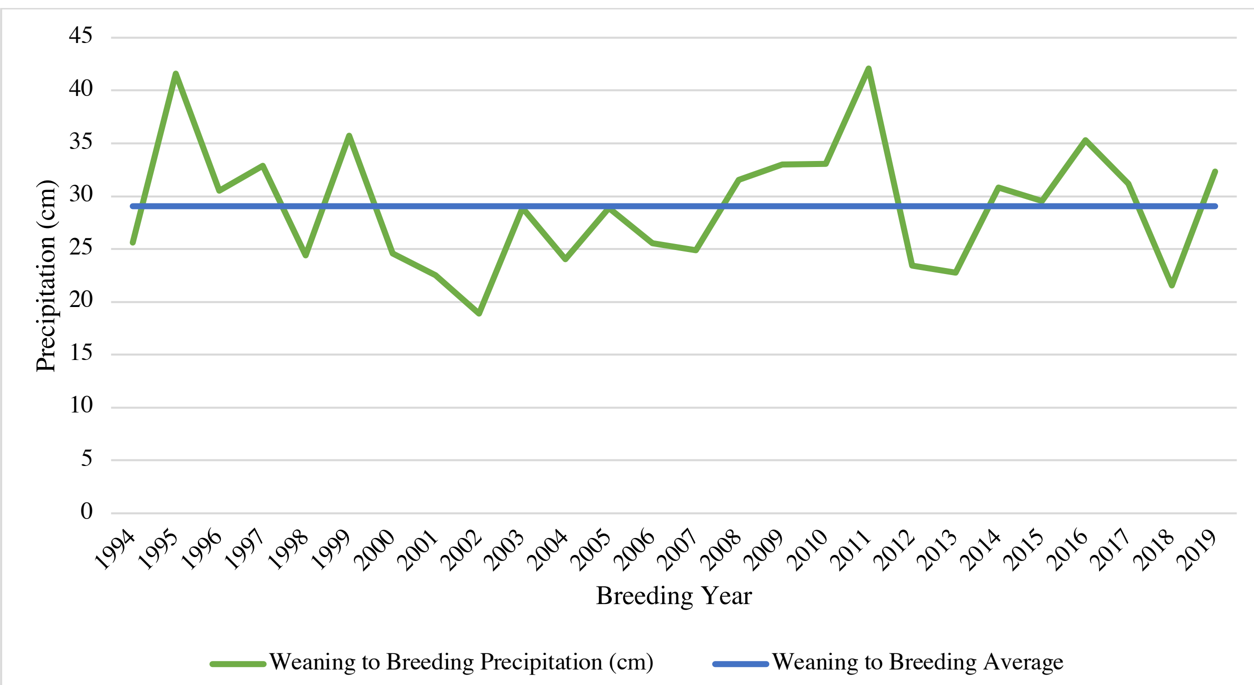

Figure 3.8. Precipitation in Carbon County, Wyoming presented from yearling heifer heifers' weaning to breeding (October 1 to May 31). Presented based on breeding year.

Least squares means (LSM) were estimated to further explore the precipitation data in comparison with other traits. A linear regression model was created to calculate the LSM of HPG, FSC and PAP. Three models were created with FSC, HPG and PAP as the response variables with the factors being precipitation and AI age. The resulting LSMs of HPG, FSC and PAP were then graphed as the response variable to precipitation. A trendline was included to visualize the relationship. Following this, the quadratic and linear coefficients were calculated along with the standard error of the regression line of LSMs on precipitation. Quadratic coefficients revealed a minimal increase in PAP LSM as precipitation increased (ax^2 = 0.0045, 0.0117, 0.0095; SE = 0.0843, 0.1299, 0.1316; Figures 3.8, 3.9, 3.10). A decrease in HPG LSM as precipitation increased was demonstrated through quadratic coefficients (ax^2 = -0.0001, -0.0001, -0.0003; SE = 0.0043, 0.0071, 0.0071; Figures 3.11, 3.12, 3.13). Cumulative FSC LSM and birth to weaning FSC LSM quadratic coefficients demonstrated a decrease in FSC LSM as precipitation increased (ax^2= -0.0001, -0.0003; SE = 0.0062, 0.0089; Figures 3.14, 3.15) while weaning to breeding FSC increased with precipitation (ax^2 = 0.0001; SE = 0.0088; Figure 3.16).

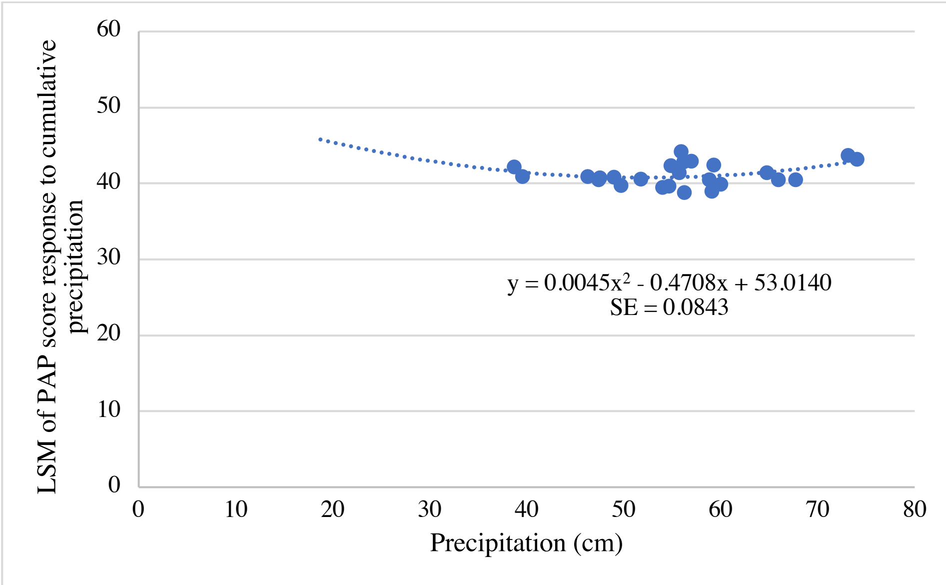

Figure 3.9. Least squared means (LSM) of pulmonary arterial pressure (PAP) score response to cumulative precipitation occurring from Angus heifer's (n = 3,834) birth to first breeding exposure located in Saratoga, Wyoming (2,150–2,411 m).

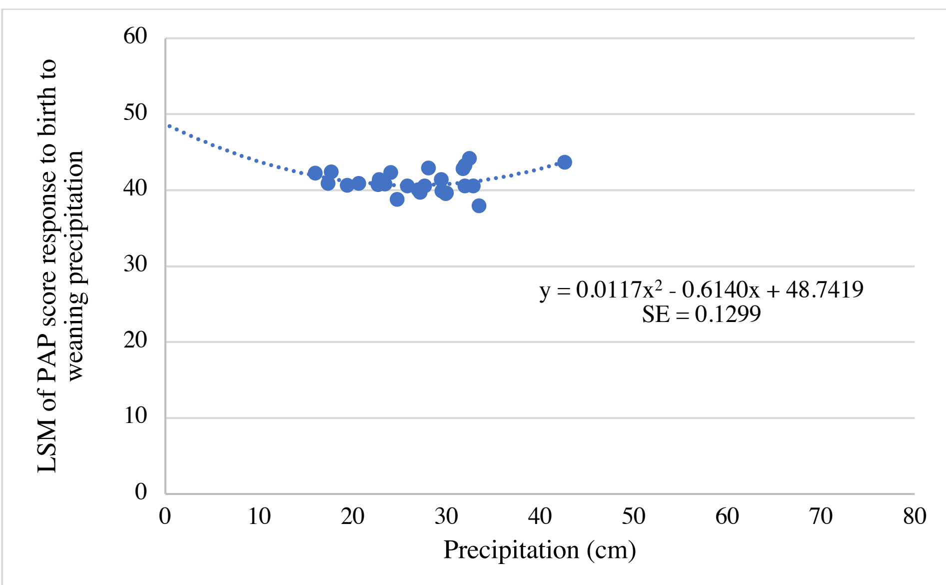

Figure 3.10. Least squared means (LSM) of pulmonary arterial pressure (PAP) score response to birth to weaning precipitation occurring from Angus heifer's (n = 3,834) birth to weaning located in Saratoga, Wyoming (2,150–2,411 m).

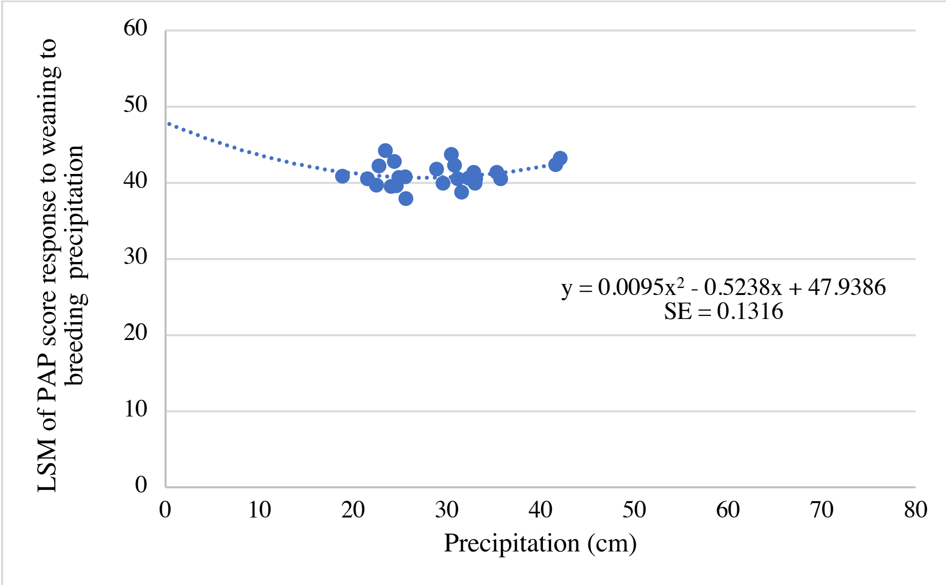

Figure 3.11. Least squared means (LSM) of pulmonary arterial pressure (PAP) score response to weaning to breeding precipitation occurring from Angus heifer's (n = 3,834) weaning to first breeding exposure located in Saratoga, Wyoming (2,150–2,411 m).

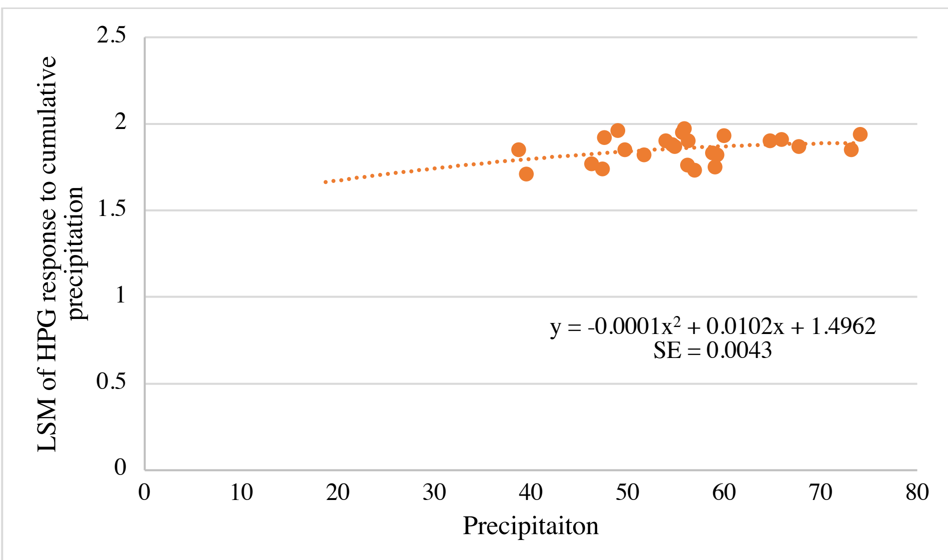

Figure 3.12. Least squared means (LSM) of overall heifer pregnancy (HPG) response to cumulative precipitation occurring from Angus heifer's (n = 3,834) birth to first breeding exposure located in Saratoga, Wyoming (2,150–2,411 m).

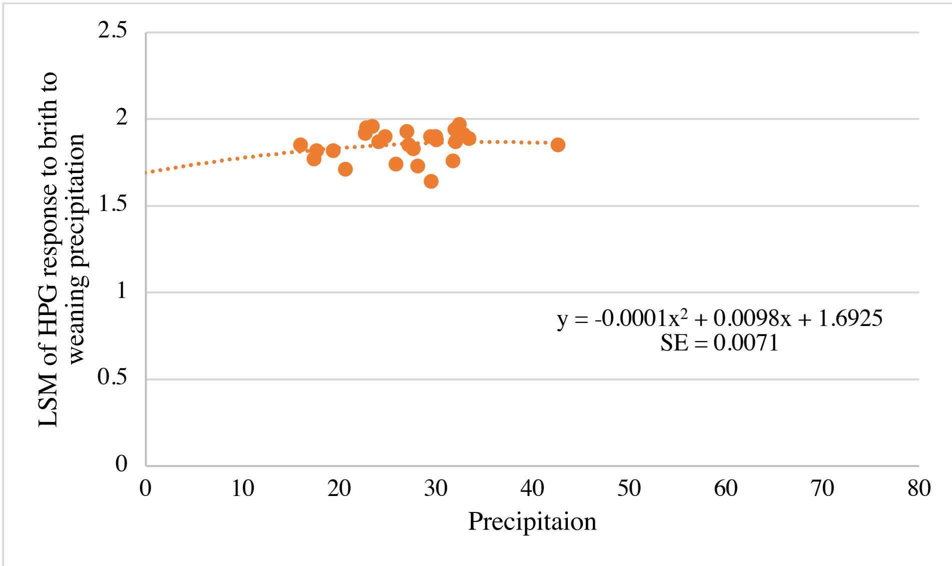

Figure 3.13. Least squared means (LSM) of overall heifer pregnancy (HPG) response to birth to weaning precipitation occurring from Angus heifer's (n = 3,834) birth to weaning located in Saratoga, Wyoming (2,150–2,411 m).

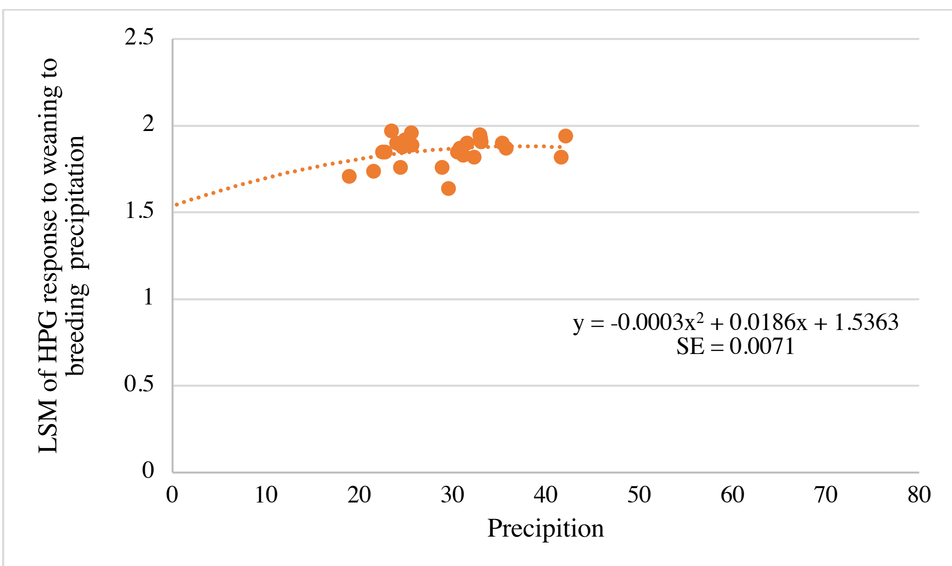

Figure 3.14. Least squared means (LSM) of overall heifer pregnancy (HPG) response to weaning to breeding precipitation occurring from Angus heifer's (n = 3,834) weaning to first breeding exposure located in Saratoga, Wyoming (2,150–2,411 m).

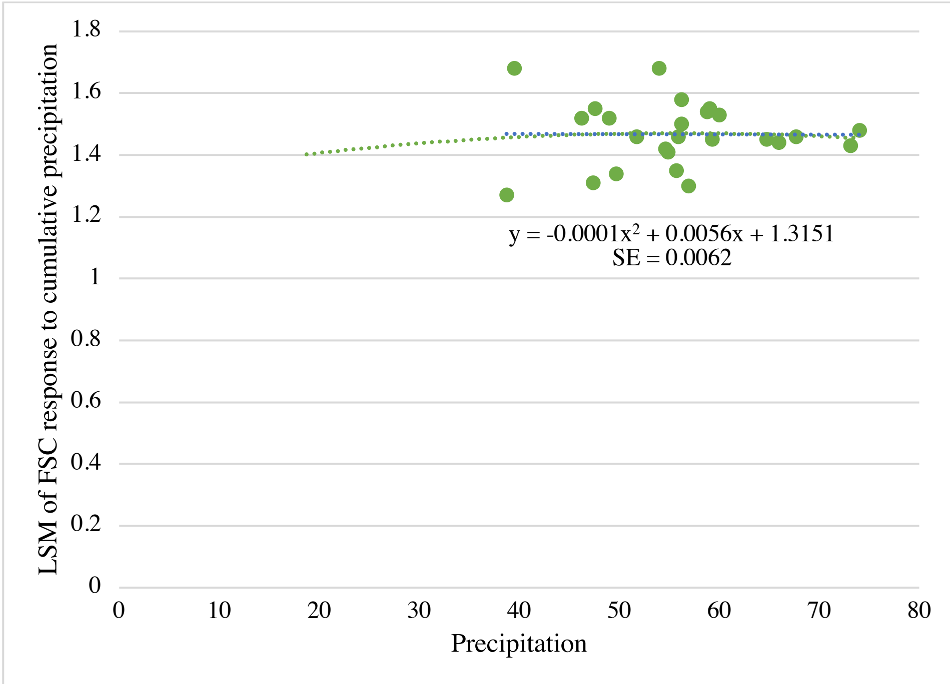

Figure 3.15. Least squared means (LSM) of first service conception (FSC) response to cumulative precipitation occurring from Angus heifer's (n = 3,834) birth to first breeding exposure located in Saratoga, Wyoming (2,150–2,411 m).

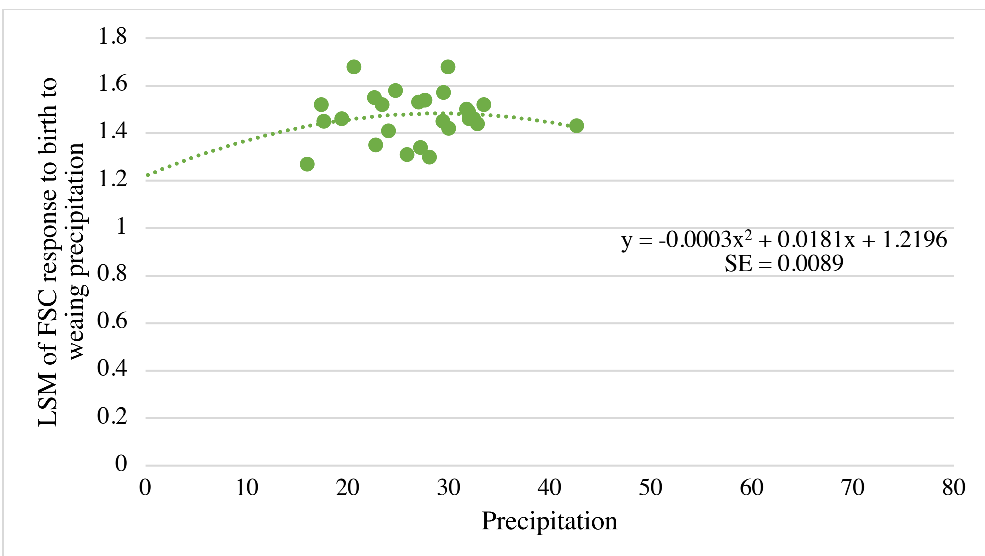

Figure 3.16. Least squared means (LSM) of first service conception (FSC) response to birth to weaning precipitation occurring from Angus heifer's (n = 3,834) birth to weaning located in Saratoga, Wyoming (2,150–2,411 m).

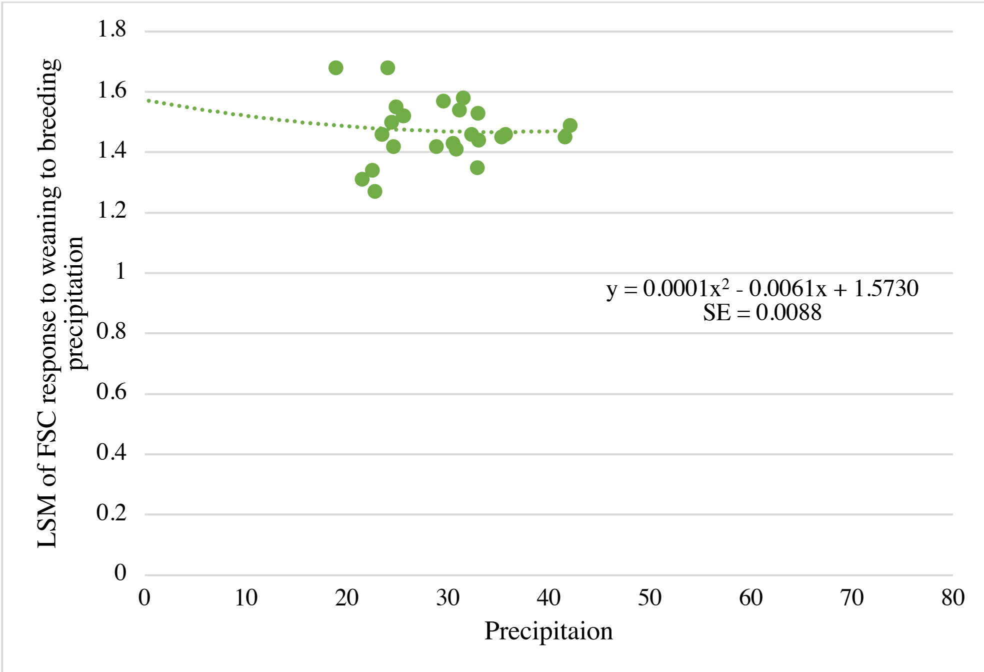

Figure 3.17. Least squared means (LSM) of first service conception (FSC) response to weaning to breeding precipitation occurring from Angus heifer's (n = 3,834) weaning to first breeding exposure located in Saratoga, Wyoming (2,150–2,411 m).

Initial Models Excluding Sire

Results from the logistical regression analysis Type III Sums of Squares were similar across precipitation classifications. Precipitation was found to be a significant predictor for HPG in models 1, 2 and 3 (P<0.01; Table 3.2). The relationships were favorable and positive, suggesting that increased precipitation led to increased overall pregnancy rates (β_i= 0.06 to 0.07; P<0.01; Table 3.2). This could be due to increased nutrition, because of increased grass growth due to abundant precipitation (Cavero et al., 2017). This precipitation would be advantageous for dryland production systems that rely solely on precipitation. However, irrigated pastures would also be impacted by increased precipitation due to irrigation water flowing directly from the Brush Creek system that is supplied by snow melt (Bai et al., 2019). Timing of the precipitation did not matter from a biological standpoint for the heifers. Precipitation was key to development, regardless of the heifer's developmental stage in which the precipitation was received.

Pulmonary arterial pressure was an important predictor of FSC ($P<0.05$) and HPG ($P<0.01$). A favorable and negative relationship was observed, suggesting that heifers with PAP females had higher conception rates relative heifers with higher PAP (β_i=-0.0091 to -0.0168; $P<0.01$; Table 3.2). When animals suffer from elevated PAP, the cause is reduced oxygen due to the hypoxic environment. During a state of hypoxia, tissue will become necrotic (Holt & Callan, 2007). This could potentially negatively impact the uterine environment. If the uterus experiences reduced oxygen levels, it is plausible that the uterine environment would be negatively affected. Due to the fetus being highly sensitive to changes in the uterine environment, embryonic loss may occur if a shift in oxygen supply occurs. The placenta is the facilitator of the exchange of gases and liquids from the dam to the fetus. If the dam is hypoxic, it is plausible that the fetus is not receiving enough oxygen, even in considering that the uterus is a low oxygen environment (Jauniaux et al., 2005). A dam with a high PAP score may have reduced oxygen levels due to reduced lung capacity as a result of pulmonary hypertension in comparison to low PAP individuals not in pulmonary hypertension; therefore, this physical difference may explain pregnancy rate differences between high and low PAP females.

Yearling weight was an important predictor of FSC ($P<0.01$). A favorable and positive relationship was observed suggesting that increased YW led to increased FSC (β_i= 0.00120 to 0.00124; $P<0.01$; Table 3.2). This parallels previous literature that a certain weight must be reached for heifers to be pubertal and conceive at FSC (Shaffer et al., 2011). The significance observed in the analysis involving YW suggested that a greater YW would lead to a higher number of pubertal females that are biologically able to conceive at first service. Yearling weight was not a significant indicator of HPG. A potential reason for this could be because of the increased age of the females at exposure. Heifers were typically 14 months at first service (i.e., 421.46 days ± 20.95 days), and as old as 17 months at last exposure to a natural service bull during the last stages of the breeding season. By 17 months of age, most Angus heifers should be pubertal (Young et al, 1978). Weight has become less of an issue because even smaller framed, later maturing heifers have had a chance to become pubertal and conceive.

Coefficient of determination for the models values were relatively low (0.013 to 0.017; Table 3.2). This result parallels with previous reports in literature. Fertility traits, particularly growth traits responding to fertility, have been reported as 0 (Bergmann and Hohenboken, 1992). This could be due to the numerous factors affecting the trait that were not included into the model, such as AI technician, age at AI, natural service bull exposed, age of dam, and post-weaning gain along with many others (Bergmann and Hohenboken, 1992; Shaffer et al., 2011; Foxworthy, 2019).

Table 3.2. Slope coefficients and R^2 estimates for models assessing effects of precipitation classification, PAP and YW on FSC and HPG of yearling Angus heifers (n = 3,834) raised at altitude (2,150–2,411 m).

Model	Response[1]	Precipitation			PAP	YW	R^2
		Cumulative	Birth to Weaning	Weaning to Breeding			
	FSC	0.01363			-0.00927*	0.00121*	0.01417
Model 1	*HPG*	0.05886*			-0.01681*	-0.00007	0.01712
	FSC		0.01745		-0.00912*	0.00120*	0.01406
Model 2	*HPG*		0.05469*		-0.01636*	-0.00003	0.01457
	FSC			0.01141	-0.00915*	0.00124*	0.01384
Model 3	*HPG*			0.07099*	-0.01656*	0.00012	0.01548

* = significant P-value from ANOVA model.
[1]FSC= first service conception; HPG=overall heifer pregnancy; PAP= pulmonary arterial pressure; YW=yearling weight; R^2=coefficient of determination.

Models Including Sire

Results from the sire model were similar to the initial models. Precipitation was an indicator of HPG ($P<0.05$). Yearling weight was also a source of variation for FSC ($P<0.01$).

Differences were observed for PAP as an predictor of reproductive success. It was still an indicator for HPG (*P*<0.01). However, PAP in the sire model was a tendency to predict FSC for models 1, 2 and 3 (*P*=0.0721; *P*=0.0777; *P*=0.0774; Table 3.3). These results suggested that the sire effect in the model was influencing the significance of PAP on FSC. It is known that there is a genetic effect on both PAP and fertility (Cammack et al., 2009; Speidel et al., 2020). Heritability of PAP score is also greater than fertility traits. Generally, the heritability of PAP score is moderately heritable, ranging from 0.24 to 0.41 (Shirley et al., 2008; Zeng et al., 2016; Speidel, 2020). Comparatively, FSC heritability estimates range from 0.03 to 0.20 and HPG estimates range from 0.04 to 0.27 (Dearborn et al., 1973; Doyle et al., 2000; Cammack et al., 2009; Sanchez-Castro, 2021). Due to this, inclusion of sire in the model would affect the significance of PAP as a predictor of fertility. PAP was not as strong of an indicator for FSC as HPG, suggesting that genetics play a larger role in influencing FSC. Additional environmental effects could be affecting HPG rather than the genetic effect of sire, allowing for PAP to be a stronger indicator trait for HPG.

Slope coefficients were the same as previous models, suggesting that sire does not affect the relationship between fixed effects and response effects (Table 3.3). Coefficients of determination were similar for fixed effects; however, random effects and the overall model saw an increase in coefficient of determination values. This could be due to the increased relationship of sire and response variables.

Table 3.3. Slope coefficients and R^2 estimates for models assessing effects of precipitation classification, PAP and YW with sire as a random effect on FSC and HPG of yearling Angus heifers (n = 3,834) raised at altitude (2,150–2,411 m).

		Precipitation					R^2		
Model	**Response**[1]	**Cumulative**	**Birth to Weaning**	**Weaning to Breeding**	**PAP**	**YW**	**Fixed effects**	**Random effects**	**Full model**
	FSC	0.01762			-0.00833[!]	0.00130*	0.00524	0.02570	0.03094
Model 1	*HPG*	0.06157*			-0.01853*	-0.00010	0.00737	0.02670	0.03407
	FSC		0.02350		-0.00816[!]	0.00128*	0.00513	0.02576	0.03089
Model 2	*HPG*		0.05179*		-0.01806*	-0.00005	0.00491	0.02735	0.03226
	FSC			0.01209	-0.00817[!]	0.00134*	0.00491	0.02508	0.02999
Model 3	*HPG*			0.07418*	-0.01832*	0.00007	0.00563	0.02760	0.03322

* = significant P-value from ANOVA model.
[!] = tendency P-value from ANOVA model.
[1]FSC= first service conception; HPG=overall heifer pregnancy; PAP= pulmonary arterial pressure; YW=yearling weight; R^2=coefficient of determination.

CONCLUSIONS

As stated previously, heifer fertility traits are extremely variable and typically affected by physiological and environmental influences (Thomas et al., 2007; Cammack, 2009). Physiological effects can include body weight, age of puberty and the maturation of the hypothalamic-pituitary-ovarian (HPO) axis (Perry, 2016). However, for beef production systems that are located at or above 1,500 meters, herds also contend with hypoxic conditions due to the low oxygen levels at high elevation. This causes stress on the pulmonary vascular system, known as pulmonary hypertension. As the body progresses through the stages of HAD, the heart is stressed to the point where congestive heart failure can occur. However, PAP score is a known indicator trait for this condition (Holt and Callan, 2007). It was observed in this study that elevated PAP scores in heifers are an important source of variation for HPG and FSC in the initial model (P<0.05). Accounting for genetic variation by including sire effect in the model, led to PAP also being an important source of variation for HPG (P<0.01) and a tended to be an indicator for FSC (P<0.10).

The effect of precipitation on heifer fertility has only been evaluated in limited situations (Thomas et al., 2007; Scasta et al., 2015b;). Drought effects producers across the United States; however, it is of particular concern for producers located in the western US that rely on dry rangelands or snowpack-supplied irrigation to grow forage. Due to this, the effect of precipitation from birth to weaning, weaning to breeding and cumulative precipitation on reproductive success was assessed. It was found that regardless of developmental classification, level of precipitation was an important predictor of HPG. Not only was it indicator for HPG for each precipitation classification, but also for the original model and for the model that included the genetic term of sire (P<0.01).

Finally, YW was included in the model and was found to be important across models for FSC (P<0.01). Overall, these effects proved to be important indicators of fertility, which could potentially serve to assist producers in making management decisions. Producers could use PAP score as a culling criterion when selecting replacements in order to avoid fertility depression caused by elevated PAP scores. In addition, producers can make adjustments to management during years of below average precipitation. This could mean maximizing forage by altering grazing plans, feeding hay later into the spring months if feasible, and in drought conditions, reduced stocking or destocking. Additionally, shifting trends in beef cattle size and climate should be considered when managing beef herds. Beef cattle frame size is increasing, from an average cow size of 475 kg in 1975 to 612 kg in 2009. Increasing cow size could negatively affect rangelands if managers are not aware of how increasing cow size alters stocking rates from historical rates. Rangelands that historically supported 100 head of small framed cows (450 kg) can only support 78 large framed cows (635 kg; Scasta et al., 2019). Overgrazing caused by stocking rates that do not account for increase in cow size could compound drought stress further, negatively affecting forage production, thus not meeting nutritional requirements of developing females and subsequently depressing fertility. In addition, research suggests that drought conditions could intensify in the Southern and Central U.S. and combined with lengthened warming periods (Naumann et al., 2018). This will further stress rangelands and the cattle managed on them. These environmental and physiological stressors could potentially compound on the stress of increased PAP score, negatively affecting female performance. Overall, these effects should be taken into consideration when managing heifer fertility

IMPLICATIONS

Results suggest that precipitation had a positive influence upon overall heifer reproductive performance at the CSU-BIC, regardless of when the precipitation is received. In addition, low PAP score is advantageous to HPG, and has a tendency to influence FSC. These results could be utilized by producers to not only select for low PAP replacement females at altitude, but also bring awareness to the need to alter management strategies to match current climate effects to assist heifers in adapting to the climate. By managing more intensively in low precipitation years through forage supplementation and altering stocking rates, producers could potentially combat negative effects of reduced precipitation in order to prevent a decline in fertility rates of first calf heifers.

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