RELATIONSHIPS AMONG HEIFER TRAITS, EARLY-LIFE PRODUCTIVE TRAITS, AND LIFETIME PRODUCTIVITY WITHIN ANGUS AND SIMMENTAL FEMALE CATTLE

by

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(ABSTRACT)

Data from 946 Angus and 351 Simmental females were used to quantify relationships between calfhood and early-life traits of females with fertility in the first two breeding seasons, and with calf production in the first, in three and in eleven years of life. These traits were used to develop prediction equations for fertility using logistic regression methodology. For productive performance, three methodologies were compared: least squares, ridge regression and principal components regression.

For heifers of both breeds, fertility was associated with birth date, weaning weight ratio and weaning-yearling relative growth rate (RGR). The only calfhood trait that consistently affected fertility in the second breeding season was birth weight of the cow. Fertility of first parity Simmentals was also associated with birth-yearling RGR. First calving season traits explained a higher proportion of variation in second breeding season fertility than calfhood traits of the cow. Among these traits, calving date, calving ease score and sex of the calf were the most important. The combination of birth date and weaning-yearling RGR produced the best models to predict heifer fertility for both breeds. Fertility in the second breeding season was best predicted for Angus cows when calving date, calving ease score and sex of the calf were used as regressors. For Simmental cows, fertility in the second breeding season was best predicted from birth weight of the calf and calving ease score.

The regression of weaning weight of the first calf on pre-selected calfhood traits was used to evaluate models produced by least squares, ridge regression and principal components regression. Although biased, the regression coefficient estimates produced by ridge and principal components regression had smaller variances than estimates obtained from least squares. Between the two alternatives to least squares, ridge regression produced better results than principal components regression. Ridge and least squares regression were quite similar in their regression coefficient estimates, in prediction sum of squares (PRESS)-like statistics and, to a lesser extent, in conceptual predictive criteria (C_p)-like statistics. For prediction, the performance of models produced by least squares and by ridge regression were very similar.

For analyses of the production traits, least squares regression models for all possible combinations of pre-selected regressor variables were fit. Birth date of the female was negatively associated with the weaning weight of the first calf, and with number of calves weaned, total weaning weight of calves produced and average weaning weight of calves in the first three years of productive life. Age of the dam affected early-life production traits of daughters, as well as the average weaning weight of calves produced per year of productive life and calf survival in eleven years. Heavier females at birth tended to produce smaller number of calves and lower calf weaning weight through their lives than females lighter at birth. Overall female productivity was consistently more positively associated with yearling than with weaning growth traits. Among traits observed in the first calving season, calving date, calving ease score, sex and weaning weight of the calf were associated with subsequent production. Weaning weight of the first calf was always positively associated and it was the most important variable to predict female production, except for survival rate. Prediction equations for production in three years included birth date, birth weight of the female, calving ease in the first parturition, sex of the calf and weaning weight of the first calf. This latter variable was the only one useful to predict production in eleven years. Average calf weaning weights in the first three years of production were best predicted using yearling weight ratio or weaning-yearling ADG and first calf weaning weight. Models including age of the female's dam best predicted weaning weight of calves per year of productive life in eleven years and calf survival.

Dedication

To my wife, Eliana and our baby.

With love.

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Introduction

Traditionally, the emphasis on increasing beef production efficiency by purebred breeders has been through the selection of bulls. For most breeds, this has been possible through national sire evaluation, which has allowed a widespread use of sire EPDs for many economically important traits.

However, Dickerson (1978) presented an analysis showing that almost 60 % of the total life cycle energy intake (input) relative to edible meat production (output) must be allocated to the beef breeding female. Most of this input represents a very sizable "up front" investment by the producer. In the United States, beef heifers usually produce their first calves at two years of age, and beef cows are culled from their herds at an average age of five to six years, mostly for health, reproductive problems or low weaning weight of their calves. Therefore, a producer has supported them for 40 to 50 % of their life by the time they have weaned their first calf (Staigmiller et al., 1990).

In order to protect this cow herd investment, one of the most important decisions that the cow-calf producer is faced with is how to select replacement heifers to enhance production. This production is a function of reproduction, maternal attributes and growth rate of the calves the females produce. Unfortunately, selection of females to enhance production traits is not straightforward. These traits require repeated observations of a cow's production during her lifespan. Therefore, by the time her lifetime production traits are fully expressed it would be too late for the selection to take place because she would already be dead or culled.

In the American beef industry, the first time replacement heifers generally face selection is at weaning. A second round of selection often is made before the first breeding season. At both ages, females are selected based upon phenotypic merit for different developmental traits - some function of weaning and(or) yearling weights and(or) conformation score. The efficacy of the use of heifer EPDs is limited because, by the time selection should be made, their estimates are not available or they have low accuracies. In addition, from a management standpoint, the optimal time to select replacement heifers would be before the first breeding season. The non-replacement heifers could then be turned into capital at an earlier date and better feeding and management could be provided the replacement heifers.

Several detailed studies, using different techniques, have evaluated the relationships between calfhood and early-life productive traits observed in the females with their future productive performance as cows. Many of these calfhood traits and some early-life traits have been suggested and have been used as selection criteria predictive of future cow production. Females born earlier in their season may be preferred over those born later (Bourdon and Brinks, 1983). Age at puberty is related to pre and postweaning development (e.g., Nelsen et al. 1982; Smith et al., 1989), and to heifer fertility (e.g., Milagres et al., 1979; Makarechian et al., 1985). Heifers that conceive earlier in their first breeding season calve earlier and wean heavier calves than those that conceive later (Morrow and Brinks, 1968; Short and Bellows, 1971; Lesmeister et al., 1973). Late calving cows tend to rear fewer calves during their lives than those that calve early in the season (Fagerlin, 1968; López de Torre and Brinks, 1990). Furthermore, selection based on female calfhood traits could affect subsequent reproductive performance (Barlow, 1978; Koch et al., 1982; Baker and Morris, 1984; Mackinnon et al., 1990a) and lifetime productivity (Boston et al., 1975a; Brown et al., 1979; Etienne and Martin, 1979; Hays and Brinks, 1980; Stewart and Martin, 1983; Davis et al., 1987).

The objectives of this dissertation were to examine the relationships among several calfhood traits, early-life reproductive and productive traits (first parity) and lifetime productivity (through three and through eleven years of productive life) in Angus and Simmental females. The usefulness of calfhood traits, early-life productive and early-life reproductive traits to develop prediction equations for female fertility in the two first breeding seasons and lifetime cow production and productivity was also investigated. Logistic regression methodology was used to study fertility and three regression methodologies (ordinary least squares, ridge and principal components) were evaluated for prediction of production traits. In addition, repeatability of progeny weaning weights were estimated using least squares and restricted maximum likelihood analysis.

1.0 Chapter 1. Prediction of Fertility in the First Two Breeding Seasons from Calfhood Traits and Traits Observed in the First Calving Season of Angus and Simmental Females

It is well documented that reproduction is the main factor limiting production efficiency of beef cattle (Dickerson, 1970; Dziuk and Bellows, 1983; Koch and Algeo, 1983) and that the largest loss of the potential calf crop occurs because cows fail to become pregnant (Wiltbank et al., 1961; Bellows et al., 1979).

The first important aspect of female reproduction concerns age at puberty and the extent to which age at puberty is related to fertility in the first breeding season and to subsequent cow reproductive performance. Therefore, selection and management of replacement beef heifers should take cognizance of the physiological processes that influence puberty.

It has been shown that age at puberty is related to pre and postweaning development (Wiltbank et al., 1966, 1969; Arije and Wiltbank, 1971; Cundiff et al., 1974; Laster et al., 1972, 1976; Nelsen et al., 1982; Smith et al., 1989, among others). For example, Laster et al. (1972) found that body weights of heifers that conceived by 15 months of age were significantly heavier than those of heifers that failed to conceive. Milagres et al. (1979), Aman et al. (1981), Cunningham et al. (1981) and Makarechian et al. (1985) reported that heifers that were heavier or had higher rates of gain during the postweaning period had higher calving rates at two years of age than lighter or slower-growing females. Maturation rate also seems to be related to age at puberty and fertility in the first breeding season. Etienne and Martin (1979) concluded that selection favoring low postweaning relative growth rate (early maturing heifers) would have strong favorable effects on reproduction. Fleck et al. (1980) and Ferrell (1982) indicated that condition of heifers during the postweaning period influenced first exposure pregnancy rates. Those females that were either thin or fat prior to the breeding season had more difficulty conceiving.

After the first parturition, new factors affecting female fertility come into play. It is known that pregnancy rates tend to be lowest in the second and third breeding seasons and highest in the first and later parturitions. Results suggest that these low fertility rates for the second and third breeding seasons may be related to pre and postpartum nutrition. Energy intake affects female development, and after the first parturition the young cows are still growing and lactating during the breeding season. Nutrient intake may not be sufficient to sustain maintenance, growth, lactation and reproduction (Azzam et al., 1989; Buddenberg et al., 1989; Short et al., 1990). Additionally, postpartum anestrus has been shown to be affected by at least two other factors: suckling (Williams, 1990) and calving difficulty (Price and Wiltbank, 1978a).

The first time beef heifers face selection generally is at weaning. A second round of selection often is conducted before the first breeding season. At both ages, females are selected mostly upon phenotypic merit for different developmental traits; some function of weaning and(or) yearling weights and(or) conformation scores. Culling decisions made on first-parity cows are mostly for reproductive failure.

An understanding of the phenotypic relationships between female reproductive performance and traits that are or can be observed prior to the start of the breeding season may be useful to the cattle breeder in allowing the proper selection emphasis on specific traits and in predicting fertility of individual females. Therefore, the objectives of this chapter were to identify and quantify the relationships between traits observed prior to the first breeding season and female fertility in the first and second breeding seasons and the relationships between traits observed in the first calving season and female fertility in the second breeding season. These traits were to be used as regressors to develop prediction equations for fertility in the first and second breeding seasons of Angus and Simmental females.

1.1 Literature Review

1.1.1 Fertility in the First Breeding Season

Successful reproduction of replacement beef heifers is dependent upon the physiological processes that influence the timing of puberty. Conception rate is lower at puberty than it is after the heifer has shown several estrus cycles. Therefore, heifers need to reach puberty four to six weeks before the start of the breeding season to maximize fertility (Byerley et al., 1987; Staigmiller et al., 1990), and the number of heifers becoming pregnant is correlated with the number exhibiting estrus early in the breeding season (Short and Bellows, 1971). Also, heifers that conceive during the early part of their first breeding season tend to conceive early in later years (Lesmeister et al., 1973). Under these circumstances, age at puberty is likely to be one of the most important production traits, particularly in beef herds in which breeding seasons are restricted. Relationships among nutrition, growth, puberty and pregnancy in different biological types of cattle are of major importance in attempts to increase production efficiency in beef cattle. These and other aspects of puberty have received attention from a number of authors.

Several researchers have shown large differences among cattle breeds or breed crosses in age at puberty of heifers (Reynolds et al., 1963; Short and Bellows, 1971; Brown et al., 1972b; Laster et al., 1972, 1976; Gregory et al., 1978; Dow et al., 1982; Ferrell, 1982; Nelsen et al., 1982; Patterson et al., 1991). In the study of Laster et al. (1972), 14 breed groups varying in growth rate, mature size and lactation potential were represented. Large differences in weight at puberty were found among the breed crosses, but the differences in weight at puberty were similar to the differences in weight at weaning and at the beginning of the breeding period. Also, heifers that reached puberty by 15 months of age were heavier at the beginning of the breeding season than those that failed to reach puberty by 15 months of age. Using the same breeds as in the previous study, Laster et al. (1976), found that Jersey crossbred females were youngest (322 days) at puberty, Limousin and Charolais crosses were oldest (both 398 days) and Hereford-Angus, South Devon and Simmental crosses were intermediate (371, 364 and 372 days, respectively). For weight at puberty, Jersey crosses were lightest (219 kg), followed by Hereford-Angus and South Devon (266 and 274 kg), next were Limousin and Simmental crosses (292 and 286 kg), and Charolais crosses were the heaviest (303 kg). Daily relative growth rate from weaning to 400 days of age was smallest for Jersey crosses (.18%), intermediate for Angus and Herefords (.19%) and highest for the other breed crosses (.20 to .22%). Dam age affected age and weight at puberty, with heifers from younger dams reaching puberty at an older age and at a lighter weight. This factor also had a significant effect on conception rate of Angus and Hereford crossbred heifers. Pregnancy rate was highest in heifers from four and three year old dams, respectively, for the Hereford and Angus breeds.

Ferrell (1982) evaluated the effects of nutrition on several traits of heifers of different breeds. He found that, on average, Angus heifers were older (410 versus 348 days) and lighter (309 versus 328 kg) at puberty than Simmental heifers. Both breeds had similar pregnancy rates during the first breeding season (92.8 versus 92.0%), but Angus calves were lighter at birth (31.9 versus 38.6 kg) and experienced easier deliveries than Simmental calves. Additionally, pregnancy rate in the second breeding season was higher for Angus than for Simmental cows (88.4 versus 79.0%).

Studies concerning the effects of preweaning maternal performance on age at puberty and subsequent reproductive performance can also frequently be found in the literature (Cundiff et al., 1974; Laster et al., 1976; Gregory et al., 1978; Smith et al., 1989; Gregory and Maurer, 1991). For example, in the study by Laster et al. (1976) dam age affected age and weight at puberty of crossbred heifers, with heifers from younger dams reaching puberty at an older age and at lighter weight. Average age at puberty of heifers for different ages of dam were 387, 368, 353 and 357 days and puberty weights were 258, 267, 269 and 276 kg for two, three, four and five year or older dams, respectively. Authors commented that preweaning maternal performance affected subsequent reproductive performance of offspring and that there was an optimum preweaning growth rate to maximize breeding performance of yearlings. Similarly, Smith et al. (1989) found that heifers from two-year old dams were oldest at puberty and first calving and thus calved later in the year as first-calf heifers.

The effect of nutrition on postweaning rate of gain and consequently on age at puberty has also been shown to be important (Wiltbank et al., 1969; Wiltbank, 1970; Arije and Wiltbank, 1971; Short and Bellows, 1971; Smith et al., 1976a; Fleck et al., 1980; Granger et al., 1990). Results of Arije and Wiltbank (1971) and Smith et al. (1976a) suggested that increasing average daily gain or yearling weight would decrease age at puberty. However, Wiltbank et al. (1969), studying the effects of breed and nutrition on age and weight at puberty, found that heifers on the high level of feed were significantly heavier at puberty than heifers on the low level of feed, indicating that some factor other than weight was involved in determining age at puberty in heifers on the high level of feed. The Fleck et al. (1980) study was designed to determine the effects of periodic weight change from birth to 30 months of age on Hereford heifer development, reproduction and performance at parturition. Conclusions were that heifers with high gains during the first winter as weanlings had higher breeding efficiency when bred as yearlings, had larger pelvic areas as two year olds, gave birth to larger calves, had less calving difficulty at first parturition and had higher breeding efficiency at the subsequent breeding. Calf growth to weaning was positively related to the first winter (weaning to yearling) gain of the dam. Heifers with high second winter gain had less calving difficulty at first parturition, slightly higher milk production and slightly higher breeding efficiency when rebred. Second winter gain of the dam had a high negative relationship with calf growth to weaning, but no explanation was given for this conclusion.

More recently, the effects of breed and diet on heifer postweaning growth and development was verified by Granger et al. (1990). They found that age at puberty did not differ between Angus and Brangus heifers (510 versus 499 days, respectively) but was affected by diet. As daily gain increased, age at puberty tended to decrease, although weight at puberty did not differ among diets. They commented that even with calving being delayed until heifers were 2.5 years of age, heifers that lost weight during the immediate postweaning period tended to have lower calving rates.

The way in which increased growth was accomplished in these previous experiments was basically through management (altered weight gain through nutrition). The relationship between growth traits, age at puberty and fertility when growth differences result from genetic differences within a breed rather than from differences in nutrition has been less intensively studied.

Again, much of the work on heifer fertility in the first breeding season is related to the effects of heifer age and body weight on pregnancy rate. Among others, Arije and Wiltbank (1971), Milagres et al. (1979), Aman et al. (1981), Cunningham et al. (1981), Makarechian et al. (1985) and DeRouen and Franke (1989) reported that heifers that were heavier or had higher rates of gain during the postweaning period had higher calving rates at two years of age than the lighter or slower growing females. For example, a two year study of factors affecting age and weight at puberty in Hereford heifers raised under the same nutrition was carried out by Arije and Wiltbank (1971). Sire of the heifer, year and day of birth within year significantly influenced age and weight at puberty. Heifers born later in the calving season were lighter and younger at puberty, and high preweaning growth rate and heavy weaning weights were associated with early age at puberty and heavy weight at puberty. Results indicated that heifers did not reach puberty until they started to make faster weight gains after the slow winter growth.

Similarly, Ellis (1974) reported that Hereford heifers that calved at 24 months were eight days older than heifers that did not calve by that age, and Milagres et al. (1979) concluded that only 52% of Hereford heifers under 12 months of age at the start of the breeding season calved, whereas 72% of those between 13 and 15 months at the start of the same season calved. In that experiment, heifer breeding age had no influence on calving rate for heifers first calving at 30 or 36 months of age.

Selection for milk production and growth may be related to age and weight at puberty. Results presented by Laster et al. (1979) and Ferrell (1982) suggest that breeds that have been selected for high levels of milk production reach puberty at a younger age and at a lighter weight, relative to mature size, than breeds that have been selected primarily for beef production. These authors commented that some of these differences might be related to direct maternal effects expressed through higher rates of preweaning gains by calves of high milk producing breeds.

In a review concerning biological ramifications of selection for preweaning growth in cattle, Barlow (1978) concluded that selection for preweaning growth would decrease age at puberty and that there seemed to be a maximum preweaning growth rate for optimum fertility of yearling heifers within a particular genotype. In another review, Morris (1980b) concluded that among herds or among years within herds, differences in first joining weight were related to first pregnancy rates, particularly when mean weights were low. For heifers treated alike, within herd-year relationships between fertility and weights were not very clear, but it appeared that there might be a threshold specific to each herd at the lower end of the weight distribution. The author commented that more information would be needed at the upper end of the weight distribution also.

One year later, Aman et al. (1981) studied the relationships among age and weight at first conception and growth traits prior to the breeding season. Heifers were born in the fall and were placed with bulls at an average age of 15 months to calve at approximately 26 month of age. The average calving rate was 63.9%; and for those heifers that did calve, weaning, yearling and prebreeding weights were approximately 7, 10 and 12% greater, respectively, than those of heifers that did not calve. The preweaning period was the most important period of growth in determining weight and age at conception. Each increase of .1 kilogram in preweaning daily gain increased weight at conception by 19.3 kg and decreased age at conception by 10.3 days.

More recently, Byerley et al. (1987) designed an experiment to determine if pregnancy rates of crossbred beef heifers bred at puberal estrus differed from those of heifers bred at their third estrus. While pregnancy rates were 57 and 78%, respectively, for heifers bred in the first and third estrus, weight at breeding did not influence pregnancy rates. The probability that a heifer bred at her first estrus became pregnant increased with increasing age (regression coefficient for the logistic model, $b = -.021$), but age was not a significant factor for fertility of heifers bred at their third estrus ($b = -.005$). These results indicated that the higher fertility at the third estrus might be related to maturational changes associated with cycling activity.

Similarly, calving rate and calving date in purebred and crossbred beef heifers exposed to calve first at 24, 30 or 36 months of age were studied by DeRouen and Franke (1989). Regression coefficient estimates revealed that heifers that were older at the start of the breeding season had higher calving rates (.41% per day) at 24 months, but not at 30 or 36 months of age. Weight at the start of the breeding season, adjusted for heifer age, influenced calving rate at 30 (.32% per kg) and 36 months (.23% per kg) but not at 24 months of age. Also, heifers weighing more at the start of the breeding season calved earlier when exposed to calve at 24 months (-.11 days for each kilogram of heifer weight). Results suggested a 37% increase in calving rate for heifers born at the beginning of a 90-day calving season versus heifers born at the end of the season, when first calving was at 24 months of age.

In contrast, Fiss and Wilton (1989), analyzing the effects of breeding system, cow weight and milk yield on several measures of reproductive performance in beef cattle, determined that a 100 kg increase in heifer weight at the beginning of the breeding season increased age at first calving by 11.3 days and days to pregnancy for heifers by 3.8 days. Services per pregnancy for heifers, however, was not significantly affected by weight, indicating that large heifers tended to cycle later, but that this had no effect on probability of conception.

Wolfe et al. (1990) conducted an experiment to determine whether selection for growth traits affected age and weight at puberty. They used three lines of Hereford cattle selected for weaning weight, final weight and final weight plus muscling score, a control Angus line and reciprocal crosses among these lines. Heifers in lines selected for growth traits were 20 days younger at puberty than were heifers in the control line, probably resulting from the combination of direct and maternal genetic effects. The authors concluded that selection for weaning weight, final weight or final weight and muscling score had no detrimental effect on age at puberty in heifers.

Although there is no apparent genetic antagonism between selection for growth and female fertility (Buttram and Willham, 1989; Fiss and Wilton, 1989; Mackinnon et al., 1990a), many criteria to select replacement heifers may result in increased size of the market animal (Fitzhugh and Taylor, 1971). Increased mature size of the cow-herd increases maintenance requirements and may result in detrimental effects on both increased birth weight and frequency of dystocia and, consequently, poorer rebreeding performance (Rice and Wiltbank, 1970; Laster et al., 1973a).

The concern with herd maintenance costs and the increased dystocia observed in cattle of large mature size has led to some interest for altering the shape of the growth curve. There is a general consensus about the positive relationship between mature size and time taken to mature, and this relationship has held true for size defined either as weight or as height (Nelsen et al., 1982). The relationships between mature size and rate of maturing with biological efficiency of production have long been debated (Brody, 1945; Kleiber, 1947), and a negative genetic relationship between mature size and productivity but a positive relationship between rate of maturing and productivity were reported by Humes and Munyakazi (1989). It would be most desirable to increase growth rate of cattle, but with little increase on both birth and mature weights. This seems to be possible, since evidence shows considerable genetic variability in the shape of the growth curve in beef cattle (Taylor and Young, 1966; Blaxter, 1968; Fitzhugh and Taylor, 1971; Brown et al., 1972a, b; Smith et al., 1976a, b; Brown et al., 1988; Jenkins et al., 1991). Smith et al. (1976a, b) suggested that selection for relative growth rate would effectively increase growth rate at market ages relatively more than mature weight, and Smith and Cundiff (1976) concluded that selection for postweaning or postnatal relative growth rates would increase the degree of maturity at 452 days of age, without increasing mature weight. Additionally, these relative growth rates were favorably correlated with daily metabolizable energy intake and metabolizable energy per unit of live weight gain. The authors concluded that selection for either postweaning or postnatal relative growth rates might be more appropriate for maternal stocks than for terminal sire breeds.

The use of proportional growth as a strategy for changing the shape of the growth curve was described by Fitzhugh and Taylor (1971). This generally is known as relative growth rate, which is an expression of the percentage weight gain per day. They estimated the genetic variation, heritabilities and genetic correlations for maturing rate and degree of maturity of Hereford females and concluded that there was as much genetic variation in degree of maturity at birth, six, 12 and 18 months of age as in body weight itself, and that the heritabilities were also similar. High inter-age genetic correlations of degree of maturity showed that animals more mature in body weight at any age tended to be more mature at other ages and that animals heavier than average at maturity tended to be less mature than average at each of the studied ages.

The weight-age curves of Angus and Hereford females were used by Brown et al. (1972a, b) to obtain rate of maturing, weight and weight gains at specific ages during the interval from four months of age to maturity. The genetic correlations between weight gains and mature weights suggested that emphasizing female gains up to 12 months of age would have reduced mature weight in the Hereford females but would have had virtually no effect on mature weight of Angus females. However, the genetic correlations between mature weights and weight gains after 12 months suggested that for both breeds, selection of heifers making large gains would have led to an increase in mature weight of the progeny. Similarly, phenotypic correlations indicated that the fastest gaining animals prior to eight months grew to smaller mature weights and that large gains after eight months were indicative of heavier mature weights. Concerning rate of maturing, the genetic correlation estimates suggested a large positive genetic relationship between gains and rate of maturing in both groups from birth to 16 months of age. The phenotypic correlations within both groups indicated that faster gaining animals to 12 months of age were earlier maturing than their slower growing contemporaries.

The effects of selection for each of seven calfhood traits (classified in four quartiles, from right to left on the normal curve) on later adult performance for conception rate and progeny weaning weight were examined in an unselected Angus population (Etienne and Martin, 1979). Although age at puberty was not assessed, the study of the association between calfhood traits and fertility provided valuable insight into the matter. Heifers from the second and third weaning weight ratio quartiles had higher pregnancy percentages than those from either of the extremes quartiles. The authors commented that the higher fertility observed for the second and third quartiles over the first one could be due to negative effects of fatness on conception. Similarly, selection for postweaning growth rate produced a negative secondary selection differential for fertility, whereas selection for low postweaning relative growth rates would lead to a higher pregnancy percentage. Low growth rate relative to growth already attained would suggest early maturing animals in the postweaning phase. After analyses of relationships of all calfhood traits with cow productivity, they concluded that when selecting heifers, one should favor heavy weaning weight, heavy yearling weight and rapid postweaning gain in order to promote heavy weaning weights of the progeny. However, this approach would lead to reduction in pregnancy rate and percentage of calf crop weaned of these females as cows. The only strong influence on reproduction was low postweaning growth rate, which would mean selecting for early maturity.

The relationships among mature size, maturation rate and lifetime maternal productivity of Angus cows were also investigated by Stewart and Martin (1983). They found that the regression of maternal characters on mature size was quadratic in every instance, with optimal cow size to maximize weight of calf weaned being 18 to 25 kg heavier than the optimal size for those characters associated with fertility (number of calves produced and number of calves weaned). In their experiment the relationships between maturation rate and maternal performance were not statistically significant.

In the work of Marshall et al. (1984) the relationship of lifetime productivity with mature weight and maturation rate in Red Poll cows was investigated. Results showed that mature cow weight was linearly related to a simple measure of productivity (average weight of calves weaned), but quadratically related to the measures that included reproduction. This suggested that selection based on average weight of calves would in the long run increase mature cow weights past the optimum for a measure of productivity that involved reproduction.

1.1.2 Fertility in the Second Breeding Season

The major factor determining the likelihood of a cow becoming pregnant during the breeding season is postpartum anestrus or the interval from parturition to estrus (Wiltbank, 1970). After embryo mortality and postnatal losses are considered, failure of 15 to 20% of the U.S. cow herd to wean a calf annually is due primarily to cows that fail to rebreed within 85 days after calving (Williams, 1990). Furthermore, cows that conceive late in the breeding season produce substantially smaller calves at weaning, and cows that calve late the first time tend to initiate a pattern that eventually will make rebreeding difficult in a subsequent year. After parturition, cows are infertile for a variable period of time. This postpartum infertility may be caused by four factors: general infertility, lack of uterine involution, short estrus cycles and postpartum anestrus (Short et al., 1990).

Among these factors, the first three are considered minor components of postpartum infertility. According to Short et al. (1990), the general infertility component is common to any estrus cycle and reduces potential fertility by 20 to 30%. Uterine involution prevents fertility only during the early postpartum period (< 20 days) and is not related to anestrus. From a practical point of view, uterine involution is not a problem for beef cattle because very few cows would exhibit estrus early enough after calving for uterine involution to interfere with conception (Kiracofe, 1980). Short estrus cycles also prevent fertility in the first 30-40 days after calving, although they may occur later as well. Ovulations following estrus that are destined to start a short cycle are normal and generally accompanied by release of a fertilizable ovum. However, no pregnancy is detected, apparently because the corpus luteum regresses before the ovary receives a signal from the uterus that pregnancy exists (Odde, 1990).

Postpartum anestrus is the major component of postpartum infertility and is affected by several minor factors: season, breed, parity, dystocia, presence of a bull and carryover effects from the previous pregnancy, as well as two major factors: suckling and nutrition. These major factors have direct effects on anestrus but also interact with one or more other factors to control postpartum anestrus (Short et al., 1990).

Season is an important factor associated with postpartum interval. In spring calving herds grazed on pasture, there is a negative relationship between interval to estrus and calving date of individual cows. In the study reported by Warnick (1955), season was included in the analysis as Julian calving date of spring calving cows. For Angus and Hereford cows the author presented regressions coefficients of postpartum estrus on calving date of -.51 and -.64, respectively. Morris et al. (1978), working with single-suckled spring-calving Angus cows in New Zealand, obtained a regression coefficient of first post-partum estrus on calving date of -1.0, meaning that for each day of delay in calving there was a corresponding one day advance until the first estrus occurred. Consequently, for each day later that a cow calved, her calving interval was decreased by .85 days. In these cases, Julian calving date effects could be true season effects associated with light and temperature differences, or the effect could be confounded with nutritional changes during the spring. Subsequent work has confirmed that as the spring calving season progresses, postpartum interval decreases and that cows calving from late spring to early fall have shorter postpartum intervals than cows calving from late fall to early spring (Bellows and Short, 1978; Peters and Riley, 1982a, b; Smeaton et al., 1986). According to Hauser (1984) and Garel et al.(1987), these seasonal effects are not due to nutritional and management differences, but are true seasonal effects related to changes in day length. However, seasonal effects may be modified by other factors such as nutrition and suckling, and they are probably less evident when females are submitted to a short breeding season and good nutritional management (Hauser, 1984; Montgomery et al., 1985).

Concerning breed effects on postpartum interval, Short et al. (1990) pointed out that beef breeds that are milked have shorter postpartum interval than suckled beef breeds, but when dairy cows are suckled, they have longer postpartum interval than beef cows. The same authors commented that it is not known how genotype affects postpartum interval but that effects may be due to true physiological differences among breeds, and(or) they may be due to confounding effects such as differences in amount of milk produced or appetite and feed intake.

The effect of age and parity on postpartum interval is due mostly to the difference between two- and three-year-old or older cows, with young cows having longer postpartum interval and lower reproductive potential. Dystocia also is associated with age and will increase postpartum interval and delay rebreeding (Brinks et al., 1973; Laster et al., 1973a; Bellows and Short, 1978; Doornbos et al., 1984).

Nutritional effects on postpartum anestrus result from the interplay among variables such as quantity and quality of feed intake, nutrient reserves stored in the body and competition for nutrients from physiological functions other than reproduction (Short et al., 1990). According to Short and Adams (1988), the allocation of nutrients to various body functions follows a sequence such that priority is given to functions that maintain the life of the individual and then to propagate the species. The approximate order of allocation of nutrients to various body functions would be as follows: 1) basal metabolism, 2) activity, 3) growth, 4)basic energy reserves, 5) pregnancy, 6) lactation, 7) additional energy reserves, 8) estrous cycle and initiation of pregnancy and 9) excess energy reserves. The energy reserves can constitute almost 50% of an animal's maximum possible weight, and one of the simplest ways to estimate comparative nutrient reserves is the use of body condition scores (Short et al., 1990).

The effect of nutrition on postpartum reproduction depends on whether nutritional differences exist before or after calving. In general, the differences that exist prior to calving, estimated by precalving condition scores, are more important than those that exist after calving. The relationship between precalving condition scores and postpartum interval is not linear. Negative effects are greatest at very low scores, become less as condition score increases, and have very little effect as condition score passes seven (Short et al., 1990).

According to Williams (1990), suckling is by far the most important factor affecting postpartum anestrus. The suppression of cyclic ovarian activity during the postpartum period is characteristic of a variety of species, including suckled beef cows. Additionally, in non-suckled dairy cattle, the effects of milk yield on reproductive performance have been reported by many workers, with a general concordance that cows yielding more milk have lower fertility (Olds et al., 1979; Fonseca et al., 1983; Faust et al., 1988). In a review about suckling and postpartum reproduction in beef cows, Williams (1990) reported that the mean interval from parturition to first ovulation in suckled cows ranged from 50 to 100 days and that the interval to first estrus was from 65 to 104 days.

The important question would be what factors really adversely affect postpartum interval in beef cows: lactation, suckling or the nutritional requirements to support lactation. In an attempt to separate the effects of lactational energy demands, presence of mammary tissue and suckling, Short et al. (1972) compared postpartum intervals of suckled, nonsuckled and nonsuckled mastectomized cows. The suckled cows in their experiment had a postpartum interval to first estrus of 65 days, contrasting with the 25 days and 12 days observed for the nonsuckled and nonsuckled mastectomized cows, respectively. By adjusting nutrient intake to maintain constant body weight among groups, these authors concluded that both suckling and the presence of mammary tissue without suckling can delay postpartum estrus independent of lactational energy demands. However, Beal et al. (1990), in crossbred beef cows, concluded that the partial correlations of postpartum interval with the amount of milk collected by machine milking at an average of 66 days postcalving did not indicate that cows that produced more milk experienced longer postpartum intervals.

In the study of Lubritz et al. (1989) about factors affecting milk production in beef cattle, it could not be determined whether the same physiological system that resulted in heavier birth weights also would cause cows to produce more milk and wean heavier calves or whether heavier calves would create a demand for more milk and the cows would respond to that stimulus. However, the effect of sex of the calf on milk production was not significant in their study, suggesting that the former was a more likely explanation, because male calves were heavier than female calves and yet did not stimulate an increase in milk production.

The neuroendocrine control of anestrus in cattle and its relationship with suckling was recently reviewed by Williams (1990). The author concluded that the postpartum anestrus observed in suckling cows is linked to an attenuation of neuroendocrine signals that subserve gonadal function. During late gestation, high concentrations of placental estrogen inhibit the synthesis of LH, and pituitary stores of LH are depleted at parturition. However, following parturition the restoration of pituitary LH stores occurs relatively quickly in beef cows. In suckled cows, this increase is paralleled by concomitant increases in releasable pools of LH and in the ability of hypothalamic centers to respond to positive feedback effects of estradiol within three to four weeks after calving. Prior evidence had suggested that pulsatile release of LH is a requisite for normal cyclicity in cows (Rahe et al., 1980). However, this requisite pattern of pulsatile LH secretion, which accompanies similar hormonal changes in nonsuckled cows within two to three weeks after calving, occurs in only 30 to 50% of the suckled animals. The period of acyclicity that continues in the remainder of cows is exacerbated by poor body condition and may persist in some females for periods exceeding 100 days. This implies that suckling either interferes with the release of GnRH from the hypothalamus and(or) that the pituitary gland is unable to respond appropriately to GnRH stimulation (Williams, 1990). This author presented a model for suckling-induced inhibition of pulsatile LH release, in which sensory stimulation of the teat by suckling, or other exaggerated stimuli, may evoke reflexes via the spino-cervical tract. The chronic presence of this stimulus would increase the sensitivity of hypothalamic neurons, such as those involving the opioid peptides, to estradiol negative feedback. This in turn would potentiate opioid or adrenergic tone and decrease spontaneous firing of the pulse generator.

It has been shown that effects peculiar to the calf, for example differences in difficulty and duration of labor, preweaning growth rate, nursing frequency, nursing intensity or nursing duration, are related to postpartum interval. Fast growing, larger calves and(or) calves consuming more milk will have dams with longer postpartum intervals (Reynolds et al., 1978; Bellows et al., 1982). The sex of the calf may be considered in this category. Some researchers have shown that first postpartum estrus is delayed when cows give birth to male calves (Warnick, 1955; Morris et al., 1978; Bellows et al., 1982). Morris et al. (1978) found a postpartum interval difference of 3.4 days between cows that gave birth to male calves and those that gave birth to female calves. Results of Bellows et al. (1982) indicated that dams nursing male calves returned to estrus more slowly and had a lower pregnancy rate than did dams nursing female calves. These results may be related to the finding that male calves obtain more milk from the dams than female calves (Reynolds et al., 1978), and are probably related to the higher nutrient demand and(or) suckling stimulus.

Calving difficulty is a major factor in calf losses at or near birth (Wiltbank et al., 1961; Brinks et al., 1973; Laster and Gregory, 1973; Price and Wiltbank, 1978a, b) and contributes to lengthened postpartum anestrus and poorer subsequent reproduction (Brinks et al., 1973; Laster et al., 1973a; Morris, 1980a; Doornbos et al., 1984; Patterson et al., 1991). In addition, during the subsequent years the heifers that had dystocia wean fewer calves which are lighter than their contemporaries (Anderson and Bellows, 1967; Brinks et al., 1973).

Several factors have been associated with calving difficulty. Sire and dam breeds, age of the cow, gestation length, sex, weight and body measurements of the calf, abnormal presentation, pelvic measurements and body condition of the dam and date of calving have been subject of study by a number of authors. Although all these factors are related to dystocia, the literature is not conclusive with respect to the relative importance of each one on calving difficulty. For example, Philipsson (1976) attributed to parity the most important effect influencing calving difficulty. In two year old heifers, dam weight at calving was reported to be the most important factor influencing this trait, and pelvic area appeared to have a threshold effect (Makarechian et al., 1982; Makarechian and Berg, 1983). In contrast, studies by Morrison et al. (1985) and Johnson et al. (1988) indicated that calf birth weight was the most important factor. In the review presented by Price and Wiltbank (1978b), the occurrence of dystocia in heifers was found to be primarily a function of size of the calf and pelvic area of the dam. Also, calving difficulty has been shown to be greater in large-type breeds than in small-type breeds. When codifying calving difficulty of heifers on a increasing scale of difficulty, from one to five, Ferrell (1982) observed calving difficulty averages of 2.1 and 3.5, respectively, for Angus and Simmental females. Additionally, posterior or abnormal presentations of the calf, although being observed in only two to six percent of all calvings, were responsible for 20 to 40% of the dystocia cases recorded by Meijering (1984).

Meijering (1984) presented an extensive review about causes, relations and implications of dystocia in cattle. The most important factors of non-genetic origin listed as having an impact on calving performance were age and parity of the dam, sex of the calf, nutritional status of the dam and season of calving. There was an overwhelming amount of evidence that both dystocia and stillbirth incidence were much higher at first than at second and later calvings. Reported frequencies were three to four times higher for dystocia and two to four times higher for stillbirth in heifers than in older females. By that time, there was general agreement in the literature that the frequency of dystocia for male calves was about twice as high as for female calves. The author commented that sex differences in dystocia frequency might to a large extent be attributable to a difference in size, male calves having larger body dimensions. After correction for differences in birth weight, the difference in dystocia rate between sexes was greatly reduced, but it still was significant in a number of studies. Concerning levels of nutrition during gestation, heifers fed above or below standard levels might either become obese or have insufficient pelvic development, with negative effects on calving performance. A calving season effect on dystocia was limited to North-west European observations, with dystocia rate being more frequent in autumn and early winter than in spring and summer. The review also showed that heritability estimates for dystocia were relatively low and that, since a strong genetic correlation of dystocia with birth weight had been shown, there was little room for selection against dystocia without altering birth weight. More recently, Naazie et al. (1989) studied the relative effect of dam's body and pelvic measurements, calf birth weight, sire birth weight and some relative measure of calf birth weight and dam weight at calving (a ratio, for example) on calving difficulty. The full model explained 32.5% of the variation in calving difficulty score with calf birth weight being the most important variable, accounting for 17.8% of the variation, followed by dam weight at calving (1.3%). Sex of the calf did not influence calving difficulty score except when calf birth weight was excluded from the model.

Laster et al. (1973a) evaluated the influence of sire and dam breed, dam age, calf sex and birth weight on dystocia and the effects of dystocia on subsequent reproductive performance. The incidence of dystocia in two year old cows was 36% higher than in three year old and 45% higher than in four and five year old cows. Simmental sires mated to Angus and Hereford females produced more calving difficulty than Angus and Hereford sires mated to the same dam breeds(32.6 versus 9.9 and 15.8%). The regression coefficient of calving difficulty on calf birth weight showed that for each one kilogram increase in birth weight there was an increase of 2.3% in calving difficulty. Sex of the calf also had a significant effect on the incidence of dystocia, with a higher percentage of calving difficulties in male births (28%) than in female births (17%). However, when birth weight was held constant, only dam age was significantly associated with percent calving difficulty. Finally, 14% fewer cows experiencing dystocia were detected in estrus during the first 45 days of the breeding season, they had a 16% lower conception rate, and were 5.8 days later calving than were cows not experiencing dystocia at calving.

In the same year, Brinks et al. (1973) studied 2,733 parturitions of Hereford calves, scoring calving ease on a scale which ranged from one (the most difficult) to six (unassisted birth). The effects of year, sex of calf, age of dam and day of calf birth on calving difficulty were highly significant. They found that heifers experiencing calving difficulty at two years of age weaned 11% fewer calves of those born the first year and 14% fewer calves per cow exposed the second year, when compared to contemporaries that had no difficulty at the first parity. The calves from three year old cows that had calving difficulty in the first parturition were born an average of 13 days later and were 21 kg lighter at weaning than calves from three years old dams that experienced no difficulty at two years of age. They also commented that, since dystocia was associated with a greater occurrence of death of calves, its undesirable effects on subsequent reproduction were partially offset by the favorable effects of suppressing suckling and lactation on estrous cycle activity.

In Simmental females, the effect of calving difficulty (categorized as requiring no assistance, an easy pull and a hard pull or a cesarean section) on reproductive performance was investigated by Meacham and Notter (1987). When compared with cows that calved without assistance at first calving, cows experiencing easy pulls were 1.7% less likely to calve as three year olds, and those that did calve had longer (4.9 days) calving intervals. Cows with a hard pull were 9.0% less likely to calve as three year old cows and those that did had calving intervals 19.6 days longer.

Patterson et al. (1991) evaluated reproductive traits in crossbred heifers fed different diets during the postweaning period. Results showed that heifers reared on the high plane of nutrition had less dystocia than heifers fed at lower planes of nutrition, and that dystocia affected subsequent reproduction. Regressions indicated that interval to first estrus from parturition increased 3.9 days with an increase of one unit of calving difficulty score (scaled from 1 to 4, according to the amount of traction required to extract the fetus).

Similarly, the effects of duration of labor on postpartum reproduction in beef heifers and cows were investigated by Doornbos et al. (1984). Duration of labor was longer in heifers than in cows (54.1 versus 22.5 hours), and duration of labor for dams giving birth to male calves averaged 8.2 minutes longer than for delivery of females calves. Additionally, more short labor dams exhibited estrus by the beginning of the breeding season than prolonged labor dams (91.4 versus 81.7%), and pregnancy rate of short labor females was higher than pregnancy rate of the prolonged labor group (89.5 versus 76.6%)

In the dairy industry, calving interval has been used as a measure of reproductive efficiency in adult cows. However, in beef operations, a limited breeding season is usually employed, so calving interval may not provide any supplementary information to calving date. Also, calving date is a reproductive trait that is easily recorded and, under limited breeding season management, it is economically important because earlier calving dates are usually associated with heavier weaning weights of the calves (Fagerlin, 1968; Laster et al., 1973b; Lesmeister et al., 1973; DeRouen and Franke, 1989; Marshall et al., 1990).

Although Baker et al. (1985) reported that earlier calving primiparous heifers had longer calving intervals to second breeding than later calving heifers, the use of calving date rather than calving interval as a selection criterion has recently been advised by a number of authors (Bourdon and Brinks, 1983; Bailey et al., 1985; López de Torre and Brinks, 1990). Comparing calving date and the interval between successive calvings as measures of reproductive efficiency in beef cattle, Bourdon and Brinks (1983) suggested that calving date would be more repeatable and heritable, demonstrating the better efficiency of calving date than calving interval in selection and culling decisions. Meacham and Notter (1987) concluded that genetic variation exists for first calving date in Simmental cattle and that it could be used in sire selection as a measure of daughter's reproductive ability. They also suggested that variation in the first calving date might result from genetic differences in age at puberty. Age at the start of the breeding season did not affect first calving date in their study. Other researchers have developed modifications of calving date and calving interval in an attempt to account for the discontinuous pattern of the estrous cycle or to adjust for the time when cows are not exposed to the bull (Bailey et al., 1985; López de Torre and Brinks, 1990).

1.1.3 Statistical Approaches to Analyze Fertility

Most traits of economic importance in cattle breeding present a continuous phenotypic distribution; and linear statistical models, in particular least squares methodology, have usually been used to analyze such traits. In order to produce unbiased regression coefficient estimators with minimum variances using least squares procedures, one must assume that the errors (ε_i) are random variables, normally distributed, with mean zero and constant variance (σ^2). If these assumptions cannot be made, ordinary least squares is unable to produce estimators in the class of the best (minimum variances) of all linear unbiased estimators. This is the case of fertility, which presents a binary distribution of phenotypes. At the end of the breeding season the *i*th female is either pregnant (probability $= P_i$) or not pregnant (probability $= 1\text{-}P_i = Q_i$). Such traits generally are coded numerically for analysis as one for a "success" and zero for a "failure". Traits of this kind are known as threshold traits (Falconer, 1989), and should be analyzed by statistical procedures other than the ones usually used for continuous traits (Gianola, 1982).

The binomial nature of fertility violates two assumptions underlying the least squares methodology (Myers, 1990). First, for n distinct data points there are n probabilities $P_1, P_2, \ldots, P_n$ each of which is a parameter of *a Bernoulli distribution.* Therefore it is clear that ε_i cannot be continuous since only two values are possible; namely, it can be either $\varepsilon_i = 1 - P_i = Q_i$ or $\varepsilon_i = 0 - P_i = - P_i$. As a result, there can be no assumption of normality on the model errors. The second assumption which is violated is the homogeneous variance assumption, because the $Var(\varepsilon_i) = P_iQ_i$. Since P_i varies with the level of regressor variables, the error variance (σ_i^2) is not homogeneous.

Gianola (1980, 1982) warned of problems associated with least squares analyses of binomially scored traits. He commented that although probability estimates are unbiased, they are not guaranteed to be in the range zero to one, and that the best linear predictors may not yield a good approximation of the non-linear predictors in terms of minimum variances when data are binomial. Further, when estimating genetic parameters, the total genetic variances in the observed scale contain increasing amounts of nonadditive genetic variance as heritability increases and the trait prevalence deviates from 50%.

Several studies involving fertility have ignored this point by using linear models to analyze binomial data (e.g. Etienne and Martin, 1979; Solbu, 1982; Taylor et al., 1985; Mackinnon et al., 1990b; Williams et al., 1991). The later authors commented that if the sample size is large, inferences can be made about regression coefficients as if the error term were assumed to be normally distributed. The normal approximation of the binomial distribution could justify that argument. However, heterogeneity of variances still persists. Among the practical disadvantages of using least squares analysis for traits of binomial distribution are the decreased sensitivity of the statistical tests and the non-minimun error variance on the estimators (Philipsson, 1976).

There are different approaches to counteract the analytical problems associated with threshold traits. Falconer (1989) pointed out that although characters of this sort appear at first sight to be outside the quantitative genetics field, when subjected to genetic analysis they are found to be inherited in the same way as continuously varying traits. The assumption of an underlying continuous variable has been applied by some authors in studies designed to estimate genetic parameters (Deese and Koger, 1967; Johnson and Notter, 1987; Mackinnon et al., 1990b). Johnson and Notter (1987) used a linear model to estimate heritabilities from binomial reproductive data that had been derived from a simulated underlying normal distribution of genetic effects governing fertility. They found that heritability estimates on the binomial scale were only slightly lower than those on the underlying scale. It had been previously shown that this downward bias increases as the frequencies of the binomial classes approaches either zero or one (Lush et al., 1948).

Alternatively, a more statistical approach to accommodate heterogeneous error variances by generalized least squares procedures can be made using weighted least squares (Azzam et al., 1989; Buddenberg et al., 1989). In this case each observation (y_i) would be weighted by the reciprocal of its binomial variance ($1/P_iQ_i$). Many commercial computer packages contain a weighted least squares routine, and the user is often free to insert the weight. However, it would be more appropriate to use iterative reweighed least squares procedures where the estimated weights from the previous run are used in the estimation of the parameters in the next iteration (Myers, 1990).

While weighted least squares is not an unreasonable approach to the regression situation with binary response, an approach that produces the same results but that has increased in popularity is to model the mean response against the regressors through logistic functions. This produces the maximum likelihood estimation of the regression coefficients (Byerley et al., 1987; Myers, 1990). This assumption of a binomial distribution for fertility studies with the use of logistic regression has been made by some authors (Byerley et al., 1987; Fiss and Wilton, 1989; Buttram and Willham, 1989). A more complete description of this procedure will be made in the next section.

1.2 Materials and Methods

1.2.1 Materials

1.2.1.1 Population and Management

Data for this study originated from the Angus and Polled Simmental purebred herds owned by Nichols Farms. The property is composed of 1,200 hectares, located in southwest Iowa and divided into several farms and two bull test buildings. The main business of the organization is the sale of bulls and semen through a few exclusive dealers.

The birth, weaning and yearling records of 946 Angus and 351 Simmental heifers were used in the analysis of fertility in the first breeding season. Among the Simmental heifers, 58 were categorized as 75% (62.5 to 87.5%) Simmental and 293 were categorized as purebred (>87.5%) Simmental. Angus females were born from 1975 to 1978, in 1981 and from 1983 to 1987. Simmental females were born in 1981, 1983 and from 1985 to 1988. The distributions of females according to year of birth and weaning disposition are presented in Tables 1 and 2, respectively for the Angus and Simmental breeds. The years 1979, 1980 and 1982 for Angus females and 1982 and 1984 for the Simmental females were excluded from the data set either because yearling weights were not recorded or because they were not recorded until the end of the breeding season.

For the examination of fertility during the female's second breeding season, the birth, weaning, yearling and first calving season reproductive records of 768 Angus and 237 Simmental first parity cows and the birth records of their calves were used (Tables 3 and 4). Simmental cows were either purebred (194 animals) or 75% Simmental (43 animals). The females used in the evaluation of fertility in the second breeding season included only those animals that calved in the first calving season. Simmental females that were born in 1988 were not used and there was a further culling of data of 42 Angus and three Simmental first parity cows. Among those females, 19 Angus and the three Simmentals were culled as two year olds. The remaining Angus females (23 head) were eliminated as three year olds, but their second breeding season reproductive records were not available (Tables 5 and 6). Culling reasons were related to reproductive complications in the first calving season (abortion, death of calf or severe dystocia). Some cows were culled because of failure in suckling the calf, and a few died. This culling process certainly biased upwards the observed fertility in the second breeding season, particularly for the Angus herd.

Most of the females were born during the 60 to 90 day calving period each year, with the peak of births being observed in April (Tables 7 and 8). Within 24 hours after birth, all calves were identified and weighed, and their birth dates were recorded. They were reared by their dams on alfalfa pasture and were creep fed during the entire preweaning period. Calves were weaned and individually weighed in the first week in November each year at a mean age of approximately 205 days. At that time male and female calves were separated. Female calves kept for breeding, and used in this study, were selected mostly at weaning from an initial population of 1,982 Angus and 556 Simmental heifers. Proportions of heifers retained for mating were .478 for Angus (Table 1) and .631 for Simmental (Table 2). Selection criteria were basically the general disposition and age-adjusted weaning weight. Eliminated female calves were fed out for slaughter or were sold. Inspection of the selection sheets and of the means of variables observed for selected and not selected females at weaning showed also a tendency by the farmer to keep older and consequently heavier heifers (Tables 9 and 10). Smaller selection pressure observed for Simmental females was due mainly to the fact that this population was expanding during the period of the study.

Management and feeding of the herd of selected females was typical of Midwest U.S. management procedures. The heifers were fed their first winter on alfalfa hay, oat crop silage and corn silage. Yearling weights of the selected heifers were recorded in May of the year following their birth.

Reproductive management was characterized by a 63-day breeding season starting on June 20th each year. All heifers were exposed to artificial insemination during the initial third of the breeding season, after which they were placed in individual bull groups. Approximately a third of the first parturition cows were exposed to artificial insemination, and then were placed with individual bull groups. The remaining two thirds of first parturition cows were submitted to natural mating only. Very few outside bulls were used, and all the natural service bulls had passed fertility and breeding soundness examinations. Therefore, in this study, bull reproductive performance was not considered as an important factor affecting female fertility, which is an assumption made by most authors when analyzing female fertility (e.g. Bourdon and Brinks, 1982; Ferrell, 1982; Byerley et al., 1987; Mackinnon et al., 1990a). However, Azzam and Nielsen (1987) and Buddenberg et al. (1990) found service sire to be a highly significant source of variation in calving date across parities, and conception rate was found to be related to the semen price in dairy cattle by Taylor et al. (1985).

Although early pregnancy diagnosis was routine in the herd, among years these tests varied in dates and personnel. Consequently results were not always comparable. Therefore, fertility at the end of the breeding season was determined by a recorded abortion or the birth of a calf (alive or dead). Embryonic death and short-term abortions were not recorded and were not considered as conceptions. For computation, fertility was codified as one if a female calved or had a recorded abortion and zero otherwise.

After the breeding season, heifers together with cows were allowed to graze brome grass and, during the winter, they grazed corn stalk aftermath and were fed alfalfa hay. Each year before the start of the calving season, pregnant females were grouped into heifer and cow groups with the former receiving closer attention at calving. Calving ease scores were categorized at first calving as: 1-no difficulty, no assistance; 2-minor difficulty, some assistance; 3-major difficulty, calf puller used. The very few cesarean sections observed (two cases) were included in category three for calving ease score. Four cases of abnormal presentation were observed and removed from the data set, because such an event does not necessarily represent a degree of calving difficulty. After birth the same management and recording procedures used for dams as calves were applied for heifers′ first calves.

1.2.1.2 Variable Descriptions

From birth weights and dates, weaning weights and ages and yearling weights and ages, 16 calfhood traits were defined for each heifer, as follows:

- Birth date

Birth date was the day of birth of the female in her calving season, counted in days starting from the day when the first female calf was born in that season.

- Birth weight

- Actual weaning weight

- Weaning age

- Actual yearling weight

- Yearling age

The information provided by birth date, weaning age and yearling age was basically the same, since weaning and yearling weights were recorded in a short period of time (one to three days) each year. Therefore, in the statistical analysis only birth dates were used as an indicator of age.

- Adjusted weaning weight (205-day weight)

- Adjusted yearling weight (365-day weight)

These two weights were adjusted to the standard age according to the following equations:

$$\frac{(\text{actual weaning weight} - \text{birth weight})}{\text{actual age}} \times 205 + \text{birth weight}$$

$$\frac{(\text{actual yearling weight} - \text{actual weaning weight})}{(\text{number of days between weights})} \times 160 + \text{adjusted weaning weight}$$

- Weaning weight ratio

- Yearling weight ratio

These two weight ratios were relative to the contemporary group average actual weights.

- Preweaning average daily gain (birth-weaning ADG)

- Postweaning average daily gain (weaning-yearling ADG)

- Postnatal average daily gain (birth-yearling ADG)

- Preweaning relative growth rate (birth-weaning RGR)

- Postweaning relative growth rate (weaning-yearling RGR)

- Postnatal relative growth rate (birth-yearling RGR)

Relative growth rate (RGR) was calculated by the method of Fitzhugh and Taylor (1971) and Smith and Cundiff (1976). It was reported as the percentage of change in body weight per day, according to the formula:

$$RGR = \frac{(\log \textit{second weight} - \log \textit{first weight})}{(\textit{second age} - \textit{first age})} \times 100$$

Additionally, age of a heifer's dam at the time of her birth, year of birth and percentage Simmental groups were recorded.

Additional traits pertinent to fertility in the second breeding season were as follows:

- Calving date
- Birth weight of the calf
- Calf birth weight ratio
- Sex of the calf
- Calving ease score

Calving date was recorded similarly to the recording of birth date of the heifer. Calf birth weight ratio was relative to the contemporary group average weight, and calving ease scores were recorded as previously described.

1.2.2 Methods

All statistical analyses were conducted within breed. Descriptive statistics (frequencies, means and standard deviations) were calculated for all variables according to weaning disposition (selected versus not selected) and fertility in the first and second breeding season. Analyses were performed using SAS (1990).

Fertility in the first and in the second breeding season was analyzed using logistic regression methodology. The objectives associated with regression methodology in this study were: the detection of the degree of importance of each variable or group of variables in explaining variation in fertility response, quantification of the amount of change in the probability of conception associated with changes in the regressor variables and the use of these variables to obtain models to predict fertility in the two first breeding seasons.

Fertility was assumed to follow the binomial distribution with the probability of the ith female to be pregnant at the end of the breeding season equalling P_i and the probability of her not being pregnant at the end of the season $Q_i = 1 - P_i$. To accommodate the binomial response assumption to the use of a logistic regression model, which produces the maximum likelihood estimation of the coefficients, the following expression was used:

$$P_i = \frac{1}{1 + \exp^{\text{-Linear Model}}} \qquad (i = 1, 2, \ldots, n)$$

where n is the number of females upon whom fertility records were available and the linear model is of the form $\beta_0 + \sum_{j=1}^{k} \beta_j x_{ij}$, with the intercept ($\beta_0$) and k regression coefficients (β_j) associated with individual or combinations of regressor variables (x_{ij}). For example, when the objective was to explain the proportion of the variation in fertility associated with birth date (or age), the linear model consisted of the intercept and of the birth date as a unique regressor variable. It should be pointed out that the logistic model is not linear itself, although there is a linear model in its exponential part.

In the evaluation of the contribution of individual regressor variables on fertility in the first and second breeding seasons, two models were initially fit for each variable: a model containing the variable's linear effect only and a model containing its linear and quadratic effects. The model with the higher overall level of statistical significance (smallest probability value) was presented. For the study of fertility in the first breeding season, the following continuous regressor variables were evaluated: birth date, age of dam, birth weight, actual weaning and yearling weights, weaning and yearling weight ratios, 205-day weight, 365-day weight, birth-weaning, weaning-yearling and birth-yearling average daily gains, and birth-weaning, weaning-yearling and birth-yearling relative growth rates.

For the study of fertility in the second breeding season the effects of these same heifer traits were examined. Additionally, the continuous effects of calving date and of the calf-related variables birth weight and birth weight ratio were evaluated. The effects of sex of the calf and first parturition calving ease score on fertility in the second breeding season and the effects of year of birth and Simmental percentage on fertility in both breeding seasons were treated as categorical.

Besides the evaluation of the impact of these individual variables on fertility in the first and second breeding seasons, stepwise type procedures were used in order to select the most appropriate models for fertility prediction. Before the stepwise procedures were applied, an initial elimination of variables with redundant effects was made, with the ones presenting the most significant effects being retained. The inclusion of redundant variables in the models would not provide any additional information and would generate unnecessary multicollinearity. Two-way interactions between all main effects were also investigated. A significance level of 5% was used in variable selection.

1.2.2.1 Statistical Tests on the Logistic Models

To test whether the logistic model was an adequate description of the data, to select among several possible logistic models and to make inferences regarding the role of individual or sets of regressor variables in the logistic regression, differences in the likelihood ratio statistics, also called *deviances*, were used. This is a way to measure the quality of the logistic regression fit when comparing the maximum of the likelihood of the model in use with the maximum that would be experienced if one were to produce a perfect fit of the pregnant-not pregnant data, with no use of regressors. In this aspect it is analogous to the difference sum of squares in a linear regression context, where models are compared based upon residual sums of squares. A brief description of this *deviance* statistics can be given as follows: The most complicated model, the one containing the greatest numbers of parameters and producing the largest likelihood would be

$$y_i = P_i + \varepsilon_i \qquad (i = 1, 2, \dots, n)$$

where y_i is the zero or one response observed (pregnant or not pregnant), n is the number of females and P_i is the probability of the ith female to be pregnant. In this case the regressor variables are ignored and the estimation of n parameters, $P_1, P_2, \dots, P_n$, is necessary.

The maximum likelihood function to estimate these n parameters, **P**, would be

$$L(\hat{\mathbf{P}}) = \prod_{i=1}^{n} (P_i)^{y_i}(1 - P_i)^{1 - y_i} \qquad (i = 1, 2, \dots, n)$$

However, a model that makes use of the impact of the regressor variables on fertility is available, as follows

$$L(\hat{\mathrm{B}}) = \frac{\prod_{i=1}^{n_1} (\exp^{\text{-Linear Model}})}{\prod_{i=1}^{n} (1 + \exp^{\text{-Linear Model}})}$$

were n_1 is the number of pregnant females and $\hat{\mathrm{B}}$ is a vector of maximum likelihood regression coefficient estimates.

The *deviance* (λ) statistic is given by

$$\lambda(\mathrm{B}) = -2log\left[\frac{L(\hat{\mathrm{B}})}{L(\hat{\mathbf{P}})}\right]$$

All inferences concerning any regressor or subset of regressors are dependent upon how much the presence of a regressor (or a subset of the k possible regressors) contributes to the reduction in *deviance.*

The first tests made were to verify if the regressor(s) were necessary in the logistic model or if the model containing them was not different from the model containing just the intercept. In other words this test was to determine if the reduction in *deviance* attributable to the regressor(s), $\beta_1x_1, \beta_2x_2, \dots, \beta_lx_l$ was statistically significant.

When testing l parameters ($l \leq k$), the amount of reduction in *deviance* attributable to the model $\beta_1x_1, \beta_2x_2, \dots, \beta_lx_l$ is given by

$$\lambda(\beta_1, \beta_2, \dots, \beta_l \backslash \beta_0) = -2log\left[\frac{L(\hat{\beta}_1x_1, \hat{\beta}_2x_2, \dots, \hat{\beta}_lx_l)}{L(\hat{\mathbf{P}})}\right] - \left\{-2log\left[\frac{L(\hat{\beta}_0)}{L(\hat{\mathbf{P}})}\right]\right\}$$

$$= -2log\left[\frac{L(\hat{\beta}_1x_1, \hat{\beta}_2x_2, \dots, \hat{\beta}_lx_l)}{L(\hat{\beta}_0)}\right]$$

The larger this difference in *deviance*, the larger the variation explained by the regressors. This likelihood ratio statistic, $\lambda(\beta_1, \beta_2, \dots, \beta_l \backslash \beta_0)$, is approximately distributed as a random variable χ^2 with l degrees of freedom, under the null hypothesis on the coefficients. That is

$$H_0{:}\beta_1, \beta_2, \dots, \beta_l = 0$$

$$H_1{:}\beta_1, \beta_2, \dots, \beta_l \neq 0$$

The null hypothesis is rejected if $\lambda(\beta_1, \beta_2, \dots, \beta_l \backslash \beta_0) > \chi^2_{\alpha, l}$.

When testing individual regressor variables, the hypotheses tested were

$$H_0{:}\beta_j = 0$$
$$H_1{:}\beta_j \neq 0$$

with the null hypothesis being rejected if $\lambda(\beta_j \backslash \beta_0) > \chi^2_{\alpha, 1}$.

1.2.2.2 Measures of Performance of the Logistic Models

As was said before, in addition to hypothesis testing to evaluate the role of individual or sets of variables on fertility expression in the two breeding seasons, the logistic regression models were also used to assess the proportion of the χ^2 explained by the models as well as in predicting female fertility in the two breeding seasons.

Again using model *deviances*, an analog to the least squares coefficient of determination was used to assess the proportion of the observed variation in fertility attributable to the models. It is the *deviance* experienced by the model containing the intercept and l regressors given the intercept in relation to the *deviance* produced by a model containing only the intercept, as follows

$$\frac{\lambda(\beta_1, \beta_2, \dots, \beta_l \backslash \beta_0)}{\lambda(\beta_0)}$$

The quality of the logistic regression models in terms of prediction was also assessed using the following statistics: averaged width of the confidence intervals of the responses, averaged absolute residuals and the association between the predicted probabilities and observed responses. The averaged width of the confidence interval of the responses was calculated as follows

$$\frac{\sum_{i=1}^{n} (\mathit{Upper} - \mathit{Lower})_i}{n} \qquad (i = 1, 2, \ldots, n)$$

where n is the number of females and *Upper* and *Lower* are respectively the upper and lower bounds of the 95% probability of the confidence interval on the responses.

The averaged absolute residuals were calculated as follows

$$\frac{\sum_{i=1}^{n} | P_i - \hat{P}_i |}{n} \qquad (i = 1, 2, \ldots, n)$$

The association between predicted probabilities and observed responses considered all possible pairs of observations (y_i, y_j), $i \neq j$, such that the observed responses for the y_i's equal zero (not pregnant), and the observed responses for the y_j's equal one (pregnant). There were $n_i \times n_j$ possible pairs of observations (number of not pregnant x number of pregnant females), and each pair could be in one of three categories:

Concordant if $\hat{P}_i < \hat{P}_j$

Discordant if $\hat{P}_i > \hat{P}_j$, and

Tied if $\hat{P}_i = \hat{P}_j$.

The proportion of each category was calculated in relation to the total possible number of pairs ($n_i \times n_j$).

1.3 Results and Discussion

1.3.1 Fertility in the First Breeding Season

Descriptive statistics with means of all heifer calfhood traits and fertility percentages in the first breeding season according to year of birth and means and standard deviations across years are presented in Tables 11 and 12 for Angus and Simmental females, respectively. Average fertility for Angus heifers was 86%, varying from 77% to 92%, respectively, for heifers born in 1975 and in 1983. For Simmental females average fertility was 83%, varying from 69 (1981) to 92% (1987). These average fertilities are close to the upper limit of the conception rate range observed in the literature for two-year old beef heifers submitted to restricted breeding seasons in the United States, which varies from 50 to 89% (Short and Bellows, 1971; Fleck et al. 1980; Aman et al. 1981; Doornbos et al. 1984; Buttram and Willham, 1989; DeRouen and Franke, 1989; Fiss and Wilton, 1989). This figure may reflect the relatively high level of nutrition for development and female reproduction and the selection for fertility that these herds have experienced. After weaning, Angus and Simmental heifers were fed to average a daily gain of .67 and .69 kg, respectively. Short and Bellows (1971) reported final pregnancy rates of 50 and 86% for Angus-Hereford crossbred heifers fed to gain .23 and .45 kg/day, respectively. Also selection for reproduction has been practiced in the herds, through the culling of not pregnant females and the selection of young males for scrotal size. Despite the controversy about genetic variation for fertility in beef cattle, moderate estimates of heritability have been reported, suggesting that selection for conception rate would be effective (Deese and Koger, 1967; Mackinnon et al., 1990b). Also yearling scrotal circumference is reported to be highly heritable, and it is related to both male and female reproductive efficiency (King et al., 1983; Bourdon and Brinks, 1986).

1.3.1.1 Individual Regressor Regression Models

The means of variables observed at birth and from birth to yearling age according to fertility in the first breeding season and year of birth are presented in Tables 13 and 14 for Angus, and Tables 15 and 16 for Simmental females.

The effect of birth date, age of dam and the effects of each of the 13 calfhood traits (Tables 13 and 14 for Angus and 15 and 16 for Simmental females) on fertility in the first breeding season were assessed by logistic regression. Additionally the effects of year of birth for both breeds and percentage Simmental were investigated. The effect of birth year on fertility in the first breeding season was not significant for Angus females (P=.25), but it was significant for Simmental heifers (P=.04). The statistical significance of the year effect for the Simmental breed was attributable to the significantly lower fertility rate observed in 1981 (69%); there were no significant differences in fertility among the remaining years. The observed variation in fertility attributable to this variable was 1.5 and 3.7%, respectively, for Angus and Simmental females.

Pregnancy rate may differ among years basically as a result of fluctuations in nutrition and management among years, although other factors such as annual variation in the performance of both artificial insemination personnel (estrus detection and insemination skills), and bull reproductive efficiency are likely to be important. Among the authors that included the effect of year in their analysis, DeRouen and Franke (1989) found this effect to be an important source of variation in calving rate of primiparous beef females and Azzam et al. (1989) found the combined effect of pasture group and year to affect first service conception rate in beef cattle.

The two categories of Simmental females in the present study, purebreds and 75% Simmental, did not differ in first breeding season conception rates (81 versus 83%, P=.68). Comparison in female fertility according to Simmental grading was not found in the literature. However, Meacham and Notter (1987) observed no differences between purebreds and 75% Simmental females in first and second calving dates, first calving interval and percentage of cows that returned to calve as three year olds.

The performance of the 15 selected individual regressor models in terms of proportion of the variation in fertility explained, model χ^2 and its associated probability, width of the 95% confidence limits on the responses, average absolute residuals and association between predicted probabilities and observed responses are presented in Tables 17 and 18, respectively, for the Angus and the Simmental breeds. For these same models, the regression coefficient estimates associated with each regressor variable, their standard errors and their tests of significance are presented in Tables 19 and 20, respectively, for Angus and Simmental females. Also shown in these two tables are variables for which the linear versus the linear plus quadratic model was the better representation of the data.

An overview of Tables 17 and 18 suggests that the proportions of the variation explained by the models throughout the study were low. At this point it is necessary to address some comments about the use of the proportion of the variation explained by a model (analogous to the coefficient of determination, R^2, in least squares procedures) as a criterion to measure the quality of fit in regression methodology. The question would be, what is an acceptable value for R^2? There is no unique answer for this question, although researchers in any field feel gratified to see high values for this statistic. However, the magnitude of the proportion of the variation explained by a model depends on a series of factors, such as the scientific phenomenon that has been modeled, the sample size and the number of parameters included in the model. Some scientific fields allow a much better accuracy in modelling than others. Additionally, a one parameter model for a sample size of two observations produces 100% R^2, and, for a given data set, the higher the number of regressor variables included in the model, the higher the R^2 produced. Therefore, when using R^2 as a criterion for comparing different models, the ideal situation would be to have the same data set and the same number of parameters being estimated in each case. For a situation in which the responses are observed on a zero-one scale, as in the case of fertility, it is possible to have a satisfactory model in terms of prediction, presenting 100% predicted probability to observed response concordant pairs, but a model that still explains only a small proportion of the variation observed in the responses.

Values of the proportion of the total variation in fertility explained by a given model were not found in the literature reviewed. However, when analyzing another reproductive trait of categorical expression, calving difficulty, the proportions of the observed variation accounted for by models containing several regressors were found to be rather low, varying from 15 to 24% (Brinks et al., 1973; Price and Wiltbank, 1978b).

Variation in fertility in the first breeding season for the Angus breed was influenced by birth date ($P < .01$), actual weaning weight ($P = .01$), weaning weight ratio ($P = .01$) and weaning-yearling relative growth rate ($P < .01$). For the Simmental breed, variation in fertility was affected by weaning weight ratio ($P = .04$) and weaning-yearling relative growth rate ($P = .04$).

Birth date was by far the most important factor associated with first breeding season fertility of Angus heifers (Table 17). It was highly significant, and it accounted for a higher proportion of variability (4.7%) than any other variable. Its prediction superiority to other variables was evidenced by three criteria: the production of the smallest width of both the confidence interval of the responses (5.9%) and the average absolute residuals (23.5%) and the highest association between predicted probability and observed response (63.7% concordant and 34.8% discordant pairs). The average birth date observed for Angus heifers was 30 days, ranging from 1 to 98 days, associated with predicted fertility probabilities ranging from 94 to 43%. Angus heifers that calved in their first calving season, on average, were 10 days older than the ones that did not calve (Table 13). Although the effect of birth date on fertility was fit linearly, its effect on the predicted probability was not linear due to the non-linear relationship between the dependent variable and the regressors in the logistic model. Therefore, a delay of 10 days (day one to day 10) in the birth of a female corresponded to a decrease of 2% (from 94 to 92%) in her predicted fertility in the first breeding season, while a delay in birth date from day 80 to day 90 was associated with a decrease of 8% in the predicted fertility (from 58 to 50%).

The effect of birth date approached statistical significance (P=.06) as a source of variation in fertility of Simmental females. The relationship between birth date of the Simmental females within the calving season and fertility in the first breeding season was the same as that observed for Angus females. That is, older heifers had a higher probability of being pregnant by the end of the breeding season than younger ones.

The relationships between birth date, puberty and fertility in the first breeding season of beef females have been under investigation by a number of authors (Ellis, 1974; Milagres et al., 1979; Byerley et al., 1987; DeRouen and Franke, 1989). For Angus and, to a certain extent for Simmental heifers, the findings of this study were in agreement with the majority of these authors. Ellis (1974) reported that Hereford heifers calving at 24 months of age were on average eight days older than heifers that did not calve. Milagres et al. (1979) concluded that only 52% of Hereford heifers under 12 months of age at the start of the breeding season calved, whereas 72% of those between 13 and 15 months at the start of the same season calved. More recently, Byerley et al. (1987) found pregnancy rates of 57 and 78%, respectively, for crossbred heifers bred at their first and third estrus. In their study, logistic regression methodology was used to measure the association between age and pregnancy; and a non-linear relationship between age and fertility in the first breeding season was also seen. The probability that a heifer conceived at her first estrus increased with increasing age (regression coefficient = -.021), but age was not a significant factor for fertility of heifers bred at their third estrus. Similarly, DeRouen and Franke (1989) reported that a 37% increase in calving rate would be expected for heifers born at the beginning of a 90-day calving season versus heifers born at the end of the season when first calving was at 24 months of age.

The effects of preweaning development on fertility in the first season were evaluated by using weaning weights, weaning weight ratios, preweaning weight gains and preweaning relative growth rates as regressor variables for fertility. The two weaning weight measurements were actual weaning weight and weaning weight adjusted to 205 days of age. Neither one of these weights was an important source of variation for fertility in the first breeding season of Simmental females. For the Angus breed, the statistical significance of the linear and quadratic effects of actual weaning weight ($P = .01$) and the absence of statistical significance of the effect of 205-day weight ($P = .10$) on heifer fertility suggested that the age component of actual weaning weight accounted, at least in part, for the 1.2% of variation in fertility explained by that variable (Table 17). However, the relationships between age adjusted and actual weaning weights with fertility in the first breeding season were basically the same as evidenced by the similarity of their regression coefficients (Table 19). The maximum predicted probability for fertility in the first breeding season (85.1%) was observed for Angus heifers weighing 245 kg, but with very little difference in predicted fertility for heifers weighing 210 kg or more at weaning.

The effects of weaning weight ratio on fertility in the first breeding season were significant for Angus ($P = .01$) and Simmental ($P = .04$) heifers. The pattern of the relationship between fertility and weaning weight ratio was similar for both breeds, with the probability of females being pregnant at the end of the breeding season increasing with the increase in their weaning weight ratios. For the Angus breed, this pattern was similar to the one observed for actual weaning weight effects on fertility with one difference: the probability of pregnancy plateaued when actual weaning weights were 210 kg or higher. Such a plateau was not evident for weaning weight ratio. The effects of the two other preweaning growth related traits, birth-weaning average daily gain and birth-weaning relative growth rate, did not approach statistical significance. The values observed for width of confidence interval of the response, average absolute residuals and predicted probability to observed response association for models containing preweaning growth-related traits presented little variation among traits and within breeds, but there was a tendency for better performance for models containing weaning weight ratios.

Animals may differ in their preweaning development basically through differences in their genetic potential for growth and because of differences in the milking ability of their dams. In this study, there were no significant effects of age of Angus and Simmental dams on the fertility of their daughters in their first breeding season ($P = .46$ and $P = .39$, respectively for Angus and Simmentals). This is in disagreement with most of the results from the literature. Preweaning maternal performance, related to milk production and reflected by age of the dam, has often been an important factor affecting weight and age at puberty of beef females (Cundiff et al., 1974; Laster et al., 1976; Gregory et al., 1978; Smith et al., 1989), and consequently fertility in the first breeding season (Laster et al., 1976). Usually conclusions were that heifers produced by younger or older dams reached puberty at an older age and a lighter weight and they also had a lower pregnancy percentage than heifers calved by middle aged cows.

Actual weaning weights and consequently weaning weight ratios of the heifers were not adjusted for age of their dams in the present study. The lack of an age of dam effect on fertility therefore led to the conclusion that significant effects of actual weaning weight and(or) weaning weight ratio on fertility would be related either to differences in weaning age and(or) to differences in the genetic potential for growth among heifers. After logistic models were fitted with combinations of regressor variables to obtain prediction equations (to be discussed), the former hypothesis seemed to be more probable since none of the weaning traits were statistically significant in models which included birth date.

Relative growth rate, which is the percentage of weight gain per day relative to the final weight of the individual, was described by Fitzhugh and Taylor (1971). They commented that animals more mature at any age tended to be more mature at other ages as well and that selection for increasing degree of maturity at any age would tend to increase relative growth rate at early ages (< 12 months) and decrease it at later ages. Brown et al. (1972b) concluded that large gains at young ages were associated with early maturing individuals and Etienne and Martin (1979) pointed out that late maturing individuals tended to have higher values of postweaning relative growth rate than early maturing animals. Further, lower postweaning relative growth rate indicated closer proximity to the asymptotic mature size of the individual. The possibility of changing mature size and rate of maturation of beef cattle using relative growth rate measurements was also examined by a number of authors (Smith and Cundiff, 1976; Smith et al., 1976a; Kemp, 1990)

In this study, the linear and quadratic effects of weaning-yearling relative growth rate ($P < .01$) were the second in importance in explaining variation in fertility for Angus (1.6%, Tables 17 and 19). Predicted fertility was maximum (88%) for heifers growing .22% per day from weaning to the yearling age, but it was relatively constant (fertility above 80%) for heifers growing from .15 to .30% per day. Predicted fertility was slightly reduced for heifers growing less than .15% per day, achieving a minimum (72%) for heifers with .10% weaning-yearling relative growth rate. A drastic reduction in first breeding season fertility was observed for Angus heifers growing more than .30% per day, at an approximate average rate of -20% of predicted fertility for each .05% increase in weaning-yearling relative growth rate. The effect associated with this variable also was an important source of variation in first breeding season fertility of Simmental heifers ($P = .04$), accounting for 1.3% of the observed variation (Table 18). However, for that breed, the relationship between weaning-yearling relative growth rate and fertility was essentially linear, with predicted fertility decreasing from 92% for females growing .10% per day to 69% for females growing .35% per day.

In general, high relative growth rates were observed for heifers that were born later in the calving season and that, consequently, were lighter at weaning. However these younger females had relatively higher postweaning gains than the older females such that, at yearling age, the weight differences between younger and older females were reduced. There was a partial association between age and relative growth rate traits, but this dependency was taken into account in later analyses, when birth date and relative growth rates were jointly fit in multiple regressor models. Therefore, in this study, weaning-yearling relative growth rate would be an indicator of the degree of maturity of the heifers at the beginning of the breeding season, with females having lower weaning-yearling relative growth rate being more mature.

The effects of relative growth rate on heifer fertility have not received much attention in the literature. One of the few experiments was conducted by Etienne and Martin (1979), whose results are in agreement with those of this study. They divided an unselected female Angus population in four quartiles according to several calfhood traits, including weaning-yearling relative growth rate. Quartile averages were .27, .28, .30 and .31% weight gain per day. The use of this trait as a retrospective selection criterion affected reproduction of heifers, with low weaning-yearling relative growth rate being associated with higher pregnancy rates.

With the exception of weaning-yearling relative growth rate, the effects of all other postweaning weight traits on fertility in the first breeding season were not significant (Tables 17 and 18). The importance of the effects of postweaning rate of gain on age at puberty and reproductive performance in the first breeding season has been shown to be significant by several authors (Wiltbank et al., 1969; Wiltbank, 1970; Short and Bellows, 1971; Ferrell, 1982; Granger et al., 1990). These studies generally involved comparisons among heifers of different breeds and(or) heifers fed on different diets. Results of experiments associating within breed variation observed in postweaning weight traits with variation in fertility of females submitted to the same nutritional management were not conclusive. For example, Fleck et al. (1980) reported that, although rapid growth from weaning to yearling age was beneficial for good reproduction of young cows through their second breeding as two year olds, growth during the second winter as bred heifers was beneficial but not as important as the first winter growth. Aman et al. (1981) concluded that neither preweaning nor postweaning growth influenced first breeding season conception, but that preweaning growth rate was more important in determining weight and age at conception (large weight gains being associated with heavier and younger heifers at conception). Also, DeRouen and Franke (1989) found that weight at the start of the breeding season, adjusted for heifer age, did not influenced calving rate at 24 months.

1.3.1.2 Multiple Regressor Regression Models

In order to detect the importance of combinations of variables in explaining variation in conception rate, six regression models were fit (Tables 21 and 22). In this case not only the relationships between regressors and conception rate were important, but also the interrelationship among regressors was involved. Year of birth was not included in any of these models, because this variable cannot be used as an information source when attempting to predict future pregnancy rate of heifers. Percentage Simmental was not included for two reasons: First its effect on fertility was not significant and second its exclusion would allow uniformity between models for the two breeds in terms of regressors. Additionally, two way interactions were not included at this point because their number would have been extremely large.

The first model fit was the complete or full model, including all linear and all quadratic effects of variables observed at birth and from birth to yearling age. Therefore, for the 15 variables a total of 30 parameters were estimated. The maximum variation in fertility explained by these variables was 11.5 and 9.2%, respectively, for Angus and Simmental females. Width of the confidence interval of the responses of overparameterized models are usually large and the absolute residuals are usually low. The concordance of association between predicted probability and observed response for Angus and Simmental was, respectively, 71.7 and 69.3%. In general the performance of the models associated with Angus females was better than the performance of the models fitting data from Simmental females. The main reason for that could be the differences in sample size between the two herds, the Angus data being about three-fold that of the Simmental.

In order to verify the impact of birth date on the amount of variation explained by the complete model, the linear and quadratic effects of this variable were removed. For Angus heifers the variation accounted for by the complete model was reduced by more than 60%. In the case of Simmental females, the removal of birth date reduced the variation accounted for by the model by 37%. These results confirm that age of the heifer at the start of the breeding season is an important factor associated with fertility in the first breeding season and that this factor seemed to be more important for Angus than for Simmental females. This might be related to differences between these two breeds in rates at which they reach puberty as well as in mean age and weight at puberty. Weight and age at puberty reported by Ferrell (1982) were 410 days and 309 kg , respectively, for Angus heifers and 348 days and 328 kg for Simmental heifers. Additionally Laster et al (1979) suggested that breeds selected for high milk production reach puberty at a younger age and at a lighter weight, relative to mature weight, than breeds selected solely for beef production. These differences might be related to direct maternal effects expressed through higher rates of preweaning gain by calves of high milk producing breeds (Arije and Wiltbank, 1971).

The next model was fit to evaluate the relationship between developmental traits, represented by all weights, weight ratios, weight gains and relative growth rates and female fertility in the first breeding season. There were 26 variables included in these models, which accounted for 4.2 and 6.5% of the variation observed in fertility for the Angus and Simmental breeds, respectively (Tables 21 and 22). Comparison within each breed of the complete model (30 variables) with the model just described shows that the model containing developmental traits accounted for about 37 and 71% of the maximum variation explained in heifer fertility of the Angus and Simmental herds, respectively. Similarly an evaluation of these models in terms of the association between their predicted probabilities and the observed responses showed that, for the Simmental breed, the model containing developmental traits was closer to the complete model (69.3 versus 65.4% of concordant pairs) than the closeness observed for the Angus breed (71.7 versus 63.4% of concordant pairs). At least one conclusion could be drawn from the comparison between these two models within each breed. That was, when modelling female fertility in the first breeding season, growth related traits seem to be relatively more important for the Simmental than for the Angus breed. This fact has not been documented previously, and whether this tendency is pertinent only to the herds and under the conditions included in this study or if it could be generalized to other herds of the same breeds is not known.

In order to evaluate individual effects of preweaning and postweaning developmental traits on female fertility in the first breeding season, the previous model was segmented into two others: a model containing the effects of weaning weight, weaning weight ratio, preweaning average daily gain and preweaning relative growth rate, and a model containing the effects of yearling weight, yearling weight ratio, postweaning average daily gain and post weaning relative growth rate (Tables 21 and 22, respectively, for Angus and Simmental females). The effect of birth weight of the heifers was omitted because it was not statistically significant and to allow the comparison of preweaning and postweaning models with the same number of regressors. Again results tended to differ between breeds. For Angus females, preweaning and postweaning growth related traits accounted for similar amounts of variation in heifer fertility, 2.5 versus 2.3%, representing 22 and 20% of the total variation explained by the complete model, respectively, for preweaning and postweaning growth models. For Simmental females, the model containing preweaning growth traits accounted for 2.5% (or 27%) of the explained variation in fertility and the model including postweaning growth related traits accounted for 4.4% (or 48%) of the explained variation in first breeding season fertility. The same observations concerning these two models for the two breeds can be made for their performance in terms of the association between predicted probability and observed responses. A model containing only preweaning growth related traits predicted fertility as well as a model containing only postweaning growth related traits for the Angus breed, but the later model would have predicted fertility better than the earlier model for the Simmental breed. It should be pointed out that when models were previously fit using individual regressors, none of the postweaning growth related traits were statistically significant, with the exception of weaning-yearling relative growth rate for both breeds. Again, no reference was found in the literature to support these observations, and it is not known whether or not they could be extended to other Angus and Simmental populations.

In order to select the best model in terms of prediction of fertility in the first breeding season, stepwise procedures were used. A model was fit to each breed, consisting of the linear and quadratic effects of all possible regressor variables and all possible two-way interactions between linear effects. As expected, several variables presenting redundant information to the model were identified. Redundant regressor variables are undesirable in the model because they do not contribute additional information, and they generate collinearity. Therefore, from each group of regressors presenting redundancy (e.g. actual weaning weight, 205-day weight and weaning weight ratio), the variable with the highest significance level (smallest probability value) when fitted alone was retained to represent the group and the others were eliminated.

The best model to predict fertility in the first breeding season of Angus females was described as follows

$$P_i = \frac{1}{1 + \exp^{-(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i})}} + \varepsilon_i \qquad (i = 1, 2, \dots, 946)$$

where P_i is the probability of the ith heifer to be pregnant, and the β estimates, their associated standard errors and statistical significance were as follows

$$\hat{\beta}_0 = -1.09 \pm 1.36$$
$$\hat{\beta}_1 = -.032 \pm .005 \quad (P < .01)$$
$$\hat{\beta}_2 = 33.38 \pm 11.48 \quad (P = .01)$$
$$\hat{\beta}_3 = -66.71 \pm 23.34 \quad (P = .01)$$

and

x_{1i} = birth date of the ith heifer
x_{2i} = weaning-yearling relative growth rate of the ith heifer
x_{3i} = square of weaning-yearling relative growth rate of the ith heifer

This selected model presented a χ^2_3 equal to 44.5 ($P < .01$), explained 5.7% of the observed variation in fertility in the first breeding season (or 50% of the variation observed by the complete model), and produced an average of 8.1% width of the confidence interval of the responses, 23.2% average absolute residuals and 65.3% of concordant predicted probability versus observed response pairs (Table 21).

The predicted probabilities of fertility in the first breeding season for this model, plotted according to weaning-yearling relative growth rates and for five birth dates are graphically presented in Figure 1. The maximum probability of conception for an Angus heifer in her first breeding season (96%) was for females born on the first day of their calving season and having .25% weight gain per day, between weaning and yearling age. The behavior of the two variables involved in this selected model was not different from their behavior when used alone as regressors. Fertility was reduced as birth date of the heifers increased but not in a linear manner. Again, the negative effects of delayed birth on fertility were more evident as birth date of the heifers progressed. Fertility was always higher for females having intermediate values of weaning-yearling relative growth rate (from 15 to 30%). However, the weaning-yearling relative growth rate range over which this higher fertility was observed reduced as birth date increased.

For Simmental females the best model to predict fertility in the first breeding season was as follows:

$$P_i = \frac{1}{1 + \exp^{-(\beta_0 + \beta_1 x_{1i})}} + \varepsilon_i \qquad (i = 1, 2, \dots, 351)$$

where P_i is the probability of conception of the ith heifer, and the β estimates, their associated standard errors and statistical significance were as follows

$$\hat{\beta}_0 = 2.10 \pm .27$$
$$\hat{\beta}_1 = .063 \pm .028 \quad (P = .02)$$

and x_{1i} = birth date x weaning-yearling relative growth rate of the ith heifer.

This model had a χ^2_1 equal to 5.4 (P = .03), explained 1.7% of the observed variation in fertility in the first breeding season (or 18% of the variation observed by the complete model) and produced an average 10.4% width of the confidence interval of the responses, 27.9% average absolute residual and 57.7% of concordant predicted probability versus observed response pairs (Table 22).

For the Simmental model, the predicted probabilities of fertility in the first breeding season as affected by the interaction between birth date and weaning-yearling relative growth rates are graphically presented in Figure 2. The interaction factor in this model allows some conclusions regarding the joint effects of birth date and weaning-yearling relative growth rate. For Simmental females that were born early in their calving seasons, and consequently entered their first breeding season at an advanced age, the probability of conceiving in that season was high, varying very little according to the level of weaning-yearling relative growth attained. As heifers entered their first breeding season at a younger age, the effect of weaning-yearling relative growth rate became more important. Young heifers, but heifers that grew faster in the preweaning period and consequently had lower weaning-yearling relative growth rates, were closer to their asymptote mature weight at the beginning of the breeding season and were more likely to conceive than young heifers that had lower preweaning weight gain, relatively higher postweaning relative growth rates, and were farther from their asymptote mature weight. It should be also pointed out that although the effect of the interaction between birth date and weaning-yearling relative growth rate was significant, the effect of birth date on fertility of Simmental heifers was not significant when fitted as a unique regressor variable.

The maximum probability of a Simmental heifer to conceive in her first breeding season (89%) was predicted for females born on the first day of their calving season and having .10% weight gain per day, between weaning and yearling age. Again, the relationship between weaning-yearling relative growth rate when fit alone and here, when fit interacting with birth date, was not different.

In general, the overall performance of the selected model for Simmental females was inferior to the performance of the selected model for Angus females, no matter what criterion was used to compare them. These differences in performance could be due either to sampling, to differences in sample sizes for the two breeds or even to more systematic unidentified sources of variation for the Simmental herd.

1.3.1.3 Practical Application of the Prediction Models

Two valid questions at this point would refer to the possible implications of the selection applied on heifers prior to the breeding season and the practical usefulness of the logistic models in predicting female fertility in the first breeding season.

The data available to fit fertility in the first breeding season originated from heifers selected mostly at weaning, with heavier and older females being preferred over lighter and younger females. Consequently the ranges of the regressor variables in this study, and particularly the ones associated with weaning weight and calving date, were narrower than the range expected to be observed in unselected female populations. The range of the regressor variable is important because it is associated with the standard errors of the regression coefficients and with the prediction variances. The larger the range of the regressor variables, the smaller the standard error of the regressions coefficients and prediction variances and the better the prediction capabilities of the model (Myers, 1990).

Concerning the practical application of the logistic models in predicting heifer fertility, the producer could use them in two ways. First would be to rank potential replacement females according to their probability of conception, then either keeping the ones presenting the highest predicted fertility or culling the ones presenting the lowest predicted fertility.

Another way to make practical use of the logistic equations in predicting fertility would be to categorize this event as it really happens in nature, that is, a heifer either conceives during her first breeding season or she does not. In Table 23 the distribution of Angus and Simmental females according to their observed fertility in the first breeding season and their fertility predicted by the selected models is presented. In this case a heifer was predicted to be *pregnant* if her predicted fertility was equal or above .50 and *not pregnant* if her predicted fertility was below .50. For the Angus heifers, the overall fertility in the first breeding season was 810 of 946 or 85.6%. This high fertility percentage *per se* makes it difficult for a model to predict better than a random allocation of 85.6%

of heifers to the fertile category. However, when using the selected model, it was possible to obtain 845 of 946 or 89.3% of correct predicted responses, or 3.7% better than making use of no model at all. The importance of a 3.7% increase in the accuracy of identifying animals that would conceive during the breeding season is dependent upon the size of the population in which it is applied and economic characteristics unique to each operation.

For the Simmental herd, once more the poorer performance of the logistic regression model was evident. For this breed, the overall fertility in the first breeding season was 291 of 351 or 82.9%. When making use of the selected model to predict fertility and after categorizing these predictions, there was no increase in the percentage of correct predicted responses. Basically the selected model for the Simmental breed failed to identify any heifers with predicted probability of conception lower than .50. In this case the usefulness of the prediction model would be limited to the ranking of the females.

A possible problem with this approach would be the determination of where to set the threshold for fertility. Defining a threshold at .50 probability might be convenient for categorizing predicted probabilities if the occurrence of the variable in question were not dominated by one of two the categories. However, when the variable expression is dominated by one category, as pregnancy in this study, another threshold might have been more appropriate. Additionally, a given fertility threshold might be conservative for some producers and adequate for others.

1.3.2 Fertility in the Second Breeding Season

For examination of fertility in the second breeding season, the effects of all variables included in the evaluation of fertility in the first breeding season plus the effects of variables observed at calving in first parity cows and in their calves were considered. Arithmetic means of all traits observed on the females as calves (from birth to weaning) and means and standard deviations across years of birth and fertility in the second breeding season are presented in Tables 24 and 25, respectively, for Angus and Simmental females. Similarly, Tables 26 and 27 present arithmetic means of traits observed on females from weaning to yearling age and Tables 28 and 29 present arithmetic means of variables observed on first parity cows and on their calves, respectively, for the Angus and Simmental breeds.

Average fertility in the second breeding season of Angus females was 85%, varying from 76 to 92% for females born in 1984 and 1987, respectively. Second breeding season fertility for Simmental females averaged 78%, varying from 71 (1985 and 1987) to 89% (1981). Conception rates of first parity beef females when bred at approximately two years of age obtained from U.S. literature ranged from 57 to 79%, although few values below 70% were documented (Bellows et al., 1982; Doornbos et al., 1984; Azzam et al., 1989; Buttram and Willham, 1989; Marshall et al., 1990). Average fertility of Angus first parity cows in the present study was above the upper limit of these values, while average fertility of the Simmental first parity cows was close to the upper limit of the values usually observed. Differences among beef breeds in postpartum reproductive performance have been documented (Bellows and Short, 1978; Short et al., 1990). Buttram and Willham (1989) found significant differences in second breeding season conception rates among synthetic lines that differed in mature size. Among other breeds, the small line was composed of 45% Angus and 5% Simmental and the large line was composed of 37% Angus and 35% Simmental. Calving rate for these two lines were 79.4 and 67.3%, respectively. Reasons for differences among breeds in postpartum reproductive performance are not known. These differences may be due to true physiological differences among breeds and(or) they may be due to confounding effects such as differences in the amount of milk produced and the degree of calving difficulty experienced in the previous calving. Simmental females are known to experience higher levels of dystocia (Laster et al., 1973a; Price and Wiltbank, 1978a) and to be better milkers than Angus females (Notter et al. 1978; Gaskins and Anderson, 1980).

Another possible cause of the higher fertility observed for the Angus herd in this study was the more intense additional culling of Angus females after their first calving season. Most of these eliminations were related to reproductive complications of the cows in their first calving season, therefore biasing upwards fertility in the second breeding season of Angus more than fertility of Simmental females.

1.3.2.1 Individual Regressor Regression Models

The same procedures used in the evaluation of the effects of individual variables on fertility in the first breeding season were used for the second breeding season study. The effects of year of birth, percentage Simmental, calving ease score and sex of the calf were tested by fitting these variables as categorical. Calving ease score was considered categorical because a change of one unit in calving ease could affect fertility differently according to level of calving ease to which this change was applied. When studying the effects of dystocia on reproductive performance, several authors have either categorized the data into two groups (dystocia versus not dystocia) or considered degree of dystocia as a continuous variable (Brinks et al., 1973; Laster et al., 1973a; Doornbos et al., 1984; Patterson et al., 1991). All other variables were considered continuous.

The effect of year of birth on fertility in the second breeding season was not significant for Simmental females ($P = .14$) but accounted for 3.0% of the observed variation in fertility. However, the effect of this variable was significant for Angus cows ($P < .01$) and explained 3.4% of the observed variation in fertility. The lower fertility rates of Angus females born in 1977, 1976 and 1986 accounted for the statistical significance of the year effect.

These results were opposite to the results obtained for the importance of year causing variation in the first breeding season fertility of the two breeds. Reasons for these results are not known. However, annual fluctuations in nutrition, climatic conditions and management would be expected to affect fertility of primiparous cows more than fertility of heifers, because nutritional demands for first parturition cows are higher since they are growing and lactating. The importance of yearly variation in pregnancy rate of primiparous cows has been considered in a number of studies (Lesmeister et al., 1973; Etienne and Martin, 1979; Buddenberg et al., 1989; Buttram and Willham, 1989; Marshall et al., 1990).

The two categories of Simmental females represented in this study, purebreds and 75% Simmental, did not differ significantly in their pregnancy in the second breeding season. Average pregnancy rates for these two groups were, respectively, 77 and 84% (P = .36). The same comments made for fertility in the first breeding season are valid here, but it should be pointed out that the magnitude of the difference between the two groups was larger for pregnancy rate in the second breeding season, and that, although not statistically significant, observed fertility was higher for the group (75% Simmental) that would benefit most from heterosis residual in the upgrading program from which the females were produced.

The performances of the 15 logistic regression models having as regressors either the linear or the linear and quadratic effects of traits observed at birth and from birth to yearling age on fertility in the second breeding season are presented in Tables 30 and 31, respectively, for the Angus and the Simmental breeds. In the same tables, performance of the models is shown. For the models involving heifer traits observed at birth and from birth to yearling age, the regression coefficient estimates, their standard errors and their statistical tests of significance are presented in Tables 32 and 33, respectively, for Angus and Simmental females. Regression coefficients, standard errors and tests of significance for the effects of calving date, birth weight of the calf and calf birth weight ratio, and the effects of calving ease score (expressed relative to calving ease = 3) and sex of the calf (expressed relative to female calves) are shown in Tables 34 and 35 for the Angus and the Simmental breeds, respectively.

An overview of the relative importance of traits observed in females as calves and heifers on their reproductive performance in the the two breeding seasons (Tables 17 and 30 for Angus and 18 and 31 for Simmental) shows a general tendency for the reduction of importance of these traits to describe variation in fertility from the first to the second breeding season. This would be expected, but some exceptions to this general tendency were also observed and were consistent between breeds. There was an increase in the relative importance of age of the dam, birth and yearling weight of the heifer and birth-yearling relative growth rate of the heifer in explaining variation in fertility in the second breeding season.

Despite the fact that the effect of birth date on fertility in the second breeding season was not significant for either Angus ($P = .07$) or Simmental females ($P = .64$), there was a positive association between age at the start of the second breeding season and fertility for the Angus breed. This same positive association was evident when evaluating the effect of birth date on fertility in the first breeding season. At least in part, the relationship between birth date and fertility in the second breeding season was related to the association between birth date, and consequently age at the start of the first breeding season, with calving date of the heifer's first offspring. Pearson correlation coefficients between birth date of the heifer and calving date were .15 ($P < .01$) and .07 ($P = .25$), respectively, for Angus and Simmental females. Several studies have shown a reproductive advantage of heifers that bred early and, as a result, calved early their first year (Short and Bellows, 1971; Lesmeister et al., 1973). The relationship between calving date and reproductive performance in the first two breeding seasons for both breeds led to the conclusion that the age factor was more important in Angus than in Simmental females.

Although the effect of age of dam did not significantly contribute to variation in fertility in the second breeding season ($P = .07$ for Angus and $P = .17$ for Simmental females), the relative importance of this variable was unexpectedly higher for fertility in the second breeding season than for fertility in the first breeding season (Tables 32 and 33 versus Tables 18 and 19, respectively, for the Angus and Simmental breeds). Dam age effects on age at puberty and on the reproductive performance of heifers are well documented, females produced by middle aged dams being heavier and younger at puberty, and achieving higher pregnancy rates than females produced by younger or older dams (Cundiff et al., 1974; Laster et al., 1976; Gregory et al., 1978; Smith et al., 1989). Examination of the estimated regression coefficient for this variable in Angus females (Table 32) revealed that the probability of conception of first parity cows increased with the aging of their dams. This observation has not been documented in the literature, and reasons why the magnitude of the age of dam effect on fertility increased from the first to the second breeding season and why this was more evident for Angus than for Simmental females are not known.

The effect of female's own birth weight on fertility in the second breeding season was significant ($P = .02$) for both breeds and, among the calfhood traits, it accounted for the highest proportion of variation in fertility, .9 and 2.1%, respectively, for Angus and Simmental cows (Tables 30 and 31). The relationship between birth weight of the female and her productive performance in the second breeding season was negative for both breeds and stronger for Simmental than for Angus cows (Tables 32 and 33). Also, this relationship was more nearly linear for the Angus than for the Simmental breed. There was a decrease in predicted fertility in the second breeding season from 3 to 7% for Angus and from 4 to 9% for Simmental females, for a five kilogram increase in birth weight, respectively, from 25 to 30 and from 40 to 45 kg. It is possible that negative effects of a heifer's birth weight on her reproductive performance in the second breeding season were mediated through either birth weight of her progeny and(or) the occurrence of dystocia. These possibilities were tested later when logistic models were fit for multiple regressors. The effect of birth weight of the heifer in those analyses did not retain statistical significance when fit together with birth weight and calving ease score in her first calving season. Pearson correlations between birth weight of females and birth weight of their first calves were .16 ($P < .01$) and .09 ($P = .17$), respectively, for Angus and Simmental females. It has been shown that there is a positive association of birth weight of calves and calving difficulty and that both phenomena affect subsequent fertility (Brinks et al., 1973; Price and Wiltbank, 1978a, b; Meijering, 1984; Naazie et al., 1989). Estimated heritability values for birth weight in beef cattle have been high (e.g. .46, Cundiff et al., 1986), and birth weight of a bull could be useful in selecting calving ease bulls for natural service of heifers (Meijering, 1984). The relationships between dam birth weight, calf birth weight and calving difficulty have not been intensively studied. According to Naazie et al. (1989), the correlation between dam birth weight and calf birth weight was .06 ($P > .05$) and the correlation between dam birth weight and calving difficulty was .09 ($P < .05$).

Besides birth weight of the female, the only calfhood trait significantly affecting fertility in the second breeding season was birth-weaning relative growth rate for Simmental females ($P = .04$, Table 31). In this case animals with higher rates of daily growth from birth to yearling age relative to their yearling weight had higher predicted fertility than animals with lower relative growth rates (Table 33). Higher relative growth rates would be observed if the females were relatively lighter at birth and relatively heavier at yearling age. In this study significant proportions of variation in fertility were not attributable to variation in yearling weights but significant variation in fertility was associated with variation in birth weight of the females. Therefore the effect of birth-weaning relative growth rate could be associated with birth weight of the females. Winder et al. (1990) commented that measures of relative growth rate were negatively correlated with the beginning weight of the evaluation period, and Smith and Cundiff (1976) reported the genetic correlation between birth weight and birth-yearling relative growth rate to be -.61.

The magnitude of the effects of variables observed in the first calving season on fertility in the second breeding season was much greater than variation associated with calfhood traits. For example, the average χ^2 proportion explained by models with single calfhood variables was .2 and .6%, respectively, for Angus and Simmental females. For traits observed in the first calving season, the average χ^2 proportions were 2.2 and 1.7% for the Angus and the Simmental breeds, respectively. Additionally, three of the five variables observed in the first calving season were statistically significant sources of variation in fertility in the second breeding season for both breeds.

Calving date was the most important individual variable causing variation in fertility of first parity Angus cows ($P < .01$). Variation in this variable accounted for 5.4% of the observed variation in fertility, and concordance was observed in 66.4% of the predicted probability-observed response pairs (Table 30). There was a continuous decline in fertility with increasing birth date, a 1 and 6%

decline for each 10 days delayed calving, respectively, for the first and the last 10 days of the season (Table 34). In contrast, for the Simmental breed, there was no significant variation in fertility associated with calving date (P = .51), although the relationship between fertility and calving date was also negative (Table 35). The direct relationship between calving date and fertility in the following season has not been reported in the literature. However, the use of calving date has been advised by a number of authors as a selection criterion to select beef females, either because earlier calving dates were associated with heavier weaning weights of the calves (Fagerlin, 1968; Laster et al., 1973b; Lesmeister et al., 1973; DeRouen and Franke, 1989; Marshall et al., 1990) or because earlier calvers tended to follow that pattern throughout their lifetime (Bourdon and Brinks, 1983; Bailey et al., 1985; López de Torre and Brinks, 1990; Staigmiller et al. 1990).

The effects of birth weight of the calf and calf birth weight ratio were not statistically significant sources of variation in fertility for the Angus breed (P = .43 and P = .30, respectively; Table 30), but these variables were important sources of variation on fertility of Simmental females(P = .02 and P = .05, respectively; Table 31). For the Simmental breed, the relationships between fertility and both calf related traits were similar, a decrease in fertility in the second breeding season with increased birth weight of calves (Table 35). Again, the relationship between fertility and the regressor variable was not linear. For example, an increase of in calf birth weight from 25 to 30 kg reduced predicted fertility by 4%, while an increase from 50 to 55 kg decreased predicted fertility by 11%. Similarly, an increase of 15% in calf birth weight ratio from 65 to 80% was associated with a decrease in predicted fertility of 4%, while an increase in calf birth weight ratio from 125 to 140% led to a reduction of 10% in fertility. The effect of birth weight of the calf extending the postpartum interval to first estrus and reducing fertility for Simmental females might have occurred due to a higher proportion of dystocia with heavier calves, to a higher amount of milk consumed by larger calves, to a possible longer gestation length associated with heavier calves or to a combination of these factors. Birth weight of the calf is highly related to calving difficulty both in heifers and in cows (Meijering, 1984). Larger and faster-growing calves consume more milk and their dams have a longer postpartum interval (Bellows et al., 1982; Short et al., 1990). Also shorter gestation periods are associated with easier calvings (Meijering, 1984; Short et al., 1990). In the present study, average birth weights were 32.9±4.0 kg, and 37.7±4.1 kg, respectively for Angus and Simmental calves, and frequencies of dystocia (calving ease scores of 2 or 3) were 14.8 and 26.2%, respectively, for Angus and Simmental females. However, when fitting Simmental fertility models containing the effects of birth weight of the calf together with calving ease score, there was no reduction in the importance of either regressor as a source of variation in the dependent variable. Therefore, birth weight of the calf of Simmental females seemed to affect their fertility in the second breeding not only through dystocia, but also through other factors, possibly involving milk consumption and suckling.

The categorical effect of calving ease score in the first parity on fertility in the second breeding season of females of both breeds was highly significant ($P < .01$ and $P = .01$, and Tables 30 and 31, respectively, for Angus and Simmental females). Predicted fertilities for first-parity cows experiencing calving ease scores of one, two and three were 88, 75 and 67% for Angus and 83, 71 and 50% for Simmental females. Therefore, Angus cows experiencing dystocia were 13 (score two) or 21% (score three) less likely to calve and Simmental cows were 12 (score two) or 33% (score three) less likely to calve as three years old than were cows not experiencing dystocia. The detrimental effects of a difficult parturition on fertility were higher when calving ease scores went from two to three than when they went from the one to two score category. Also, the impact of calving ease score two on fertility seemed to be similar for both breeds, but the reduction in fertility of Simmental cows experiencing score three in the first parturition seemed to be greater than the reduction in fertility suffered by Angus cows. Calving difficulty has been considered a major factor in poor subsequent reproduction of cows (Brinks et al., 1973; Laster and Gregory, 1973; Price and Wiltbank, 1978a, b). In Simmental females, Meacham and Notter (1987) observed that cows experiencing easy pulls were 1.7% less likely to calve as three year olds and cows experiencing hard pulls were 9.0% less likely to calve as three year old cows. Similarly, Patterson et al. (1991) reported that interval from parturition to first estrus increased 3.9 days with an increase of one unit of calving difficulty score (scaled from one to four, according to the amount of traction required to extract the calf).

Predicted fertility in the second breeding season for Angus cows nursing female calves was 6% higher than fertility of cows nursing male calves (89 versus 83%, $P = .01$). For the Simmental breed fertility also was higher for cows nursing females calves (7%), but the difference in fertility was not statistically significant ($P = .24$). The effect of sex of the calf on fertility might be related to differences in birth weight and(or) differences in calving difficulty between the sexes. In this study, least squares means and standard errors for birth weight of male and female calves were $34.0 \pm .2$ and $32.0 \pm .2$ ($P < .01$), and $38.7 \pm .4$ and $36.5 \pm .4$ ($P < .01$), respectively, for Angus and Simmental calves. Also the occurrence of calving difficulty (scores two and three) was higher for cows producing male calves than for cows producing female calves. Calving was considered difficult in 22 and 7% ($P < .01$, chi-square statistic) of Angus heifers delivering male and female calves, respectively. For Simmental cows delivering male and female calves, calving difficulty was observed in 37 and 15% ($P < .01$) of the parturitions, respectively. These results are in agreement with most reported experiments (Brinks et al., 1973; Laster et al., 1973a; Price and Wiltbank, 1978a, b; Bellows et al., 1982; Meijering, 1984; Short et al., 1990).

The effect of sex of calf on subsequent reproduction might also be manifested independently of birth weight and calving difficulty. It is known that male calves tend to weigh more and gain more rapidly during the preweaning period. According to Reynolds et al. (1978), male calves obtain more milk from their dams than female calves; and the effect of sex of the calf on dam fertility, independent of weight or calving difficulty, was demonstrated by Bellows et al. (1982) and Doornbos et al. (1984). Their results indicated that dams nursing male calves had lower condition scores, returned to estrus more slowly and had lower pregnancy rate than did dams nursing female calves. These experiments involved females of different ages and it would be expected that the sex effect on postpartum reproduction would be greater for heifers than for older females. The importance of sex of the calf on reproduction of Angus dams through milk consumption was suggested from results of later analyses, where the significant effect of sex was maintained even when fit together with calving ease score.

1.3.2.2 Multiple Regressor Regression Models

The importance of combinations of different groups of variables in explaining variation in fertility in the second breeding season was assessed by fitting seven regression models (Tables 36 and 37). The effects of year and percentage Simmental were not included in these models.

The first model was the complete model, including all linear and quadratic effects of the 15 calfhood traits of the females, the linear and the quadratic effects of calving date, calf birth weight and calf birth weight ratio, and the categorical effects of calving ease score and sex of the calf. The maxima of the observed variation in fertility explained by these variables were 13.6 and 25.0%, respectively, for Angus and Simmental females. Average width of the confidence interval of the response was the largest for these models (28.2 and 52.2, respectively, for Angus and Simmental cows) among all single regressor or other multiple regressor models. The opposite were true for average absolute residuals of the Angus (22.0) and Simmental (25.4) complete models, which were the smallest among all models studied. These figures were expected and are related to the number of parameters included in the models. Similarly, concordant associations between predicted probability and observed responses, 75.2% for Angus and 83.5% for Simmental females, were the highest among all models. For fertility in the second breeding season, the Simmental complete model seemed to be better in terms of explaining variability and prediction than the Angus model, although being associated with larger average width of confidence intervals of the response and larger average absolute residuals.

In an attempt to verify the relative importance of female calfhood traits versus variables observed in the first calving season on variation of first parity cow fertility, the model previously described was fit, but with the effects of variables observed during the calving season removed. The variations in fertility accounted for by these models were 45 and 68% of the total variation explained by the complete model, respectively, for Angus and Simmental cows. Therefore, it seemed that including traits observed during the calving season in order to explain fertility was relatively more important for Angus than for Simmental females.

The same conclusion, i.e., the relatively greater importance of traits observed in the calving season for Angus females when modeling fertility in the second breeding season, was obtained from fitting the next models. These models, which included only those variables observed during the calving season, explained 8.1 and 5.9% of the variation in fertility, representing 60 and 24% of the total variation explained by the complete models, respectively, for Angus and Simmental females. Additionally, the predicted probability-observed response performance of the model containing calfhood traits was better for the Simmental breed (78.1 versus 65.3 concordant pairs, Table 37), while this performance criterion was better for the Angus model including traits observed during the calving season (69.9 versus 65.3, Table 36).

The next three models were fit to evaluate the usefulness of a heifer's growth related traits in explaining variation in pregnancy rate in the second breeding season. The first model included the effects of all weights, weight ratios, weight gains and relative growth rates. The second and third models included the effects of these same variables, but when observed from birth to weaning or from weaning to yearling, respectively. The amount of variation in fertility in the first breeding season (Tables 21 and 22) versus the amount of variation in the second breeding season (Tables 36 and 37) accounted for by growth related traits was basically the same for the Angus breed (4.2 versus 4.4%), and twice as high for the Simmental breed (13.1 versus 6.5%). However, when considering the maximum variation explained in the first and in the second breeding seasons (complete models), these numbers represented 37 versus 32% and 71 versus 52%, respectively, for Angus and Simmental females.

For the Angus breed the relative importance of calfhood traits observed from birth to weaning in explaining variation in fertility was twice that of variation explained by traits observed from weaning to yearling age (2.5 versus 1.2%, Table 36), which contrasted with the relative importance of these two phases in explaining variation in first breeding season fertility for this breed (2.5 versus 2.3%). For the Simmental breed, variation in fertility in both breeding seasons was associated more closely with growth traits observed during the preweaning phase than with growth traits observed in the postweaning phase (2.5 versus 4.4%, Table 22 and 5.4 versus 6.3%, Table 37). Therefore, growth related traits observed in the preweaning phase of Angus females seemed to be more important in explaining variation in fertility in the second breeding season than postweaning growth related traits. The opposite was observed for Simmental females, for which growth traits observed in the postweaning phase accounted for more variation in second breeding season fertility than did preweaning growth traits.

In order to select the best model in terms of prediction of fertility in the second breeding season, stepwise procedures were used. The variables 205-day weight, weaning weight ratio, 365-day weight, yearling weight ratio and birth weight ratio of the calf were not included in the the stepwise procedures because they provided the same information as actual weights and were considered redundant in previous analyses. All possible two-way interactions between regressor variables were considered.

The best model to predict fertility in the second breeding season of Angus females was described as follows

$$P_{ijk} = \frac{1}{1 + \exp^{-(\beta_0 + \beta_1 x_{1i} + \gamma_j + \delta_k)}} + \varepsilon_{ijk} \qquad \begin{array}{l} (i = 1, 2, \ldots, 768) \\ (j = 1, 2 \text{ or } 3) \\ (k = \text{male or female}) \end{array}$$

where P_{ijk} is the probability of the *i*th heifer with the *j*th calving ease score and producing a calf of the *k*th sex to be pregnant, and the parameter estimates, their associated standard errors and statistical significance were as follows

$$\hat{\beta}_0 = 2.06 \pm .47$$

$$\hat{\beta}_1 = -.032 \pm .006 \quad (P < .01)$$

$$\hat{\gamma}_1 = 1.20 \pm .45 \quad (P < .01)$$

$$\hat{\gamma}_2 = .39 \pm .50 \quad (P = .43)$$

$$\hat{\gamma}_3 = 0$$

$$\hat{\delta}_{\text{male}} = -.47 \pm .23 \quad (P = .03)$$

$$\hat{\delta}_{\text{female}} = 0$$

and, x_{1i} is the calving date of the *i*th cow.

This model had a χ^2_4 equal to 48.0 (P < .01), explained 7.8% of the observed variation in fertility during the second breeding season (or 57% of the variation observed by the complete model), and produced 9.5% average width of the confidence interval of the response, 23.2% average absolute residuals and 69.0% of concordant predicted probability versus observed response pairs (Table 36).

The plot of predicted probability of conception in the second breeding season for this selected model, according to calving date, sex of the calf and calving ease score in the first breeding season, is presented in Figure 3. Again, the detrimental effects of increasing calving date, increasing calving difficulty and heifers nursing males calves on subsequent reproduction in the Angus breed is evident.

For Simmental females the best model to predict fertility in the first breeding season was as follows

$$P_{ij} = \frac{1}{1 + \exp^{-(\beta_0 + \beta_1 x_{1i} + \gamma_j)}} + \varepsilon_{ij} \qquad \begin{array}{l} (i = 1, 2, \ldots, 237) \\ (j = 1, 2 \text{ or } 3) \end{array}$$

where P_{ij} is the probability of conception of the *i*th heifer having the *j*th calving ease score. The parameter estimates, their associated standard errors and statistical significance were as follows

$$\hat{\beta}_0 = 1.89 \pm 1.88$$

$$\hat{\beta}_1 = -.046 \pm .023 \quad (P = .04)$$

$$\hat{\gamma}_1 = 1.36 \pm .61 \quad (P = .03)$$

$$\hat{\gamma}_2 = .84 \pm .63 \quad (P = .17)$$

$$\hat{\gamma}_3 = 0$$

and, x_{1i} is birth weight of the calf of the ith cow.

This model had a χ^2_3 equal to 10.2 ($P < .01$), explained 4.2% of the observed variation in fertility during the second breeding season (only 19% of the variation explained by the complete model), and produced 8.1% average width of the confidence interval of the responses, 32.2% average absolute residuals and 61.3% of concordant predicted probability versus observed responses pairs (Table 37).

The effects of birth weight of the calf and calving ease score on fertility in the second breeding season of Simmental females are graphically presented in Figure 4. The relationships of the regressors with fertility did not differ from the relationships when individual regressor models were fitted. Fertility in the second breeding season of Simmental females was negatively affected by heavy calves and by dystocia, although there was no statistically significant difference between fertility of cows that had calving ease scores of one and two in the first parturition.

Similarly to what was observed for fertility in the first breeding season, the overall performance of the Simmental selected model was inferior to the performance of the Angus selected model. The logistic regression model for the Simmental breed was unable to assign a predicted fertility below .40.

1.3.2.3 Practical Applications of the Prediction Models

The same comments made in the section about fertility in the first breeding season concerning the implications of the selection made on females prior to the breeding season are valid here. The data available to fit fertility in the second breeding season originated from heifers mostly selected at weaning. Additionally, the culling both of females that did not calve and of females experiencing reproductive complications in the first calving season was made. Again, these procedures probably affected the range of the continuous regressor variables, and they altered the frequencies of categorical variables as well, particularly calving ease scores. The reduction in the range of the regressor variable might have affected the standard errors of regression coefficients and prediction variances (Myers, 1990), and the elimination of females that did not calve and females with severe reproductive disorder might have biased the estimation of the regression coefficients (Kendall and Stuart, 1960).

The ways the selected models could be used to aid culling decisions after the calving season are the same as described for selection of heifers prior to their first breeding season. That is, the producer could either rank first parity cows according to their probability of pregnancy in the second breeding season or he(she) could categorize predicted fertility between pregnant and not pregnant females.

The distributions of Angus and Simmental females according to their observed and predicted pregnancy status are presented in Table 38, using .50 as an arbitrary threshold value to categorize fertility.

The average fertility for Angus first parity cows was 654 of 768 or 85.2%. When making use of the selected model in order to predict and categorize cows prior to the breeding season, it would be possible to identify 668 of 768 or 87.0% of the cows that did conceive. That means an advantage of 1.8% if the producer used the regression equation rather than making use of no model at al. This number might seem rather small, but its importance would increase if applied over large cow herds.

The inferior predicting ability of the Simmental model was once more evidenced when making use of categorized fertility. The average fertility in the second breeding season of Simmental females was 186 of 227 or 78.5%, which would be the same value obtained if the selected model were used. Only three Simmental cows were correctly predicted as not pregnant ($P_i < .50$), three cows were erroneously predicted as not pregnant and 51 were erroneously predicted as pregnant.

1.4 Conclusions

The results of this study indicate that the individual effects of birth date, weaning growth related traits and weaning-yearling relative growth rate are important sources of variation in fertility of Angus and Simmental heifers. Birth date was more important for Angus than for Simmental heifers. This might have been related to the earlier maturing of Simmental females observed by other authors. However, for both breeds younger heifers at the start of the breeding season were less likely to conceive.

Weaning weight ratio of heifers of both breeds and actual weaning weight of Simmental females were positively related to heifer fertility.

Females with higher weaning-yearling relative growth rates were probably further from their asymptotic mature weights, and were less likely to conceive than females with lower weaning-yearling relative growth rate. Conception rates were highest for Angus heifers growing from .15 to .30% per day and increased continuously for Simmental females as weaning-yearling relative growth rate decreased.

Among individual traits observed in cows as calves, the only one that consistently affected fertility in the second breeding season was birth weight. Cows that weighed more at birth were less likely to conceive in their second breeding season. This might have been related to direct effects of birth weight of the cows on the birth weight of their first calves.

For Simmental females, fertility in the second breeding season was also associated with birth-yearling relative growth rate. The likelihood of first parturition Simmental cows to conceive during their second breeding season increased continuously with an increase in their birth-yearling relative growth rate. Results suggested that this effect might have been, at least in part, related to the association between cow and calf birth weight.

In general, traits observed during the first calving season explained a higher proportion of the variation in fertility in the second breeding season than calfhood traits of the cow. Among these traits, calving date and calving ease score were the most important. For Angus females, the effect of calving date seemed to be associated with a heifer's own birth date as a calf. Females born late in their calving seasons tended to calve later when producing their first calves and to have a higher probability to fail to rebreed. Calving ease scores at first parturition were strongly associated with subsequent reproduction.

Sex of the calf affected fertility of Angus first parity cows. Dams nursing males calves were less likely to conceive than dams nursing female calves. This effect seemed to be related not only to the higher incidence of dystocia and higher birth weight observed for male calves, but possibly to their capacity of getting more milk from their dams.

Prediction of heifer fertility based upon regression models including combinations of calfhood traits, and prediction of first parity cow fertility based upon regression models including combinations of traits observed in the first calving season, were shown to be possible and to have practical applications.

When modeling heifer fertility, growth related traits seemed to be relatively more important for Simmental and age at the start of the breeding season, assessed by birth date, seemed to be more important for Angus heifers. The combination of these two variables provided the best models to predict fertility in the first breeding season for both breeds.

Fertility in the second breeding season was best predicted for Angus cows when calving date, calving ease score and sex of the calf were used as regressors. For Simmental cows, fertility in the second breeding season was best predicted when birth weight of the calf and calving ease score were included in the model.

In general, prediction equations were better for Angus than for Simmental females. Whether this superiority was related to sampling, to differences in sample sizes of the two data sets or to some unidentified biological causes is not known.

2.0 Chapter 2. Alternatives to Least Squares in Multiple Linear Regression to Predict Early-Life Production from Calfhood Traits of Angus and Simmental Females

Testing the efficacy of calfhood traits and of early-life reproductive and productive performance of cows to predict their future productivity has been the objective of several experiments, in both beef and dairy cattle. Calfhood traits most frequently used are adjusted weaning and yearling weights, weaning and yearling weight ratios relative to herd average, pre and postweaning daily gain, height and conformation scores (Vesely and Robison, 1972; Boston et al., 1975a; Brown et al., 1979; Etienne and Martin, 1979; Davis et al., 1983a; Kirkpatrick et al., 1985; Davis et al., 1987). Their accuracy as indicators of cow production is dependent upon the degree of genetic and phenotypic relationship between these traits and female reproductive performance, progeny survival and progeny weaning weight.

Different methodologies can be used to evaluate the degree of association between pre-breeding traits and subsequent productive performance of the heifers. Product-moment correlations, principal component analyses, linear discriminant analyses and canonical correlations have been used (Koch and Clark, 1955; Boston et al., 1975a; Brown et al., 1979; Davis et al., 1983b; Davis et al., 1985). These methodologies indicate the degree of association between early-life traits or linear combinations of traits with female production. When attempts have been made to quantify the cause-effect relationships, least squares regression methodology has been the method of choice (Vesely and Robison, 1972; Honnette et al., 1980; Davis et al., 1983a; Stewart and Martin, 1983; Kirkpatrick et al., 1985; Tigges et al., 1986).

Although ordinary least squares regression has commonly been used to predict lifetime productivity from calfhood and early-life production traits, it may not be the most efficient procedure, mainly because of the possibility of serious multicollinearity among the regressor variables (Hocking et al., 1976).

Multicollinearity exists when the regressor variables are not truly independent of one another and may contain redundant information. These sorts of variables are expected to be found when regressing early-production and lifetime productive traits of cows on calfhood traits of heifers, early-life reproductive and early-life productive traits. Many of the potential regressors are correlated among themselves either because they are genetically and(or) environmentally correlated or because they have part-whole relationships.

When multicollinearity is severe, it produces instability and improperly signed regression coefficients, it reduces the power of statistical tests, and it may produce inaccurate prediction equations. Multicollinearity becomes harmful when estimation or hypothesis testing is affected more by the multicollinearity existing among the regressor variables than by relationships existing between the response variable and the regressor variables (Mason et al., 1975). Fortunately alternative estimation procedures designed to combat multicollinearity do exist. They are a deviation from ordinary least squares and belong to the class of biased estimation techniques. Two of the most popular procedures are ridge regression and principal components regression (Hoerl and Kennard, 1970a, b; Hawkins, 1973)

In the present study, ordinary least squares regression, ridge regression and principal components regression were compared to identify the method of choice for the analysis of the relationships among female calfhood traits, early-life production traits and early-life reproductive traits with cow production. The relationships among several calfhood traits observed in Angus and Simmental females with performance in their first year of production (first calf weaning weight) were used in the comparison among the three regression methods.

2.1 Literature Review

2.1.1 Methods of Multiple Linear Regression

2.1.1.1 Ordinary Least Squares

The standard model for multiple linear regression with *n* observations on *p* input variables (the intercept and *k* regressors) is $y = X\beta + \varepsilon$. The X is a *n* x *p* design or incidence matrix of rank *p*, y is a *n* x *1* vector of observations (dependent variables), β is a *p* x *1* vector of unknown constants (the intercept and *k* regression coefficients), and ε is a vector of *n* x *1* random disturbances or model errors associated with the y's. Under this model, the least squares estimates of the unknown β's are the Gauss-Markov-linear functions of the y's. They are unbiased and have minimum variances. Point and interval estimates of linear functions of these coefficients and prediction intervals for future observations have the analogous optimal properties. Although these properties are theoretically satisfying, the fact that an estimator has minimum variance in the class of unbiased estimators does not guarantee that its variance is small (Myer and Willke, 1973). In fact, the results in practice are frequently unacceptable because of the large variances of the estimates of the regression coefficients.

A common cause of this variance inflation is the near-degeneracy of the incidence or design matrix (X), that is, the problem of multicollinearity.

The term multicollinearity, *multi* implying many and *collinear* implying linear dependencies, describes a condition in the regressor variables. It exists when the regressor variables are not truly independent one from another and, rather, contain redundant information. The sources of multicollinearity were reviewed by Mason et al. (1975) and Kleinbaum et al. (1988). The former author divided those sources into three groups: an over-defined model, sampling techniques, and physical constraints on the model or in the population.

An over-defined model is one in which there are more regressor variables than observations. This situation is frequently found in medical research where many pieces of information are taken on each individual in a study. This source of multicollinearity is not frequent in the field of animal science when fixed models are used. However, when mixed models are used, e.g., for breeding value estimation, usually there are more parameters to estimate than observations.

The second source of multicollinearity arises when either knowingly or unknowingly, the experimenter only samples a subsection of the total space of the regressor variables; and this section may be highly dominated by one or more of the relationships. A hypothetical example of this might occur in an industrial situation when one wishes to predict profits from knowledge of variables such as income and labor costs. An analysis of data of this type might reveal a positive linear relationship between income and labor costs because higher labor costs coincided with higher prices which in turn resulted in increased income. Mason et al. (1975) commented that this kind of multicollinearity is not inherent to the model since the data could have been collected during periods when labor costs were increasing yet prices were holding constant or decreasing due to an overabundance of supply of this particular product.

The third source of multicollinearity, physical constraints on the model or in the population, is similar to the previous one, but exists regardless of sampling technique employed. An example would be when using regressor variables that are biologically correlated with one another (such as age, weight and height in animals). Another example of multicollinearity in this group (Kleinbaum et al., 1988) is when one uses as predictors a higher power of other continuous variables (often called the natural polynomials) or combinations of two or more regressor variables (the interactions).

The consequences of multicollinearity were described by Mason et al. (1975) and Myers (1990). One effect of multicollinearity is instability of the regression coefficients, meaning coefficients whose values are very much dependent upon the particular data set from which they were generated. According to Myers (1990), small changes in the dependent variables and the removal of one or a set of regressors from the model may lead to large changes and perhaps changes of signs in the remaining coefficients. In addition, the absolute values of the coefficients are large, meaning that the squares of the estimated regression coefficients are overestimated. Prediction of response within the observed range of the dependent variable, for combinations of regressor variables, may still be good. However, prediction at points that represent extrapolation outside the range of the data can be strongly affected by multicollinearity.

Another consequence of multicollinearity is reduction of the power of statistical tests due to the larger standard errors of the coefficients. However, the detrimental effects of multicollinearity do not include the model's fit. Least squares procedures ensure that the residual sum of squares (and other statistics based upon it, such as the coefficient of determination, R^2) will be as good as the data allow. Therefore, under multicollinearity, the residuals in the regression analysis may be very small but yet the coefficients may be poorly estimated.

It should be pointed out that, unless the experiment is completely balanced, there will always be some degree of multicollinearity. The questions now would be how can the existence of serious multicollinearity be detected, how bad or how much damage is it provoking and, once detected, how can the analyst deal with the problem? Procedures that identify and quantify the severity of multicollinearity, and the theory behind them, have been described in a number of papers (Hoerl et al., 1970a, b; Hocking et al., 1976; Belsley et al., 1980; Myers, 1990). Most of these procedures are also available in statistical packages, such as SAS (1990).

Procedures for Detection of Multicollinearity: The degree of multicollinearity is reflected in the eigenvalues of the correlation matrix ($X^{c\prime}X^c$, where X^c is an incidence matrix of centered and scaled regressors, to be described more fully later). The most frequently used collinearity diagnostic is the variance inflation factor. As the multicorrelation of any predictor with other predictors approaches unity, the corresponding variance inflation factor becomes infinite. For any predictor orthogonal to all other predictors, the variance inflation factor is 1.0 (Marquardt and Snee, 1975). Other multicollinearity diagnostics commonly used are the eigenvalues and the condition numbers associated with each dependency, and the proportion of the inflation of the variance of the estimated regression coefficients associated with each dependency. A complete description concerning these statistics will be given in the Materials and Methods section of this chapter.

Procedures for Overcoming Multicollinearity: Once severe multicollinearity has been detected, there are basically two ways to combat it. First would be using classical procedures in the context of ordinary least squares regression, namely regressor variable selection (or elimination), transformation of the regressor variables and augmentation of the data (mainly concerning the range of the regressor variables). Regressor variable selection is probably the most common procedure that has been used to overcome the problems attributed to multicollinearity, and there are several techniques that can be used. Stepwise regression or some variation thereof, tests on subsets of regressors and all possible regressions are some examples, the latter method being the most desirable according to several authors (Furnival, 1971; Hocking, 1976; Myers, 1990). If the variables involved in a multicollinearity are not included in the model, the problem would not arise. However, if the regressor variables excluded from the model are good predictors of the response variable, results could be disastrous (Mason et al., 1975). Marquardt and Snee (1975) commented that selection of regressor variables as a technique for reducing the degree of multicollinearity implies a simplistic two-valued classification logic, where any predictor variable must either be important or unimportant. Large prediction biases can result from elimination of *non-significant* predictors. They also commented that in such cases, it may be better to use a little bit of all the variables (by shrinking the information provided by each one) rather than all of some variables and none of the remaining ones. This is exactly what biased estimators do (to be seen later).

Variable transformation, a technique mostly used to allow a better fit of a model or to normalize the distribution and(or) to stabilize the variance of the errors, may be attempted. These transformations often reduce the dimensionality of the regressor system while retaining some of the informational content of all regressors. For example, in the case of two regressors x_1 and x_2 which are highly correlated, redefining a variable $x_1 + x_2$, or perhaps forming ratios, might produce an effective result (Myers, 1990).

Finally, amelioration of the severity of the multicollinearity problem through augmentation of the data may not be possible either because of economical constraints, changes in the population under study, or simply because none are available, as in the case of observational studies. However, augmentation of the data is frequently mentioned as the best, and sometimes the only method of removing multicollinearity from data (Mason et al., 1975).

The second way to combat multicollinearity would be using procedures other than ordinary least squares to analyze the data. A number of alternatives to least squares have been recommended. The resulting estimators are biased, but they may be preferable to least squares estimators because they would have smaller variances. The hope is that, by accepting some bias, a larger reduction in the coefficient variances would be achieved such that an overall reduction in mean square error would result (Draper and Nostrand, 1979). The most popular of these biased estimators are the ridge regression and the estimators based on principal components (Hocking et al., 1976).

2.1.1.2 Ridge Regression

Ridge regression was first described by A. E. Hoerl in 1962. He observed that when inversion of a matrix was difficult due to nonorthogonality, adding a small positive number, κ, to the diagonal of the design matrix would facilitate inversion. The family of estimates resulting from this procedure has many mathematical similarities with the portrayal of quadratic response functions. For this reason, estimation and analysis built around it have been labeled *ridge regression* (Hoerl and Kennard, 1970a). Technically, ridge regression involves adding a constant κ ($0<\kappa\leq\infty$) to the diagonal of the correlation matrix among regressors before inverting it for least squares estimation. At the time it was first described, computer limitation in terms of memory and speed did not allow the application of Hoerl's observations to realistic statistical problems. With the advent of faster computers, Hoerl and Kennard (1970a, b) reintroduced the concept and presented the ridge-trace, a method for showing in two dimensions the effects of nonorthogonality. In the middle seventies, an incredible number of publications on this method of analysis appeared in the literature (e.g., Hoerl et al., 1975; Alldredge and Gilb, 1976; Hocking et al., 1976; Brown, 1977; Draper and Nostrand, 1979). Most of these publications were related to procedures for selecting the best κ-value. Statistics most frequently used for the choice of κ were reviewed by Myers (1990) and include DF-trace, the stability of the coefficients, variance inflation factor, PRESS_κ and C_k, a C_p-like statistic (to be seen later). Ridge regression has been used in fields such as economics and chemistry (Alldredge and Gilb, 1976; Vinod, 1976, Norton et al., 1984).

2.1.1.3 Principal Components Regression

Another biased estimation technique for combating multicollinearity is principal components regression (Massy, 1965; Hawkins, 1973; Hocking et al., 1976). With this method, least squares estimations are performed on a set of artificial variables called the *latent vectors* or, more frequently, the *principal components* of the correlation matrix. According to their performance, the analyst eliminates the least important principal components hoping to obtain a substantial reduction in the variance of the regression coefficient estimates. Like ridge regression, this method produces biased estimates of the regression coefficients, but it may result in estimation and prediction that are superior to ordinary least squares.

The new transformed variables (principal components) are essentially a rotation of the original regressor variables in an attempt to follow streams of multicollinearity. The principal components are orthogonal to each other, but the same magnitude of variance as observed in the original analysis (ordinary least squares) is retained after the transformation. What happens is that the total original variance is redistributed among the principal components. If multicollinearity is severe, there will be at least one very small eigenvalue, and elimination of the principal components associated with the small eigenvalues may reduce substantially the total variance in the model and produce an appreciable improvement in the overall model performance. The process of elimination of principal components is similar to that of least squares variable screening. However, the process is safer with principal components because orthogonality does exist and therefore regressor variables (the principal components) are independent of one another. Once the final model is selected in the principal components space, the regression coefficient estimates are transformed back to the original variables. As in the process of selecting a κ-value in ridge regression, difficulty arises in the decision of how many components should be dropped, if any. Myers (1990) listed a series of statistics (error mean square, PRESS, C_p, etc) that can be used in this process.

A more complete description of procedures for ridge regression and principal components regression will be given in the next section of this chapter, the Materials and Methods.

2.2 Materials and Methods

2.2.1 Materials

2.2.1.1 Data

The birth, weaning and yearling records of 771 Angus and 226 Simmental females and the weaning records of their first calves were used in the evaluation of ordinary least squares regression, ridge regression and principal components regression as a method for assessing the relationships between calfhood traits of the heifers and weaning weight of their first progeny. Cow-calf pairs were a subset of the original 946 Angus and 351 Simmentals used in the first chapter of this dissertation, and that weaned their first calves. Data from Simmental females born in 1988 were not used because weaning weights of their calves were not available. Culling reasons of first parity females are listed in Tables 5 and 6, for Angus and Simmentals, respectively. Additional data elimination included females that gave birth to twins in the first parity (five Angus and one Simmental) and missing information on calves (16 Angus and nine Simmentals). Among the Simmental cows, 41 were categorized as 75% (62.5 to 87.5%) Simmental and 185 were categorized as purebred (>87.5%) Simmental.

Details concerning management of breeding females were presented in the Materials and Methods section of the previous chapter. Most of the calves were born during the 60- to 90-day calving season, with the peak (65%) being observed in April each year. After birth all calves were identified and weighed, and their birth dates were recorded. They were reared by their dams on alfalfa pasture and were creep fed during the entire preweaning period. Calves were weaned and their weights were recorded in the first week of November each year at a mean age of approximately 205 days. No outside bulls were used. Angus calves were sired by 40 bulls, and Simmental calves were sired by 13 bulls. Weaning weight expected progeny differences (EPDs) for sires of calves used in analysis were from the 1991 spring national sire evaluations, obtained from the American Angus Association and the American Simmental Association.

2.2.1.2 Variable Description

As defined in the Materials and Methods section of the previous chapter, from birth weights and dates, weaning weights and ages and yearling weights and ages, the following 14 calfhood traits were defined for each heifer: Birth date, birth weight, actual weaning weight, 205-day weight, weaning weight ratio, actual yearling weight, 365-day weight, yearling weight ratio, birth-weaning ADG, weaning-yearling ADG, birth-yearling ADG, birth-weaning RGR, weaning-yearling RGR and birth-yearling RGR. Additionally, age of a heifer's dam at the time of her birth and percentage Simmental groups were recorded.

Production in the first parity was defined as the actual weaning weight of the first calf adjusted for sex of the calf, year of birth, calf's sire weaning weight EPD, and percentage Simmental (for Simmentals).

2.2.2 Methods

All statistical analyses were conducted within breeds. Descriptive statistics (means and standard deviations) were calculated for all variables, and product moment correlation coefficients between pre-selected regressor variables were calculated for both breeds. Analyses were performed using procedures included in SAS (1990) and four SAS-subroutines (1991), RPALL, REPEXACT, CPRIDGE and PC developed at the Consulting Center of the Virginia Tech Statistics Department.

Preliminary analyses were performed using ordinary least squares methodology. Individual tests of significance of all two-factor interactions in the presence of the two main effects were made. None of the interactions achieved a minimum significance level (all $P > .05$), and interactions consequently were not included in further models.

In order to compare the three regression methodologies, a final subset of potentially important regressor variables was necessary for each breed. Therefore, all 15 potential regressor variables were subject to variable screening. The objective of this screening was the elimination of regressor variables that either presented redundant information and(or) had minor relationship with weaning weight of the first calf. Additionally, this variable elimination was important to restrict the number of regressor variables and therefore to reduce computational costs when using the SAS-subroutines to perform ridge and principal components regression. The two final subsets of regressor variables (one for each breed) were assumed to be essential to model female production in the first calving season and were to be used in all further analyses.

In order to select the regressor variables included in these final subsets, two models initially were fit for each one of the regressor variables: a model including the variable's linear effect only and a model including its linear and quadratic effects. The model presenting the higher overall level of statistical significance (smallest probability value) was chosen as the one that best described the relationship between dependent and independent variables. Variables associated with probability values of lower than or equal to .20 were selected to be part of the final subset model for each breed. Because the level of multicollinearity was expected to be high within these models, a series of multicollinearity diagnostics was then performed to quantify the severity and to detect which regressor variables were involved.

2.2.2.1 Multicollinearity Diagnostics

The statistics that were used to detect multicollinearity are described by Myers (1990) and included in SAS (1990). They can be divided into two groups. The first group is useful in showing the strength of the linear dependencies and the degree of inflation in the variance of each regression coefficient. Variance inflation factor, eigenvalues and condition numbers belong to this group. The second group, composed of the variance proportion statistic, is designed to determine what proportion of the variance of each coefficient is attributable to each dependency (or to each multicollinearity).

Variance inflation factor (VIF) is the most popular multicollinearity diagnostic. It represents the inflation that the variance of each regression coefficient experiences above the ideal situation, i.e., when there is orthogonality. If the VIF for a given regression coefficient is large, that regressor variable has strong linear association with one or more of the remaining regressors. For example, a VIF of 33.8, as presented by Hoerl and Kennard, 1970b, indicates that the expected squared distance of the coefficient estimate, $\hat{\beta}$, from β is 33.8, which is more than 33 times what it would be for an orthogonal system. The VIF for the *j*th regression coefficient can be written as

$$\mathrm{VIF}_j = \frac{1}{1 - \mathrm{R}_j^2}$$

where R_j^2 is the coefficient of multiple determination of the regression produced by regressing the variable x_j against all other regressor variables, the x_i $(i \neq j)$. Therefore, the higher the multiple correlation among regressors, the lower the denominator and the higher the VIF.

The second diagnostic is the eigenvalues of the correlation matrix ($X^{c\prime}X^c$, where X^c is an incidence matrix of centered and scaled regressors). They play an important role in defining the multicollinearity that exists in a set of regression data. *Centered and scaled* means that, if x_{ji} is the

ith measurement on the regressor variable x_j in the natural units, then $\bar{x}_j = \sum_{i=1}^{n} x_{ji}/n$ is subtracted from x_{ji} and the resulting $x_{ji} - \bar{x}_j$ is divided by S_j, where

$$S_j = \sqrt{\sum_{i=1}^{n} (x_{ji} - \bar{x}_j)^2}\ .$$

Recalling that the $X^{c\prime}X^c$ matrix is in correlation form, there is what is called eigenvalue decomposition (Graybill, 1976) such that there exists an orthogonal matrix

$$V = [v_1, v_2, v_3, \dots, v_k],$$

and that

$$V' (X^{c'} X^{c}) V = \text{diagonal} (\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_k)$$

where λ_i are the eigenvalues of the correlation matrix, $X^{c\prime}X^c$. If multicollinearity is present, at least one $\lambda_i \cong 0$. The number of small eigenvalues of the correlation matrix relates to the number of strong linear dependencies among regressor variables. If all eigenvalues are close to unity, the system is close to orthogonality.

In detecting severity of multicollinearity, what matters may not be the smallness of the eigenvalues but the values of the j eigenvalues in relation the the largest eigenvalue in the system, that is, the spectrum of the eigenvalues (Belsley et al., 1980). This leads to the third multicollinearity diagnostic, which is called the condition number (CN) of the correlation matrix. It is defined as

$$\text{CN}_j = \frac{\lambda_{maximum}}{\lambda_j}$$

Ideally this CN should be close to unity, and large values of this statistic are evidence that serious multicollinearity exists. The number of large CN values indicates the number of linear dependencies involved in the system.

The three previously described diagnostics (VIF, eigenvalues and CN) are designed to detect and to show the strength of multicollinearity. They do not address how much each dependency affects the estimation of each regression coefficient. The fourth diagnostic used, variance proportions, is useful in determining what proportion of the variance of each coefficient is attributable to each linear dependency. Considering the eigenvalue decomposition of the correlation matrix (X'X), scaled but not centered, the intercept will be involved, so there would be one additional eigenvalue, λ_0, due to the increase in the dimension of $(X'X)^{-1}$. In this case the variance-covariance matrix, $(X'X)^{-1}$, can be written as

$$(X'X)^{-1} = [v_0, v_1, v_2, \dots, v_k] \text{ diagonal } [1/\lambda_0, 1/\lambda_1, 1/\lambda_2, \dots, 1/\lambda_k] \ [v_0, v_1, v_2, \dots, v_k]'$$

and the variances of the $p = k + 1$ regression coefficients, apart from σ^2, are in the main diagonal of $(X'X)^{-1}$. If υ_{ji} is the ith element in the eigenvector associated with λ_j, it can be written that

$$c_{ii} = \sum_{j=0}^{k} \frac{\upsilon_{ji}^2}{\lambda_j}$$

where $c_{ii} = \dfrac{\text{Var } \hat{\beta}_i}{\sigma^2}$.

To quantify the extent to which the variance of $\hat{\beta}_i$ is attributable to the collinearity represented by the eigenvalue λ_j, (p_{ji}), the following expression can be used

$$p_{ji} = \frac{\upsilon_{ji}^2 / \lambda_j}{c_{ii}} .$$

Once multicollinearity has been identified, the next step is to analyze the data sets of pre-selected variables by least squares, ridge regression and principal components regression, and to compare the performance of these methods.

2.2.2.2 *Ordinary Least Squares Regression*

The standard linear model with *n* observations on *k* regressor variables was assumed. The data and the model are represented in matrix notation as,

$$y = X\beta + \varepsilon$$

where X is the $n \times k$ design or incidence matrix of rank *k*. Solutions for this system of equations are given by

$$\hat{\beta} = (X'X)^{-1}X'y$$

In the comparison between least squares regression and the two biased linear regression estimators, the following single number statistics were used: error mean square (EMS), prediction sum of squares (PRESS) and conceptual predictive criteria (C_p).

The EMS in the context of least squares, described in most statistical texts, is as follows

$$\text{EMS} = \frac{(y - X\hat{\beta})'(y - X\hat{\beta})}{n - p}$$

where $p = k + 1$ parameters being estimated, that is, *k* regression coefficients and the intercept. It is an indicator of the bias that may be encountered by underfitting a model and that would be incorporated into the coefficient estimates and predictions. Therefore, in model selection one should favor models with small EMS.

The PRESS statistic is a very important criterion for validation of a regression model (Stone, 1974; Snee, 1977). It is particularly useful when comparing models that will be used for prediction. It is similar to data splitting when that is used as a cross validation mechanism, either for the choice of the best model or for the study of model stability and predictive performance. However, in PRESS statistics each observation, one at a time, is set aside from the data set, and the remaining $n-1$ observations are used to estimate the regression coefficients for the model. At the end, the model is fit n times and there are n prediction errors or PRESS-residuals for each observation, i.e.,

$$y_i - \hat{y}_{i,-i} = e_{i,-i}, \quad \text{for } i = 1, 2, \ldots, n.$$

These PRESS-residuals are prediction errors with $\hat{y}_{i,-i}$ being independent of y_i. Thus each model will have n PRESS-residuals associated with it, and the PRESS statistic is given by

$$\text{PRESS} = \sum_{i=1}^{n} (y_i - \hat{y}_{i,-i})^2 = \sum_{i=1}^{n} (e_{i,-i})^2$$

Therefore, for the choice of most appropriate model, one might favor the model with the smallest PRESS statistic. Computationally, and in the context of least squares, the PRESS statistic may be assessed in an equivalent, although faster and cheaper, way than the physical removal of n individual observations, one at a time. This is possible by making use of the diagonals (h_{ii}) of the Hat matrix ($\mathbf{H} = X(X'X)^{-1}X'$). In this case it is given by

$$\text{PRESS} = \sum_{i=1}^{n} \left(\frac{e_i}{1 - h_{ii}} \right)^2$$

This is the manner in which it is computed by SAS (1990).

The C_p (Kennard, 1973; Mallows, 1973) is the third statistic used in model evaluation. It represents the trade-off between underfitting (and consequently, biasing the estimates) and overfitting (and consequently, enlarging the variances of the estimates) the model. It should be emphasized as a model selection criterion when both the interpretation of regression coefficients and prediction are important. By definition it is represented by

$$C_p = \sum_{i=1}^{n} [\mathrm{Var}\,\hat{y}_i] + \frac{[\mathrm{Bias}\,\hat{y}_i]^2}{\sigma^2}$$

After some substitutions and assuming that there is a *true* model with no bias and a *true* σ^2, its computation for a p-parameter regression model simplifies to

$$C_p = p + \frac{(s^2 - \hat{\sigma}^2) \times (n-p)}{\hat{\sigma}^2}$$

where s^2 is the EMS for the model in question and $\hat{\sigma}^2$ is the estimate of σ^2, usually from the most complete model. One should favor models with small C_p.

2.2.2.3 *Ridge Regression*

The ridge regression estimates of the vector of coefficients, β, were found by solving for $\hat{\beta}_\kappa$ in the system of equations

$$(\mathrm{X'X} + \kappa\,\mathbf{I})\,\hat{\beta}_\kappa = \mathrm{X'y}$$

Thus,

$$\hat{\beta}_\kappa = (\mathrm{X'X} + \kappa\,\mathbf{I})^{-1}\,\mathrm{X'y}$$

where, $\kappa \geq 0$ is the *shrinkage parameter.*

The various procedures for choosing κ are designed to select values that are in the interval of κ for which there is improvement in the estimation of the coefficients and in the prediction quality of the models. For these values, what is obtained in reduction of the variance of the estimates would more than compensate for the increase in bias. The choice of κ would be based on the values of the following statistics: EMS_{κ}, PRESS_{κ}, C_{κ} and degrees of freedom trace (DF-trace). The first three are said to be stochastic methods for choosing κ because they involve the *y*-data and, as a result, the choice of κ is a random variable. The DF-trace is a nonstochastic method for choosing κ because it is a function only of the regressor data. In this case the choice of κ is determined by the nature of the collinearity itself, and κ is not a random variable. The three stochastic methods for choosing κ are equivalent to EMS, PRESS and C_p, respectively used in the context of least squares, and are also used in the comparison of the performance of ridge regression with ordinary least squares and principal components regression.

EMS_{κ} is calculated in the same way EMS is calculated in ordinary least squares, but with ridge regression estimates $(X\hat{\beta}_{\kappa})$ replacing least squares estimates. Computations were made using the SAS-subroutine RPALL, and a plot was used in order to visualize the relationship of EMS_{κ} with κ.

The DF-trace (Tripp, 1983) criterion is based on the matrix $\mathbf{H}_{\kappa}$, which plays the same role as the Hat matrix in ordinary least squares. The DF-trace is given by the trace of this matrix, as follows

$$\text{trace}\,(\mathbf{H}_{\kappa}) = \text{trace}\,[X^{c}\,(X^{c\prime}X^{c} + \kappa\,I)^{-1}\,X^{c\prime}] = \sum_{l=1}^{k} \frac{\lambda_l}{(\lambda_l + \kappa)}$$

If there is multicollinearity and with the use of increasing values of κ, this criterion will initially decrease drastically, followed by a stabilization. Since the DF-trace is actually indicative of the effective degrees of freedom in the regression, or the effective rank of the incidence matrix, a value for

κ should be chosen at which the trace is stable. For this procedure, a plot of DF-trace against κ values was made. In the calculations of DF-trace according to different values of κ, the SAS-subroutine RPALL was used.

In the calculation of PRESS$_\kappa$, the prediction at the ith point for a particular κ was made by eliminating the ith point, recomputing the centered and scaled regressor data, recomputing the ridge regression and recomputing $\hat{y}_{i,-i,\kappa}$. As in the use of PRESS in the context of ordinary least squares, κ values and models presenting smaller values of PRESS$_\kappa$ would be preferable to the ones presenting larger values. In order to better visualize the relationship between different values of κ and PRESS$_\kappa$, a plot was used. In calculations, the SAS-subroutine REPEXACT was used, according to the following expression

$$\text{PRESS}_\kappa = \sum_{i=1}^{n} e^2_{i,-i,\kappa}$$

According to Myers (1990), the actual elimination of data points, one at a time with ridge regression being computed repeatedly, would limit the applicability of this approach only to moderate or small data sets. That happened in this study, when the calculation of the exact PRESS$_\kappa$ was possible only for the Simmental data set (226 observations). Alternatively, the following approximation to PRESS$_\kappa$ is possible if the exact procedure cannot be used in large data sets:

$$\text{PRESS}_\kappa = \sum_{i=1}^{n} \left[\frac{e_{i,\kappa}}{1 - (1/n) - h_{ii,\kappa}} \right]^2$$

where $e_{i,\kappa}$ is the ith residual for a specific value of κ, and $h_{ii,\kappa}$ is the ith diagonal element of $\mathbf{H}_\kappa$. Myers (1990) pointed out that this approximation is quite good whenever sample size is not small and sample data contain no high leverage observations, i.e. no large Hat diagonals. That was the case with the Angus data set used in this study. The SAS-subroutine RPALL was used for the calculation of this statistic.

The use of the SAS-subroutine REPEXACT was computationally the most demanding (mainly in terms of time) among all other subroutines used. For example, when calculations of exact PRESS$_{\kappa}$ for the Angus data set were attempted, the VM Batch machine six was used and exceeded its limit. That machine allows 200 Mb of virtual machine size and a maximum of six CPU hours for a job.

Finally, the statistic C$_{\kappa}$ is based on the same kind of variance and bias trade-off previously described for C$_{p}$. The SAS-subroutine CPRIDGE was used in calculations, according to the following expression

$$C_{\kappa} = \frac{SS_{res.,\kappa}}{\hat{\sigma}^2} - n + 2 + 2\,\mathrm{trace}\,[\mathbf{H}_{\kappa}]$$

where SS$_{res.,\kappa}$ is the residual sum of squares using ridge regression and $\hat{\sigma}^2$ comes from the residual mean square from ordinary least squares estimation. To visualize the effectiveness of different values of κ, a plot of C$_{\kappa}$ against κ was used. The choice of κ would be the one provoking the largest decrease in C$_{\kappa}$

According to these statistics, a single value of κ was selected for each data set, representing the one that allowed the best improvement in model performance. The ridge regressions using this selected κ value were then compared with the models from ordinary least squares and principal components procedures.

2.2.2.4 Principal Components Regression

With this method, least squares estimations are computed on a set of artificial variables called *the principal components*. Once more, making use of the eigenvalue decomposition it is known that there exists an orthogonal matrix $\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \dots, \mathbf{v}_k]$, such that

$$\mathbf{V}' (\mathbf{X}^{c'}\mathbf{X}^{c})\, \mathbf{V} = \text{diagonal}\,(\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_k).$$

In this case the ordinary least squares model can be written in the following way

$$\mathbf{y} = \beta_0 \mathbf{1} + \mathbf{X}^{c}\, \mathbf{V}\mathbf{V}'\beta + \varepsilon,$$

because $\mathbf{V}\mathbf{V}' = \mathbf{I}$, or equivalently

$$\mathbf{y} = \beta_0 \mathbf{1} + \mathbf{Z}\alpha + \varepsilon,$$

where $\mathbf{Z} = \mathbf{X}^{c}\mathbf{V}$ is the new n x k incidence matrix and $\mathbf{V}'\beta = \alpha$ is a k x 1 vector of the new transformed coefficients, $\alpha_1, \alpha_2, \dots, \alpha_k$. The columns of $\mathbf{Z}$ are the k new variables, the principal components.

After estimation of the regression parameters, tests on principal components and model performance evaluation, the principal component associated with the smallest eigenvalue, i.e., the one associated with the highest linear dependency (or multicollinearity), was eliminated. A new principal component regression was run with the new set of $k - 1$ principal components. This process was repeated until the principal components model of choice was achieved. At that point, the regression was transformed back to the original trait, with solutions for the k regression coefficients being given as follows

$$\hat{\beta}_{pc} = \mathbf{V}_{sel.}\, \alpha_{sel.}$$

where $\hat{\beta}_{pc}$ is the vector of regression coefficients in the original metric, $V_{sel.}$ is the partition of the matrix of normalized eigenvectors of $X^{c\prime}X^{c}$ related to the components that where kept, and $\alpha_{sel.}$ is the vector of least squares estimates of the selected principal components.

The criteria used to select the best principal component models for the two data sets and to compare these models with the ones fit using ordinary least squares and ridge regression were the statistics EMS, PRESS and C_p. The computations of these statistics are exactly the same as in ordinary least squares, but with the principal components replacing the original regressor variables. They were assessed using the SAS-subroutine CP.

2.3 Results and Discussion

In Table 39, descriptive statistics with means and standard deviations of all calfhood traits and first calf weaning weight adjusted for sex, year of birth, sire weaning weight EPD and percentage Simmentals (for Simmentals) are presented for both breeds.

In the adjustment of weaning weight of the calves, models containing sire identification as a categorical variable versus models containing sire weaning weight EPD as a covariate were compared. For both breeds, models containing sire effects as class variables accounted for larger proportions of sums of squares than models containing sire EPD as a covariate (R^2 equals .53 versus .31 and .56 versus .38, for Angus and Simmental calves, respectively). However, sire EPD as a covariate rather than sires as categorical variables was used in the weaning weight adjustments because preliminary analysis showed a partial confounding between sire and weaning age of the calves. The same confounding was not observed for sire EPDs. Regression coefficient estimates of weaning weights of their progeny on sire EPD's, .55 ± .32 and .50 ± .17, respectively, for Angus and Simmentals, were not close to their expectation, 1. Weaning weight adjustments in this study were applied to actual weights rather than age-adjusted weights, whereas EPD estimation in national sire evaluation is based upon age-adjusted weaning weights. Additional analyses confirmed that when age-adjusted calf weaning weights were regressed on sire EPD, regression coefficients were much closer to their expectations (.88 ± .22 and 1.23 ± .17, respectively for Angus and Simmentals).

In the adjustment procedures, besides sire EPDs, the effects of year of birth ($P < .01$), sex of the calf ($P < .01$) and percentage Simmental ($P < .05$) also were significant. For Angus and Simmental calves, respectively, males were 30 and 25 kg heavier at weaning than females, and purebred Simmental calves were 12 kg heavier at weaning than 75% Simmentals.

2.3.1 Selection of the Final Subsets of Regressor Variables

To compare the three regression methodologies, a final model containing potentially important regressor variables was necessary for each breed. To obtain these subsets of regressors, a variable screening was conducted regressing weaning weight of the first calf on individual calfhood trait regressor variables. A model containing only the linear effect of each regressor variable and a model containing both its linear and its quadratic effect were tested to identify which best described the relationship between calfhood trait of the female and weaning weight of her first calf. The performances of the 15 individual regressor models in terms of coefficient of determination (R^2), regression coefficient estimates associated with each regressor variable, their standard errors and their tests of significance are presented in Tables 40 and 41 for Angus and Simmentals, respectively.

For both breeds a probability value of .20 was set as the upper limit for the inclusion of regressor variables in the final subsets. However, for Angus, inspection of tests of significance and estimated regression coefficients on age adjusted (205 or 365 day) weights and actual (weaning or yearling) weights revealed that the relationships involving age adjusted and actual weights were basically the same (Table 40). The inclusion of both of them in the final subset model would not have provided any additional information. Therefore, in the screening process the regressor variable, either actual or age adjusted weight, that presented the highest significance level was selected. The following 11 variables were selected to constitute the final subset for the Angus breed: Birth date, birth date squared, age of dam, age of dam squared, actual weaning weight, weaning ratio, actual yearling weight, yearling weight ratio, and birth-weaning, weaning-yearling and birth-yearling ADG. For the Simmental breed, the final subset of regressor variables was: Birth date, age of dam, age of dam squared, 205-day weight, birth-weaning ADG, and birth-weaning, birth-yearling and the square of birth-yearling RGR.

2.3.1.1 Multicollinearity Diagnostics

It is well known that body weights at different ages, average daily gains and relative growth rates in different phases, and weaning and yearling weight ratios are correlated either because of genetic and(or) environmental correlations or because they have part-whole relationships (e.g., Brown et al., 1972a, b; Smith and Cundiff, 1976; Kemp, 1990; Winder et al., 1990). Similarly, it is known that age of a dam affects weaning weight of her progeny (e.g., Mangus and Brinks, 1971; Lubritz et al., 1989). Weights of growing animals taken at fixed times are positively correlated, simply because older animals tend to weigh more. Therefore, some degree of multicollinearity would be expected in the final models containing subsets of pre-selected regressor variables.

Indeed, examination of the pairwise correlation coefficients among the 11 pre-selected regressor variables for Angus (Table 42) and eight pre-selected regressor variables for Simmentals (Table 43) revealed the possibility of serious multicollinearity. For Angus, over 25% of all possible pairwise correlations were above .50, and 78% of all possible correlations were different from zero ($P < .05$). Strong pairwise correlations were particularly evident between growth related traits, where 52% of 21 possible correlations were above .50. The same conclusions were achieved for the Simmental pre-selected regressor variables. i.e., 36% of all possible pairwise correlations were above .50, and

71% of all of them were different from zero (P < .05). Again, pairwise correlations between growth related traits were consistently positive and generally high, ranging from .16 (P=.02) to .99 (P<.01).

Clearly, for both sets of regressor variables, all possible relationships among regressor variables would fit the third of the three sources of multicollinearity described by Mason et al. (1975) and Kleinbaum et al. (1987), i.e., the multicollinearity due to physical constraints on the model or in the population. That is the case of regressor variables that are biologically correlated with one another (such as weaning and yearling weights), that have part-whole relationships (such as birth-weaning and birth-yearling ADG), or that are a higher power of another continuous regressor variable (such as age of dam and age of dam squared).

However, looking at pairwise correlations between regressors does not allow quantification of the severity of multicollinearity (Myers, 1990). A situation is possible in which all one to one relationships between regressor variables are trivial (low values of pairwise correlations) but three or more variables might still exhibit strong simultaneous relationships. Additionally, pairwise correlations, by themselves, are not useful in detecting how much damage multicollinearity is provoking. That is why other methods of multicollinearity detection were used. These are presented in Tables 44 and 45, respectively, for Angus and Simmental models. Inspection of eigenvalues, condition numbers and variance inflation factors for both models showed that there was at least one strong linear dependency among regressor variables for the Angus model, and at least two strong dependencies for the Simmental. Variance proportions indicated how much damage in each regression coefficient estimate was related to each dependency.

For the Angus model, the smallest eigenvalue, .003, associated with condition number 1,310.4 (Table 44), reflected a dependency that was damaging to estimated regression coefficients of birth-weaning ADG, weaning-yearling ADG and birth-yearling ADG. The variances of the least squares estimates of regression coefficients for these variables were inflated, in the same order, by 36-, 161-

and 135-fold compared to what would be observed in an orthogonal system. Using the statistic variance proportions, presented in the same table, it was possible to determine what proportion of the variance of each regression coefficient estimate was attributable to the dependency (or multicollinearity) associated with this eigenvalue. Thus, 80, 99 and 99% of the variances associated with the estimation of regression coefficients for birth-weaning, weaning-yearling and birth-yearling ADG, respectively, were associated with this dependency.

A secondary and less important dependency, associated with eigenvalue .022 and condition number 193.2, inflicted some damage in the estimation of the regression coefficients associated with birth date (VIF = 16.8), actual weaning weight (VIF = 26.0) and weaning weight ratio (VIF = 7.3). For these variables, and in the same order, 58, 63 and 40% of the variances of regression coefficient estimates were associated with this dependency. Finally, an even less important dependency for the Angus model was associated mainly with the variables age of dam and age of dam squared. Inflation of the variance of the regression coefficients was the same for both variables (17.6), and this dependency accounted for a similar amount of variation in the regression estimates for both of them.

The strongest linear dependency for the Simmental model was associated with eigenvalue .001 and condition number 3,091.4 and involved the regressor variables birth-yearling RGR and birth-yearling RGR squared (Table 45). This dependency was responsible for 97 and 95% of the 433- and 412-fold inflation on the variance of the least squares estimates of the regression coefficients, respectively, for the linear and quadratic effects of birth-yearling RGR. The second strongest dependency observed in the Simmental model involved the variables 205-day weight, birth-weaning RGR, birth-weaning ADG and, to a lesser extent, birth date. This dependency affected mostly the least squares estimation of the regression coefficients associated with 205-day weight (85% of the VIF = 213.2) and birth-weaning ADG (87% of the VIF = 262.4). It damaged much less the estimation of the regression coefficients associated with birth-weaning RGR (72% of the VIF = 10.2) and birth date (46% of the VIF = 3.6). Interestingly, the next strongest linear dependency (number 6, Table 45) involved solely the variables age of dam and age of dam squared. Although

95% of the variances in the least squares estimates of the regression coefficients of these variables were attributed to this dependency, inflation of the variances above orthogonality was relatively moderate (17- and 16-fold for the linear and the quadratic effects of age of dam, respectively). This is the kind of multicollinearity one has to deal with in a model, because it is probably not provoking any redundant information. Rather the inclusion of the linear and quadratic effects may be necessary to model the relationship between dependent and independent variables.

Once multicollinearity was detected and shown to be inflating variances of the least squares regression coefficient estimates and, consequently, causing model instability, one of the alternatives would be trying to eliminate much of the multicollinearity without resorting to alternatives to least squares. This could be attempted by eliminating one or more regressors from the models, by trying some transformations of the regressor variables, or trying to augment the data and the range of regressor variables (Marquardt and Snee, 1975; Mason et al., 1975; Myers 1990). However, in the context of this chapter, the objectives were to attempt alternatives to ordinary least squares, namely, the use of ridge regression and principal components regression. Therefore, it was assumed that these two sets of regressor variables were the ones that best described the relationships between calfhood traits of the females and the weaning weight of their first calves for the two breeds in this study.

2.3.2 Alternatives to Ordinary Least Squares Regression

2.3.2.1 Ridge Regression

The first task was the selection of κ values for both models that would result in greater benefits from the reduction in variances than the damage associated with bias. Since the parameters, the βs, are unknown, bias could not be calculated. Therefore, κ-values for both models had to be chosen that resulted in improvements in the estimates. The procedures for visualizing that improvement and for choosing κ involved MSE_κ, $PRESS_\kappa$, C_κ, DF-trace, and stability of the regression coefficients.

Initially, κ-value increments of .001, .005, .01, .05 starting from zero were tested for both models to locate the region in which greatest improvement was observed. For the Angus model, most of the improvement was achieved when the κ-value changed from .01 to .05. Most improvement for the Simmental model was achieved when the κ-value went from .001 to .005. An increment of κ above these values initially led to a stabilization of $PRESS_\kappa$, C_κ and DF-trace, followed by a continuous increase in C_κ. In those ranges of κ-value, the relationship between EMS_κ and κ tended to be positive and linear, which would be expected due to the increased bias from increasing values of κ.

Once the approximate ranges within which model performances were most improved were defined, the next step was to use a finer grid of κ-values in order to select the best ones. Ridge regressions with an increment of κ-value of .003 (from zero up to .039) for Angus, and an increment of κ-value of .0002 (from zero up to .0024) for Simmental were performed. Results are presented in Tables 46 and 47, respectively, for Angus and Simmental models. Also presented in the same tables were the inflation of the standard errors of regression coefficient estimates ($\sqrt{VIF}$) for different values of κ. Graphic representation of the variation of single number statistics, EMS_κ, DF-trace, $PRESS_\kappa$ and C_κ, according to increasing values of κ are shown in Figures 5 and 6, respectively, for Angus and Simmentals.

For Angus, initial increments of κ affected mainly regression coefficient estimates that were prominently involved with multicollinearity. That was the case of the numerical reduction observed for the regression coefficients associated with birth-weaning, weaning-yearling and birth-yearling ADG. Together with this reduction, substantial reductions in the inflation of the standard errors of the estimates were observed (Table 46). To a lesser extent, a second group of estimates that were affected by increasing values of κ were the ones involved with dependency 10 (Table 44), namely birth date, actual weaning weight and weaning weight ratio. Eight out of 11 ordinary least squares regression coefficients ($\kappa = 0$) were estimated with an inflation in standard errors of at least 3-fold the ones that would be observed without multicollinearity. At κ equals .015, all ridge regression coefficients were estimated with an inflation in standard errors of, at most, 3-fold the ones for an orthogonal design.

Improvement in model performance, according to single number criteria, was more evident for κ up to .015 (Table 46, Figure 5). In relation to a κ almost three times as high (.039), a κ-value of .015 led to a reduction in $PRESS_\kappa$ of 79%, reduction in C_κ and DF-trace of 78 and 65%, respectively, and only a third of the inflation in MSE_κ. Considering all these single number criteria, the inflation of standard errors and the relative stability of regression coefficients, .015 was chosen as the best κ-value for the Angus model.

Incremental κ-values for the Simmental model affected mainly the estimation of regression coefficients associated with the linear and the quadratic effects of birth-yearling RGR. These variables were involved in the strongest dependency observed for the Simmentals (dependency 8, Table 45), and substantial reductions in the inflation of the standard errors of the regression coefficient estimates were achieved for increasing values of κ. For the other regressor variables, as κ-value increased, there was a continuous reduction in the inflation of their standard error estimates, but those reductions were much smaller than the ones previously described. Regression coefficient estimates for the variables birth date, age of dam, age of dam squared and 205-day weight and the inflation of their standard errors, as well, experienced very little variation regardless of the κ-value used. This would mean that these regression coefficients were estimated with almost the same accuracy for different values of κ.

Using single number criteria to facilitate the choice of κ-value, most of the gain in reduction of variance and stability of the model was achieved by a value of .0008. At this value, the reduction in $PRESS_\kappa$ was 83% of the reduction associated with a κ-value three times higher, and with a smaller cost in terms of bias (Table 47, Figure 6). Additionally, C_κ basically achieved a plateau at that value and the rate of decrease in DF-trace was getting smaller, meaning that most of improvement in the estimation of the coefficients was accomplished up to that point.

Finally, the choice of these κ-values would not have varied too much if more emphasis had been given to $PRESS_\kappa$, C_κ or DF-trace. According to Myers (1990), these three methods for choosing κ would not necessarily result in the same κ-value. However, their utilization would produce a similar κ-value when data sets do not contain high leverage points, i.e., points that are not associated with extreme values in the regressor space.

2.3.2.2 Principal Components Regression

Analogous to the problem of choosing κ in ridge regression, the question with principal components regression would be how many components to drop from the model.

A total of eleven (Angus) and eight (Simmental) principal components regression models were fit. The first model was fit considering all principal components together, which is equivalent to ordinary least squares. Sequentially, the principal component associated with the smallest eigenvalue (largest linear dependency) was dropped. A new principal components regression containing $n - 1$ principal components was then fit and a new set of regression coefficients was estimated. The improvement in the prediction and estimation capabilities of this new model was assessed by PRESS and C_p statistics. The effect of the exclusion of one principal component on variance and bias was assessed by change in EMS, and the effect of this elimination on the quality of fit of the model was shown by a reduction in R^2. This process of individual elimination of principal components continued with two, three, etc, principal components being dropped until a unique component was left. For each principal component regression fit, the regression coefficients were transformed back into the original scale. All these statistics are presented in Tables 48 and 49 for Angus and Simmentals, respectively.

For models of both breeds, the best performance was observed when only one principal component was dropped. For Angus, that principal component was associated with the linear dependency that was damaging primarily the estimation of regression coefficients for the variables birth-weaning, weaning-yearling and birth-yearling ADG, and to a lesser extent actual yearling weight (dependency 11, Table 44). After the removal of the first principal component, regression coefficient estimates of these variables were primarily affected. For Simmentals, the first principal component eliminated was associated with the linear dependency involving primarily the linear and quadratic effects of birth-yearling RGR (dependency 8, Table 45). To a smaller degree, this linear dependency also involved the variables birth date, 205-day weight and birth weaning ADG. For both models, the removal of an additional principal component deteriorated regression quality, as evidenced by increase in PRESS, C_p, and EMS and by reduction in the R^2.

2.3.3 Comparison among Ordinary Least Squares, Ridge and Principal Components Regression

Comparative performance of least squares, ridge and principal components regression models are presented in Tables 50 and 51 for Angus and Simmentals, respectively. In general, regression coefficient estimates for variables that were not involved in multicollinearity did not differ by much, regardless of the regression method used. For variables that were involved in multicollinearity , variation among estimates was much greater. That would be expected because of greater instability in the coefficient estimates.

For both breeds, EMS's were larger from ridge and principal components than from least squares regression because of the bias associated with the addition of κ to the diagonal of the design matrix and because of the elimination of one principal component. Ridge regression methodology produced smaller values of $PRESS_\kappa$ and C_κ than values of PRESS and C_p produced by least squares and principal components regression. Principal components regression was superior to least squares in these two single number statistics. The superiority of the models producing biased estimators over least squares was greater when model performances were assessed by C_p and C_κ than when assessed by PRESS and $PRESS_\kappa$.

For Angus, reductions in the PRESS-like statistic were .42 and .22% going from least squares to ridge and from least squares to principal components regression, respectively. These reductions were associated with very small differences among the methods in the average squared press-residuals ($e^2_{i,-i}$): 1,028 (least squares), 1,024 (ridge) and 1,026 (principal components). When C_p-like statistics were used, ridge regression and principal components regressions produced, respectively, values that were 26 and 14% smaller than the C_p produced by least squares.

Similarly, for the Simmental models PRESS-like statistics were .53 and .31% smaller, respectively, for ridge and principal components regression than for least squares regression. Associated average values of squared press-residuals were similar among the three methods, being 1,086 (least squares), 1,080 (ridge) and 1,082 (principal components). In relation to least squares, fitting a ridge regression model produced a reduction in C_p-like statistic of 10% while fitting a principal components regression model produced a reduction of 3%.

For these two data sets and for the included pre-selected sets of regressor variables, it was clear that between the two alternatives to least squares, ridge regression produced better results than principal components regression. Ridge and least squares regression were similar both in their regression coefficient estimates and in the single number criteria used to compare them. These statistics always favored ridge regression, but the differences were very small, especially for the PRESS-like statistic.

Before answering the question about what would be the best methodology, either ridge regression or least squares regression, it is necessary to recall what would be required from the regression model. Myers (1990) pointed out that the emphasis that different statistics should be given in model evaluation is dependent upon the question, *"What will be done with the model?"* If one is trying to use regression methodology for interpretation of the coefficients, a compromise between small variance and small bias is most important. That compromise is assessed by C_p-like statistics. In such a case, one would favor ridge regression over ordinary least squares. In the present study, the use of regression methodology is mostly for prediction. Therefore, some sort of cross-validation statistic, such as PRESS, would be more useful. For these two data sets and with the regressor variables used, the differences in PRESS statistics among the three methods were minimum, although always favoring ridge regression.

Two additional points should be considered prior to a decision. First, computational costs differ among these methods. This aspect, *per se*, strongly favors least squares regression. Second, one should consider the assumption made in this study that the models to be compared would have all pre-selected variables included, with no further regressor variable screening. This was necessary to create a certain degree of multicollinearity and to allow comparison among the three methodologies. As already mentioned, the multicollinearities involved in the two data sets used in the present study were due basically to physical constraints on the models. In this case, sensitivity of the results to variable selection is somewhat eased. That is because constraints are always present, and it would not matter as far as prediction is concerned which of the variables involved in the multicollinearity is removed from the estimated model (Mason et al., 1975). In reality, when using any one of these three methodologies, some sort of additional variable screening would probably have been made. Consequently, multicollinearity problems would have been less severe, and the performance of the three methodologies would be expected to be even more similar. Therefore, under the assumptions of this study, the method of choice to be used in the formulation of prediction equations in the next chapter will be ordinary least squares.

2.4 Conclusions

For analytical problems in which regression coefficient estimates and prediction were shown to be compromised by the existence of multicollinearity among regressor variables, ridge and principal components regression methodologies were evaluated and produced regression coefficient estimates with smaller variances than the estimates obtained from ordinary least squares regression. Ridge regression methodology produced smaller values of $PRESS_\kappa$ and C_κ than the values of PRESS and C_p produced by least squares and principal components regression. Principal components regression was superior to least squares in these two single number statistics. The superiority of the models producing biased estimators over least squares was greater when model performances were assessed by C_p and C_κ than when assessed by PRESS and $PRESS_\kappa$.

For the two data sets and for the pre-selected sets of regressor variables used in this study, it was clear that between the two alternatives to least squares, ridge regression produced better results than principal components regression. Ridge and least squares regression were quite similar in their regression coefficient estimates, in PRESS-like statistics and, to a lesser extent, in C_p-like statistics. These single number statistics always favored ridge regression.

If regression methodology is to be used for prediction, the performances of least squares and ridge regression were very similar. Under those circumstances one should favor the method easier to apply and with the lower computational cost, i.e., ordinary least squares. However, if one is trying to use regression methodology for interpretation of regression coefficients, ridge regression may be preferable over least squares.

3.0 Chapter 3. Prediction of Early-Life Production from Calfhood Traits of Angus and Simmental Females and of Lifetime Productivity from Calfhood and Early-Life Production Traits of Angus Females

The main problem in getting accurate predictors of cow efficiency is to identify precise and easy ways to obtain input estimates. The most precise, undoubtedly, would be measuring units of input energy either through individual feed consumption data of the dam and the calf or estimating it as a function of calf and cow weights. Body weights may be acceptable indicators of input energy, because nutritional requirements are generally regarded to be dependent on weight (Klosterman et al., 1968; Turner et al., 1974). Two potential difficulties may arise from them. First, the collection of feed consumption data of the dam and her progeny is costly and laborious, being almost impossible to apply in most commercial situations; and the collection of cow weights on a yearly basis is not practiced by most producers. The second problem is the time needed for the full expression of cow production traits. These traits require repeated observations of a cow's production during her life span. By the time her lifetime production traits are expressed, it would be too late for selection to take place because she would already be dead or culled. Additionally, if selection decisions are delayed, the average cow age increases, and annual genetic progress may decrease.

Variables measuring cow production and cow productivity (production per unit of time) come into play when either individual feed consumption data or cow weights are not available to estimate input. These variables reflect reproductive performance of the female, calf survival and calf performance in subsequent parities. In this sense they may be considered analogous to milk production of dairy cows in successive lactations, but with calf weaning weight replacing milk yield as the trait of major economic importance. Cows may affect weaning weights of their progeny in two ways: by contributing to their calf's genotype through their breeding value for growth and by offering them a good or poor preweaning environment through their milking ability (Neville, 1962; Rutledge et al., 1971; Reynolds et al., 1978; Boggs et al., 1980; Lubritz et al., 1989; Beal et al., 1990).

Any accurate predictor of lifetime cow production or productivity that can be estimated using traits expressed early in the heifer or cow's life would be useful for culling decisions in beef herds. The development of such cow efficiency predictors has been attempted by a number of authors (Vesely and Robison, 1972; Marshall et al., 1976; Dinkel and Brown, 1978; Davis et al., 1987).

In the present chapter, ordinary least squares regression methodology was used to study the relationships among several calfhood traits, early-life (first parity) reproductive traits, early life productive traits and lifetime productive traits. The usefulness of calfhood, early-life productive and early life reproductive traits as predictors of lifetime cow production and productivity were investigated. Additionally, repeatability of progeny weaning weights was estimated using least squares and restricted maximum likelihood analysis.

3.1 Literature Review

3.1.1 Relationships between Calfhood Traits, Early-Life Traits and Lifetime Production

The relationship between weaning weight and yearling weight of beef heifers with the subsequent weaning weight of their progeny has been examined in a number of studies (Koch and Clark, 1955; Vesely and Robison, 1972; Brown et al., 1979; Etienne and Martin, 1979; Davis et al., 1983a; Kirkpatrick et al., 1985). Correlations quantifying these relationships have generally been low, but always with a general trend for the association of progeny traits with dam yearling traits to be positive and larger than corresponding values involving dam weaning traits. Thus, there is a consensus among most authors that selection of replacement heifers for superior progeny weaning weights would best be accomplished by using heifer yearling traits as selection criteria.

A possible explanation for these lower correlations of progeny weaning performance with dam weaning traits than for dam yearling traits might be the higher values of yearling weight heritability and genetic correlation with cow mature size (Brown et al., 1972b; Smith and Cundiff, 1976), if mature cow size were positively related to cow productivity and efficiency (Hays and Brinks, 1980; Olson et al., 1982).

The development of empirical selection indexes for beef cattle using multiple regression techniques, using the phenotypic information on the parent to predict the aggregate phenotypic/economic value of the progeny, was attempted by Vesely and Robison (1972). The phenotypic/economic value of the progeny was calculated from their weaning weight and type score at weaning adjusted for sex. Analyses were run on an intra-sire basis. Multiple regression analyses were based on several models. One of them was fitted to the data that would predict the value of calves born to two- and three-year-old heifers. That is, the resulting equation would be applicable to females that had not produced a calf. Regressor variables included age of the heifer, birth, weaning and 18 month weights and type score of the heifer, age of the heifer's dam when she was born and weight measurements of the heifer's dam. The final prediction equation (R^2 = .49) included age of the heifer (positive regression coefficient, b), type score of the heifer at weaning (negative b), weight of the heifer at 18 months of age (positive b) and the linear and quadratic effects of age of the heifer's dam when she was born (u-shaped relationship). The authors commented that higher type scores of heifers at weaning might had been related to fatter calves, for a given weight, and that those fatter female calves had developed into dams producing calves of lower economic value. The negative effects of age of a dam on the performance of her daughter were attributable to the higher milk production and consequently better nutrition of heifers raised by middle age dams and subsequently to the excessive fatness of the heifer when raising her first calf.

The age of dam effect did not persist on female performance beyond the first calf. The prediction equation (R^2 = .48) applicable to females that had produced one or two calves included the effects of weaning weight of the female, body weight of the female in fall of the year preceding birth of the calf, average type score of previous calves and average weaning weight of previous calves. Regression coefficient estimates for all these variables had positive signs.

Similarly, Olson et al. (1982) examined the effect of cow size on cow productivity (adjusted calf weaning weight per cow exposed). They divided mature Hereford cows into four groups according to their size: small, medium, large and very large cows. Calves out of large cows had the highest birth weight (with no detrimental effect on calving ease), the fastest preweaning growth rates and thus, the highest adjusted weaning weights. The mean preweaning average daily gain and adjusted weaning weight of calves out of very large cows was below average. According to the authors, this could be the consequence of poorer maternal ability of very large cows adversely affecting the performance of their progeny.

These results, among others, support another possible explanation for the observed lower value of heifer weaning traits, when compared to yearling traits, as an indicator of future cow production. It is known that the negative environmental and(or) genetic relationship between maternal and direct effects for preweaning offspring growth affects more adversely the relationship between weaning traits of the heifer and her productivity as a cow than the relationship of her yearling traits and her cow productivity. Experiments have demonstrated that excessive fattening during growth prior to sexual maturity is detrimental to the lactation ability of dairy females (Swanson, 1967). In beef cattle, the detrimental effects of high growth rate or good maternal environment during the beef heifer's preweaning growth period upon her subsequent maternal ability have been documented in several studies (Christian et al., 1965; Mangus and Brinks, 1971; Koch, 1972; Kress and Burfening, 1972; Vesely and Robison, 1972; Holloway and Totusek, 1973; Seifert, 1975; Lubritz et al., 1989).

In Herefords, Mangus and Brinks (1971) found that heifers from two-, three-, four- and 12-year-old and older dams had lower actual average weaning weights than those of progeny from five- through 11-year-old dams. In contrast, the weaning weights of the heifer's subsequent progeny were highest for females produced by younger and older dams. According to Vesely and Robison (1972), the linear and quadratic partial regression coefficients of age of the dam on the weaning economic value of the first calf of her daughters were, respectively, -1.82 and .11 units of economic value per year of age.

Boston et al. (1975a) reported product-moment correlations between heifer growth and weaning weight and cow productivity in Angus and Hereford populations. Correlations were generally small, although 92% of the Angus and 100% of the Hereford correlations were positive. Weaning performance of the first calf was less closely related to weaning weight traits of the dam (from .13 to .19) than it was to yearling weight traits (from .18 to .30). According to the authors, a negative environmental and(or) genetic relationship between maternal and direct effects for growth might had been the cause for the lower correlations observed between weaning performance of heifers and the weaning weight of their progeny. However, correlation results indicated that selection of replacement heifers based on weaning and(or) yearling weight should result in some increase in progeny weaning weight.

Similarly, the effects of age of cow and age of the cow's dam when she was born on her subsequent milk yield and on weaning weight of her calves were evaluated by Lubritz et al. (1989). Highest milk yields were observed for cows born to and reared by two-year-old dams, milk yields were intermediate for those calved by three- and four-year-old dams and yields were lowest in daughters of mature dams. Cows born to and reared by older dams produced less milk and weaned lighter calves.

All these results suggested that mature, higher milking dams may be detrimental to the future performance of their female progeny and that age of the dam should be considered in evaluation of cow performance and when selecting replacement heifers.

The relationship between mammary development, milk yield and growth rate in heifers was examined in a review by Sejrsen (1978). The author stated that a major part of the development of the mammary gland takes place between birth and first calving, mainly in the period before and around onset of puberty, and in the last part of the pregnancy. Mammary growth and development are under hormonal control, and prolactin and growth hormone are of major importance. Increased energy intake during the rearing period can have a negative influence on prolactin and growth hormone concentration in the blood. Since these hormones stimulate mammary development, mammary growth and therefore milk yield can be inhibited. Additionally, high levels of energy can have a negative influence on the amount of secretory tissue in the udder and, consequently, a negative influence on milk production. However, animals with high genetic growth potential seem to have higher growth hormone concentrations in the blood and consequently better mammary growth and higher milk yield.

Low values of the correlation between weaning weight of heifers and the weaning performance of their calves were also observed by Hohenboken et al. (1973) and by Hays and Brinks (1980). The former authors examined the phenotypic correlations among characters of twin Hereford heifers and their progeny performance. Size of the heifer at eight months of age was a poor reflection of any measure of preweaning performance of her progeny. Correlations between progeny preweaning performance and size of the heifer at 15 months were slightly higher and always positive. The best two variables to predict progeny preweaning gain were 15 month height and eight to 15 month weight gain, but together they accounted for only 4% of the variation. According to Hays and Brinks (1980), some heifers may be heavier at weaning because of greater growth potential which they transmit to their offspring, thus causing a positive correlation with progeny growth; whereas other females may be heavy because they were raised by higher milk producing cows, thus causing a negative relationship. These two factors appear to balance each other causing the correlation to be small.

Whittle and Marlowe (1979) reported several correlations between first calf weaning weight, average weaning weight of all calves (up to six parturitions) and the heifer performance as a calf. The authors commented that a rapidly growing heifer in average or below average condition at 18 months of age would produce a first calf likely to have an adjusted weaning weight less than that of her subsequent offspring. A similar heifer, but in better condition, would likely produce a first calf that is closer to the average of her subsequent calves. The highest correlation with adjusted weight of a heifer's first offspring was with 18 month condition score of the heifer ($r = .24$). The highest correlations with average weight of all offspring involved 12 month weight ($r = .15$) and 18 month weight ($r = .18$). Prediction equations accounted, at most, for 10% of the total variation in calf weaning weight.

Etienne and Martin (1979) projected the effects of selection in retrospect for each of seven calfhood traits on later performance of Angus cows for conception rate, number of progeny weaned and weaning weight ratio. Cows were classified as first through fourth quartile with regard to each of seven calfhood traits. Selection differentials for each of these traits and secondary selection differentials for cow productivity traits were estimated. Selection based on weaning weight ratio, yearling weight ratio or postweaning daily gain ratio of a female would have increased weaning weight of her progeny while producing small but generally negative effects on her reproductive efficiency as a cow. Relative growth rate of the female was negatively related to reproductive measures while producing negligible effects on progeny weaning weight. The authors concluded that selection of heifers based on calfhood traits indicative of growth would be relatively ineffective in changing productivity of these females as cows. They commented that this situation would be somewhat similar to that in the dairy industry where the cow must be milked in order to estimate her productive capability with any degree of accuracy.

The relationships between growth curve characteristics (maturation rate and mature weight) and measures of lifetime cow productivity (YH = years in the herd, NC = number of calves weaned, TW = total calf weight weaned, TWA = total calf weight plus mature cow weight produced, AW = average calf weaning weight and TWY = calf weight weaned per year in the herd) and in efficiency of conversion (ME = predicted cow metabolizable energy required per kg calf produced) were investigated in a herd of Red Poll females by Marshall et al. (1984). Regressions of maternal lifetime productivity measures on mature cow weight were quadratic for YH, NC, TW and TWA with optimal cow weight being 606, 600, 605 and 628 kg, respectively, for those four traits. AW and ME were positive linear functions of cow mature weight. Regression coefficients of YH, NC, TW, TWY and TWA on maturation rate were negative. AW and ME were not significantly related to maturation rate.

Similar relationships have been observed between calfhood traits of the heifer and cow-calf efficiency. For example, Kirkpatrick et al. (1985), using data from beef (Hereford), dairy (Holstein) and beef x dairy cows raised in two locations, developed prediction equations of cow efficiency. Efficiency was defined as the ratio of calf weaning weight output over three parities to lifetime feed input of the cow and her calves. Dam weight or dam weight to height ratio at weaning of the calf in combination with progeny weaning weight accounted for 56 or 59% of the variation in weaning efficiency. Equations based solely on traits measured early in the life of the cow were of less predictive value. Yearling weight and weight to height ratio explained 22 and 25% of the variation in weaning efficiency, respectively. Equations using a measure of cow size or condition and progeny weight produced the best equations from both Wisconsin and South Dakota data. These equations performed well when validated on independent data. However, the authors did not consider the part-whole relationship between efficiency and progeny weights. Additionally, yearling weight and weight to height ratio of the dam, the best early traits for prediction of efficiency in the Wisconsin data, accounted for less than 1% of the variation in weaning efficiency in the South Dakota data.

In another cow-calf efficiency experiment, Davis et al. (1983b), using crossbred females, evaluated the relationship of cow efficiency ratios to traits of the dam and progeny weaned. Ratios of output to input were used to estimate efficiency, where outputs included weaning weights of progeny plus salvage value of the dam, and inputs included creep feed consumed by progeny plus feed consumed by the dam. Results suggested that weights, heights and weight to height ratios of dams at 240 days of age were not significantly correlated with subsequent efficiency of calf production, indicating that early-life indirect selection for lifetime cow efficiency would be ineffective. However, females exhibiting more efficient weight gains from 240 days to first calving tended to become more efficient dams. Using the same data, Davis et al. (1987) concluded that predictors of lifetime production obtained at the end of first or second parity were of variable value. Ratio predictors and multiple regression equations based on first parity progeny and dam traits did not have sufficient accuracy ($R^2<.30$) to be useful in the prediction of lifetime efficiency. However, lifetime efficiency was predicted with improved accuracy ($R^2\geq.30$) when information available at the conclusion of the second parity was utilized. Further increases in accuracy resulted from the inclusion of third parity data. Again, the authors did not consider that weaning weight of calves and cow lifetime efficiency have a part-whole relationship.

The effect of age of contemporary females at the start of their first breeding season on their subsequent production has not been studied. Rather, lifetime production of beef females calving first at two versus three years of age has been subject of several studies. Núñez-Dominguez et al. (1991)

observed that heifers that were bred to calve as two-year-olds had a .7% higher pregnancy rate, 3.7% lower calving rate, 8.0% lower calf survival at 72 hours post-partum and 13.7% lower calf crop weaned for their first calving than did heifers bred to calve as three-year-olds. However, when considering cumulative female performance up to 12 years of age, females first calving as two-year-olds experienced 1.1 more breeding seasons, had 1.2 more pregnancies, gave birth to 1.1 more calves, produced 1.0 more calves alive at 72 hours post-partum and weaned .9 more calves than females first calving as three-year-olds. The authors commented that if breeding heifers at one year of age has no adverse consequences on subsequent reproductive and maternal performance, then this practice would yield a greater lifetime performance than breeding heifers as two-year-olds, because the former system would potentially produce an extra calf.

The relationship between early-reproduction and cow lifetime productivity has not received much attention. Lesmeister et al. (1973) analyzed the effect of first calving date in beef heifers on lifetime production using production records from Angus and Hereford cows. An initial calving group was determined for each heifer based on the relative birth date of her first calf. A subsequent calving group was similarly assigned to each additional calf from the same cow. Heifers calving initially in the earlier (first and second) groups tended to calve earlier throughout the remainder of their productive lives than heifers calving initially in later groups. Calving group affected the percentage of calves surviving from birth to weaning, with the percentage survival decreasing continually for each 21 days later that calves were born during the calving season. Also, cows calving early the first time produced more kilograms of calf in their lifetime. Most of the difference in average annual lifetime production was associated with increased production at the first calving. Although initial calving group had no significant direct effect on weaning weight at subsequent calvings, it significantly affected subsequent calving group and calving group significantly affected calf weaning weights. The authors recommended that a larger proportion of replacement heifers than needed should be bred, pregnancy tested and culled at the end of the breeding period if they were not pregnant. Earlier conception and calving were associated with greater lifetime reproduction and production.

Another reproductive trait that may affect subsequent lifetime productivity is calving ease score. According to Brinks et al. (1973), Hereford heifers experiencing calving difficulty as two-year-olds weaned 11% fewer calves of those born the first year and 14% fewer calves per cow exposed the second year when compared to contemporaries that had no difficulty at first parturition. The calves from three-year-olds that had calving difficulty at two years of age were born an average of 13 days later and were 21 kg lighter at weaning than calves from three-year-old dams that experienced no difficulty when calving at two years of age.

In a review, Morris (1980b) pointed out that first-calf heifers experiencing calving difficulty produced fewer calves at their first and second calvings than those with easy calvings. Additionally, calving date effects on the average weaning weight of calves at constant weaning dates were large but were not always repeatable on later calves of the same cows. Because the record of a cow's first calf constitutes part of her lifetime record, there was a positive correlation between first calving date and lifetime average calving date and a negative correlation between first calving date and lifetime average calf weaning weight because of the part-whole relationship. The fact that early-life traits might involve a part-whole relationship with lifetime production also was identified by Saoud and Hohenboken (1984). The later authors avoided the part-whole relationship influence on the estimation of regression coefficients by excluding the first year of production from the calculation of the lifetime production trait.

More recently, the relative date of first calving of beef heifers was studied in relation to production efficiency and subsequent productive performance by Marshall et al. (1990). Average performance was evaluated by calving groups (CG), where CG1 included records of heifers calving (and calves born) during the first 21 days of the calving season for a particular year, CG2 included those calving from 22 through 42 days and CG3 included those calving after 42 days. Progeny actual weaning weights were heavier for heifers calving earlier in the season than for progeny of heifers calving later. The heavier weaning weights were associated with higher cumulative feed energy intakes, but this potential disadvantage was more than offset by the higher weaning weight and earlier calving date.

Their conclusions were that within a limited calving season, earlier calving dams tended to be more efficient because a greater proportion of their annual production cycle was spent in a productive (lactating) mode, diluting maintenance costs as a fraction of total costs.

3.1.2 Repeatability of Progeny Weaning Weights

The reliability of early progeny weaning performance as an indicator of cow future productivity depends on repeatability of weaning records of maternal half-sibs. Repeatability of progeny weaning weight in beef cattle has been intensively studied using many traditional statistical techniques such as intraclass correlation of maternal half-sibs, regression of later offspring records on the records of the previous offspring and product-moment correlations between consecutive offspring performance records of a dam (Taylor et al. 1960; Thompson, 1971; Boston et al. 1975b).

Among these methods, the most extensively used has been the intraclass correlation of maternal half-sibs. According to several publications from 1961 until 1986, the average value of of the estimated repeatabilities was .38, varying from .26 to .52 (Berg, 1961; Minyard and Dinkel, 1965; Hohenboken and Brinks, 1969, 1971; Thompson, 1971; Kress and Burfening, 1972; Boston et al., 1975b; Turner and Shrode, 1986).

Among those authors, Boston et al. (1975b), using Angus and Hereford weaning records, obtained different estimates of repeatability from pairs of records at different ages of dam and different levels of separation. As the level of separation between pairs of records increased, the magnitude of repeatability estimates decreased. Also the standard errors of the estimates increased as the number of records (as result of selection) decreased. Conclusions were similar to those previously obtained by Cunningham and Henderson (1965), in which it appeared that the predictive value of early records for production in later life was not as great as was often assumed. Turner and Shrode (1986), using calf average daily gain to weaning to estimate Angus and Hereford cow productivity, reported that the removal of sire effects from the data reduced the estimate of repeatability. In this case, the correlation among genes received by calves from the same sire would contribute to repeatability on a cow basis. Therefore, in herds where the occurrence of repeated mating is observed, the inclusion of sire effects in the model might lead to more realistic repeatability estimates.

Currently, the preferred method for variance component estimation for unbalanced data has been restricted maximum likelihood (REML), which was first described by Patterson and Thompson (1971). Associated with this method, mixed models algorithms have been used. They allow the incorporation of the relationships among animals via the numerator relationship matrix (Henderson, 1972), which is advantageous because it maximizes the use of the information available.

Using REML and fitting a sire, maternal-grand-sire and dam within maternal-grand-sire model, Wright et al. (1987) estimated components of variance and covariance for weaning weight of Simmental cattle. From the dam variance, an estimate of the permanent environmental variance was calculated to be 49.5 kg^2, which represented 7.4% of phenotypic variance and 35.7% of the dam variance. Weaning weight repeatability of maternal half sibs was estimated to be .21, which was smaller than most results previously described in the literature. The authors commented that this result was expected because of the higher level of unaccounted sources of variation from the field data used in that study, while research or experiment station data had been used in most previous studies.

The main problem with REML as a method to estimate variance and covariance components is that it uses algorithms requiring first and second derivatives of the log likelihood functions, such as the Expectation-Maximization algorithm and Fisher's Method of Scoring. Though relatively quick to converge, these algorithms require the inverse of a matrix of size equal to the number of random effects times the number of traits to be analyzed in each round of iteration, which is computationally demanding. More recently, Meyer (1989) developed a REML algorithm to estimate variance and covariance components from animal models with several random effects without using information from derivatives of the likelihood function, that is, the Derivative-Free Restricted Maximum Likelihood (DFREML).

3.2 Materials and Methods

3.2.1 Materials

3.2.1.1 Data

The same 771 Angus and 226 Simmental cow-calf pairs as described in the previous chapter contributed data for the study of the relationships between calfhood traits and production in the first parity (first calf weaning weight). For the first three years of productive life of Angus females, data were available from 1,622 calves from 672 dams that survived through five years of age. When production through 11 years was analyzed 1,118 calves from 209 Angus dams that survived through 13 years of age contributed data.

In the estimation of progeny weaning weight repeatability, the records of 2,881 calves of 672 Angus cows were used. Data from Simmental females were excluded from analysis of production beyond first parturition and from the estimation of repeatability because of low numbers. Culling reasons of females are listed in Tables 5 and 6, for Angus and Simmentals, respectively. Additional data were eliminated due to females that gave birth to twins and to missing information on calves.

Details concerning management of breeding females and calves were presented in Materials and Methods sections of the two previous chapters.

3.2.1.2 Variable Description

As defined in the Materials and Methods sections of the previous chapters, from birth weights and dates, weaning weights and ages and yearling weights and ages, the following 14 calfhood traits were defined for each female: Birth date, birth weight, actual weaning weight, 205-day weight, weaning weight ratio, actual yearling weight, 365-day weight, yearling weight ratio, birth-weaning ADG, weaning-yearling ADG, birth-yearling ADG, birth-weaning RGR, weaning-yearling RGR and birth-yearling RGR. Additionally, age of a heifer's dam at the time of her birth, year of birth and percentage Simmental groups were recorded. From the first parturition, the following variables were recorded: Calving date, calving ease score (1 = no assistance and 2 = some assistance), and sex (1 = male and 2 = female), birth weight and weaning weight of the calf.

For the calculation of production traits, actual weaning weights of calves were adjusted for sex, year of birth and sire of the calf, age of the dam and percentage Simmental (when that was appropriate). Records were not adjusted to a standard weaning age in order that variation among cows in calving date would be reflected in the data. As in the previous chapter and for the same reasons, sire effect was accounted for by fitting sire weaning weight EPDs as a covariate rather than by including sire as a categorical variable.

Besides production in the first parity (calf weaning weight), the following five variables were calculated for each female to express production (first two variables) and productivity (last three variables) either in the first three or in the first eleven years of productive life.

- Number of calves weaned.

- Total weaning weight of calves produced.

Calculated by adding the adjusted weaning weights of all calves produced in the first three or eleven years of productive life.

- Average weaning weight of calves produced.

  Calculated by dividing the total weaning weight of calves produced by the number of calves weaned.

- Weaning weight of calves produced per year of productive life.

  Calculated by dividing the total weaning weight of calves produced by the number of years of productive life a cow had been kept in the herd. Years of productive life was calculated as the time between birth date of the earliest born calf in the cow's first year of production and the time of weaning of her last calf.

- Calf survival from birth to weaning age.

  Calculated as the number of calves a cow weaned divided by the number of calves that were born, multiplied by 100.

Production and productivity variables were calculated for cows that weaned their first calf. The two production variables are primarily a function of the cow's ability to survive to a given age and the regularity in her conception, whereas the three productivity variables are primarily a function of the genetic and maternal contributions of the cow to her calves' survival and phenotype for growth.

3.2.2 Methods

Descriptive statistics (means and standard deviations) were calculated for all variables according to period of productive life and, for production in the first parturition, breed. Analyses were performed using procedures included in SAS (1990) and the PRESALL SAS-subroutine (1991), developed at the Consulting Center of the Virginia Tech Statistics Department.

3.2.2.1 Regression Analysis

From the previous chapter, recall that prediction results obtained by using ordinary least squares regression methodology were not seriously compromised by the level of multicollinearity present when regressing weaning weight of the first calf on heifer calfhood traits. The same multicollinearity diagnostics were performed for the additional variables included in this chapter. Results, in terms of eigenvalues, condition numbers and variance inflation factors, were within the same range as those observed in the previous chapter for the Angus data set. Therefore, ordinary least squares regression was used through this study.

First year production shares a part-whole relationship with production traits (number of calves weaned and total weaning weight of calves produced) for the first three or eleven years of productive life. Therefore, records of the first offspring were excluded from the calculation of production traits when they were regressed on traits observed in the first parturition. The same procedure was used by Saoud and Hohenboken (1984). For presentation of results in subsequent narrative, tables and figures, values of 1 and 230 kg (average weaning weight of the first calf) were added to the intercept of the regression models involving number of calves weaned and total weaning weight of calves produced, respectively.

In order to account for differences in the number of calves born and weaned for cows producing calves with the same survival proportions and(or) weaning weight averages, weighted least squares regression models were used when the dependent variable was either average weaning weight of calves or calf survival from birth to weaning age. Weights were the variables used as denominator in their calculations, i.e., number of calves born and number of calves weaned, respectively.

In multiple linear regression, the consideration of all subsets of regressors is a technique that has long been considered as the one to produce the optimum subset of predictors (Hawkins, 1973; Hocking, 1976). Limitations of this method are the possibility of a very large number of subregressions to be fitted, as the number of regressors increases. Several algorithms have been developed to accomplish the computations of all possible regressions, regression coefficients and model single number criteria (Hocking, 1976; Myers, 1990). In this study, the SAS-subroutine PRESALL was used to perform all possible regressions. For *k* regressor variables and C^i_k representing the combination of *k* different regressors taken in quantities of *i* regressors at a time, this algorithm fits $N = 1 + \sum_{i=1}^{k} C^i_k$ regression models and estimates N/2 regression coefficients for each regressor variable. Additionally, it calculates single number criteria (PRESS, the summation of absolute PRESS residuals, C_p, R^2 and error mean square) for each model and sorts all models according to those criteria. These single number criteria are useful in model evaluation. Their calculation and interpretation were described in the Materials and Methods section of the previous chapter.

Initial analyses showed that in order to fit 32,768 regression models and to obtain 16,384 estimates for each one of 15 regressor variables for the Angus data set (771 observations), the subroutine PRESALL would require close to maximum resource limits (6 hours of CPU time and 200 Mb of storage size) provided by the Batch machine six at the Virginia Tech Main Frame computer.

Therefore, in order to reduce the number of regressor variables and, additionally, to eliminate regressor variables that either presented redundant information and(or) had minor relationship with the dependent variable in question, all potential regressor variables were subject to variable screening. This variable screening was similar to the ones used in the previous chapters, i.e., two models were fit for each continuous regressor variable: a model including the variable's linear effect only and a model including its linear and quadratic effects. Between the two, the model presenting the smallest probability value was chosen as the one that best described the relationship between independent and dependent variables. The variables sex of calf and calving ease score observed in the first parturition were only fit linearly. In order to obtain systems with, at most, 15 regressor variables, a probability value of .10 was established as the upper limit for selecting a regressor variable to be part of the final subset of regressor variables. As in the previous chapter, all two-way interactions were tested in the presence of the two main effects and none was significant (all $P > .05$).

The method of fitting regression models with all possible combinations of regressor variables also allowed evaluation of stability of estimated regression coefficients in the system. This is somewhat analogous to the sensitivity analysis frequently used in economics, when the interest is not a single result of an analysis but the full range of all possible outcomes (Fabrycky and Thuesen, 1976). Therefore, in this study the ranges of estimated regressions coefficients are presented, together with their associated tests of statistical significance and the relative frequencies of regression coefficients according to their signs.

3.2.2.2 Repeatability Analysis

Repeatability (r), the intraclass correlation of temporally or spatially repeated observations on the same individual (Falconer, 1989), was calculated using two methodologies, least squares and REML analyses.

Fitting a model containing the fixed effects of sex and year of birth of the calf and the covariates calf's sire weaning weight EPD and age of cow (linear and quadratic effects), least squares analysis was performed and progeny weaning weight repeatability was calculated as

$$r = \frac{\hat{\sigma}_c^2}{\hat{\sigma}_c^2 + \hat{\sigma}_e^2}$$

where $\hat{\sigma}_c^2$ is the variance among cows (differences among cows due to all genetic variance plus the proportion of the environmental variance that is permanent) and $\hat{\sigma}_e^2$ is the temporary environmental variance, which represents differences among measurements within cows.

Expected mean squares from the analysis of variance were

$$\text{Among cows} = \sigma_e^2 + k\,\sigma_c^2$$
$$\text{Within cows} = \sigma_e^2$$

The value for k was determined as

$$k = \frac{1}{(s-1)}\left(n. - \sum_{i=1}^{s} n_i^2/n.\right)$$

where s is number of cows, n_i is number of calves from the ith cow and n. is total number of calves.

The approximate standard error for the least squares repeatability estimate was calculated according to the formula provided by Becker (1984).

The objective of including the calf's sire weaning weight EPD as a covariate in the repeatability model was to account for differences among breeding values of sires as they affected the weaning weight of their calves. However, since EPD accuracies were less than one, only part of that variation was removed.

Using an animal model containing the fixed effects of sex and year of birth of the calf and linear and quadratic effects of age of dam as covariate, REML calculation of weaning weight repeatability, according to the derivative free approach (Meyer, 1989), was given by

$$r = h^2 + c^2$$

where h^2 is the heritability of calf weaning weight and c^2 is the cow component due to non-additive genetic and permanent environmental effects. The standard error of this estimate was calculated directly from the variance-covariance matrix of the estimates of h^2 and c^2, provided by the algorithm.

3.3 Results and Discussion

Means and standard deviations of 15 calfhood traits and first calf weaning weight of Angus and Simmental females are presented in Table 39. The same statistics of calfhood traits, variables observed in the first calving season and variables indicative of productive performance of Angus females whose production was analyzed through three or eleven potential years are presented in Tables 52 and 53.

Models containing linear and quadratic effects of all calfhood traits accounted for 19.3 and 25.7% of the variation in weaning weight of the first calf from Angus and Simmental cows, respectively. These values are between the 10% obtained by Whittle and Marlowe (1979) and the 51% obtained by Vesely and Robison (1972). Differences in R^2 among studies are expected because data sets (including number of observations) and regressor variables (number and which ones have been considered) vary among studies. Variation in the five production traits of Angus females measured in two periods of productive life, accounted for by calfhood traits and(or) by traits observed in the first calving season, are presented in Table 54. In the same table, explained variation in production traits was considered both when information from the first calf was included in the calculation of the production trait and when it was not. When production in the first year was considered, the effect of first year of production was largely a part-whole relationship with the production trait. As expected that was more evident for models involving production in terms of calf weights than for models involving total number of calves weaned or survival. In order to avoid part-whole relationships Saoud and Hohenboken (1984) excluded information concerning the first year of production in their analyses. The same procedure was applied in this study.

Values of R^2 for complete models involving the different production traits are within the range found in the literature (e.g. Marshall et al. 1976; Kirkpatrick et al. 1985; Davis et al. 1987). In general smaller values of R^2 were observed for models having as dependent variables production traits more related to overall fertility and calf survival (number of calves weaned, total weaning weight of calves and calf survival from birth to weaning) than models involving annual average production (average weaning weight of calves and average weaning weight of calves per year of productive life). A possible explanation would be the observed higher values of heritability and repeatability for weaning weight than for fertility and survival (Brown et al., 1972a; Koch et al., 1982; Buddenberg et al., 1989; Mackinnon et al., 1990b).

3.3.1 Prediction of Production and Productivity

3.3.1.1 Weaning Weight of the First Calf

The values of R^2, regression coefficient estimates, their standard errors and tests of statistical significance are presented in Tables 40 and 41 for Angus and Simmentals, respectively, for analyses in which a linear or a linear plus quadratic model were fit relating each calfhood trait to weaning weight of a cow's first calf.. After variable screening, the final subset of regressor variables for the

Angus breed included birth date, birth date squared, age of dam, age of dam squared, actual weaning weight, weaning weight ratio, actual yearling weight, yearling weight ratio, weaning-yearling ADG and birth-yearling ADG. For the Simmental breed the final subset of regressor variables was composed of birth date, age of dam, age of dam squared, birth-yearling RGR and birth-yearling RGR squared.

The distribution of signs and ranges of regression coefficient estimates and their probability values are presented in Tables 55 and 56 for Angus and Simmental, respectively, from models in which all possible combinations of regression variables were included.

In general, heifers born earlier in their season weaned heavier first calves than females that were born later. For Simmentals, all regression coefficient estimates for birth date were negative and, for each delay of 30 days in the birth of a heifer, weaning weight of her first calf was reduced from 7.2 to 9.3 kg. For Angus, birth date of the heifer generally was negatively associated with the weaning weight of her first calf (76% of the regression coefficient estimates). For this breed, the relationship between birth date and weaning weight of the first calf was negative and curvilinear (Tables 40 and 55).

For both breeds, the relationship between age of dam when the heifer was born and the weaning weight of her first calf was best described as curvilinear. When fit linearly, regression coefficient estimates for this variable tended to represent slopes not different from zero (Tables 55 and 56, for Angus and Simmentals, respectively). However, the shape of the curves were different between breeds. For Angus, heifers born to and reared by younger or older dams produced first calves that were lighter than the ones produced by cows out of dams of intermediate age. For Simmentals, the relationship between age of the cow's dam and weight of her first progeny presented an u-shape. The same relationships were observed later, when the best models to predict weaning weight of the first calf were selected.

For Simmentals, the only additional regressor variable included in the final subset was birth-yearling RGR. Although 25% of the regression coefficients estimates of the linear effect of this variable were negative, the relationship was best described when the quadratic effect was included in the models (Tables 41 and 56).

For Angus females, results when six growth traits were included as regressor variables were more difficult to interpret because of inter-relationships among them. However, some generalization are possible. When regression coefficients of preweaning growth traits (actual weaning weight and weaning weight ratio) were estimated for all possible regression models, there was relative equality between the number of estimates with positive sign versus the number of estimates with negative sign. Estimates of these regression coefficients were greatly dependent upon which others regressor variables were included in the model. Regression coefficient estimates for postweaning growth variables (actual yearling weight, yearling weight ratio and weaning-yearling ADG) and for the growth variable, birth-yearling ADG, consistently had more positive than negative regression coefficients (from 72 to 100% of all possible estimates, Table 55). At least one conclusion can be made from these results. The future performance of a cow's first offspring is more positively associated with that female's yearling growth trait than with her growth through weaning.

For both breeds, all possible regression models were ranked according to single number criteria in model evaluation PRESS, summation of absolute PRESS residuals,C_p, R^2 and error mean square. Although attempts were made to select the model that performed best according to these criteria as a whole, when the best model differed according to different criteria, the choice always favored the model presenting the lowest value of the PRESS statistic. Recall from the previous chapter that the PRESS statistic is particularly important in evaluating predictability of models and, in this chapter, models were selected to predict future productive performance of females.

For Angus and Simmentals, the best models to predict weaning weight of the first calf of the *i*th female were as follows:

$$189.7 + 3.1\,(\mathrm{SE} = 1.9, \mathrm{P} = .11)\,x_{1i} - .27\,(\mathrm{SE} = .15, \mathrm{P} = .07)\,x_{2i} + \\ + .090\,(\mathrm{SE} = .033, \mathrm{P} < .01)\,x_{3i} \qquad (i = 1, 2, \ldots, 770) \text{ for Angus}$$

and

$$254.8 - 6.9\,(\mathrm{SE} = 3.1, \mathrm{P} = .03)\,x_{1i} + .54\,(\mathrm{SE} = .23, \mathrm{P} = .02)\,x_{2i} - \\ - .27\,(\mathrm{SE} = .14, \mathrm{P} = .05)\,x_{4i} \qquad (i = 1, 2, \ldots, 226) \text{ for Simmentals,}$$

where the SE's are the standard errors of the regression coefficient estimates, x_{1i} and x_{2i} are, respectively, age of dam and age of dam squared of the *i*th female, x_{3i} is the yearling weight of the *i*th female and x_{4i} is the birth date of the *i*th female.

These models accounted for 10.3 (Angus) and 11.9% (Simmentals) of the variation in weaning weight of the first calf, which represented, respectively, 53.4 and 50.2% of the maximum variation explained by complete models.

Graphic representations of the predicted weaning weight of first calves of Angus and Simmental females, according to these models, are presented in Figure 7. The maximum weaning weight of Angus first calves was predicted for heifers calved by 5.7-year-old cows. In contrast, for Simmentals the minimum first calf weaning weight was predicted for heifers produced by 6.4-year-old dams. The effects of age of dam on the future productive performance of her daughter have been shown to be important (e.g., Mangus and Brinks, 1971; Vesely and Robison, 1972; Lubritz et al., 1989). In general, results suggested that mature, high milking dams may cause reduced future performance of their female progeny. For Simmentals, but not for Angus females, results of this study are in agreement with the literature. The only explanation for the different relationship between age of an Angus dam versus that of a Simmental and their daughter's first calf weaning weight would be that the relatively higher milk production of middle aged Angus dams than younger or older dams was not enough to be detrimental to the future performance of their daughter's first progeny. Rather, that relatively higher milk production would be beneficial.

For each additional 50 kg an Angus heifer weighed at yearling age, her predicted first calf weaning weight would be increased by 4.5 kg, i.e., an increase of about 2.0%. The importance of the effects of yearling growth traits of the female on her progeny future performance was also observed by Vesely and Robinson, 1972; Brown et al, 1979; Whittle and Marlowe, 1979; and Hays and Brinks, 1980. None of the growth traits were included in the Simmental model.

Age of the Simmental heifer was an important factor for first calf weaning weight production. There was a continuous decline of 8.1 kg (or 3.5%) in weaning weight of the first calf for each additional 30 days in birth date of the female. Several authors have shown that age of heifer at the start of the breeding season (two versus three years old) affects performance of their calves and their lifetime productivity (Cundiff et al., 1974; Núñez-Dominguez et al., 1991). Studies relating variation in age of heifers born in the same season to performance of their offspring were not found in the literature.

The magnitude of the values of model R^2's and of variation in predicted weaning weights according to different values of the regressor variables may lead to the impression that application of these equations, and others to follow in subsequent sections of this chapter, have little economic importance. That seems to be true when considering animals as units. However, when large numbers of replacement heifers are considered, controlling 10-12% of the variability of the production trait and an increase of 2-3% in that trait might be important.

3.3.1.2 Total Number of Calves Weaned

Presented in Tables 57 and 58 are results of individual regressor models for number of calves weaned by Angus females. Based on the probability values of the statistical tests ($P \leq .10$), the following regressor variables were selected to model number of calves weaned in three years: Birth date, age of dam, age of dam squared, birth weight, actual yearling weight, actual yearling weight squared, yearling weight ratio and yearling weight ratio squared as calfhood traits, and, as traits observed in the first calving season, calving date, calving ease score, and sex and weaning weight of the calf. Although presenting a probability value smaller than .10, the variable 365-day weight was not included in the final subset because it would not provide any additional information to actual yearling weight. Among these regressor variables, the only ones that retained statistical significance to be part of the final subset to model number of calves weaned in eleven years of production were birth weight of the heifer, calving date and weaning weight of the first calf. Additionally, birth-yearling RGR of the female was incorporated.

The distribution of signs ranges and the probability values of regression coefficient estimates from models in which all possible combinations of regression variables were included are presented in Tables 59 and 60.

The relationship between birth date of the female and the number of calves she produced in the first three years of her productive life was negative for all possible regression models. For each month of delay in the female's birth the number of calves she would wean in the first three years would be reduced by from 3.2 to 8.3%. Reports concerning effects of birth date of the female on the number of calves she would wean were not found in the literature. However, older heifers at the start of the breeding season would tend to be bred earlier than younger heifers and, as a result, they would calve early in their first season. Several studies have shown that these early calvers tend to follow that pattern throughout their lifetime and to stay longer in their herds (Lesmeister et al., 1973: Staigmiller et al., 1990).

The age of dam effect on the number of calves in the first three years of production was best described by a curvilinear pattern that is different from the one observed between this regressor variable and weaning weight of the first calf (Tables 40 and 55 versus Tables 57 and 59). The number of calves weaned was smaller for females born to dams of intermediate age. It seems that the benefits of a good maternal environment provided by middle age dams on the performance of their daughter's first progeny were not beneficial for their daughter's prolificacy during the first three years of production.

Among calfhood growth traits, birth weight of the female was always negatively related to her prolificacy both in the first three and in eleven years of production. A 5 kg increase in the birth weight of the heifer was associated with a reduction from 5.0 to 6.5% in the number of calves she would have weaned in the first three years of production and from 2.3 to 8.5% in the number of calves she would have produced in eleven years. For number of calves weaned during the first three years of production, the importance of this variable and its consistency were confirmed subsequently, when the final model was selected. The effect of female's own birth weight on her future prolificacy might had been mediated through either birth weight of her offspring and(or) the occurrence of dystocia. Results presented in the first chapter of this dissertation and from the literature (e.g., Brinks et al., 1973; Naazie et al., 1989) are consistent with a positive association of birth weight of calves and calving difficulty, and that both phenomena affect subsequent fertility.

The association between yearling performance of the heifer and her subsequent prolificacy in the three first years of production was best described as curvilinear (Tables 57 and 59). Number of calves weaned during 11 years of productive life was a positive linear function of birth-yearling RGR of the females (Tables 58 and 60). Postweaning growth traits of the heifer have been shown to be more positively related to her future productive performance than preweaning traits (Boston et al., 1975a; Whittle and Marlowe, 1979; Hays and Brinks, 1980). When regressing maternal lifetime productivity measures on mature cow weight, Marshall et al., (1984) also found a quadratic relationship for number of calves weaned.

The inclusion of information observed in the first calving season increases the predictive performance of regression models for lifetime production (e.g., Etienne and Martin, 1979: Kirkpatrick et al., 1985). Traits observed during the first calving season are important because they are biologically correlated with future production and productivity. They also are important because they may reflect the cow's ability to survive to a given age. That being the case, they would mostly affect production rather than productivity traits. For number of calves weaned during the first three years of production, four variables observed during the first calving season were selected: Calving date, calving ease score, sex and weaning weight of the calf. Calving date and weaning weight of the first calf were also in the subset of regressor variables to predict number of calves weaned in eleven years of production. For both periods, the relationship between number of calves produced and first calving date was always negative, regardless of other regressor variables included in the models. The later the birth date of the first calf, the smaller the number of weaned calves its dam produced. These results are in agreement with the literature (Laster et al., 1973a; Lesmeister et al., 1973).

The number of weaned calves during the first three years of productive life was affected by dystocia and sex of the first calf. In three years of productive life, cows that produced male calves in the first parturition produced up to 6.5% fewer calves than cows whose first calf was female. Similarly, cows experiencing dystocia in the first parturition produced up to 10.0% fewer calves. These results are related to the lower conception rate of females that experienced dystocia and that gave birth and nursed male calves during their first year of production in comparison with females experiencing no dystocia and nursing female calves (Chapter one). They also are supported by findings of several authors (e.g., Brinks et al., 1973; Morris, 1980b; Doornbos et al., 1984).

Weaning weight of the first calf was positively associated with number of calves a cow weaned in both periods. For each additional 20 kg in the weaned weight of the first calf, there was an increase of about 3.6% in the number of calves weaned in three years and up to 3.4% more calves weaned in eleven years of production. The effect of this variable may be related to the association between weaning weight of the first progeny and the number and weaning weights of subsequent progeny. In beef cattle, average weaning weight repeatability, according to several publications, was .38 (for data from this study, it was .35 and .45, according to two estimation methods, to be seen later), and low weaning weight of calves was the second most common reason for culling females in this herd (Table 5).

The best model to predict number of calves weaned during the first three years of productive life was

$$2.7 - .0043\,(\mathrm{SE} = .0019,\ \mathrm{P} = .03)\,x_{1i} - .023\,(\mathrm{SE} = .008,\ \mathrm{P} < .01)\,x_{2i} -$$
$$- .18\,(\mathrm{SE} = .09,\ \mathrm{P} = .03)\,x_{3i} + .0037\,(\mathrm{SE} = .0009,\ \mathrm{P} < .01)\,x_{4i} \qquad (i = 1, 2, \ldots, 672)$$

where x_{1i} is the birth date of the ith female, x_{2i} is her birth weight, x_{3i} is her calving ease in the first parturition (1 = no difficulty, 2 = some difficulty) and x_{4i} is the weaning weight of her first calf. This model explained 10.9% of the observed variation for the trait, or 50.9% of the variation explained by the complete model.

The graphical representation of this model is presented in Figure 8. All relationships between regressors and dependent variables were linear. A delay of 30 days in the birth of a female resulted in a reduction of 6.5% in the number of calves she would wean during the first three years of her productive life. An additional 5 kg in her birth weight would be associated with a reduction of 5.8% in the number of calves produced during the first three years. A female experiencing calving difficulty in the first parturition would produce 9% fewer calves during the first three years and, for each 20 kg increase in the weaning weight of her first calf, she would produce 3.7% more calve the next two seasons.

The number of calves weaned in eleven years of productive life was best predicted by a model containing a single regressor variable, as follows

$$2.5 + .017\,(\mathrm{SE} = .008,\ \mathrm{P} = .03)\,x_{1i} \qquad (i = 1, 2, \ldots, 209)$$

were x_{1i} is the weaning weight of the first calf of the ith female. This model accounted for 5% of the observed variation in this trait or 16.2% of the variation explained by the complete model.

The positive and linear relationship between weaning weight of the first calf and number of calves weaned in eleven years of production is graphically presented in Figure 9. For a 20 kg increase in weaning weight of the first calf there would be an associated increase of 3.4% in the number of calves weaned by its dam in eleven years of productive life.

3.3.1.3 Total Weaning Weight of Calves Produced

In Tables 61 and 62 the results of individual regressor models for total weaning weight of calves produced by Angus females are presented. The same regressor variables included in the final subsets when modelling number of calves weaned were selected to model total weaning weight produced. Three other variables (actual weaning weight, birth-yearling ADG and birth-yearling ADG squared) were added to the subset to model total weaning weight during the first three years of production. The fact that the regressor variables used to model number of calves and total weaning weight of calves were basically the same, in addition to the agreement in signs of regression coefficients and similarity in R^2's, support the conclusion that variation in total weaning weight produced was due more prominently to variation in the number of calves produced than variation in individual weaning weights and that, although measured in different units, these two production traits are basically the same.

In Tables 63 and 64 are presented the distribution of signs, ranges of regression coefficients and their probability values from models in which all possible combinations of regression variables were included.

Results were similar to those observed for number of calves weaned. Females born earlier in the season and born to and reared by middle age dams tended to produce more kilograms of weaned calves in their first three years of production than younger females and females whose dams were either younger or older. Again, these effects did not persist when production through eleven years was analyzed.

Among preweaning growth traits, birth weight of the female was negatively associated with her future productive performance. For each 5 kg heavier a female was at birth, her future production would be reduced by 25.0 to 39.0 kg of calf weight weaned in the first three years and by 61.0 to 94.5 kg of calf weight weaned in eleven years of productive life. Once more, the effect of a female's own birth weight on her future production might have been mediated through either birth weight of her offspring and(or) the occurrence of dystocia. The majority (99%, Table 63) of the regression coefficient estimates for weaning weight of the female were positively associated with total weaning weight of calves produced in the first three years. Results from the literature are not conclusive about the relationship between female preweaning growth and the weaning weight of her progeny. For example, this association was reported as positive by Boston et al. (1975a) and by Etienne and Martin (1979) and negative by Vesely and Robison (1972). In the present study, weaning weights of the heifers were not adjusted for age. At weaning, heavier heifers were also older, and the combination of these two factors might had accounted, at least in part, for the positive association.

Actual yearling weight and yearling weight ratio were curvilinearly associated with weaning weight of calves in the first three years, with maximum production for females weighing 399 kg at yearling age and(or) having a yearling weight ratio of 102%. The distribution of signs and ranges of regression coefficient estimates for birth-yearling ADG was somewhat awkward. From all possible regressions it was not possible to conclude whether or not the relationship was linearly positive or curvilinear. This inconsistency was probably because of the interrelationships among regressor variables included in the models. Birth-yearling RGR, the only yearling trait included in the subset to model production through eleven years, was positively associated with total weaning weight of calves.

The importance of variables observed in the first calving season in predicting total weaning weight of calves produced was basically the same as observed for number of calves. A majority of the regression coefficient estimates for calving date were negative (56% for production in three years, Table 63 and 100% for eleven years, Table 64). At its limit, for each 20 days later a female gave birth to her first calf there was a decrease in her future weaned calf production of 45.0 kg in three years and 150 kg in eleven years. Again, these results are in agreement with the literature (Lesmeister et al., 1973; Marshall et al., 1990). Calving ease score of the first calf was always negatively related to weaning weight of calves produced in the three first years of female production. Females experiencing some calving difficulty in their first parturition produced from 24.3 to 35.2 kg less weaned weight of calves than females experiencing no difficulty. Sex of the first calf also affected subsequent production. Females that gave birth and nursed male calves produced from 27.5 to 31.0 less weaning weight of calves in the first three years. Once more, these results seem to be related to the reduction in conception rate of first parturition cows that experienced dystocia and that gave birth to male calves (chapter one). The importance of these two variables was diluted across years, such that it was not important when production through eleven years was analyzed.

Female progeny weaning weight production in the first year was positively associated with production both in the first three and in eleven years of productive life (Tables 65 and 66, respectively). For each additional 20 kg in calf weaning weight a female produced her first year there was an associated increase in production from 18.8 to 22.0 kg in the first three years and from 26.0 to 98.0 kg in eleven years of productive life. The importance of this variable in predicting female production was confirmed when it was included in the selected models.

The selected model to predict the total weaning weight in the first three years of production was:

$$\begin{aligned} &513.2 - 1.2\,(\mathrm{SE} = .4,\ \mathrm{P} < = .01)\, x_{1i} - 5.9\,(\mathrm{SE} = 2.1,\ \mathrm{P} < .01)\, x_{2i} + \\ &\quad + 35.1\,(\mathrm{SE} = 14.3,\ \mathrm{P} = .02)\, x_{3i} + 1.0\,(\mathrm{SE} = .2,\ \mathrm{P} < .01)\, x_{4i} \qquad (i = 1, 2, \dots, 672) \end{aligned}$$

where x_{1i} is the birth date of the ith female, x_{2i} is her birth weight, x_{3i} is the sex of her first calf (1 = male, 2 = female) and x_{4i} is the weaning weight of her first calf. This model explained 11.8% of the observed variation for the trait, or 49.4% of the variation explained by the complete model.

Graphic representation of this model, when sex of the first calf was male, is presented in Figure 10. Relationships between regressor variables and dependent variable in this model were basically the same as observed when all possible regressions were fit. That is, female production in the first three years was negatively associated with birth date and birth weight of the female and positively associated with her production in the first year.

For total weaning weight of calves during eleven years of productive life, the selected model was as follows:

$$346.1 + 5.0\,(\mathrm{SE} = 1.8,\ \mathrm{P} < .01)\, x_{1i} \qquad (i = 1, 2, \ldots, 209)$$

where x_{1i} is first calf weaning weight of the ith cow. This single regressor model accounted for 7.9% (24.4% of the R^2 of the complete model) of the variation in the production trait. The same linear relationship between weaning weight of the first calf and number of calves weaned in eleven years was observed for total weaning weight produced (Figure 11).

3.3.1.4 Average Weaning Weight of Calves

Performances of models having as regressors individual variables observed from birth to yearling age and in the first calving season of Angus females and, as the dependent variable, average weaning weight of calves produced in the first three years and in eleven years of productive life are presented in Tables 65 and 66, respectively. To model average weaning weight of calves produced during the first three years, birth date, actual weaning weight, weaning weight ratio, actual yearling weight, yearling weight ratio, weaning-yearling ADG, birth-yearling ADG, birth weight of the first calf, first calf calving ease score and first calf weaning weight were selected as regressor variables. The variable 365-day weight was not included in the final subset of regressor variables because it would not provide any additional information to actual yearling weight. For average weaning weight of calves produced in eleven years of productive life, the final subset of regressor variables included the calfhood traits birth weight, 365-day weight, yearling weight ratio, birth-yearling ADG, birth-yearling RGR, and of the traits observed in the first calving season birth weight, sex and weaning weight of the calf.

Results of all possible regression models fit for all possible combinations of these regressor variables are presented in Tables 67 and 68 for productivity in the first three and in eleven years of productive life, respectively.

Birth date of the female was linearly and mostly negatively associated with productivity in the first three years of productive life (97% of the regression coefficient estimates, Table 67). The same relationship was observed for the production traits weaning weight of the first calf, number of calves and total weaning weight produced in the first three years of production. The effect of birth date on a female's future productive performance did not have the same importance when these variables were measured through eleven years, meaning that the impact of this calfhood trait on female production was probably diluted over time.

Among preweaning growth traits, female birth weight was negatively related to average weaning weight of her progeny in eleven years of productive life (100% of negative signs). It is not clear which biological causes would have accounted for this relationship. Weaning performance of the female (actual weaning weight and weaning weight ratio) was mostly positively associated with average weaning weight of calves produced during the first three years. Up to 20% of any increase in the weaning weight of a female would be reflected in the average weaning weight of her progeny, and for an increment of 10% in the female's weaning weight ratio there would be an increase in average weaning weight of her first three offspring of up to 5.2 kg. In the literature, the association between weaning performance of a female and weaning performance of her progeny, if positive, was small (Boston et al., 1975a; Etienne and Martin, 1979, Davis et al., 1983b; Kirkpatrick et al., 1985). Hays and Brinks (1980) commented that females may be heavier at weaning either because of greater growth potential which they transmit to their offspring or because they were raised by higher milk producing cows which may be detrimental to their own milking ability, and that these two sources balance each other causing the correlation to be small.

Results relative to all possible regressions involving growth traits observed at yearling age once more are difficult to interpret because of interrelationships among traits. In general, the relationship between regressors and the dependent variable were consistently more positive when actual yearling weight (90% positive regression coefficient estimates, Table 67), yearling weight ratio (100 and 96% positive estimates, Tables 67 and 68, respectively) and birth-yearling RGR (90% positive estimates, Table 68) were involved. That consistency was confirmed later for yearling weight ratio, when it was the only calfhood trait included as regressor in the best models to predict progeny average weaning weight in both periods of productive life. Effects of female growth traits measured at yearling age on weaning performance of offspring were found to be important by a number of authors (e.g., Boston et al., 1975a; Whittle and Marlowe, 1979).

The usefulness of the traits observed in the first calving season, calf sex, birth weight, calving ease score and calf weaning weight, to predict female performance in subsequent years was evidenced when all possible regressions were fit. Average calf weaning weight in the first three years was positively associated with first calf birth weight, caving ease score and first calf weaning weight (100% positive estimates of regression coefficients). Relationships between birth and weaning weight of the first calf with future weaning weights of their maternal half-sibs exist because they share both 25% of their genes and the same preweaning maternal environment. A speculation about the observed association between calving ease observed in the first parturition and average weaning weight of the two subsequent calves would be due to the possible low calf survival of cows experiencing dystocia. If such a cow was kept in the herd, she would not have nursed a calf and, therefore, she might have been in better body condition by the next time she calved. Similar speculation can be made about the higher average weaning weight observed in eleven years of productive life when the cow's first calf was female (from 5.4 to 10.3 kg, Table 68). This effect might have been related to differences in birth weight and(or) differences in caving difficulty between sexes (chapter one) affecting the survival of first calves and, consequently , body condition and future performance of the female. Additionally, it has been shown that male calves tend to obtain more milk from their dams than female calves (Reynolds et al., 1978), which also might have led to a poorer body condition of the female by the time she started nursing her next calf.

Weaning weight of the first calf was the second most important variable to explain variation in average weaning weight of calves produced in the three first years ($R^2 = 4.9\%$, Table 65). It was by far the most important variable to explain variation in average weaning weight of calves produced in eleven years ($R^2 = 22.6\%$, Table 66). When all possible regressions were fit to model these productivity traits (average weaning weights during the first three and eleven years of productive life), regression coefficient estimates on weaning weight of the first calf were always positive and statistically significant (Tables 67 and 68). The importance of this regressor variable was confirmed later by its inclusion in both models to predict average weaning weight of calves.

The best model to predict average weaning weight of calves produced in the first three years of productive life was

$$130.8 + .63\,(\mathrm{SE} = .15,\ \mathrm{P} <= .01)\,x_{1i} + .57\,(\mathrm{SE} = .27,\ \mathrm{P} = .04)\,x_{2i} + \\ + .089\,(\mathrm{SE} = .031,\ \mathrm{P} < .01)\,x_{3i} \qquad (i = 1, 2, \ldots, 672)$$

where x_{1i} is the yearling ratio of the ith female, x_{2i} is the birth weight and x_{3i} is the weaning weight of her first calf. This model explained 12.2% of the observed variation for the trait, or 41.5% of the variation explained by the complete model.

Graphic representation of this model is presented in Figure 12.. All relationships between regressors and the productivity trait were positive and linear. An increase of 10% in the yearling weight ratio of the female would correspond an increase of 6.3 kg in the average weaning weight of her progeny in the first three years of productive life. Concerning traits of the first calf, a 5 kg increase in birth weight and a 20 kg increase in weaning weight would reflect an increase of, respectively, 2.9 and 1.8 kg in the average weaning weight of her subsequent calves.

The average weaning weight of calves produced in eleven years of productive life was best predicted by the following model:

$$142.8 + .34\,(\mathrm{SE} = .18,\ \mathrm{P} = .05)\,x_{1i} + .25\,(\mathrm{SE} = .05,\ \mathrm{P} < .01)\,x_{2i} \qquad (i = 1, 2, \ldots, 209)$$

were x_{1i} is the yearling weight ratio of the ith female and x_{2i} is the weaning weight of her first calf. This model accounted for 28.6% of the observed variation in this trait or 35.8% of the variation explained by the complete model.

The graphical representation of this model is presented in Figure 13. For an additional 10% in yearling weight ratio of the female, her predicted average calf performance would increase by 3.4 kg; and 25% of the superiority (or inferiority) of first calf weaning weight would be reflected in the prediction of her average weaning weight of calves produced in eleven years.

3.3.1.5 Average Weaning Weight of Calves per Year of Productive Life

In Tables 69 and 70, models of average weaning weight of calves per year of a female's productive life on individual variables observed from birth to yearling age and in the first calving season are presented. The following regressor variables were pre-selected to model weaning weight of calves per year of productive life in the first three years: actual yearling weight, weaning-yearling ADG and RGR, birth-yearling ADG and RGR, and first calf birth and weaning weights. Three variables were pre-selected when considering eleven years of productive life: age of dam, age of dam squared and calving date of the first calf.

Using these subsets of regressor variables, all possible regression models were fit. Distribution of signs, ranges and probabilities of regression coefficient estimates are presented in Tables 71 and 72 for the first three and eleven years of productive life, respectively.

When this productivity trait for the first three years was analyzed, most regression coefficient estimates for actual yearling weight were positive (92%, Table 71), which has been the pattern of this regressor for all production traits so far analyzed. Interpretation of the relationship between the four other growth traits of the female (weaning-yearling ADG and RGR, and birth-yearling ADG and RGR) and weaning weight of calves per year in the three first years of productive life should be made as a whole. For the weaning-yearling period, 88% of the estimated regression coefficients for ADG were positive but, for the same period, 72% of estimated regression coefficients for RGR were negative. In general, when both traits were included in the model, estimated regression coefficients were of opposite signs. The Pearson correlation between these two regressor variables was .91 ($P < .01$), providing an example of how the interdependence among regressors (or multicollinearity) affects the stability of regression coefficient estimates. The same inversion of signs was observed for the regressor variables birth-yearling ADG and birth-yearling RGR. The Pearson correlation between these two variables was .74 ($P < .01$). Among all growth variables, weaning-yearling ADG was selected to be part of the final model to predict average weaning weight of calves per year of productive life during the first three years of production.

Once more, traits observed in the first year of female production were associated with her future productive performance. First calf birth and weaning weight were positively associated with average weaning weight per year of productive life in the first three years of production. For a 5 kg increase in the birth weight of the first calf, average weaning weight of calves produced per year of productive life would increase from 2.8 to 7.0 kg. A 20 kg increase in the weaning weight of the first calf produced by a female would be associated with an increase from 2.8 to 4.0 kg in average weaning weight of calves produced each year during the first three years of her productive life.

Age of dam was the only calfhood variable included in the subset of regressors used to predict average weaning weight of calves per year of productive life through eleven years. Similarly to number and to total weaning weight of calves produced in the first three years of productive life, this variable had a curvilinear relationship with the productivity trait. In eleven years of production, females born to and reared by 5.0 year-old dams produced significantly less weaning weight of calves per year of productive life than daughters of younger or older dams.

When this productivity trait was analyzed through eleven years, the only important variable observed in the first calving season was calving date. For each 30 days later a female calved the first time, average weaning weight of her calves per year of productive life in eleven years of production would be increased from 10.2 to 11.1 kg (Table 72). This result seems to contradict most of the literature (Laster et al., 1973a; Lesmeister et al., 1973, Staigmiller et al., 1990), when the first calving date of a female was shown to be negatively associated with her lifetime production. It also seems to contradict previous results from this chapter, when negative associations between first calving date and number and total weaning weight of calves produced were observed. In general, females calving earlier their first calving season last longer in the herd than females calving later. Therefore, a positive association would be expected here. However, recall from Materials and Methods section that years of productive life were calculated as time between birth date of the earliest born calf in the cow's first year of production and time of weaning her last calf. By the time contemporary females weaned their first calf, their productive lives were about seven months. For each additional calf they weaned their productive lives were incremented by approximately 12 months. Consequently, there would be a negative association between the average weaning weight of calves per year of productive life and the length of the productive life.

The selected model to predict the average weaning weight of calves per year of productive life in the first three years of production was

$$223.6 + 57.7\,(\mathrm{SE} = 14.9,\ \mathrm{P} <= .01)\, x_{1i} + .15\,(\mathrm{SE} = .07,\ \mathrm{P} = .03)\, x_{2i} \qquad (i = 1, 2, \ldots, 672)$$

where x_{1i} is the weaning-yearling ADG of the ith female, and x_{2i} is the weaning weight of her first calf. This model explained 7.8% of the observed variation for the trait, or 32.2% of the variation explained by the complete model.

In Figure 14, the graphical representation of this model is presented. Relationships between regressor variables and independent variable in this model are the same as observed when all possible regressions were fit. That is, female productivity during the first three years was positively associated with weaning-yearling ADG of the female and with the production in the weaning weight of her first calf.

For the same trait through eleven years of productive life, the selected model contained only one trait, as follows:

$$296.8 - 16.1\,(\mathrm{SE} = 7.8,\ \mathrm{P} = .04)\,x_{1i} + 1.6\,(\mathrm{SE} = .8,\ \mathrm{P} = .05)\,x_{2i} \qquad (i = 1, 2, \ldots, 209)$$

where x_{1i} and x_{2i} are, respectively, age of dam and age of dam squared of the ith cow. This model accounted for 4.2% of the variation in the productivity trait (8.6% of the R^2 of the complete model). The same relationship observed when fitting all possible regressions was observed in this selected model (Figure 15).

3.3.1.6 Calf Survival from Birth to Weaning Age

Regression models of calf survival from birth to weaning age on individual variables observed from birth to yearling age and in the first calving season of Angus females are presented in Tables 73 and 74. The following variables were selected for the subset of regressors when calf survival was analyzed in the first three years of productive life: age of dam, age of dam squared, 365-day weight, weaning-yearling ADG, birth-yearling ADG, birth-yearling RGR, calving date and calving date squared. For calf survival during eleven years of production the variables age of dam, age of dam squared, actual yearling weight, actual yearling weight squared and calving ease score were selected. All possible regression models were performed and results are presented in Tables 75 and 76, respectively, for the first three or eleven years of productive life.

Once more, a female production trait tended to vary curvilinearly with age of dam. Maximum calf survival for the first three and in eleven years of production was observed when the female's dam was middle aged. The importance of age of the dam on survival of her daughter's progeny was confirmed later, when predictive models including this variable were selected.

When calf survival was analyzed for the first three years of production, a majority of the signs of regression coefficient estimates for 365-day weight (75%, Table 75) and all for weaning-yearling ADG were positive. Similarly, but in a curvilinear pattern, in eleven years of productive life actual yearling weight of the female affected survival of her calves. As in the previous section, interpretation of regression coefficients estimates for birth-yearling ADG and birth-yearling RGR are difficult because of the association between these two variables.

Among traits observed in the first calving season, calf survival for the first three years of a female's productive life tended to be positively associated with calving date of the first calf. Again, some speculation is possible. Later calving females have shorter periods in lactating mode than earlier calvers and, therefore, would tend to have a better body condition by the time they calve again. It is possible that these cows would provide a better maternal environment to their calves than earlier calving cows in poorer body condition. Lesmeister et al (1973) observed that calf survival was negatively associated with calving date. Calving ease score in the first parturition was associated with the future survival of calves a cow produced. The percentage of calf survival to weaning for eleven years of female production was reduced in 2.2 to 2.5% there was some difficulty in the first parturition. This might have been related to the repeatability of calving ease score and to the higher mortality observed for calves experiencing dystocia. Brinks et al. (1973) estimated the repeatability to be between 4.5 and 11.7% for various level of separation between parities.

Calf survival from birth to weaning age would best be predicted as follows:

$$98.8 - 2.3\,(\mathrm{SE} = .9,\ \mathrm{P} = .01)\,x_{1i} + .24\,(\mathrm{SE} = .09,\ \mathrm{P} < .01)\,x_{2i} \qquad (i = 1, 2, \ldots, 672),$$

for the first three years of female productive life and

$$102.2 - 3.1\,(\mathrm{SE} = 1.4,\ \mathrm{P} = .03)\,x_{1i} + .28\,(\mathrm{SE} = .14,\ \mathrm{P} = .04)\,x_{2i} \qquad (i = 1, 2, \ldots, 209)$$

for eleven years of female productive life. The x_{1i} and x_{2i} are, respectively, age of dam and age of dam squared of the ith female.

These models accounted, respectively, for 2.3 and 4.5% of the variation in calf survival, or 6.0 and 14.8% of the maximum variation explained by complete models.

The graphical representations of these models are presented in Figures 16 and 17, when calf survival was measured in the first three or in eleven years of productive life, respectively.

3.3.2 Repeatability of Progeny Weaning Weight

Repeatability estimates of progeny weaning weight using intraclass correlation of maternal half-sibs and DFREML analysis were .35 ± .08 and .45 ± .05. From the latter analysis, permanent environmental together with non-additive genetic effects were estimated to account for 14.4% of the variance while additive genetic effects accounted for 31.0% of the phenotypic variance in progeny weaning weight.

The repeatability estimate using intraclass correlation of maternal half-sibs was close to the average value observed in the literature using the same methodology (.38). Higher value was observed for the DFREML analysis when the relationship among individuals was considered. Dong and Van Vleck (1989) reported that heritability estimates of survival and calving interval in first-lactation

Holstein cows were larger using REML with an animal model than results in the literature that did not use REML with an animal model. In addition, inclusion of the relationship among animals increases the estimates of variance components (Van Vleck and Hudson, 1982; Johnson et al., 1992).

Repeatability in this study reflected the association of consecutive weaning weight records for the same female and was related to the importance of considering weaning weight of the first calf when predicting female production and productivity.

3.4 Conclusions

Results of this chapter indicate that weaning weight of the first calf of Angus and Simmental females is negatively associated with the heifer's birth date. Age of the female's dam affected the performance of her first offspring curvilinearly. For Simmentals, females produced by middle aged dams produced lighter calves while for Angus, they produced heavier calves than females produced by younger or older dams. In general, growth traits observed at weaning and yearling age were positively associated with weaning weight of the first calf for Angus. However, this association was more consistent for yearling growth traits. For Simmentals, the only growth trait associated with weaning weight of the first calf was birth-yearling RGR. Age of dam (both breeds), birth date (Simmentals) and actual yearling weight (Angus) were important variables to predict weaning weight of the first calf.

Production traits beyond the first calf weaning weight were only analyzed for Angus females. The effect of age of females persisted on early-life production traits. Birth date of females was negatively associated with the number of calves weaned, the total weaning weight of calves produced and the average weaning weight of calves during the first three years of productive life. Similarly, the effect of age of the dam was more evident for early-life production traits of the daughters, although it was also observed for average weaning weight of calves produced during eleven years of productive life and for calf survival. Results consistently favored females born to and reared by younger or older dams. Birth weights of females affected their future production. Heavier females at birth tended to produce a smaller number of calves and a lower amount of calf weaning weight through their lives than those females that were lighter at birth. The association among female birth weight, birth weight of her progeny and dystocia might have accounted for that effect. As observed for weaning weight of the first calf, overall female production and productivity were consistently more positively associated with yearling growth traits than with weaning growth traits.

Among traits observed during the first calving season, calving date was negatively associated with production traits (number of calves weaned and total weaning weight of calves produced). However, it was positively associated with productivity traits (average weaning weight of calves per year of productive life for eleven years of production and with calf survival). Speculation about this positive association is related to the way productive life was calculated and to the possible better body condition and subsequent milking ability of later calvers. Calving ease and females nursing male calves were negatively associated with early-life production (number of calves weaned and total weaning weight produced), probably because of lower conception rate in the second breeding season. However, those females experiencing dystocia the first calving season and that were kept in the herd weaned heavier calves in the next two seasons. Similarly, cows nursing female calves the first year tended to produce calves with higher weaning weight during eleven years of production than cows nursing male calves. Among all potential regressor variables, weaning weight of the first calf was always positively associated and it was the most important variable to predict female production and productivity, except for survival rate.

The usefulness of prediction equations, measured by the proportion of the variability explained by selected models, was low (R^2 from 2.3 to 28.6 %). However, when large numbers of animals are involved, controlling these relatively small amounts of variation of production traits may be economically important. Prediction equations for production traits in three years of productive life included birth date, birth weight of the female, calving ease in the first parturition (or sex of the calf) and weaning weight of the first calf. This latter variable was the only one useful to predict production traits measured in eleven years of productive life. Average calf weaning weights for the first three years of production were best predicted using a yearling growth trait of the female (yearling weight ratio or weaning-yearling ADG) and first calf weaning weight. Models including age of the female's dam best predicted weaning weight of calves per year of productive life in eleven years and calf survival.

Overall Conclusions

Selection of replacement heifers to enhance production is an important decision facing a cow-calf producer. In this dissertation, traits measured through yearling age of heifers, and in the first calving season, were examined to identify those traits which were predictive of female fertility in the two first breeding seasons and of cow lifetime productive performance. Fertility of Angus and Simmental females was studied using logistic regression methodology. Analyses to predict weaning weight of the first calf of Angus and Simmental females were conducted to compare least squares, ridge and principal components regression, to determine which method to use to analyze production traits. Production traits beyond the first year of production were analyzed only for Angus females.

Among the three methods, ridge and principal components regression produced regression coefficient estimates with smaller variances than estimates produced by least squares. For prediction, the performance of models produced by least squares and by ridge regression were very similar. In this case, the method that is easier and computationally cheaper to use (least squares) was the method of choice.

To maximize production, heifers born earlier in their own calving seasons should be favored. These heifers were more likely to conceive in their first breeding season, they calved earlier and produced heavier first calves at weaning, and they produced more weaned calves and more kilograms of weaned calves during their first three years of productive life. Beyond three years, the importance of the heifer age effect on production was diluted. The signs of the regression coefficient estimates, however, had a tendency for a negative association between birth date of the heifer and her lifetime production.

Similarly, the effect of age of a female's dam was more evident for early-life production, although it was also observed for average weaning weight of calves produced per year of productive life in eleven years and for calf survival through weaning. In general, results favored females that were born to and reared by younger or older females.

Concerning growth related traits, producers should favor heifers that are lighter at birth, heavier at yearling age and have lower weaning-yearling relative growth rate. Lighter females at birth were more likely to conceive as first-parity cows and tended to produce more calves and higher amounts of total weaning weight of calves through three years than did females that were heavier at birth. The likelihood of conception in the first breeding season was higher for heifers with lower weaning-yearling relative growth rate, probably because these heifers were closer to physiological maturity than heifers with higher relative growth rate. Overall female production and productivity were consistently more positively associated with yearling growth traits than with weaning growth traits.

Traits observed during the first calving season were useful for culling females after the first year of production. Calving date seemed to be associated with the heifer's own birth date, and was negatively associated with fertility of first parity cows, number of calves weaned and total weaning weight of calves produced. Cows that experienced calving difficulty and cows that were nursing males calves had lower rebreeding conception rate, produced a smaller number of weaned calves and a lower amount of total weaning weight of calves through three years of production than did females that experienced no dystocia or that were nursing female calves. Weaning weight of the first calf always was positively associated and it was the most important variable to predict female productive performance, except for birth to weaning survival rate of the calves.

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Appendix A. Tables

Table 1. Distribution of Angus females according to year of birth and disposition at weaning

Weaning	Year of birth										Total	Total
disposition	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	number	percentage
Selected	71	72	79	64	92	123	123	129	103	90	946	47.8
Sold	58	89	95	73	85	29	57	97	79	96	758	38.2
Feedlot	26	3	28	21	23	34	31	14	66	32	278	14.0
Total	155	164	202	158	200	186	211	240	248	218	1,982	100.0

Table 2. Distribution of Simmental females according to year of birth and disposition at weaning

Weaning	Year of birth						Total	Total
disposition	1981	1983	1985	1986	1987	1988	number	percentage
Selected	52	62	54	59	60	64	351	63.1
Sold	9	6	34	21	43	33	146	26.3
Feedlot	1	7	8	23	12	8	59	10.6
Total	62	75	96	103	115	105	556	100.0

Table 3. Distribution of Angus females present at the start of each breeding season according to birth year

Breeding	Year of birth										Total	Relative
season	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	number	percentage[1]
1st	71	72	79	64	92	123	123	129	103	90	946	46.6
2nd	53	57	66	53	76	106	94	104	81	78	768	81.2
3rd	43	48	45	39	58	63	59	92	45	73	565	73.6
4th	36	42	43	31	52	53	43	85	45	-	430	87.4
5th	32	38	35	28	38	40	38	85	-	-	334	86.8
6th	31	27	32	25	29	33	38	-	-	-	215	86.3
7th	23	24	25	24	20	33	-	-	-	-	149	84.2
8th	16	22	23	19	19	-	-	-	-	-	99	85.3
9th	15	17	17	6	19	-	-	-	-	-	74	75.0
10th	10	11	8	3	-	-	-	-	-	-	32	58.2
11th	6	5	3	2	-	-	-	-	-	-	16	50.0
12th	4	4	3	2	-	-	-	-	-	-	13	81.3
13th	3	4	3	-	-	-	-	-	-	-	10	90.9
14th	2	4	-	-	-	-	-	-	-	-	6	85.7
15th	1	-	-	-	-	-	-	-	-	-	1	50.0

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[1] Relative to the number of females present at weaning (first breeding season) or at the start of the previous breeding season (all subsequent breeding seasons).

Table 4. Distribution of Simmental females present at the start of each breeding season according to birth year

Breeding season	Year of birth 1981	1983	1985	1986	1987	1988	Total number	Relative percentage[1]
1st	52	62	54	59	60	64	351	61.3
2nd	36	52	44	49	56	54	291	82.9
3rd	33	42	31	42	40	-	188	79.3
4th	27	29	26	38	-	-	120	81.1
5th	23	24	21	-	-	-	68	82.9
6th	20	21	-	-	-	-	41	87.2
7th	18	16	-	-	-	-	34	82.9
8th	14	-	-	-	-	-	14	77.8
9th	12	-	-	-	-	-	12	85.7

[1] Relative to the number of females present at weaning (first breeding season) or at the start of the previous breeding season (all subsequent seasons).

Table 5. Distribution of Angus females according to age and reason at culling

Culling	Age, years											Total	Total
reason	2	3	4	5	6	7	8	9	10	11	≥12	number	percentage
Open	136	113	58	43	27	13	14	5	7	10	11	437	67.7
Abort	2	2	0	0	0	0	0	0	0	0	0	4	0.6
Dead calf	15	6	1	5	3	2	3	1	2	1	0	39	6.0
Performance	1	4	5	6	13	9	7	4	5	5	3	62	9.6
Died	1	4	1	3	1	3	1	0	0	0	2	16	2.5
Unknown	0	13	24	6	6	7	4	4	11	6	7	88	13.6
Total	155	142	89	63	50	34	29	14	25	22	23	646	100.0
Percentage	24.0	22.0	13.8	9.8	7.7	5.3	4.5	2.3	3.9	3.3	3.5	-	100.0

Table 6. Distribution of Simmental females according to age and reason at culling

Culling reason	Age, years 2	3	4	5	6	7	≥8	Total number	Total percentage
Open	58	47	16	9	4	2	1	138	79.7
Abort	1	0	0	0	0	0	0	1	0.6
Dead calf	2	5	3	1	0	1	0	12	7.0
Performance	0	0	0	4	0	2	2	8	4.6
Died	0	0	1	0	1	1	0	3	1.7
Unknown	0	0	6	1	1	1	3	12	7.0
Total	61	52	26	15	6	7	6	173	100.0
Percentage	34.9	30.2	15.1	8.7	3.5	4.1	3.5	-	100.0

Table 7. Distribution of Angus females according to year and month of birth

Birth	Year of birth										Total	Total
month	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	number	percentage
February	0	2	0	0	0	0	0	0	0	0	2	0.1
March	21	9	17	9	23	22	28	38	22	25	214	10.6
April	96	102	147	130	134	128	141	170	198	154	1,400	69.0
May	26	49	38	24	46	44	42	33	36	38	376	18.5
June	9	2	2	0	0	6	5	3	0	5	32	1.6
July	4	0	0	0	0	0	0	0	0	0	4	0.2
Total	156	164	204	163	203	200	216	244	256	222	2,028	100.0

Table 8. Distribution of Simmental females according to year and month of birth

Birth	Year of birth						Total	Total
month	1981	1983	1985	1986	1987	1988	number	percentage
February	1	0	0	0	0	0	1	0.2
March	1	7	9	4	10	8	39	6.8
April	51	58	75	79	86	74	423	73.8
May	8	15	12	21	20	20	96	16.8
June	2	2	1	2	3	4	14	2.4
Total	63	82	97	106	119	106	573	100.0

Table 9. Arithmetic means of variables observed from birth to weaning according to disposition and year of birth of Angus females

Variable	Weaning	Year of birth										General mean
description	disposition	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	± std.dev.
Birth date, days	Selected	28	31	28	21	25	36	39	21	40	26	30 ± 17
	Not selected[1]	40	36	35	27	32	45	52	31	47	33	37 ± 20
Age of the dam, years	Selected	4.3	5.0	4.3	4.1	5.5	5.0	4.5	5.2	4.9	5.0	4.8 ± 2.7
	Not selected	6.6	6.1	7.1	6.6	6.1	6.3	6.2	5.6	5.7	5.4	6.1 ± 3.1
Birth weight, kg	Selected	30	31	33	33	32	34	35	36	35	34	34 ± 4
	Not selected	29	29	30	31	32	32	32	33	33	32	32 ± 4
Actual weaning weight, kg	Selected	207	212	219	234	245	225	212	249	230	238	228 ± 26
	Not selected	193	186	183	189	212	175	178	212	181	203	192 ± 26
Weaning age, days	Selected	210	208	199	210	211	210	184	205	208	198	204 ± 16
	Not selected	203	202	191	204	203	201	177	196	201	191	197 ± 18
205-day weight, kg	Selected	203	210	226	229	239	221	233	250	227	246	230 ± 23
	Not selected	194	189	194	190	213	177	201	221	184	215	199 ± 27
Relative growth rate, %	Selected	.92	.92	.96	.94	.96	.90	.99	.95	.91	.98	.96 ± .07
	Not selected	.93	.92	.94	.89	.94	.85	.96	.96	.84	.96	.91 ± .09
Average daily gain, kg	Selected	.842	.873	.941	.958	1.007	.910	.968	1.044	.940	1.031	.958 ± .109
	Not selected	.807	.777	.796	.777	.885	.709	.824	.918	.734	.893	.817 ± .131
Weaning weight ratio, %	Selected	100	100	100	100	100	100	100	100	99	99	100 ± 10
	Not selected	93	88	83	81	87	78	84	85	79	85	84 ± 12

[1] Females that were sold or that went to feedlot.

Table 10. Arithmetic means of variables observed from birth to weaning according to disposition and year of birth of Simmental females

Variable	Weaning	Year of birth						General mean
description	disposition	1981	1983	1985	1986	1987	1988	± std.dev.
Birth date,	Selected	51	45	27	26	30	24	34 ± 17
days	Not selected[1]	46	67	30	34	40	35	38 ± 21
Age of the dam,	Selected	5.3	4.7	5.5	5.3	5.8	5.3	5.3 ± 2.8
years	Not selected	3.8	3.5	4.2	4.7	4.5	5.1	4.5 ± 2.7
Birth weight,	Selected	36	37	39	37	37	38	37 ± 4
kg	Not selected	30	35	35	35	35	35	35 ± 4
Actual weaning weight,	Selected	251	243	250	226	250	240	243 ± 25
kg	Not selected	249	188	206	174	202	209	200 ± 35
Weaning age,	Selected	206	210	205	204	198	190	202 ± 15
days	Not selected	216	188	204	195	188	178	192 ± 22
205-day weight,	Selected	250	239	251	227	257	257	247 ± 24
kg	Not selected	230	201	207	181	216	235	210 ± 31
Relative growth rate,	Selected	.94	.91	.90	.88	.97	.97	.93 ± .08
%	Not selected	.97	.90	.87	.82	.93	1.01	.91 ± .13
Average daily gain,	Selected	1.039	.989	1.030	.926	1.076	1.066	1.021 ± .115
kg	Not selected	.972	.811	.838	.713	.883	.976	.855 ± .155
Weaning weight ratio,	Selected	100	104	108	111	110	105	107 ± 11
%	Not selected	99	80	89	85	89	92	89 ± 14

[1] Females that were sold or that went to feedlot.

Table 11. Arithmetic means of traits observed from weaning to yearling age and fertility in the first breeding season of selected Angus females according to year of birth

Variable description	Year of birth 1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	Total Number	General mean ± std.dev.
Actual yearling weight, kg	350	344	403	363	368	372	331	388	410	398	946	373 ± 39
Yearling age, days	448	418	505	478	370	402	406	439	412	415	946	425 ± 38
365-day weight, kg	303	313	315	311	369	348	298	344	371	356	946	335 ± 37
Birth-weaning ADG[1], kg	.842	.873	.941	.958	1.007	.910	.968	1.044	.940	1.031	946	.958 ± .109
Weaning-yearling ADG, kg	.600	.626	.601	.481	.779	.764	.532	.591	.882	.734	946	.666 ± .159
Birth-yearling ADG, kg	.715	.749	.734	.690	.909	.840	.729	.803	.911	.875	946	.803 ± .099
Birth-weaning RGR[2], %	.92	.92	.96	.94	.96	.90	.99	.95	.91	.98	946	.96 ± .07
Weaning-yearling RGR, %	.22	.23	.20	.17	.26	.26	.20	.19	.28	.24	946	.23 ± .05
Birth-yearling RGR, %	.55	.57	.50	.50	.66	.59	.56	.55	.60	.59	946	.57 ± .07
Fertility, %	77	86	85	83	87	92	88	85	81	89	946	86 ± 4

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[1] ADG = average daily gain.
[2] RGR = relative growth rate.

Table 12. Arithmetic means of traits observed from weaning to yearling age and fertility in the first breeding season of selected Simmental females according to year of birth

Variable description	Year of birth 1981	1983	1985	1986	1987	1988	Total Number	General mean ± std.dev.
Actual yearling weight, kg	384	372	392	368	381	395	351	382 ± 31
Yearling age, days	365	404	434	411	413	404	351	405 ± 24
365-day weight, kg	385	349	350	336	347	356	351	353 ± 30
Birth-weaning ADG[1], kg	1.039	.989	1.030	.926	1.076	1.066	351	1.021 ± .115
Weaning-yearling ADG, kg	.840	.661	.621	.686	.612	.724	351	.689 ± .133
Birth-yearling ADG, kg	.951	.831	.805	.804	.835	.884	351	.852 ± .083
Birth-weaning RGR[2], %	.94	.91	.90	.88	.97	.97	351	.93 ± .08
Weaning-yearling RGR, %	.27	.22	.20	.24	.20	.23	351	.23 ± .04
Birth-yearling RGR, %	.65	.58	.53	.56	.57	.58	351	.58 ± .06
Fertility, %	69	84	81	88	92	84	351	83 ± 8

[1] ADG = average daily gain.
[2] RGR = relative growth rate.

Table 13. Arithmetic means of variables observed at birth and at weaning of Angus females according to year of birth and fertility in the first breeding season

Variable description	Pregnancy outcome	Year of birth										General mean
		1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	± std.dev.
Birth date, days	Pregnant	24	30	26	20	24	35	38	21	38	25	29 ± 15
	Not pregnant	43	34	33	29	31	44	47	23	47	35	39 ± 20
Age of the dam, years	Pregnant	4.0	4.8	4.2	3.9	5.6	5.1	4.5	5.3	5.1	5.1	4.8 ± 2.7
	Not pregnant	5.3	6.2	5.0	4.7	5.0	3.8	4.6	4.5	4.2	4.2	4.7 ± 2.5
Birth weight, kg	Pregnant	30	32	33	33	32	34	34	35	34	34	34 ± 3
	Not pregnant	30	31	33	32	32	35	35	36	35	35	34 ± 4
Actual weaning weight, kg	Pregnant	212	213	218	235	245	226	212	249	232	240	229 ± 25
	Not pregnant	192	209	225	226	239	221	212	253	223	224	223 ± 29
Weaning age, days	Pregnant	214	211	202	211	211	211	186	206	210	199	205 ± 16
	Not pregnant	197	208	195	202	207	203	180	204	201	189	199 ± 18
205-day weight, kg	Pregnant	204	211	224	229	239	221	233	249	227	246	230 ± 23
	Not pregnant	198	207	232	228	238	223	236	253	227	242	229 ± 26
Birth-weaning ADG[1], kg	Pregnant	.848	.875	.936	.957	1.007	.910	.966	1.041	.940	1.034	.958 ± .107
	Not pregnant	.821	.858	.971	.959	1.003	.916	.980	1.061	.940	1.010	.956 ± .120
Birth-weaning RGR[2], %	Pregnant	.91	.92	.96	.93	.96	.90	.99	.95	.91	.98	.94 ± .07
	Not pregnant	.95	.92	.97	.97	.97	.91	.99	.96	.93	1.00	.96 ± .08
Weaning weight ratio, %	Pregnant	102	100	100	101	100	100	100	100	101	101	100 ± 10
	Not pregnant	93	98	103	97	98	98	100	101	97	94	97 ± 11
Total number of females	Pregnant	55	62	67	53	80	113	108	109	83	80	810
	Not pregnant	16	10	12	11	12	10	15	20	20	10	136

[1] ADG = average daily gain.
[2] RGR = relative growth rate.

Table 14. Arithmetic means of variables observed at yearling age of Angus females according to year of birth and fertility in the first breeding season

Variable	Pregnancy	Year of birth										General mean
description	outcome	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	± std.dev.
Actual yearling weight, kg	Pregnant	351	344	403	366	370	272	331	388	409	398	373 ± 38
	Not pregnant	347	345	408	347	357	371	330	388	415	391	372 ± 40
Yearling age, days	Pregnant	452	420	508	479	370	403	407	439	414	416	425 ± 37
	Not pregnant	435	418	502	470	366	395	399	437	405	406	420 ± 40
365-day weight, kg	Pregnant	305	313	314	313	371	347	297	344	371	356	336 ± 37
	Not pregnant	297	312	320	297	357	346	298	345	373	357	331 ± 37
Weaning-yearling ADG[1], kg	Pregnant	.584	.623	.602	.486	.786	.763	.531	.594	.868	.729	.665 ± .157
	Not pregnant	.652	.648	.595	.452	.737	.778	.537	.576	.938	.768	.674 ± .176
Birth-yearling ADG, kg	Pregnant	.710	.748	.733	.694	.912	.839	.728	.804	.905	.875	.803 ± .098
	Not pregnant	.731	.751	.742	.671	.887	.848	.737	.802	.939	.878	.803 ± .101
Weaning-yearling RGR[2], %	Pregnant	.22	.23	.19	.16	.25	.26	.20	.19	.28	.23	.21 ± .05
	Not pregnant	.25	.24	.20	.17	.26	.27	.20	.18	.30	.26	.23 ± .06
Birth-yearling RGR, %	Pregnant	.54	.57	.50	.50	.66	.59	.56	.55	.60	.59	.57 ± .05
	Not pregnant	.57	.58	.50	.51	.66	.60	.56	.54	.61	.60	.57 ± .05
Yearling weight ratio, %	Pregnant	100	100	100	101	101	100	100	100	100	100	100 ± 8
	Not pregnant	99	100	101	96	97	100	100	100	101	98	99 ± 8
Total number of females	Pregnant	55	62	67	53	80	113	108	109	83	80	810
	Not pregnant	16	10	12	11	12	10	15	20	20	10	136

[1] ADG = average daily gain.
[2] RGR = relative growth rate.

Table 15. Arithmetic means of variables observed at birth and at weaning of Simmental females according to year of birth and fertility in the first breeding season

Variable description	Pregnancy outcome	Year of birth						General mean
		1981	1983	1985	1986	1987	1988	± std.dev.
Birth date, days	Pregnant	49	46	26	24	30	24	32 ± 16
	Not pregnant	55	42	28	32	27	25	37 ± 19
Age of the dam, years	Pregnant	5.3	4.6	5.8	5.1	5.7	5.6	5.4 ± 2.7
	Not pregnant	5.3	5.1	4.2	6.0	6.3	3.7	5.0 ± 2.8
Birth weight, kg	Pregnant	36	37	40	37	37	38	38 ± 4
	Not pregnant	37	37	37	37	38	38	37 ± 4
Actual weaning weight, kg	Pregnant	253	244	252	227	250	240	244 ± 24
	Not pregnant	246	242	244	220	254	239	240 ± 26
Weaning age, days	Pregnant	208	209	204	205	202	190	202 ± 15
	Not pregnant	202	213	205	201	198	189	202 ± 15
205-day weight, kg	Pregnant	250	240	252	228	257	257	248 ± 24
	Not pregnant	249	236	245	224	258	256	244 ± 25
Birth-weaning ADG[1], kg	Pregnant	1.042	.993	1.033	.929	1.076	1.067	1.024 ± .114
	Not pregnant	1.033	.971	1.014	.912	1.072	1.062	1.007 ± .120
Birth-weaning RGR[2], %	Pregnant	.94	.91	.90	.88	.97	.97	.93 ± .08
	Not pregnant	.95	.89	.93	.89	.94	.98	.93 ± .09
Weaning weight ratio, %	Pregnant	101	104	109	111	110	105	107 ± 10
	Not pregnant	98	103	106	108	111	105	104 ± 11
Total number of females	Pregnant	36	52	44	49	56	54	291
	Not pregnant	16	10	10	9	5	10	60

[1] ADG = average daily gain.
[2] RGR = relative growth rate.

Table 16. Arithmetic means of variables observed at yearling age of Simmental females according to year of birth and fertility in the first breeding season

Variable	Pregnancy	Year of birth						General mean
description	outcome	1981	1983	1985	1986	1987	1988	± std.dev.
Actual yearling weight, kg	Pregnant	386	373	393	372	380	394	383 ± 30
	Not pregnant	381	365	391	349	395	401	379 ± 34
Yearling age, days	Pregnant	367	403	433	411	416	404	407 ± 23
	Not pregnant	361	407	434	406	413	403	399 ± 29
365-day weight, kg	Pregnant	386	350	350	339	347	355	353 ± 29
	Not pregnant	388	343	347	321	359	360	354 ± 34
Weaning-yearling ADG[1], kg	Pregnant	.835	.667	.617	.698	.609	.717	.684 ± .130
	Not pregnant	.852	.630	.641	.627	.657	.757	.714 ± .143
Birth-yearling ADG, kg	Pregnant	.952	.836	.813	.813	.833	.881	.850 ± .079
	Not pregnant	.953	.807	.816	.768	.857	.902	.860 ± .098
Weaning-yearling RGR[2], %	Pregnant	.26	.22	.19	.24	.20	.23	.22 ± .04
	Not pregnant	.28	.21	.21	.22	.21	.24	.24 ± .05
Birth-yearling RGR, %	Pregnant	.65	.58	.53	.56	.57	.58	.57 ± .04
	Not pregnant	.65	.57	.55	.55	.56	.59	.59 ± .05
Yearling weight ratio, %	Pregnant	100	100	100	101	100	105	100 ± 8
	Not pregnant	99	98	99	95	103	101	99 ± 8
Total number of females	Pregnant	36	52	44	49	56	54	291
	Not pregnant	16	10	10	9	5	10	60

[1] ADG = average daily gain.

[2] RGR = relative growth rate.

Table 17. Performance of logistic regression models of fertility of Angus females in the first breeding season on individual variables observed at birth and from birth to yearling age

Individual regressor model[1]	χ^2 proportion explained, %	Test on model χ^2	Test on model Prob.	Width of C.I.[2], %	Average absolute res.[3], %	Predicted probability - observed response association[4], % Concordant	Discordant	Tied
Birth date	4.7	36.4	<.01	5.9	23.5	63.7	34.8	1.5
Age of the dam	.2	1.6	.46	7.3	24.6	46.2	41.2	12.6
Birth weight	.2	1.4	.51	7.0	24.6	43.6	42.2	14.2
Actual weaning weight	1.2	8.9	.01	6.8	24.3	51.8	40.6	7.6
205-day weight	.4	3.4	.10	6.9	24.5	46.1	43.0	10.9
Weaning weight ratio	.9	6.9	.01	6.0	24.4	55.1	42.9	2.0
Actual yearling weight	.1	.8	.68	7.1	24.6	44.2	38.6	17.2
365-day weight	.2	1.6	.21	6.1	24.6	51.3	45.0	3.7
Yearling weight ratio	.2	1.2	.28	6.1	24.6	49.3	46.0	4.7
Birth-weaning ADG[5]	.4	2.8	.25	6.9	24.5	44.5	40.4	15.1
Weaning-yearling ADG	.3	2.7	.26	7.1	24.6	48.9	42.5	8.6
Birth-yearling ADG	.0	.2	.92	7.2	24.7	37.5	35.7	26.8
Birth-weaning RGR[6]	.5	3.0	.09	6.0	24.5	53.6	43.8	2.6
Weaning-yearling RGR	1.6	11.5	<.01	7.0	24.3	53.3	40.5	6.2
Birth-yearling RGR	.0	.2	.63	6.1	24.7	46.6	43.5	9.8

[1] Two models were fit for each variable, one including linear and one with linear and quadratic effects. The model with the higher overal level of significance is presented here.
[2] Average width of the 95% confidence interval of the responses.
[3] Average absolute residuals.
[4] Association between the predicted probability and the observed response for all pairs of observations.
[5] ADG = average daily gain.
[6] RGR = relative growth rate.

Table 18. Performance of logistic regression models of fertility of Simmental females in the first breeding season on individual variables observed at birth and from birth to yearling age

Individual regressor	χ^2 proportion	Test on model		Width of	Average absolute	Predicted probability - observed response association[4], %		
model[1]	explained, %	χ^2	Prob.	C.I.[2], %	res.[3], %	Concordant	Discordant	Tied
Birth date	1.1	3.5	.06	10.6	28.0	56.2	41.9	1.9
Age of the dam	.6	2.0	.39	12.6	28.2	53.7	39.0	7.3
Birth weight	.2	.5	.49	10.6	28.3	48.7	43.8	7.6
Actual weaning weight	.3	1.1	.30	10.7	28.3	51.3	45.6	3.1
205-day weight	.4	1.3	.25	10.7	28.2	51.9	45.7	2.4
Weaning weight ratio	1.3	4.2	.04	10.6	28.0	55.8	42.4	1.7
Actual yearling weight	.7	2.3	.32	12.2	28.1	49.9	41.8	8.3
365-day weight	.6	2.0	.36	12.1	28.2	49.7	44.5	5.4
Yearling weight ratio	.4	1.2	.27	10.6	28.2	51.9	45.1	3.0
Birth-weaning ADG[5]	.3	1.1	.29	10.7	28.3	51.5	46.0	2.6
Weaning-yearling ADG	.8	2.5	.11	10.7	28.1	55.4	43.0	1.7
Birth-yearling ADG	1.4	4.4	.11	12.1	28.0	57.6	36.9	5.6
Birth-weaning RGR[6]	.3	.9	.64	12.2	28.3	46.8	40.8	12.4
Weaning-yearling RGR	1.3	4.1	.04	10.7	27.9	56.9	41.7	1.4
Birth-yearling RGR	1.1	4.6	.10	12.3	27.7	56.1	37.4	6.5

[1] Two models were fit for each variable, one including linear and one with linear and quadratic effects. The model with the higher overal level of significance is presented here.

[2] Average width of the 95% confidence interval of the responses.

[3] Average absolute residuals.

[4] Association between the predicted probability and the observed response for all pairs of observations.

[5] ADG = average daily gain.

[6] RGR = relative growth rate.

Table 19. Regression coefficient estimates, standard errors and tests of significance of logistic regression models of fertility of Angus females in the first breeding season on individual variables observed from birth to yearling age

Individual regressor	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
model[1]	χ^2	Prob.	χ^2	Prob.	β_0	β_1	β_2
Birth date	36.7	< .01	-	-	2.84 ± .21	-.031 ±.005	-
Age of the dam	1.0	.31	1.38	.26	2.10 ± .40	-.16 ± .15	.014 ± .013
Birth weight	1.4	.23	1.4	.24	-4.20 ± 4.99	.35 ± .30	-.0052 ± .0044
Actual weaning weight	4.2	.04	3.6	.05	-7.29 ± 4.01	.074 ± .036	-.00015 ± .00008
205-day weight	3.7	.06	3.4	.07	-7.49 ± 4.83	.081 ± .043	-.00018 ± .00009
Weaning weight ratio	6.8	.01	-	-	-.72 ± .96	.025 ± .009	-
Actual yearling weight	.7	.40	.7	.41	-3.30 ± 5.87	.026 ± .031	-.000034 ± .00004
365-day weight	1.6	.21	-	-	.71 ± .85	.0032 ± .0026	-
Yearling weight ratio	1.2	.28	-	-	.47 ± 1.22	.013 ± .012	-
Birth-weaning ADG[2]	3.0	.08	3.0	.09	-4.98 ± 3.86	14.29 ± 8.19	-7.44 ± 4.32
Weaning-yearling ADG	2.1	.15	2.4	.12	.15 ± 1.25	5.13 ± 3.56	-3.79 ± 2.43
Birth-yearling ADG	.2	.68	.2	.68	-.26 ± 5.08	5.08 ± 12.43	-3.11 ± 7.53
Birth-weaning RGR[3]	3.0	.09	-	-	4.11 ± 1.17	-2.45 ± 1.22	-
Weaning-yearling RGR	7.8	.01	9.4	< .01	-1.45 ± 1.31	30.74 ± 11.04	-68.80 ± 22.46
Birth-yearling RGR	.2	.63	-	-	2.28 ± 1.04	-.87 ± 1.81	-

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[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overal level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

Table 20. Regression coefficient estimates, standard errors and tests of significance of logistic regression models of fertility of Simmental females in the first breeding season on individual variables observed from birth to yearling age

Individual regressor model[1]	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
	χ^2	Prob.	χ^2	Prob.	β_0	β_1	β_2
Birth date	3.6	.06	-	-	2.10 ± .32	-.015 ± .008	-
Age of the dam	1.5	.22	1.1	.31	.86 ± .54	.24 ± .19	-.02 ± .01
Birth weight	.5	.49	-	-	.67 ± 1.31	.024 ± .035	-
Actual weaning weight	1.1	.30	-	-	.10 ± 1.42	.0061 ± .0059	-
205-day weight	1.3	.25	-	-	-.097 ± 1.46	.0068 ± .0059	-
Weaning weight ratio	4.2	.04	-	-	-1.35 ± 1.43	.028 ± .014	-
Actual yearling weight	1.8	.18	1.7	.18	-16.50 ± 13.03	.092 ± .068	-.00012 ± .00009
365-day weight	2.0	.16	2.1	.14	-14.96 ± 11.86	.094 ± .066	-.00013 ± .00009
Yearling weight ratio	1.2	.28	-	-	-.48 ± 1.89	.021 ± .019	-
Birth-weaning ADG[2]	1.1	.29	-	-	.26 ± 1.26	1.30 ± 1.24	-
Weaning-yearling ADG	2.5	.11	-	-	2.77 ± .77	-1.70 ±1.07	-
Birth-yearling ADG	3.7	.06	4.0	.06	-14.96 ± 8.93	40.04 ± 20.77	-23.96 ± 12.01
Birth-weaning RGR[3]	.9	.35	.9	.35	-9.03 ± 11.08	22.42 ± 23.75	-11.74 ± 12.67
Weaning-yearling RGR	4.1	.04	-	-	3.10 ± .78	-6.62 ± 3.29	-
Birth-yearling RGR	2.9	.09	3.3	.07	-23.46 ± 15.55	90.81 ± 52.93	-81.60 ± 44.83

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[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overal level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

Table 21. Performance of logistic regression models of fertility of Angus females in the first breeding season on combinations of variables observed at birth and from birth to yearling age

Model description	Number of variables	χ^2 proportion explained, %	Width of C.I.[1], %	Absolute res.[2], %	Predicted probability-observed response[3],%		
					Concordant	Discordant	Tied
The complete model, including the linear and quadratic effects of variables observed at birth and from birth to yearling age.	30	11.5	21.1	21.7	71.7	27.7	0.6
The same model as previously described but with the linear and quadratic effects of birth date excluded.	28	4.5	21.5	23.5	63.4	35.7	1.0
The model including the linear and quadratic effects of all weights, weight ratios, average daily gains and relative growth rates, but excluding the linear, and quadratic effects of age of the dam.	26	4.2	20.5	23.6	63.4	35.6	1.0
The model including the linear and quadratic effects of weaning weight, weaning weight ratio, and pre-weaning average daily gain and relative growth rate.	10	2.5	13.2	24.0	59.5	39.0	1.5
The model including the linear and quadratic effects of yearling weight, yearling weight ratio, and post-weaning average daily gain and relative growth rate.	10	2.3	13.5	24.1	58.5	39.7	1.8
The selected model,containing the linear and quadratic effects of post-weaning relative growth rate and the linear effect of birth date.	3	5.7	8.1	23.2	65.3	33.8	0.9

[1] Average width of the 95% confidence interval of the responses.
[2] Average absolute residuals.
[3] Association between the predicted probability and the observed response for all pairs of observations.

Table 22. Performance of logistic regression models of fertility of Simmental females in the first breeding season on combinations of variables observed at birth and from birth to yearling age

Model description	Number of variables	χ^2 proportion explained, %	Width of C.I.[1], %	Absolute res.[2], %	Predicted probability-observed response[3],% Concordant	Discordant	Tied
The complete model, including the linear and quadratic effects of variables observed at birth and from birth to yearling age.	30	9.2	38.8	25.7	69.3	30.3	0.4
The same model as previously described but with the linear and quadratic effects of birth date excluded.	28	6.7	37.8	26.4	65.8	33.6	0.7
The model including the linear and quadratic effects of all weights, weight ratios, average daily gains and relative growth rates, but excluding the linear and quadratic effects of age of the dam.	26	6.5	36.0	26.5	65.4	34.0	0.7
The model including the linear and quadratic effects of weaning weight, weaning weight ratio, and pre-weaning average daily gain and relative growth rate.	10	2.5	23.7	27.6	59.0	39.9	1.1
The model including the linear and quadratic effects of yearling weight, yearling weight ratio, and post-weaning average daily gain and relative growth rate.	10	4.4	23.6	27.1	63.0	36.1	0.8
The selected model, containing the effect of the interaction between birth date and weaning-yearling relative growth rate.	1	1.7	10.4	27.9	57.7	40.7	1.7

[1] Average width of the 95% confidence interval of the responses.
[2] Average absolute residuals.
[3] Association between the predicted probability and the observed response for all pairs of observations.

Table 23. Distribution of Angus and Simmental females according to their observed fertility in the first breeding season and their predicted fertility by logistic models and categorized as pregnant ($P_i \geq .50$) or not pregnant ($P_i < .50$)

Observed	Breeds and predicted fertility					
	Angus			Simmental		
fertility	Not pregnant	Pregnant	Total	Not pregnant	Pregnant	Total
Not pregnant	37	99	136	0	60	60
Pregnant	2	808	810	0	291	291
Total	39	907	946	0	351	351

Table 24. Arithmetic means of variables observed at birth and at weaning of Angus females according to year of birth and fertility in the second breeding season

Variable	Pregnancy	Year of birth										General mean
description	outcome	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	± std.dev.
Birth date, days	Pregnant	24	31	26	18	24	35	39	21	39	24	28 ± 15
	Not pregnant	26	29	26	28	27	37	38	26	35	26	31 ± 15
Age of the dam, years	Pregnant	4.0	4.9	4.3	3.9	5.8	5.1	4.6	5.3	5.1	5.2	4.9 ± 2.7
	Not pregnant	3.4	4.1	4.0	4.0	4.7	4.2	3.7	5.6	4.7	5.0	4.3 ± 2.3
Birth weight, kg	Pregnant	30	31	33	33	32	34	34	35	34	34	33 ± 3
	Not pregnant	28	34	33	35	33	34	36	37	34	36	34 ± 4
Actual weaning weight, kg	Pregnant	213	212	218	235	244	227	211	248	230	241	230 ± 25
	Not pregnant	213	208	217	237	246	218	218	251	236	232	228 ± 25
Weaning age, days	Pregnant	214	207	198	213	212	211	184	206	209	200	205 ± 16
	Not pregnant	212	209	200	203	208	209	185	202	213	199	202 ± 16
205-day weight, kg	Pregnant	205	211	224	228	238	222	232	247	226	247	230 ± 23
	Not pregnant	207	205	222	239	243	214	238	256	228	238	231 ± 23
Birth-weaning ADG[1], kg	Pregnant	.851	.877	.935	.950	1.004	.915	.964	1.034	.936	1.039	.958 ± .106
	Not pregnant	.873	.837	.923	.994	1.022	.879	.989	1.068	.948	.984	.959 ± .103
Birth-weaning RGR[2], %	Pregnant	.91	.93	.96	.92	.96	.90	.99	.95	.91	.98	.94 ± .07
	Not pregnant	.96	.88	.95	.95	.97	.89	.99	.96	.91	.93	.94 ± .07
Weaning weight ratio, %	Pregnant	102	100	99	101	100	101	100	100	100	101	100 ± 10
	Not pregnant	103	98	99	101	100	97	103	101	102	97	101 ± 10
Total number of females	Pregnant	48	51	52	44	66	94	71	94	62	72	654
	Not pregnant	5	6	14	9	10	12	23	10	19	6	114

[1] ADG = average daily gain.

[2] RGR = relative growth rate.

Table 25. Arithmetic means of variables observed at birth and at weaning of Simmental females according to year of birth and fertility in the second breeding season

Variable description	Pregnancy outcome	Year of birth 1981	1983	1985	1986	1987	General mean ± std.dev.
Birth date, days	Pregnant	49	45	26	24	31	35 ± 16
	Not pregnant	52	50	28	25	27	34 ± 16
Age of the dam, years	Pregnant	4.8	4.9	6.0	5.0	5.4	5.2 ± 2.6
	Not pregnant	9.6	3.3	5.3	6.3	6.4	5.7 ± 3.2
Birth weight, kg	Pregnant	36	36	40	37	36	37 ± 4
	Not pregnant	38	39	39	39	38	39 ± 4
Actual weaning weight, kg	Pregnant	253	241	254	229	246	244 ± 24
	Not pregnant	247	255	245	215	257	247 ± 28
Weaning age, days	Pregnant	208	210	206	205	196	205 ± 14
	Not pregnant	205	206	204	204	202	204 ± 12
205-day weight, kg	Pregnant	250	236	254	230	256	244 ± 24
	Not pregnant	247	254	247	216	261	249 ± 26
Birth-weaning ADG[1], kg	Pregnant	1.045	.978	1.040	.939	1.070	1.011 ± .114
	Not pregnant	1.020	1.047	1.016	.867	1.090	1.026 ± .124
Birth-weaning RGR[2], %	Pregnant	.94	.91	.90	.89	.98	.92 ± .08
	Not pregnant	.92	.91	.91	.84	.95	.91 ± .07
Weaning weight ratio, %	Pregnant	101	103	110	112	109	107 ± 11
	Not pregnant	99	109	106	106	114	108 ± 11
Total number of females	Pregnant	32	41	31	42	40	186
	Not pregnant	4	11	13	7	16	51

[1] ADG = average daily gain.

[2] RGR = relative growth rate.

Table 26. Arithmetic means of variables observed at yearling age of Angus females according to year of birth and fertility in the second breeding season

Variable	Pregnancy	Year of birth										General mean
description	outcome	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	± std.dev.
Actual yearling weight,	Pregnant	353	343	400	366	369	373	330	387	411	398	374 ± 37
kg	Not pregnant	343	343	407	365	370	366	339	396	402	400	374 ± 41
Yearling age,	Pregnant	452	417	505	481	371	403	406	440	413	417	426 ± 38
days	Not pregnant	450	419	505	471	367	401	408	434	417	415	427 ± 40
365-day weight,	Pregnant	307	312	313	313	370	348	297	343	372	357	336 ± 36
kg	Not pregnant	300	311	317	313	370	342	304	351	366	356	334 ± 38
Weaning-yearling ADG[1],	Pregnant	.590	.620	.594	.488	.781	.762	.537	.592	.887	.724	.654 ± .150
kg	Not pregnant	.545	.644	.623	.477	.780	.773	.538	.624	.813	.778	.662 ± .160
Birth-yearling ADG,	Pregnant	.715	.748	.728	.693	.908	.842	.730	.800	.912	.874	.805 ± .098
kg	Not pregnant	.699	.739	.742	.700	.917	.827	.742	.829	.881	.876	.799 ± .098
Weaning-yearling RGR[2],	Pregnant	.22	.23	.20	.17	.26	.26	.20	.19	.28	.23	.22 ± .05
%	Not pregnant	.20	.24	.21	.16	.26	.27	.20	.20	.26	.25	.22 ± .05
Birth-yearling RGR,	Pregnant	.54	.58	.50	.50	.66	.60	.56	.54	.60	.59	.57 ± .05
%	Not pregnant	.56	.56	.50	.50	.66	.59	.55	.55	.59	.58	.56 ± .05
Yearling weight ratio,	Pregnant	101	100	99	101	100	100	100	100	100	100	100 ± 7
%	Not pregnant	98	100	99	101	100	98	103	102	98	101	100 ± 9
Total number of	Pregnant	48	51	52	44	66	94	71	94	62	72	664
females	Not pregnant	5	6	14	9	10	12	23	10	19	6	114

[1] ADG = average daily gain.
[2] RGR = relative growth rate.

Table 27. Arithmetic means of variables observed at yearling age of Simmental females according to year of birth and fertility in the second breeding season

Variable description	Pregnancy outcome	Year of birth					General mean ± std.dev.
		1981	1983	1985	1986	1987	
Actual yearling weight, kg	Pregnant	385	368	392	374	378	378 ± 31
	Not pregnant	388	393	393	358	387	386 ± 25
Yearling age, days	Pregnant	367	404	435	412	411	406 ± 24
	Not pregnant	364	400	433	411	416	412 ± 22
365-day weight, kg	Pregnant	386	346	351	341	344	352 ± 31
	Not pregnant	389	369	349	326	354	355 ± 26
Weaning-yearling ADG[1], kg	Pregnant	.829	.655	.604	.699	.611	.677 ± .138
	Not pregnant	.887	.712	.646	.692	.603	.672 ± .124
Birth-yearling ADG, kg	Pregnant	.950	.822	.810	.818	.830	.843 ± .085
	Not pregnant	.962	.885	.819	.779	.839	.845 ± .069
Weaning-yearling RGR[2], %	Pregnant	.26	.22	.19	.24	.20	.22 ± .04
	Not pregnant	.28	.23	.21	.25	.19	.22 ± .05
Birth-yearling RGR, %	Pregnant	.65	.58	.52	.56	.57	.58 ± .05
	Not pregnant	.64	.58	.54	.54	.56	.56 ± .04
Yearling weight ratio, %	Pregnant	100	99	100	102	99	100 ± 8
	Not pregnant	101	106	100	98	102	102 ± 6
Total number of females	Pregnant	32	41	31	42	40	186
	Not pregnant	4	11	13	7	16	51

[1] ADG = average daily gain.

[2] RGR = relative growth rate.

Table 28. Arithmetic means of variables observed in the first calving season of Angus females according to year of birth and fertility in the second breeding season

Variable	Pregnancy	Year of birth										General mean
description	outcome	1975	1976	1977	1978	1981	1983	1984	1985	1986	1987	± std.dev.
Calving date, days	Pregnant	25	17	20	23	28	20	42	25	44	27	27 ± 17
	Not pregnant	43	18	31	37	41	33	42	42	43	46	39 ± 22
Birth weight of the callf, kg	Pregnant	32	31	33	29	34	34	33	33	34	34	33 ± 4
	Not pregnant	31	35	33	30	35	33	33	32	35	36	33 ± 4
Calf birth weight ratio, %	Pregnant	101	99	101	99	100	100	100	100	99	100	100 ± 11
	Not pregnant	96	110	98	105	103	97	100	99	103	106	101 ± 13
Calving ease score[1]	Pregnant	1.3	1.3	1.4	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.2 ± .6
	Not pregnant	1.4	2.0	1.5	1.8	1.6	1.3	1.1	1.2	1.4	1.2	1.4 ± .7
Percentage of male calves	Pregnant	51	47	53	44	45	55	61	52	40	44	50 ± 6
	Not pregnant	75	60	50	43	60	58	69	60	84	83	65 ± 12
Total number of females	Pregnant	48	51	52	44	66	94	71	94	62	72	654
	Not pregnant	5	6	14	9	10	12	23	10	19	6	114
Fertility, %		91	89	79	83	87	89	76	90	77	92	85 ± 6

[1] Codified as: 1 = no difficulty, no assistance; 2 = minor difficulty, some assistance; and 3 = major difficulty, calf puller used.

Table 29. Arithmetic means of variables observed in the first calving season of Simmental females according to year of birth and fertility in the second breeding season

Variable description	Pregnancy outcome	Year of birth 1981	 1983	 1985	 1986	 1987	General mean ± std.dev.
Calving date, days	Pregnant	31	22	23	30	33	28 ± 17
	Not pregnant	44	26	29	26	24	28 ± 19
Birth weight of the calf, kg	Pregnant	37	37	37	37	41	37 ± 4
	Not Pregnant	37	39	38	37	38	38 ± 4
Calf birth weight ratio, %	Pregnant	99	99	100	99	98	99 ± 11
	Not pregnant	101	102	102	101	105	103 ± 10
Calving ease score[1]	Pregnant	1.2	1.1	1.2	1.3	2.1	1.3 ± .5
	Not pregnant	1.8	1.1	1.5	1.0	1.5	1.6 ± .7
Percentage of male calves	Pregnant	41	44	48	64	48	49 ± 9
	Not pregnant	50	64	62	43	63	59 ± 9
Total number of females	Pregnant	32	41	31	42	40	186
	Not pregnant	4	11	13	7	16	51
Fertility, %		89	79	71	86	71	78 ± 8

[1] Calving ease codified as 1 = unassisted, 2 = easy pull and 3 = hard pull, cesarean or abnormal presentation.

Table 30. Performance of logistic regression models of fertility of Angus females in the second breeding season on individual variables observed at birth, from birth to yearling age and in the first calving season

Individual regressor model[1]	χ^2 proportion explained, %	Test on model		Width of C.I.[2], %	Average absolute res.[3], %	Predicted probability - observed response association[4], %		
		χ^2	Prob.			Concordant	Discordant	Tied
Birth date	.5	3.2	.07	6.8	25.2	54.3	42.6	3.0
Age of the dam	.6	4.0	.06	6.8	25.1	51.2	39.5	9.3
Birth weight	.9	5.8	.02	6.8	25.1	52.5	39.3	8.2
Actual weaning weight	.1	.5	.47	6.9	25.3	49.8	44.1	6.1
205-day weight	.0	.2	.66	6.9	25.3	45.4	44.1	10.4
Weaning weight ratio	.0	.1	.77	6.8	25.3	42.0	42.5	15.5
Actual yearling weight	.3	1.9	.39	7.9	25.2	46.1	42.3	11.6
365-day weight	.2	1.5	.47	8.0	25.3	49.6	42.8	7.6
Yearling weight ratio	.5	3.4	.18	7.9	25.2	46.1	45.5	8.4
Birth-weaning ADG[5]	.0	.0	.94	6.8	25.3	46.1	42.2	11.7
Weaning-yearling ADG	.0	.2	.70	6.4	25.3	47.0	43.9	9.1
Birth-yearling ADG	.1	.4	.54	6.9	25.3	49.2	43.7	7.1
Birth-weaning RGR[6]	.0	.1	.75	6.8	25.3	42.5	43.3	14.2
Weaning-yearling RGR	.0	.1	.73	6.9	25.3	44.7	42.4	12.9
Birth-yearling RGR	.4	2.6	.11	6.9	25.3	53.4	43.9	2.7
Calving date	5.4	42.9	$<.01$	5.8	23.0	66.4	32.3	1.3
Calf birth weight	.2	1.7	.43	6.7	24.2	45.2	37.0	17.7
Calf birth weight ratio	.2	1.1	.30	6.9	25.5	49.8	45.6	4.6
Calving ease score[7,8]	2.8	22.3	$<.01$	5.8	23.7	27.0	10.0	63.0
Sex of the calf[8]	.9	6.5	.01	6.2	23.6	31.0	19.1	50.0

[1] Two models were fit for each variable, one including linear and one with linear and quadratic effects. The model with the higher overal level of significance is presented here.

[2] Average width of the 95% confidence interval of the responses.

[3] Average absolute residuals.

[4] Association between the predicted probability and the observed response for all pairs of observations.

[5] ADG = average daily gain.

[6] RGR = relative growth rate.

[7] Codified as: 1 = no difficulty, no assistance; 2 = minor difficulty, some assistance; and 3 = major difficulty, calf puller used.

[8] Fitted as categorical variables.

Table 31. Performance of logistic regression models of fertility of Simmental females in the second breeding season on individual variables observed at birth, from birth to yearling age and in the first calving season

Individual regressor model[1]	χ^2 proportion explained, %	Test on model		Width of C.I.[2], %	Average absolute res.[3], %	Predicted probability - observed response association[4], %		
		χ^2	Prob.			Concordant	Discordant	Tied
Birth date	.1	.2	.64	14.1	33.7	51.0	43.4	5.6
Age of the dam	1.5	3.6	.17	16.5	33.2	53.4	38.3	8.3
Birth weight	2.1	5.3	.02	13.8	33.1	59.3	34.3	6.3
Actual weaning weight	.8	2.0	.38	16.3	33.5	53.0	39.9	7.1
205-day weight	.6	1.4	.24	14.1	33.6	54.8	43.5	1.7
Weaning weight ratio	.2	.5	.47	14.2	33.7	52.4	44.8	2.8
Actual yearling weight	1.1	2.7	.10	14.0	33.4	58.6	38.8	2.6
365-day weight	.1	.3	.58	14.1	33.7	52.8	43.2	4.0
Yearling weight ratio	.6	1.6	.21	14.0	33.6	56.7	41.3	2.2
Birth-weaning ADG[5]	.3	.6	.42	14.2	33.7	52.8	44.8	2.4
Weaning-yearling ADG	.0	.1	.82	14.3	33.8	45.4	45.2	9.4
Birth-yearling ADG	.0	.0	.87	14.1	33.8	45.5	39.5	15.0
Birth-weaning RGR[6]	.2	.6	.44	14.2	33.7	52.4	44.8	2.8
Weaning-yearling RGR	.1	.3	.57	14.2	33.7	52.4	44.8	2.8
Birth-yearling RGR	1.6	4.0	.04	13.9	33.2	57.7	41.0	1.3
Calving date	.6	1.4	.51	16.7	33.6	50.7	44.5	4.8
Calf birth weight	2.0	4.9	.02	14.0	33.1	55.7	36.9	7.3
Calf birth weight ratio	1.5	3.7	.05	14.0	33.3	55.5	38.9	5.5
Calving ease score[7,8]	3.7	9.4	.01	13.8	32.3	34.6	14.0	51.4
Sex of the calf[8]	.6	1.4	.24	14.7	33.6	29.7	20.4	49.9

[1] Two models were fit for each variable, one including linear and one with linear and quadratic effects. The model with the higher overal level of significance is presented here.

[2] Average width of the 95% confidence interval of on the responses.

[3] Average absolute residuals.

[4] Association between the predicted probability and the observed response for all pairs of observations.

[5] ADG = average daily gain.

[6] RGR = relative growth rate.

[7] Codified as: 1 = no difficulty, no assistance; 2 = minor difficulty, some assistance; and 3 = major difficulty, calf puller used.

[8] Fitted as categorical variables.

Table 32. Regression coefficient estimates, standard errors and tests of significance of logistic regression models of fertility of Angus females in the second breeding season on individual variables observed from birth to yearling age

Individual regressor model[1]	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
	χ^2	Prob.	χ^2	Prob.	β_0	β_1	β_2
Birth date	3.3	.07	-	-	2.09 ± .22	-.011 ± .006	-
Age of the dam	3.6	.06	-	-	1.35 ± .19	.10 ± .04	-
Birth weight	5.8	.02	-	-	4.15 ± 1.02	-.071 ± .029	-
Actual weaning weight	.5	.47	-	-	1.09 ± .92	.0029 ± .0040	-
205-day weight	.2	.66	-	-	2.20 ± 1.04	-.0020 ± .0045	-
Weaning weight ratio	.1	.77	-	-	2.05 ± 1.06	.0030 ± .0105	-
Actual yearling weight	2.0	.16	2.0	.16	-7.02 ± 6.28	.047 ± .033	-000061 ± .000043
365-day weight	1.0	.31	.9	.33	-5.12 ± 6.42	.039 ± .038	-.000054 ± .000056
Yearling weight ratio	3.5	.06	3.6	.06	-18.50 ± 11.06	.406 ± .218	-.0020 ± .0011
Birth-weaning ADG[2]	.0	.94	-	-	1.82 ± .93	-.074 ± .963	-
Weaning-yearling ADG	.25	.70	-	-	1.58 ± .44	.25 ± .65	-
Birth-yearling ADG	.4	.54	-	-	1.23 ± .85	.65 ± 1.05	-
Birth-weaning RGR[3]	.1	.75	-	-	1.32 ± 1.33	.45 ± 1.41	-
Weaning-yearling RGR	.1	.73	-	-	1.58 ± .48	.71 ± 2.08	-
Birth-yearling RGR	2.5	.11	-	-	-.08 ± 1.15	3.22 ± 2.03	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overal level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

Table 33. Regression coefficient estimates, standard errors and tests of significance of logistic regression models of fertility of Simmental females in the second breeding season on individual variables observed from birth to yearling age

Individual regressor	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
model[1]	χ^2	Prob.	χ^2	Prob.	β_0	β_1	β_2
Birth date	.2	.64	-	-	1.13 ± .37	.0047 ± .0099	-
Age of the dam	1.3	.25	2.2	.14	.85 ± .62	.25 ± .21	-.024 ± .016
Birth weight	5.2	.02	-	-	4.54 ± 1.45	-.086 ± .038	-
Actual weaning weight	1.1	.29	1.3	.26	-9.26 ± 10.67	.091 ± .086	-.00019 ± .00017
205-day weight	1.4	.24	-	-	3.18 ± 1.62	-.0077 ± .0065	-
Weaning weight ratio	.5	.47	-	-	4.16 ± 1.53	-.011 ± .015	-
Actual yearling weight	2.6	.11	-	-	4.62 ± 2.07	-.0087 ± .0054	-
365-day weight	.3	.58	-	-	2.31 ± 1.86	-.0029 ± .0052	-
Yearling weight ratio	1.6	.21	-	-	3.87 ± 2.09	-.026 ± .021	-
Birth-weaning ADG[2]	.6	.42	-	-	2.41 ± 1.41	-1.10 ± 1.37	-
Weaning-yearling ADG	.1	.82	-	-	1.11 ± .81	.27 ± 1.18	-
Birth-yearling ADG	.0	.87	-	-	1.57 ± 1.65	-.32 ± 1.94	-
Birth-weaning RGR[3]	.6	.44	-	-	.15 ± 1.86	1.57 ± 2.02	-
Weaning-yearling RGR	.3	.57	-	-	.85 ± .80	2.01 ± 3.57	-
Birth-yearling RGR	3.8	.05	-	-	-2.85 ± 2.12	7.30 ± 3.75	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overal level of significance is presented here.
[2] ADG = average daily gain.
[3] RGR = relative growth rate.

Table 34. Regression coefficient estimates, standard errors and tests of significance of logistic regression models of rertility of Angus females in the second breeding season on individual variables observed in the first calving season

Individual regressor	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
model	χ^2	Prob.	χ^2	Prob.	β_0	β_1	β_2
Calving date[1]	42.3	< .01	-	-	2.82 ± .19	-.030 ± .004	-
Birth weight of the calf[1]	1.2	.27	1.4	.23	-1.80 ± 3.50	.23 ± .21	-.0037 ± .0031
Calf birth weight ratio[1]	1.1	.30	-	-	2.65 ± .90	-.0091 ± .0088	-
Calving ease score[2, 3]	24.5	< .01	-	-	.69 ± .32	1 = 1.32 ± .33 (P < .00) 2 = .43 ± .39 (P = .27) 3 = 0	
Sex of the calf[3]	6.3	.01	-	-	2.10 ± .15	Males = -.49 ± .19 (P < .01) Females = 0	

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overal level of significance is presented here.

[2] Codified as: 1 = no difficulty, no assistance; 2 = minor difficulty, some assistance; and 3 = major difficulty, calf puller used.

[3] Fit as categorical variables. Statistical tests made relative to calving ease = 3, and sex = female.

Table 35. Regression coefficient estimates, standard errors and tests of significance of logistic regression models of fertility of Simmental females in the second breeding season on individual variables observed in the first calving season

Individual regressor	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
model	χ^2	Prob.	χ^2	Prob.	β_0	β_1	β_2
Calving date[1]	1.3	.25	1.40	.24	.86 ± .45	.034 ± .030	-.00047 ± .00040
Birth weight of the calf[1]	4.8	.03	-	-	4.55 ± 1.50	-.085 ± .039	-
Calf birth weight ratio[1]	3.6	.05	-	-	4.16 ± 1.53	-.028 ± .015	-
Calving ease score[2, 3]	9.4	.01	-	-	.00 ± .54	1 = 1.58 ± .5709 (P=.01) 2 = .89 ± .62 (P=.15) 3 = 0	
Sex of the calf[3]	1.4	.24	-	-	1.50 ± .24	Males = -.38 ± .32 (P=.24) Females = 0	

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[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overal level of significance is presented here.

[2] Codified as: 1 = no difficulty, no assistance; 2 = minor difficulty, some assistance; and 3 = major difficulty, calf puller used.

[3] Fit as categorical variables. Statistical tests made relative to calving ease = 3, and sex = female.

Table 36. Performance of logistic regression models of fertility of Angus females in the second breeding season on combinations of variables observed at birth, from birth to yearling age and in the first calving season

Model description	Number of variables	χ^2 proportion explained, %	Width of C.I.[1], %	Absolute res.[2], %	Predicted probability-observed response[3],%		
					Concordant	Discordant	Tied
The complete model, including the linear and quadratic effects of variables observed at birth, from birth to yearling age and in the first calving season.	38	13.6	28.2	22.0	75.2	24.3	0.5
The same model as previously described but with the effects of variables observed in the first calving season excluded.	30	6.1	25.4	23.8	65.3	34.0	0.7
The model including the linear and quadratic effects of calving date, birth weight and birth weight ratio of the calf, and the effects of sex of the calf and calving ease score.	8	8.1	13.6	23.1	69.9	29.5	0.6
The model including the linear and quadratic effects of all weights, weight ratios, average daily gains and relative growth rates.	26	4.4	23.5	24.2	63.1	36.0	0.9
The model including the linear and quadratic effects of weaning weight, weaning weight ratio and pre-weaning average daily gain and relative growth rate.	10	2.5	15.2	24.6	58.8	40.0	1.2
The model including the linear and quadratic effects of yearling weight, yearling weight ratio and post-weaning average daily gain and relative growth rate.	10	1.2	15.5	25.1	57.3	41.0	1.7
The selected model, containing the linear effect of calving date, and the effects of calving ease score and sex of the calf in the first calving season.	3	7.8	9.5	23.2	69.0	30.1	0.0

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[1] Average width of the 95% confidence interval of the responses.
[2] Average absolute residuals.
[3] Association between the predicted probability and the observed response for all pairs of observations.

Table 37. Performance of logistic regression models of fertility of Simmental females in the second breeding season on combinations of variables observed at birth, from birth to yearling age and in the first calving season

Model description	Number of variables	χ^2 proportion explained, %	Width of C.I.[1], %	Absolute res.[2], %	Predicted probability-observed response[3],%		
					Concordant	Discordant	Tied
The complete model, including the linear and quadratic effects of variables observed at birth, from birth to yearling age and in the first calving season.	38	25.0	52.7	25.4	83.5	16.3	0.1
The same model as previously described but with the effects of variables observed in the first calving season excluded.	30	17.0	48.4	28.2	78.1	21.7	0.3
The model including the linear and quadratic effects of calving date and birth weight of the calf, the effect of sex of the calf and the effect of calving ease score.	8	5.9	29.1	31.6	65.3	34.0	0.7
The model including the linear and quadratic effects of all weights, weight ratios, average daily gains and relative growth rates.	26	13.1	45.4	29.5	74.4	25.4	0.2
The model including the linear and quadratic effects of weaning weight, weaning weight ratio and pre-weaning average daily gain and relative growth rate.	10	5.4	30.6	32.0	66.1	33.4	0.5
The model including the linear and quadratic effects of yearling weight, yearling weight ratio and post-weaning average daily gain and relative growth rate.	10	6.3	31.1	31.7	67.2	32.2	0.6
The selected model, containing the linear effect of birth weight of the calf and the effect of calving ease in the first calving season.	2	4.2	8.1	32.2	61.3	34.5	4.3

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[1] Average width of the 95% confidence interval of the responses.
[2] Average absolute residuals.
[3] Association between the predicted probability and the observed response for all pairs of observations.

Table 38. Distribution of Angus and Simmental females according to their observed fertility in the second breeding season and their predicted fertility by logistic models and categorized as pregnant ($P_i \geq .50$) or not pregnant ($P_i < .50$)

Observed	Breeds and predicted fertility					
	Angus			Simmental		
fertility	Not pregnant	Pregnant	Total	Not pregnant	Pregnant	Total
Not pregnant	16	98	114	3	48	51
Pregnant	2	652	654	3	183	186
Total	18	750	768	6	231	237

Table 39. Arithmetic means of variables observed at birth and from birth to yearling age of Angus and Simmental females and of the weaning weight[1] of their first calves

	Arithmetic means ± standard deviation	
Variable	Angus	Simmental
Birth date, days	29 ± 16	35 ± 16
Age of the dam, years	4.8 ± 2.7	5.3 ± 2.7
Birth weight, kg	34 ± 3	37 ± 4
Actual weaning weight, kg	229 ± 25	244 ± 25
205-day weight, kg	230 ± 23	245 ± 24
Weaning weight ratio, %	100 ± 10	107 ± 11
Actual yearling weight, kg	374 ± 38	380 ± 30
365-day weight, kg	336 ± 36	352 ± 30
Yearling weight ratio, %	100 ± 8	100 ± 8
Birth-weaning ADG[2], kg	.960 ± .105	1.014 ± .115
Weaning-yearling ADG, kg	.669 ± .158	.679 ± .136
Birth-yearling ADG, kg	.806 ± .098	.845 ± .082
Birth-weaning RGR[3], %	.95 ± .07	.92 ± .08
Weaning-yearling RGR, %	.23 ± .05	.22 ± .04
Birth-yearling RGR, %	.57 ± .05	.57 ± .05
Calf weaning weight, kg	230 ± 33	243 ± 33
Number of females	771	226

[1] Adjusted for sex, year of birth, sire EPD and percentage Simmental (Simmentals).
[2] ADG = average daily gain.
[3] RGR = relative growth rate.

Table 40. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of weaning weight[1] of the first calves of Angus females on individual variables observed from birth to yearling age

Individual regressor	R^2,	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
model[2]	%	t	Prob.	t	Prob.	β_0	β_1	β_2
Birth date	3.2	2.2	.03	2.0	.05	239.3 ± 4.3	-.57 ± .26	.0067 ± .0034
Age of the dam	2.7	1.9	.06	2.1	.04	222.3 ± 4.9	3.6 ± 1.8	-.31 ± .15
Birth weight	.4	.4	.67	.5	.62	257.0 ± 75.3	-1.9 ± 4.5	.032 ± .006
Actual weaning weight	2.6	2.1	.04	-	-	207.2 ± 11.2	.099 ± .048	-
205-day weight	1.4	1.5	.14	-	-	211.4 ± 12.6	.081 ± .054	-
Weaning weight ratio	3.4	2.3	.02	-	-	199.7 ± 13.0	.31 ± .13	-
Actual yearling weight	5.5	3.0	<.01	-	-	193.8 ± 12.2	.097 ± .032	-
365-day weight	4.7	2.8	.01	-	-	198.4 ± 11.5	.094 ± .034	-
Yearling weight ratio	9.2	3.9	<.01	-	-	167.8 ± 16.1	.63 ± .16	-
Birth-weaning ADG[3]	1.3	1.5	.15	-	-	213.5 ± 11.3	17.1 ± 11.8	-
Weaning-yearling ADG	2.4	2.0	.05	-	-	219.8 ± 5.4	15.3 ± 7.8	-
Birth-yearling ADG	3.8	2.5	.01	-	-	204.6 ± 10.3	31.6 ± 12.7	-
Birth-weaning RGR[4]	.1	.2	.85	-	-	233.1 ± 16.2	-3.3 ± 17.1	-
Weaning-yearling RGR	.5	.9	.38	-	-	225.1 ± 5.8	22.1 ± 25.2	-
Birth-yearling RGR	.4	.8	.45	-	-	219.5 ± 13.9	18.4 ± 24.2	-

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[1] Adjusted for sex, year of birth and sire EPD.

[2] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[3] ADG = average daily gain.

[4] RGR = relative growth rate.

Table 41. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of weaning weight[1] of the first calves of Simmental females on individual variables observed from birth to yearling age

Individual regressor	R^2,	Test on β_1		Test on β_2		Coefficient estimates ± standard errors		
model[2]	%	t	Prob.	t	Prob.	β_0	β_1	β_2
Birth date	2.7	1.8	.08	-	-	251.3 ± 5.2	-.24 ± .13	-
Age of the dam	3.7	2.0	.04	2.1	.04	258.1 ± 8.9	-6.2 ± 3.9	.49 ± .23
Birth weight	.2	.4	.66	-	-	251.9 ± 20.0	-.24 ± .53	-
Actual weaning weight	.4	.7	.51	.7	.50	135.4 ± 168.7	.89 ± 1.37	-.0018 ± .0028
205-day weight	1.8	1.4	.15	-	-	275.5 ± 22.7	-.13 ± .09	-
Weaning weight ratio	0	.1	.93	-	-	244.9 ± 22.8	-.017 ± .211	-
Actual yearling weight	.9	1.0	.33	1.0	.33	-10.5 ± 255.7	1.30 ± 1.34	-.0017 ± .0017
365-day weight	1.1	1.1	.26	1.1	.26	-.7 ± 213.9	1.35 ± 1.19	-.0019 ± .0017
Yearling weight ratio	.1	.4	.69	-	-	231.4 ± 29.7	.12 ± .29	-
Birth-weaning ADG[3]	1.7	1.4	.17	-	-	270.3 ± 19.8	-26.9 ± 19.4	-
Weaning-yearling ADG	.2	.5	.64	-	-	237.7 ± 11.4	7.8 ± 16.5	-
Birth-yearling ADG	1.6	1.3	.21	1.3	.21	33.6 ± 170.6	500.0 ± 395.9	-295.7 ± 228.6
Birth-weaning RGR[4]	2.0	1.5	.13	-	-	282.5 ± 26.0	-42.8 ± 28.1	-
Weaning-yearling RGR	.2	.5	.64	-	-	237.8 ± 11.4	23.3 ± 50.4	-
Birth-yearling RGR	2.8	1.7	.09	1.7	.08	-207.1 ± 270.1	1,573.8 ± 925.9	-1,366.8 ± 790.4

[1] Adjusted for sex, year of birth, sire EPD and percentage Simmental.

[2] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[3] ADG = average daily gain.

[4] RGR = relative growth rate.

Table 42. Product moment correlations (top) and probability values (botton) among selected regressor variables observed at birth and from birth to yearling age of Angus females

Regressor variables	Regressor variables, correlations and probability values									
	Birth date sq.	Age of dam	Age of dam sq.	Actual wean.wt	Actual yearl.wt	B-wean. ADG[1]	W-yearl. ADG	B-yearl. ADG	Wean. wt.ratio	Yearl. wt.ratio
Birth date	.95 <.01	.08 .03	.09 .01	-.51 <.01	-.31 <.01	-.02 .60	.12 <.01	.06 .12	-.44 <.01	-.32 <.01
Birth date squared	-	.09 .01	.10 <.01	-.47 <.01	-.31 <.01	.01 .89	.08 .03	.04 .29	-.41 <.01	-.31 <.01
Age of the dam	-	-	.97 <.01	.11 <.01	.02 .62	.13 <.01	.04 .30	.11 <.01	.03 .44	-.04 .23
Age of the dam squared	-	-	-	.08 .03	-.01 .78	.12 <.01	.03 .41	.09 .01	-.002 .96	-.08 .03
Actual weaning weight	-	-	-	-	.58 <.01	.78 <.01	.03 .42	.48 <.01	.84 <.01	.53 <.01
Actual yearling weight	-	-	-	-	-	.39 <.01	.61 <.01	.72 <.01	.46 <.01	.74 <.01
Birth-weaning ADG	-	-	-	-	-	-	-.10 <.01	.43 <.01	.64 <.01	.37 <.01
Weaning-yearling ADG	-	-	-	-	-	-	-	.84 <.01	-.10 <.01	.44 <.01
Birth-yearling ADG	-	-	-	-	-	-	-	-	.27 <.01	.57 <.01
Weaning weight ratio	-	-	-	-	-	-	-	-	-	.63 <.01

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[1] ADG = average daily gain.

Table 43. Product moment correlations (top) and probability values (botton) between pairs of selected regressor variables observed at birth and from birth to yearling age of Simmental females

Regressor variables	Regressor variables, correlation and probability values						
	Age of dam	Age of dam sq.	205-d weight	Birth-wean.RGR[1]	Birth-yearl.RGR	Birth-yearl.RGR sq.	Birth-wean.ADG[2]
Birth date	-.07 .32	-.04 .59	.21 < .01	.51 < .01	.61 < .01	.61 < .01	.24 < .01
Age of the dam	-	.97 < .01	.19 < .01	.08 .23	-.07 .29	-.07 .28	.18 < .01
Age of the dam squared	-	-	.14 .03	.09 .17	-.01 .84	-.02 .82	.15 .03
205-day weight	-	-	-	.57 < .01	.16 .02	.16 .02	.99 < .01
Birth-weaning RGR	-	-	-	-	.59 < .01	.58 < .01	.68 < .01
Birth-yearling RGR	-	-	-	-	-	.99 < .01	.26 < .01
Birth-yearling RGR squared	-	-	-	-	-	-	.26 < .01

[1] RGR = relative growth rate.
[2] ADG = average daily gain.

Table 44. Multicollinearity diagnostics of the regression model of weaning weight[1] of the first calves of Angus females on selected regressor variables observed at birth and from birth to yearling age

			Regressor variables and variance proportions										
Depen- dencies	Eigen- value	Condition number	Birth date	Birth date sq.	Age of dam	Age of dam sq.	Actual wean.wt	Actual yearl.wt	B-wean. ADG[2]	W-yearl. ADG	B-yearl. ADG	Wean. ratio	Yearl. ratio
1	4.314	1.0	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.01
2	2.357	2.0	.01	.01	.01	.00	.00	.00	.00	.00	.00	.00	.00
3	1.985	2.3	.00	.00	.01	.01	.00	.00	.00	.00	.00	.00	.00
4	1.382	3.2	.01	.01	.00	.00	.00	.00	.01	.00	.00	.01	.00
5	.458	9.6	.00	.01	.00	.00	.01	.00	.00	.00	.00	.04	.25
6	.237	18.5	.00	.00	.00	.00	.00	.27	.01	.00	.01	.13	.00
7	.156	28.1	.01	.02	.00	.00	.01	.18	.03	.00	.00	.23	.35
8	.055	77.4	.30	.72	.00	.00	.12	.01	.02	.00	.00	.11	.04
9	.030	144.0	.07	.02	.78	.80	.09	.01	.02	.00	.00	.08	.03
10	.022	193.2	.58	.20	.20	.19	.63	.01	.11	.00	.00	.40	.31
11	.003	1,310.4	.02	.01	.00	.00	.14	.51	.80	.99	.99	.00	.01
Variance inflation factor			16.8	11.6	17.6	17.6	26.0	7.8	36.0	161.3	134.6	7.3	4.4

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[1] Adjusted for sex, year of birth and sire EPD.

[2] ADG = average daily gain.

Table 45. Multicollinearity diagnostics of the regression model of weaning weight[1] of the first calves of Simmental females on selected regressor variables observed at birth and from birth to yearling age

			Regressor variables and variance proportions							
Depen-dencies	Eigen-value	Condition number	Birth date	Age of dam	Age of dam sq.	205-d weight	Birth-wean.RGR[2]	Birth-yearl.RGR	Birth-yearl.RGR sq.	Birth-wean.ADG[3]
1	3.525	1.0	.01	.00	.00	.00	.01	.00	.00	.00
2	2.180	1.7	.01	.01	.01	.00	.00	.00	.00	.00
3	1.460	2.6	.01	.01	.01	.00	.00	.00	.00	.00
4	.496	7.3	.44	.00	.00	.00	.00	.00	.00	.00
5	.302	11.6	.01	.00	.00	.00	.25	.00	.00	.00
6	.032	110.3	.00	.95	.95	.00	.00	.00	.00	.00
7	.002	1,600.0	.46	.03	.03	.85	.72	.03	.05	.87
8	.001	3,091.4	.06	.00	.00	.15	.02	.97	.95	.13
Variance inflation factor			3.6	16.8	16.0	213.2	10.2	432.6	412.1	262.4

[1] Adjusted for sex, year of birth, sire EPD and percentage Simmental.

[2] RGR = relative growth rate.

[3] ADG = average daily gain.

Table 46. Performance of ridge regression models of weaning weight[1] of the first calves of Angus females on selected regressor variables observed at birth and from birth to yearling age, according to different values of κ

					Regression coefficient estimates and inflation of their standard errors											
κ	EMS$_\kappa$[2]	PRESS$_\kappa$	C_κ	DF-trace	Inter-cept	Birth date	Birth date sq.	Age of dam	Age of dam sq.	Actual wean.wt	Actual yearl.wt	B-wean. ADG[3]	W-yearl. ADG	B-yearl. ADG	Wean. ratio	Yearl. ratio
.000[4]	1,085	792,761	12.0	11.0	175.5	-.53	.0071	3.0	-.26	-.12	.045	-31.5	-49.6	94.2	.061	.47
						4.1	3.4	4.2	4.2	5.1	2.8	6.0	12.7	11.6	2.7	2.1
.003	1,086	791,194	10.6	10.2	175.0	-.50	.0067	2.7	-.23	-.074	.026	-16.2	-24.8	52.7	.053	.48
						3.7	3.1	3.8	3.8	4.3	2.2	3.7	6.1	6.2	2.5	2.0
.006	1,086	790,460	11.7	9.9	174.4	-.46	.0063	2.4	-.21	-.052	.020	-11.6	- 16.1	37.5	.045	.49
						3.4	2.9	3.5	3.5	3.9	2.0	3.0	4.2	4.2	2.4	1.9
.009	1,087	789,992	11.6	9.4	173.9	-.43	.0059	2.2	-.19	-.038	.017	-9.5	-11.7	29.5	.039	.49
						3.1	2.8	3.2	3.2	3.6	1.9	2.6	3.2	3.3	2.3	1.9
.012	1,087	789,660	9.1	9.2	173.5	-.40	.0056	2.0	-.18	-.028	.016	-8.5	-9.0	24.5	.035	.49
						2.9	2.6	3.0	3.0	3.3	1.9	2.4	2.6	2.7	2.2	1.8
.015	1,087	789,411	8.9	9.0	173.2	-.38	.0054	1.8	-.17	-.021	.015	-7.8	-7.2	21.1	.033	.50
						2.7	2.5	2.8	2.8	3.0	1.9	2.2	2.2	2.3	2.1	1.8
.018	1,087	789,216	8.7	8.8	172.9	-.36	.0051	1.7	-.16	-.015	.014	-7.3	-5.9	18.6	.031	.50
						2.6	2.4	2.6	2.6	2.9	1.8	2.0	2.0	2.1	2.0	1.7
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.033	1,089	788,641	8.1	8.1	172.2	-.27	.0042	1.2	-.12	-.00079	.013	-6.1	-2.5	11.7	.032	.49
						2.0	2.0	2.0	2.0	2.2	1.7	1.6	1.3	1.4	1.8	1.6
.036	1,089	788,577	8.1	8.0	172.1	-.26	.0040	1.2	-.11	-.00052	.013	-6.0	-2.1	11.1	.032	.49
						1.9	1.9	1.9	1.9	2.1	1.6	1.6	1.2	1.3	1.7	1.5
.039	1,089	788,521	8.0	7.9	172.1	-.25	.0039	1.1	-.11	-.0016	.013	-5.8	-1.8	10.5	.033	.49
						1.9	1.9	1.8	1.8	2.0	1.6	1.5	1.1	1.3	1.7	1.5

[1] Adjusted for sex, year of birth and sire EPD.
[2] EMS$_\kappa$ = error mean square.
[3] ADG = average daily gain.
[4] Least squares regression.

Table 47. Performance of ridge regression models of weaning weight[1] of the first calves of Simmental females on selected regressor variables observed at birth and from birth to yearling age, according to different values of κ

κ	EMS^2_κ	$PRESS_\kappa$	C_κ	DF-trace	Regression coefficient estimates and inflation of their standard errors								
					Inter-cept	Birth date	Age of dam	Age of dam sq.	205-d weight	B-wean. RGR[3]	B-yearl. RGR	B-yearl. RGR sq.	B-wean. ADG[4]
.0000[5]	1,063	245,325	9.0	8.0	-199.2	-.18	-5.8	.47	-.47	-80.1	1,807.1	-1,510.4	113.2
						1.9	4.1	4.0	14.6	3.2	20.8	20.3	16.2
.0002	1,064	244,730	8.6	7.8	-110.1	-.18	-5.8	.47	-.48	-78.6	1,669.7	-1,394.8	115.3
						1.8	4.1	4.0	13.9	3.1	19.1	18.8	15.4
.0004	1,064	244,385	8.4	7.6	-55.5	-.18	-5.8	.47	-.49	-74.3	1,362.1	-1,135.2	116.0
						1.7	4.0	3.9	12.2	2.8	15.5	15.2	13.5
.0006	1,065	244,173	8.2	7.4	-13.7	-.18	-5.8	.46	-.49	-71.6	1,214.5	-1,010.3	114.0
						1.7	4.0	3.9	11.2	2.7	13.7	13.5	12.5
.0008	1,066	244,037	8.1	7.3	19.3	-.19	-5.8	.46	-.48	-69.1	1,096.6	-910.3	111.1
						1.6	3.9	3.9	10.5	2.6	12.3	12.1	11.6
.0010	1,067	243,943	8.1	7.2	45.9	-.19	-5.7	.46	-.47	-66.9	1,000.1	-828.3	107.7
						1.6	3.9	3.9	9.8	2.5	11.2	11.0	10.9
.0012	1,068	243,888	8.0	7.1	68.0	-.19	-5.7	.46	-.45	-64.8	919.7	-759.9	104.2
						1.6	3.9	3.8	9.2	2,4	10.3	10.1	10.2
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.0020	1,070	243,789	8.0	6.8	127.6	-.20	-5.6	.45	-.40	-58.2	698.2	-570.7	90.7
						1.5	3.8	3.7	7.4	2.1	7.7	7.6	8.2
.0022	1,070	243,784	8.0	6.8	132.9	-.20	-5.6	.45	-.40	-57.5	678.0	-553.4	89.1
						1.5	3.8	3.7	7.2	2.1	7.5	7.4	8.0
.0024	1,071	243,781	8.0	6.8	137.9	-.20	-5.6	.45	-.39	-56.8	659.0	-537.1	87.6
						1.5	3.8	3.7	7.1	2.1	7.3	7.2	7.8

[1] Adjusted for sex, year of birth, sire EPD and percentage Simmental.
[2] EMS_κ = error mean square.
[3] RGR = relative growth rate.
[4] ADG = average daily gain.
[5] Least squares regression.

Table 48. Performance of principal components regression models of weaning weight[1] of the first calves of Angus females on selected regressor variables observed at birth and from birth to yearling age, according to the number of principal components dropped

					Regression coefficient											
Components dropped	EMS[2]	PRESS	C_p	R^2	Inter-cept	Birth date	Birth date sq.	Age of dam	Age of dam sq.	Actual wean.wt	Actual yearl.wt	B-wean. ADG[3]	W-yearl. ADG	B-yearl. ADG	Wean. ratio	Yearl. ratio
None[4]	1,085	792,761	12.0	18.1	175.5	-.53	.0071	3.0	-.26	-.12	.045	-31.5	-49.6	94.2	.061	.47
1	1,086	790,984	10.3	17.8	176.5	-.56	.0072	3.0	-.26	-.063	.0068	4.9	2.9	9.9	.075	.45
2	1,086	791,007	10.3	16.2	164.6	-.21	.0051	1.7	-.16	.21	-.0070	-28.5	-1.24	-4.9	-.23	.72
3	1,087	790,230	9.6	15.2	170.2	-.31	.0056	-.17	-.0096	.13	.000045	-18.8	-16.1	-.84	-.12	.66
4	1,090	791,750	10.9	12.4	165.9	-.013	.00025	-.098	-.011	-.026	.013	1.4	2.3	1.7	.086	.52
5	1,089	789,888	9.2	12.3	165.7	-.025	.00045	-.098	-.012	-.018	.031	-4.1	2.8	-.79	.16	.43
6	1,088	787,924	7.2	12.3	165.8	-.025	.00044	-.099	-.012	-.018	.029	-4.7	3.0	-.40	.17	.43
7	1,091	789,248	8.4	9.7	183.5	-.0049	-.000076	-2.1	-.017	.021	.026	4.1	5.8	10.6	.048	.12
8	1,090	786,950	6.4	9.7	184.9	-.010	-.00015	-.19	-.016	.020	.027	3.0	6.2	10.7	.043	.12
9	1,091	786,809	6.5	7.9	185.6	-.017	-.00022	.075	.0051	.029	.021	5.6	3.2	7.9	.065	.097
10	1,090	784,841	4.8	7.6	188.9	-.029	-.00038	.021	.00080	.031	.019	5.3	2.0	6.1	.073	.094

[1] Adjusted for sex, year of birth and sire EPD.
[2] EMS = error mean square.
[3] ADG = average daily gain.
[4] Least square regression.

Table 49. Performance of principal components regression models of weaning weight[1] of the first calves of Simmental females on selected regressor variables observed at birth and from birth to yearling age, according to the number of principal components dropped

					Regression coefficient								
Components dropped	EMS[2]	PRESS	C_p	R^2	Inter-cept	Birth date	Age of dam	Age of dam sq.	205-d weight	B-wean. RGR[3]	B-yearl. RGR	B-yearl. RGR sq.	B-wean. ADG[4]
None[5]	1,063	245,325	9.0	15.1	-199.2	-.18	-.5.8	.47	-.47	-80.1	1,807.1	-1,510.4	113.2
1	1,072	244,575	8.7	12.1	316.8	-.080	-5.7	.46	-1.3	-102.9	196.3	-179.1	299.5
2	1,072	245,612	9.7	10.9	284.1	-.25	-6.2	.50	-.050	-26.8	20.0	13.1	4.0
3	1,087	246,141	10.8	6.3	263.2	-.26	.20	.019	-.043	-23.9	31.0	27.2	-7.0
4	1,083	243,300	8.9	6.1	261.6	-.27	.19	.019	-.061	-10.3	26.0	22.3	-8.8
5	1,088	243,520	8.9	3.7	284.9	-.024	.24	.020	-.056	-12.4	-6.6	-5.6	-12.0
6	1,087	242,305	7.8	2.7	280.5	-.043	.018	.00061	-.023	-10.3	-18.0	-15.4	-5.5
7	1,082	239,413	5.8	2.5	281.1	-.040	-.041	-.0036	-.026	-10.4	-16.5	-14.1	-6.1

[1] Adjusted for sex, year of birth, sire EPD and percentage Simmental.
[2] EMS = error mean square.
[3] RGR = relative growth rate.
[4] ADG = average daily gain.
[5] Least square regression.

Table 50. Comparative performance of least squares, ridge and principal components regression models of weaning weight[1] of first calves of Angus females on selected regressor variables observed at birth and from birth to yearling age

Intercept and	Regression method and coefficient estimates		
regressor variables	P. components[2]	Ridge[3]	Least squares
Intercept	176.5	173.2	175.5
Birth date	-.56	-.38	-.53
Birth date squared	.0072	.0054	.0071
Age of the dam	3.0	1.8	3.0
Age of the dam squared	-.26	-.17	-.26
Actual weaning weight	-.063	-.021	-.12
Actual yearling weight	.0068	.015	.045
Birth-weaning ADG[4]	4.9	-7.8	-31.5
Weaning-yearling ADG	2.9	-7.2	-49.6
Birth-yearling ADG	9.9	21.1	94.2
Weaning weight ratio	.075	.033	.061
Yearling weight ratio	.45	.50	.47
Error mean square	1,086	1,087	1,085
PRESS or $PRESS_\kappa$	790,984	789,411	792,761
C_p or C_κ	10.3	8.9	12.0

[1] Adjusted for sex, year of birth and sire EPD.

[2] Model with one component dropped.

[3] $\kappa = .015$.

[4] ADG = average daily gain.

Table 51. Comparative performance of least squares, ridge and principal components regression models of weaning weight[1] of first calves of Simmental females on selected regressor variables observed at birth and from birth to yearling age

Intercept and regressor variables	Regression method and coefficient estimates		
	P. components[2]	Ridge[3]	Least squares
Intercept	316.8	19.3	-199.2
Birth date	-.080	-.19	-.18
Age of the dam	-5.7	-5.8	-5.8
Age of the dam squared	.46	.46	.47
205-day weight	-1.3	-.48	-.47
Birth-weaning RGR[4]	-102.9	-69.1	-80.1
Birth-yearling RGR	196.3	1,096.6	1,807.1
Birth-yearling RGR squared	-179.1	-910.3	-1,510.4
Birth-weaning ADG[5]	299.5	111.1	113.2
Error mean square	1,072	1,066	1,063
PRESS or PRESS_κ	244,575	244,037	245,325
C_p or C_κ	8.7	8.1	9.0

[1] Adjusted for sex, year of birth, sire EPD and percentage Simmental.

[2] Model with one component dropped.

[3] $\kappa = .0008$.

[4] RGR = relative growth rate.

[5] ADG = average daily gain.

Table 52. Arithmetic means (± standard deviation) of variables observed at birth and from birth to yearling age of Angus females whose production was analysed through three or eleven potential years

	Period of productive life, years	
Variable	Three	Eleven
Birth date, days	29 ± 16	26 ± 15
Age of the dam, years	4.2 ± 2.3	4.1 ± 2.0
Birth weight, kg	33 ± 3	32 ± 3
Actual weaning weight, kg	228 ± 25	219 ± 25
205-day weight, kg	228 ± 22	217 ± 23
Weaning weight ratio, %	100 ± 10	100 ± 11
Actual yearling weight, kg	370 ± 38	366 ± 34
365-day weight, kg	333 ± 37	311 ± 23
Yearling weight ratio, %	100 ± 8	100 ± 7
Birth-weaning ADG[1], kg	.949 ± .104	.904 ± .105
Weaning-yearling ADG, kg	.656 ± .160	.574 ± .092
Birth-yearling ADG, kg	.794 ± .098	.720 ± .054
Birth-weaning RGR[2], %	.94 ± .07	.93 ± .07
Weaning-yearling RGR, %	.22 ± .05	.20 ± .04
Birth-yearling RGR, %	.57 ± .05	.53 ± .04
Number of females	672	209

[1] ADG = average daily gain.
[2] RGR = relative growth rate.

Table 53. Arithmetic means (± standard deviation), or frequencies, of variables observed in the first calving season and of the productive performance of Angus females whose production was analysed through three or eleven potential years

Variable	Period of productive life, years	
	Three	Eleven
First calving date, days	31 ± 20	24 ± 18
Birth weight of the first calf, kg	33 ± 4	31 ± 4
Calving ease in the first parturition, No. (%)		
No assistance	568 (84.5)	162 (77.5)
Some assistance	104 (15.5)	47 (22.5)
Sex of the first calf, No. (%)		
Males	354 (52.7)	104 (49.8)
Females	318 (47.3)	105 (50.2)
Weaning weight of the first calf, kg	231 ± 34	225 ± 28
Total number of calves weaned	2.4 ± .8	5.3 ± 3.2
Total weaning weight of calves produced, kg	560 ± 198	1,245 ± 776
Average weaning weight of calves, kg	230 ± 25	230 ± 20
Avearge weaning weight of calves per year of productive life, kg/year	274 ± 53	256 ± 53
Calf survival from birth to weaning, %	96 ± 14	95 ± 10
Number of females	672	209

Table 54. Coefficients of determination of multiple regression models of production traits on either all traits observed from birth to yearling, or all traits observed in the first calving season or all traits observed in both phases of life of Angus females and when production in the first year was excluded (or included) from the calculation of the production trait

Period of productive life and production trait	Traits observed from birth to yearling age 30 regressors[1]	Traits observed in the first calving season 8 regressors[2]	Complete model 38 regressors
Three years	Coefficients of determination (%)		
Total number of calves weaned	13.3 (13.9)[3]	7.7 (7.8)	21.4 (21.6)
Total weaning weight of calves produced	14.0 (15.2)	8.9 (25.4)	23.9 (38.8)
Average weaning weight of calves	12.6 (19.1)	8.5 (85.4)	29.4 (91.6)
Avearge weaning weight of calves per year of productive life	8.1 (17.1)	6.6 (35.9)	24.2 (43.6)
Calf survival from birth to weaning age	10.7 (11.8)	4.2 (4.6)	13.9 (15.7)
Eleven years			
Total number of calves weaned	18.2 (20.6)	11.1 (11.2)	30.8 (33.2)
Total weaning weight of calves produced	18.2 (21.7)	15.1 (18.8)	32.5 (36.4)
Average weaning weight of calves	41.1 (45.0)	38.5 (75.5)	79.8 (87.8)
Avearge weaning weight of calves per year of productive life	26.5 (37.1)	9.4 (36.9)	49.0 (50.9)
Calf survival from birth to weaning age	26.1 (28.3)	11.7 (12.4)	30.4 (32.0)

[1] Including the linear and the quadratic effects for each one of the 15 calfhood traits.

[2] Including the linear and the quadratic effects of Julian calving date, birth and weaning weight of the calf and the effects of sex of the calf and calving ease score.

[3] When production in the first year was included.

Table 55. Distribution of signs and ranges of regression coefficients from multiple regressions of weaning weight of the first calf of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth date[2]				
Linear	390 (76)	122 (24)	-.69 (.02)	.025 (.79)
Quadratic	-	-	.0077 (.02)	-
Age of the dam[2]				
Linear	256 (50)	256 (50)	-.37 (.42)	3.8 (.05)
Quadratic	-	-	-	-.32 (.04)
Actual weaning weight	245 (48)	267 (52)	-.27 (.22)	.19 (.18)
Weaning weight ratio	161 (31)	351 (69)	-.088 (.79)	.45 (.08)
Actual yearling weight	42 (8)	470 (92)	-.0067 (.93)	.10 (<.01)
Yearling weight ratio	-	512 (100)	.43 (.19)	.67 (.01)
Weaning-yearling ADG[3]	142 (28)	370 (72)	-27.4 (.49)	33.0 (.31)
Birth-yearling ADG	70 (14)	442 (86)	-36.8 (.56)	72.2 (.32)

[1] A total of 1,024 regression models were fit and 512 regression coefficiets were estimated for each one of the 10 variables.

[2] In computation of frequencies of signs and ranges, only the linear regression coefficients were considered. When the quadratic regression coefficient was included in the model in which the minimun or the maximum value was observed, the associated quadratic effect is presented.

[3] ADG = average daily gain.

Table 56. Distribution of signs and ranges of regression coefficients from multiple regressions of weaning weight of the first calf of Simmental females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth date	16 (100)	-	-.31 (.07)	-.24 (.08)
Age of the dam[2]				
Linear	10 (63)	6 (37)	-6.9 (.03)	.083 (.92)
Quadratic	-	-	.54 (.02)	-
Birth-yearling RGR[2, 3]				
Linear	4 (25)	12 (75)	-48.8 (.32)	1,643.7 (.08)
Quadratic	-	-	-	-1,368.5 (.08)

[1] A total of 32 regression models were fit and 16 regression coefficiets were estimated for each one of the five variables.

[2] In computation of frequencies of signs and ranges, only the linear regression coefficients were considered. When the quadratic regression coefficient was included in the model in which the minimun or the maximum value was observed, the associated quadratic effect is presented.

[3] RGR = relative growth rate.

Table 57. Coefficients of determination (R^2), regression coefficient stimates, standard errors and tests of significance of regression models of number of calves weaned in the first three years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor	R^2,	Prob. of test		Coefficient estimates ± standard errors		
model[1]	%	β_1	β_2	β_0	β_1	β_2
Birth date	1.2	.04	-	2.5 ± .1	-.0040 ± .0020	-
Age of the dam	1.4	.07	.04	2.6 ± .1	-.11 ± .06	.012 ± .006
Birth weight	1.2	.04	-	3.0 ± .3	-.018 ± .009	-
Actual weaning weight	.4	.22	-	2.1 ± .3	.0015 ± .0012	-
205-day weight	0	.74	-	2.3 ± .3	.00046 ± .00136	-
Weaning weight ratio	0	.81	-	2.5 ± .3	-.00079 ± .00321	-
Actual yearling weight	1.8	.01	.01	-2.8 ± 2.0	.027 ± .011	-.000036 ± .000014
365-day weight	1.5	.02	.03	-2.2 ± 2.0	.027 ± .012	-.000039 ± .000017
Yearling weight ratio	1.0	.06	.06	-4.6 ± 3.7	.14 ± .07	-.00068 ± .00037
Birth-weaning ADG[2]	.1	.48	-	2.2 ± .3	.21 ± .29	-
Weaning-yearling ADG	.3	.31	.31	2.0 ± .4	1.2 ± 1.2	-.87 ± .86
Birth-yearling ADG	.7	.13	.13	-.14 ± 1.66	6.2 ± 4.1	-3.7 ± 2.5
Birth-weaning RGR[3]	.2	.41	-	2.1 ± .4	.35 ± .42	-
Weaning-yearling RGR	.2	.36	.36	2.9 ± .5	-4.3 ± 4.6	9.1 ± 9.9
Birth-yearling RGR	.2	.34	-	2.1 ± .3	.54 ± .57	-
Calving date[4]	2.1	$<.01$	-	2.4 ± .1	-.0052 ± .0019	-
Calf birth weight[4]	.1	.64	-	2.6 ± .3	-.0035 ± .0076	-
Calving ease score[4,5]	1.1	.04	-	2.7 ± .1	-.17 ± .08	-
Sex of the calf[4,6]	.9	.07	-	2.3 ± .1	.11 ± .6	-
Calf weaning weight[4]	4.5	$<.01$	-	1.6 ± .2	.0036 ± .0009	-

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[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 58. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of number of calves weaned in eleven years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor model[1]	R^2, %	Prob. of test β_1	Prob. of test β_2	Coefficient estimates ± standard errors β_0	β_1	β_2
Birth date	.7	.39	.38	4.8 ± .7	.043 ± .049	-.00062 ± .00070
Age of the dam	.3	.56	-	5.6 ± .5	-.060 ± .106	-
Birth weight	4.0	.03	-	10.1 ± 2.2	-.15 ± .07	-
Actual weaning weight	.2	.62	-	4.4 ± 1.9	.0042 ± .0086	-
205-day weight	.1	.79	-	4.8 ± 2.1	.0025 ± .0095	-
Weaning weight ratio	1.0	.27	-	3.2 ± 2.0	.022 ± .020	-
Actual yearling weight	1.8	.20	.19	-19.5 ± 20.1	.14 ± .11	-.00019 ± .00014
365-day weight	.1	.72	-	4.3 ± 3.0	.0035 ± .0096	-
Yearling weight ratio	.2	.66	-	4.0 ± 3.1	.014 ± .031	-
Birth-weaning ADG[2]	.3	.54	-	4.2 ± 1.9	1.3 ± 2.1	-
Weaning-yearling ADG	.1	.78	.78	7.3 ± 6.8	-6.6 ± 23.8	5.3 ± 20.6
Birth-yearling ADG	.3	.53	-	3.5 ± 2.9	2.5 ± 4.0	-
Birth-weaning RGR[3]	1.9	.13	-	.90 ± 2.96	4.7 ± 3.7	-
Weaning-yearling RGR	.2	.63	.63	7.7 ± 4.7	-22.1 ± 45.2	51.2 ± 107.2
Birth-yearling RGR	3.8	.03	-	-.77 ± 2.88	11.6 ± 5.5	-
Calving date[4]	2.7	.10	-	6.2 ± .2	-.020 ± .012	-
Calf birth weight[4]	0	.85	-	6.5 ± 1.7	-.010 ± .055	-
Calving ease score[4,5]	.5	.49	-	6.6 ± .7	-.36 ± .52	-
Sex of the calf[4,6]	1.0	.34	-	5.6 ± .7	.41 ± .43	-
Calf weaning weight[4]	5.4	.03	-	2.5 ± 1.8	.017 ± .008	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 59. Distribution of signs and ranges of regression coefficients from multiple regressions of number of calves weaned in the first three years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth date	2,048 (100)	-	-.0055 (.01)	-.0021 (.15)
Age of the dam[2]				
Linear	1,186 (58)	862 (42)	-.12 (.04)	.012 (.36)
Quadratic	-	-	.014 (.02)	-
Birth weight	2,048 (100)	-	-.026 (<.01)	-.020 (.03)
Actual yearling weight[2]				
Linear	373 (18)	1,674 (82)	-.00081 (.96)	.029 (.01)
Quadratic	-	-	-	-.000037 (.01)
Yearling weight ratio[2]				
Linear	768 (37)	1,280 (63)	-.0056 (.37)	.16 (.03)
Quadratic	-	-	-	-.00078 (.03)
Calving date	2,048 (100)	-	-.0059 (<.01)	-.00017 (.95)
Calving ease score[3]	1,227 (60)	821 (40)	-.20 (.02)	.12 (.16)
Sex of the calf[4]	-	2,048 (100)	.0068 (.46)	.13 (.06)
Calf weaning weight	-	2,048 (100)	.0033 (.01)	.0039 (<.01)

[1] A total of 4,096 regression models were fit and 2,048 regression coefficiets were estimated for each one of the 12 variables.

[2] In computation of frequencies of signs and ranges, only the linear regression coefficients were considered. When the quadratic regression coefficient was included in the model in which the minimun or the maximum value was observed, the associated quadratic effect is presented.

[3] Codified as 1 = no assistance; 2 = some assistance.

[4] Codified as 1 = males; 2 = females.

Table 60. Distribution of signs and ranges of regression coefficients from multiple regressions of number of calves weaned in eleven years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth weight	8 (100)	-	-.17 (.06)	-.046 (.60)
Birth-yearling RGR[2]	-	8 (100)	4.2 (.40)	10.1 (.29)
Calving date	8 (100)	-	-.021 (.09)	-.010 (.60)
Calf weaning weight	-	8 (100)	.013 (.16)	.017 (.03)

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[1] A total of 16 regression models were fit and eight regression coefficiets were estimated for each one of the four variables.

[2] RGR = relative growth rate.

Table 61. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of total weaning weight of calves produced in the first three years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor model[1]	R^2, %	Prob. of test β_1	Prob. of test β_2	Coefficient estimates ± standard errors β_0	β_1	β_2
Birth date	1.7	.01	-	595.6 ± 15.9	-1.2 ± .5	-
Age of the dam	1.4	.10	.05	598.1 ± 31.6	-24.4 ± 14.7	2.8 ± 1.4
Birth weight	1.0	.06	-	697.9 ± 72.8	-4.1 ± 2.2	-
Actual weaning weight	1.1	.05	-	424.4 ± 68.2	.60 ± .29	-
205-day weight	.1	.52	-	510.5 ± 77.4	.22 ± .34	-
Weaning weight ratio	.2	.45	-	500.8 ± 79.8	.59 ± .79	-
Actual yearling weight	2.3	.01	.02	-733.1 ± 503.6	6.6 ± 2.7	-.0084 ± .0035
365-day weight	2.1	.02	.02	-659.9 ± 491.1	7.0 ± 2.9	-.0097 ± .0043
Yearling weight ratio	1.3	.07	.08	-1,196.6 ± 931.6	33.5 ± 18.4	-.16 ± .09
Birth-weaning ADG[2]	.3	.31	-	490.6 ± 69.5	73.4 ± 72.8	-
Weaning-yearling ADG	.1	.49	-	543.9 ± 31.7	32.7 ± 47.0	-
Birth-yearling ADG	1.2	.09	.10	-175.5 ± 411.8	1,741.3 ± 1,010.4	-1,002.6 ± 613.8
Birth-weaning RGR[3]	.1	.65	-	516.4 ± 97.4	46.7 ± 103.5	-
Weaning-yearling RGR	.4	.28	.27	700.0 ± 131.9	-1,245.4 ± 156.8	2,742.3 ± 2,461.7
Birth-yearling RGR	.4	.25	-	472.9 ± 81.2	163.1 ± 142.5	-
Calving date[4]	2.3	< .01	-	666.6 ± 7.2	-1.3 ± .4	-
Calf birth weight[4]	0	.95	-	654.9 ± 59.7	.11 ± 1.80	-
Calving ease score[4,5]	.8	.10	-	607.1 ± 24.3	-33.2 ± 20.1	-
Sex of the calf[4,6]	1.1	.05	-	525.9 ± 22.6	29.2 ± 14.5	-
Calf weaning weight[4]	5.9	< .01	-	339.6 ± 49.9	.99 ± .21	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 62. Coefficients of determination (R^2), regression coefficient stimates, standard errors and tests of significance of regression models of total weaning weight of calves produced in eleven years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor model[1]	R^2, %	Prob. of test β_1	Prob. of test β_2	Coefficient estimates ± standard errors β_0	β_1	β_2
Birth date	.4	.48	.48	1,133.9 ± 178.5	-8.5 ± 12.0	.12 ± .17
Age of the dam	.3	.57	-	1,305.1 ± 117.6	-14.6 ± 25.6	-
Birth weight	4.5	.02	-	2,452.5 ± 520.1	-37.9 ± 16.3	-
Actual weaning weight	.3	.56	-	982.7 ± 455.8	1.2 ± 2.1	-
205-day weight	.1	.74	-	1,080.6 ± 499.6	.76 ± 2.29	-
Weaning weight ratio	1.3	.21	-	651.0 ± 480.2	5.9 ± 4.8	-
Actual yearling weight	1.9	.17	.16	-5,328.3 ± 4,869.5	36.2 ± 26.2	-.050 ± .035
365-day weight	.3	.58	-	851.2 ± 726.4	1.3 ± 2.3	-
Yearling weight ratio	.5	.45	-	677.2 ± 752.9	5.7 ± 7.5	-
Birth-weaning ADG[2]	.4	.48	-	930.0 ± 452.9	348.4 ± 497.9	-
Weaning-yearling ADG	0	.93	-	1,278.8 ± 334.4	-49.0 ± 575.2	-
Birth-yearling ADG	.7	.38	-	628.1 ± 707.5	864.1 ± 979.3	-
Birth-weaning RGR[3]	2.2	.11	-	85.1 ± 715.9	1,242.8 ± 765.1	-
Weaning-yearling RGR	0	.96	-	1,263.5 ± 274.9	-63.2 ± 1,330.8	-
Birth-yearling RGR	4.7	.02	-	-388.4 ± 696.6	3,100.7 ± 1,314.1	-
Calving date[4]	2.7	.10	-	1,442.6 ± 50.9	-5.0 ± 3.0	-
Calf birth weight[4]	0	.97	-	1,455.1 ± 422.6	-.34 ± 13.4	-
Calving ease score[4,5]	.5	.51	-	1,551.8 ± 163.2	-84.6 ± 127.2	-
Sex of the calf[4,6]	1.7	.21	-	1,264.3 ± 165.3	130.4 ± 104.7	-
Calf weaning weight[4]	7.9	< .01	-	345.1 ± 424.4	5.0 ± 1.9	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 63. Distribution of signs and ranges of regression coefficients from multiple regressions of total weaning weight of calves produced in the first three years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth date	16,384 (100)	-	-1.2 (<.01)	-.42 (.52)
Age of the dam[2]				
Linear	8,192 (50)	8,192 (50)	-.32.0 (.03)	5.3 (.10)
Quadratic	-	-	3.5 (.01)	-
Birth weight	16,384 (100)	-	-7.8 (<.01)	-5.0 (.05)
Actual weaning weight	208 (1)	16,176 (99)	-.22 (.52)	.75 (.02)
Actual yearling weight[2]				
Linear	1,522 (9)	14,862 (91)	-.14 (.57)	7.1 (<.01)
Quadratic	-	-	-	-.0089 (<.01)
Yearling weight ratio[2]				
Linear	-	16,384 (100)	1.2 (.95)	34.6 (.05)
Quadratic	-	-	-	-.17 (.05)
Birth-yearling ADG[2, 3]				
Linear	8,192 (50)	8,192 (50)	-222.2 (.04)	1,883.8 (.05)
Quadratic	-	-	-	-1,262.2 (.03)
Calving date	9,224 (56)	7,160 (44)	-1.5 (<.01)	.27 (.64)
Calving ease score[4]	16,384 (100)	-	-35.2 (.08)	-24.3 (.23)
Sex of the calf[5]	-	16,384 (100)	27.5 (.06)	31.0 (.03)
Calf weaning weight	-	16,384 (100)	.94 (<.01)	1.1 (<.01)

[1] A total of 32,768 regression models were fit and 16,384 regression coefficiets were estimated for each of the 15 variables.

[2] In computation of frequencies of signs and ranges, only the linear regression coefficients were considered. When the quadratic regression coefficient was included in the model in which the minimun or the maximum value was observed, the associated quadratic effect is presented.

[3] ADG = average daily gain.

[4] Codified as 1 = no assistance; 2 = some assistance;

[5] Codified as 1 = males; 2 = females.

Table 64. Distribution of signs and ranges of regression coefficients from multiple regressions of total weaning weight of calves produced in eleven years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth weight	8 (100)	-	-18.9 (.26)	-12.2 (.55)
Birth-yearling RGR[2]	-	8 (100)	1,552.3 (.31)	1,658.4 (.20)
Calving date	8 (100)	-	-5.0 (.10)	-1.5 (.68)
Calf weaning weight	-	8 (100)	1.3 (.04)	5.0 (<.01)

[1] A total of 16 regression models were fit and eight regression coefficiets were estimated for each one of the four variables.

[2] RGR = relative growth rate.

Table 65. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of average weaning weight of calves produced in the first three years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor model[1]	R^2, %	Prob. of test β_1	Prob. of test β_2	Coefficient estimates ± standard errors β_0	β_1	β_2
Birth date	1.2	.04	-	235.4 ± 1.8	-.11 ± .05	-
Age of the dam	.2	.34	-	230.7 ± 1.8	-.35 ± .37	-
Birth weight	.5	.19	.19	299.4 ± 52.3	-4.1 ± 3.1	.062 ± .047
Actual weaning weight	2.7	< .01	-	208.2 ± 7.6	.11 ± .03	-
205-day weight	.4	.22	-	221.4 ± 8.7	.047 ± .038	-
Weaning weight ratio	3.5	< .01	-	200.3 ± 8.8	.32 ± .09	-
Actual yearling weight	4.4	< .01	-	198.4 ± 8.3	.091 ± .022	-
365-day weight	4.3	< .01	-	201.1 ± 7.8	.094 ± .023	-
Yearling weight ratio	5.9	< .01	-	179.1 ± 11.3	.53 ± .11	-
Birth-weaning ADG[2]	.5	.20	-	222.0 ± 7.9	10.6 ± 8.2	-
Weaning-yearling ADG	1.7	.01	-	223.9 ± 3.6	13.0 ± 5.3	-
Birth-yearling ADG	2.7	< .01	-	210.8 ± 7.0	27.2 ± 8.7	-
Birth-weaning RGR[3]	.4	.23	-	245.4 ± 11.0	-14.1 ± 11.7	-
Weaning-yearling RGR	.3	.31	-	228.6 ± 3.9	17.2 ± 16.9	-
Birth-yearling RGR	.3	.33	-	223.6 ± 9.1	15.5 ± 16.0	-
Calving date[4]	.5	.21	-	232.7 ± 1.0	-.08 ± .06	-
Calf birth weight[4]	2.5	< .01	-	211.9 ± 7.9	.65 ± .24	-
Calving ease score[4, 5]	1.0	.09	-	227.5 ± 3.3	4.8 ± 2.8	-
Sex of the calf[4, 6]	.5	.26	-	229.9 ± 3.0	2.2 ± 1.9	-
Calf weaning weight[4]	4.9	< .01	-	206.8 ± 7.0	.11 ± .03	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 66. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of average weaning weight of calves produced in eleven years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor	R^2,	Prob. of test		Coefficient estimates ± standard errors		
model[1]	%	β_1	β_2	β_0	β_1	β_2
Birth date	1.3	.30	.24	236.0 ± 4.1	-.28 ± .27	.0045 ± .0038
Age of the dam	1.8	.14	.14	240.4 ± 5.6	-3.8 ± 2.6	.38 ± .26
Birth weight	2.9	.06	-	254.7 ± 11.7	-.69 ± .37	-
Actual weaning weight	.6	.39	-	224.1 ± 10.1	.039 ± .046	-
205-day weight	.3	.54	-	225.9 ± 11.1	.031 ± .051	-
Weaning weight ratio	1.9	.13	-	217.1 ± 10.4	.16 ± .10	-
Actual yearling weight	1.9	.16	.16	68.6 ± 113.1	.87 ± .61	-.0011 ± .0008
365-day weight	2.7	.08	-	205.0 ± 15.8	.090 ± .051	-
Yearling weight ratio	6.7	< .01	-	186.4 ± 16.2	.46 ± .16	-
Birth-weaning ADG[2]	.7	.34	-	223.3 ± 10.1	10.5 ± 11.0	-
Weaning-yearling ADG	1.2	.23	-	224.4 ± 7.2	14.8 ± 12.4	-
Birth-yearling ADG	4.7	.02	-	197.5 ± 15.0	49.0 ± 20.7	-
Birth-weaning RGR[3]	1.9	.14	-	208.7 ± 16.1	25.6 ± 17.2	-
Weaning-yearling RGR	.3	.55	-	229.4 ± 5.9	17.1 ± 28.7	-
Birth-yearling RGR	5.2	.01	-	196.3 ± 14.7	68.7 ± 27.6	-
Calving date[4]	3.1	.18	.13	232.5 ± 1.6	-.12 ± .09	.0060 ± .0043
Calf birth weight[4]	2.8	.10	-	221.7 ± 10.7	.41 ± .23	-
Calving ease score[4,5]	0	.98	-	234.4 ± 4.1	-.076 ± 3.259	-
Sex of the calf[4,6]	7.2	< .01	-	224.8 ± 4.0	6.6 ± 2.5	-
Calf weaning weight[4]	22.6	< .01	-	186.0 ± 10.3	.22 ± .05	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 67. Distribution of signs and ranges of regression coefficients from multiple regressions of average weaning weight of calves produced in the first three years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth date	499 (97)	13 (3)	-.16 (.01)	.04 (.76)
Actual weaning weight	187 (37)	325 (63)	-.19 (.28)	.20 (<.01)
Weaning weight ratio	31 (6)	481 (94)	-.14 (.40)	.52 (<.01)
Actual yearling weight	50 (10)	462 (90)	-.047 (.28)	.11 (<.01)
Yearling weight ratio	-	512 (100)	.19 (.43)	.67 (<.01)
Weaning-yearling ADG[2]	246 (48)	266 (52)	-25.8 (<.01)	41.2 (.03)
Birth-yearling ADG	478 (93)	34(7)	-93.3 (<.01)	26.8 (.09)
Calf birth weight	-	512 (100)	.14 (.62)	.78 (<.01)
Calving ease score[3]	-	512 (100)	1.3 (.66)	5.4 (.05)
Calf weaning weight	-	512 (100)	.086 (<.01)	.78 (<.01)

[1] A total of 1,024 regression models were fit and 512 regression coefficiets were estimated for each one of the 10 variables.

[2] ADG = average daily gain.

[3] Codified as 1 = no assistance; 2 = some assistance.

Table 68. Distribution of signs and ranges of regression coefficients from multiple regressions of average weaning weight of calves produced in eleven years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Birth weight	512 (100)	-	-1.4 (<.01)	-.28 (.56)
365-day weight	312 (61)	200 (39)	-.45 (<.01)	.11 (.05)
Yearling weight ratio	20 (4)	492 (96)	-.12 (.72)	2.2 (<.01)
Birth-yearling ADG[2]	179 (35)	333 (65)	-93.1 (.06)	61.2 (.08)
Birth-yearling RGR[3]	50 (10)	462 (90)	-1.1 (.98)	122.8 (<.01)
Calf birth weight	60 (12)	452 (88)	-.064 (.50)	1.1 (<.01)
Sex of the calf[4]	-	512 (100)	5.4 (.03)	10.3 (<.01)
Calf weaning weight	-	512 (100)	.053 (<.01)	.27 (<.01)

[1] A total of 256 regression models were fit and 128 regression coefficiets were estimated for each one of the eight variables.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] Codified as 1 = males; 2 = females.

Table 69. Coefficients of determination (R^2), regression coefficient stimates, standard errors and tests of significance of regression models of average weaning weight of calves per year of productive life in the first three years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor	R^2,	Prob. of test		Coefficient estimates ± standard errors		
model[1]	%	β_1	β_2	β_0	β_1	β_2
Birth date	.5	.20	-	269.4 ± 4.3	.16 ± .13	-
Age of the dam	.1	.54	-	271.9 ± 4.3	.54 ± .90	-
Birth weight	.2	.43	-	258.8 ± 19.6	.46 ± .58	-
Actual weaning weight	0	.74	-	268.2 ± 18.3	.027 ± .080	-
205-day weight	.1	.59	-	263.2 ± 20.8	.048 ± .091	-
Weaning weight ratio	0	.95	-	275.6 ± 21.4	-.013 ± .213	-
Actual yearling weight	1.9	<.01	-	225.2 ± 18.3	.14 ± .05	-
365-day weight	1.2	.04	-	233.3 ± 19.8	.11 ± .05	-
Yearling weight ratio	.5	.18	-	238.8 ± 26.8	.36 ± .27	-
Birth-weaning ADG[2]	.2	.49	.46	350.3 ± 115.6	-171.3 ± 245.4	94.9 ± 129.5
Weaning-yearling ADG	2.5	<.01	-	248.5 ± 8.4	37.9 ± 12.5	-
Birth-yearling ADG	2.8	<.01	-	221.6 ± 16.4	65.2 ± 20.5	-
Birth-weaning RGR[3]	.3	.26	.26	532.7 ± 229.7	-546.9 ± 485.2	287.7 ± 255.5
Weaning-yearling RGR	1.7	.01	-	251.1 ± 9.3	99.4 ± 40.4	-
Birth-yearling RGR	1.3	.03	-	226.9 ± 21.7	81.9 ± 38.0	-
Calving date[4]	0	.84	-	296.9 ± 2.4	.031 ± .153	-
Calf birth weight[4]	2.1	.01	-	250.8 ± 19.4	1.4 ± .6	-
Calving ease score[4,5]	0	.90	-	296.4 ± 8.1	.82 ± 6.84	-
Sex of the calf[4,6]	.7	.17	-	288.2 ± 7.4	6.4 ± 4.7	-
Calf weaning weight[4]	2.8	<.01	-	249.7 ± 16.9	.20 ± .07	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 70. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of average weaning weight of calves per year of productive life in eleven years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor model[1]	R^2, %	Prob. of test β_1	Prob. of test β_2	Coefficient estimates ± standard errors β_0	β_1	β_2
Birth date	.8	.35	-	269.1 ± 7.1	-.23 ± .25	-
Age of the dam	4.2	.04	.05	296.8 ± 16.9	-16.1 ± 7.8	1.6 ± .8
Birth weight	.2	.68	-	241.4 ± 35.7	.46 ± 1.12	-
Actual weaning weight	1.8	.15	-	300.4 ± 30.8	-.20 ± .14	-
205-day weight	.1	.72	-	268.1 ± 33.9	-.055 ± .155	-
Weaning weight ratio	1.7	.16	-	301.9 ± 32.5	-.046 ± .032	-
Actual yearling weight	.5	.44	-	227.1 ± 37.7	.079 ± .103	-
365-day weight	.5	.42	-	295.1 ± 49.2	-.13 ± .16	-
Yearling weight ratio	.2	.67	.66	48.4 ± 498.4	4.2 ± 9.8	-.021 ± .048
Birth-weaning ADG[2]	.2	.67	-	269.3 ± 30.7	-14.6 ± 33.8	-
Weaning-yearling ADG	1.3	.21	-	228.3 ± 22.6	48.7 ± 38.9	-
Birth-yearling ADG	.1	.72	-	238.9 ± 48.0	23.9 ± 66.5	-
Birth-weaning RGR[3]	.3	.51	-	224.1 ± 48.8	34.3 ± 52.1	-
Weaning-yearling RGR	1.0	.27	-	236.1 ± 18.6	99.0 ± 89.9	-
Birth-yearling RGR	.2	.63	-	279.0 ± 47.8	-43.1 ± 90.2	-
Calving date[4]	2.9	.09	-	263.2 ± 3.7	.36 ± .22	-
Calf birth weight[4]	1.0	.31	-	233.9 ± 30.7	.99 ± .97	-
Calving ease score[4,5]	.1	.77	-	259.8 ± 11.9	2.8 ± 9.3	-
Sex of the calf[4,6]	0	.88	-	262.5 ± 11.8	1.1 ± 7.5	-
Calf weaning weight[4]	.2	.65	-	258.9 ± 10.1	.021 ± .047	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.
[2] ADG = average daily gain.
[3] RGR = relative growth rate.
[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.
[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.
[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 71. Distribution of signs and ranges of regression coefficients from multiple regressions of average weaning weight of calves per year of productive life in the first three years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Actual yearling weight	5 (8)	59 (92)	-.0038 (.98)	.60 (<.01)
Weaning-yearling ADG[2]	8 (13)	56 (88)	-62.8 (.62)	359.3 (<.01)
Birth-yearling ADG	45 (70)	19 (30)	-.425.7 (<.01)	72.5 (<.01)
Weaning-yearling RGR[3]	46 (72)	18 (28)	-720.4 (.01)	255.4 (.40)
Birth-yearling RGR	21 (33)	43 (67)	-46.9 (.48)	390.9 (<.01)
Calf birth weight	-	64 (100)	.55 (.41)	1.4 (.01)
Calf weaning weight	-	64 (100)	.14 (.07)	.20 (<.01)

[1] A total of 128 regression models were fit and 64 regression coefficiets were estimated for each one of the seven variables.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

Table 72. Distribution of signs and ranges of regression coefficients from multiple regressions of average weaning weight of calves per year of productive life in eleven years of production of Angus females all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Age of the dam[2]				
Linear	8 (100)	-	-16.1 (.04)	-.78 (.67)
Quadratic	-	-	1.6 (.05)	-
Calving date	-	8 (100)	.34 (.11)	.37 (.08)

[1] A total of eight regression models were fit and four regression coefficiets were estimated for each one of the three variables.

[2] In computation of frequencies of signs and ranges, only the linear regression coefficients were considered. When the quadratic regression coefficient was included in the model in which the minimun or the maximum value was observed, the associated quadratic effect is presented.

Table 73. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of survival of calves from birth to weaning age in the first three years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor model[1]	R^2, %	Prob. of test		Coefficient estimates ± standard errors		
		β_1	β_2	β_0	β_1	β_2
Birth date	.2	.43	-	95.4 ± .9	.023 ± .029	-
Age of the dam	2.3	.01	< .01	98.8 ± 1.9	-2.3 ± .9	.24 ± .09
Birth weight	.3	.31	-	91.5 ± 4.5	.14 ± .13	-
Actual weaning weight	.1	.61	-	93.9 ± 4.2	.0092 ± .0182	-
205-day weight	.6	.11	-	88.5 ± 4.7	.033 ± .021	-
Weaning weight ratio	.5	.19	-	102.4 ± 4.8	-.063 ± .048	-
Actual yearling weight	.6	.15	-	89.4 ± 4.6	.018 ± .012	-
365-day weight	.8	.09	-	88.5 ± 4.4	.023 ± .013	-
Yearling weight ratio	0	.94	-	95.6 ± 6.2	.0047 ± .0619	-
Birth-weaning ADG[2]	.6	.13	-	89.7 ± 4.3	6.8 ± 4.5	-
Weaning-yearling ADG	.9	.06	-	92.4 ± 2.0	5.5 ± 3.0	-
Birth-yearling ADG	1.6	.02	-	86.6 ± 3.9	11.8 ± 4.9	-
Birth-weaning RGR[3]	.4	.21	-	88.6 ± 6.0	8.0 ± 6.4	-
Weaning-yearling RGR	.6	.15	-	92.9 ± 2.2	13.8 ± 9.4	-
Birth-yearling RGR	.8	.08	-	97.3 ± 5.1	-15.4 ± 8.8	-
Calving date[4]	2.2	.06	.02	97.7 ± 7.4	.077 ± .041	-.0037 ± .0016
Calf birth weight[4]	.2	.46	-	93.5 ± 4.6	.10 ± .14	-
Calving ease score[4,5]	.5	.23	-	99.2 ± 2.0	-2.0 ± 1.7	-
Sex of the calf[4,6]	0	.93	-	96.8 ± 1.8	.10 ± 1.2	-
Calf weaning weight[4]	.2	.40	-	100.4 ± 4.3	-.015 ± .018	-

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[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 74. Coefficients of determination (R^2), regression coefficient estimates, standard errors and tests of significance of regression models of survival of calves from birth to weaning age in eleven years of production of Angus females on individual variables observed from birth to yearling age and in the first calving season

Individual regressor model[1]	R^2, %	Prob. of test		Coefficient estimates ± standard errors		
		β_1	β_2	β_0	β_1	β_2
Birth date	.4	.50	-	94.7 ± 1.2	.029 ± .042	-
Age of the dam	4.5	.03	.04	102.2 ± 3.0	-3.1 ± 1.4	.28 ± .14
Birth weight	.1	.73	-	97.7 ± 6.3	-.070 ± .198	-
Actual weaning weight	1.0	.28	-	101.2 ± 5.3	-.026 ± .024	-
205-day weight	.2	.62	-	98.3 ± 5.9	-.013 ± .027	-
Weaning weight ratio	.5	.43	-	99.8 ± 5.6	-.043 ± .055	-
Actual yearling weight	3.2	.07	.08	-14.3 ± 59.2	.57 ± .32	-.00076 ± .00043
365-day weight	.4	.50	-	101.2 ± 8.5	-.019 ± .027	-
Yearling weight ratio	.2	.65	-	99.5 ± 8.7	-.040 ± .087	-
Birth-weaning ADG[2]	.7	.45	.43	68.4 ± 37.5	63.9 ± 83.9	-37.1 ± 46.6
Weaning-yearling ADG	.4	.49	-	92.8 ± 3.9	4.6 ± 6.7	-
Birth-yearling ADG	.3	.60	.59	56.7 ± 76.4	108.7 ± 208.9	-75.9 ± 142.5
Birth-weaning RGR[3]	.3	.54	-	90.2 ± 8.6	5.6 ± 9.2	-
Weaning-yearling RGR	1.0	.33	.35	81.7 ± 13.3	128.3 ± 129.7	-287.4 ± 307.7
Birth-yearling RGR	.5	.43	-	101.6 ± 7.9	-11.7 ± 14.9	-
Calving date[4]	1.2	.29	-	96.7 ± .58	.037 ± .035	-
Calf birth weight[4]	.6	.44	-	92.8 ± 5.1	.12 ± .16	-
Calving ease score[4,5]	2.8	.10	-	99.7 ± 1.9	-2.5 ± 1.5	-
Sex of the calf[4,6]	0	.86	-	97.2 ± 1.8	-.20 ± 1.1	-
Calf weaning weight[4]	.6	.48	-	100.3 ± 4.8	-.015 ± .021	-

[1] Two models were fit for each variable, including the intercept (β_0) and either the linear (β_1) or the linear and the quadratic (β_2) effects. The model with the higher overall level of significance is presented here.

[2] ADG = average daily gain.

[3] RGR = relative growth rate.

[4] First calving season information was excluded from the dependent variable to avoid part-whole relationship.

[5] Codified as 1 = no assistance; 2 = some assistance. Only linear model was fit.

[6] Codified as 1 = males; 2 = females. Only linear model was fit.

Table 75. Distribution of signs and ranges of regression coefficients from multiple regressions of survival of calves from birth to weaning age in the first three years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Age of the dam[2]				
Linear	64 (50)	64 (50)	-3.2 (<.01)	.10 (.68)
Quadratic	-	-	.32 (<.01)	-
365-day weight	32 (25)	96 (75)	-.034 (.50)	.050 (.25)
Weaning-yearling ADG[3]	-	128 (100)	.70 (.89)	7.7 (.34)
Birth-yearling ADG	48 (38)	80 (62)	-19.3 (.36)	31.9 (.18)
Birth-yearling RGR[4]	128 (100)	-	-44.1 (.03)	-7.5 (.50)
Calving date[2]				
Linear	-	128 (100)	.036 (.35)	.077 (.06)
Quadratic	-	-	-	-.0037 (.02)

[1] A total of 256 regression models were fit and 128 regression coefficiets were estimated for each one of the eight variables.

[2] In computation of frequencies of signs and ranges, only the linear regression coefficients were considered. When the quadratic regression coefficient was included in the model in which the minimun or the maximum value was observed, the associated quadratic effect is presented.

[3] ADG = average daily gain.

[4] RGR = relative growth rate.

Table 76. Distribution of signs and ranges of regression coefficients from multiple regressions of survival of calves from birth to weaning age in eleven years of production of Angus females on all possible combinations[1] of pre-selected regressor variables ($P \leq .10$)

Variable	Regression coefficients			
	Sign, No (%)		Range (Prob.)	
	Negative	Positive	Minimum	Maximum
Age of the dam[2]				
Linear	32 (100)	-	-3.1 (.03)	-.09 (.89)
Quadratic	-	-	.28 (.04)	-
Actual yearling weight[2]				
Linear	-	32 (100)	.0038 (82)	.42 (.21)
Quadratic	-	-	-	-.00056 (.21)
Calving ease score[3]	32 (100)	-	-2.5 (.09)	-2.2 (.11)

[1] A total of 32 regression models were fit and 16 regression coefficiets were estimated for each one of the five variables.

[2] In computation of frequencies of signs and ranges, only the linear regression coefficients were considered. When the quadratic regression coefficient was included in the model in which the minimun or the maximum value was observed, the associated quadratic effect is presented.

[3] Codified as 1 = no assistance; 2 = some assistance.

Appendix B. Figures

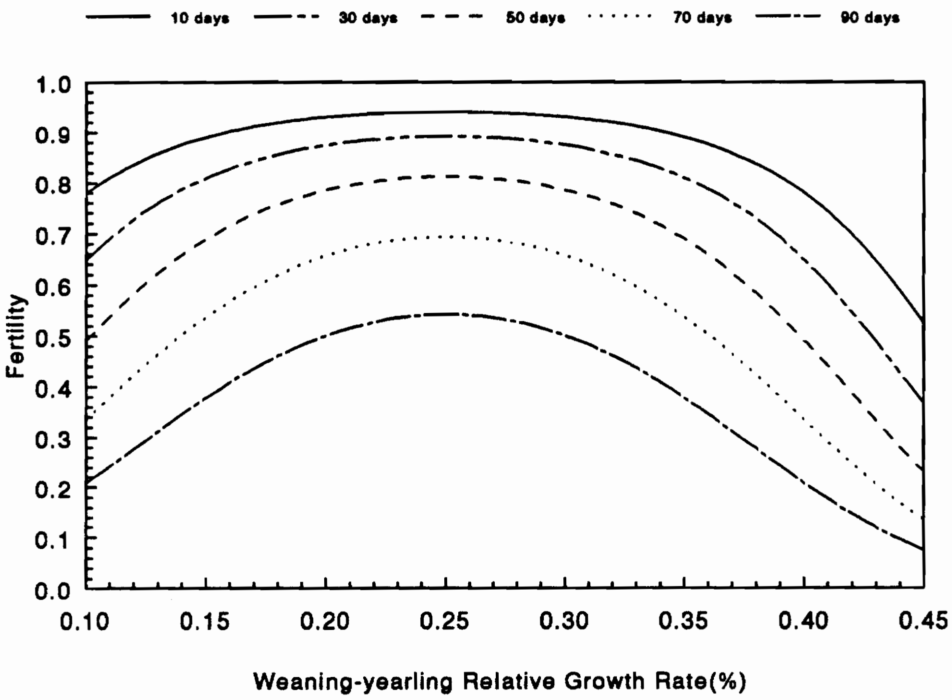


Figure 1. Regression in Angus females of fertility in the first breeding season on birth date and weaning-yearling relative growth rate.

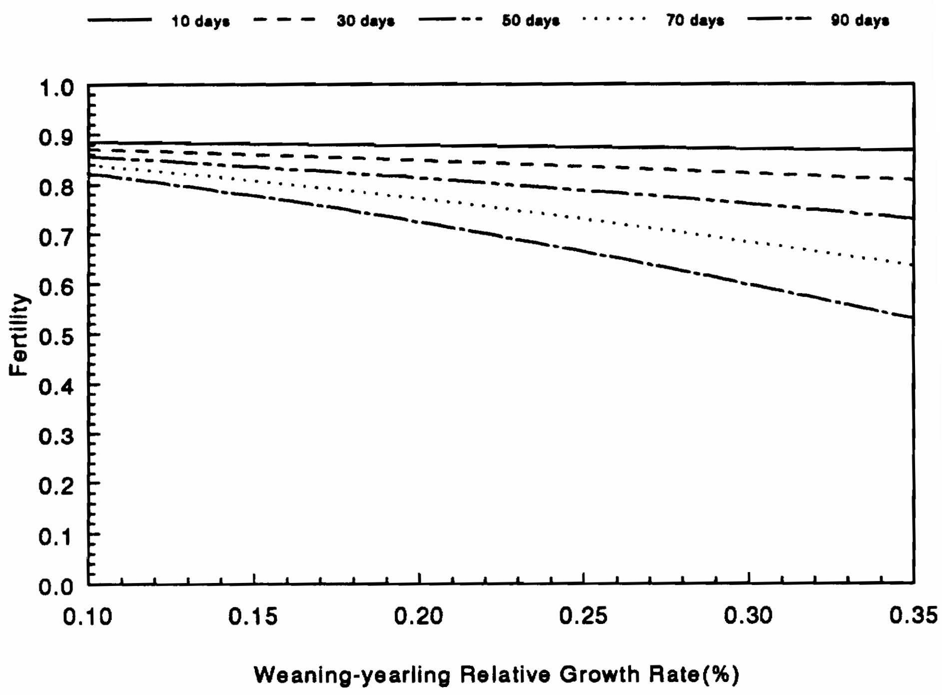


Figure 2. Regression in Simmental females of fertility in the first breeding season on the interaction between birth date and weaning-yearling relative growth rate.

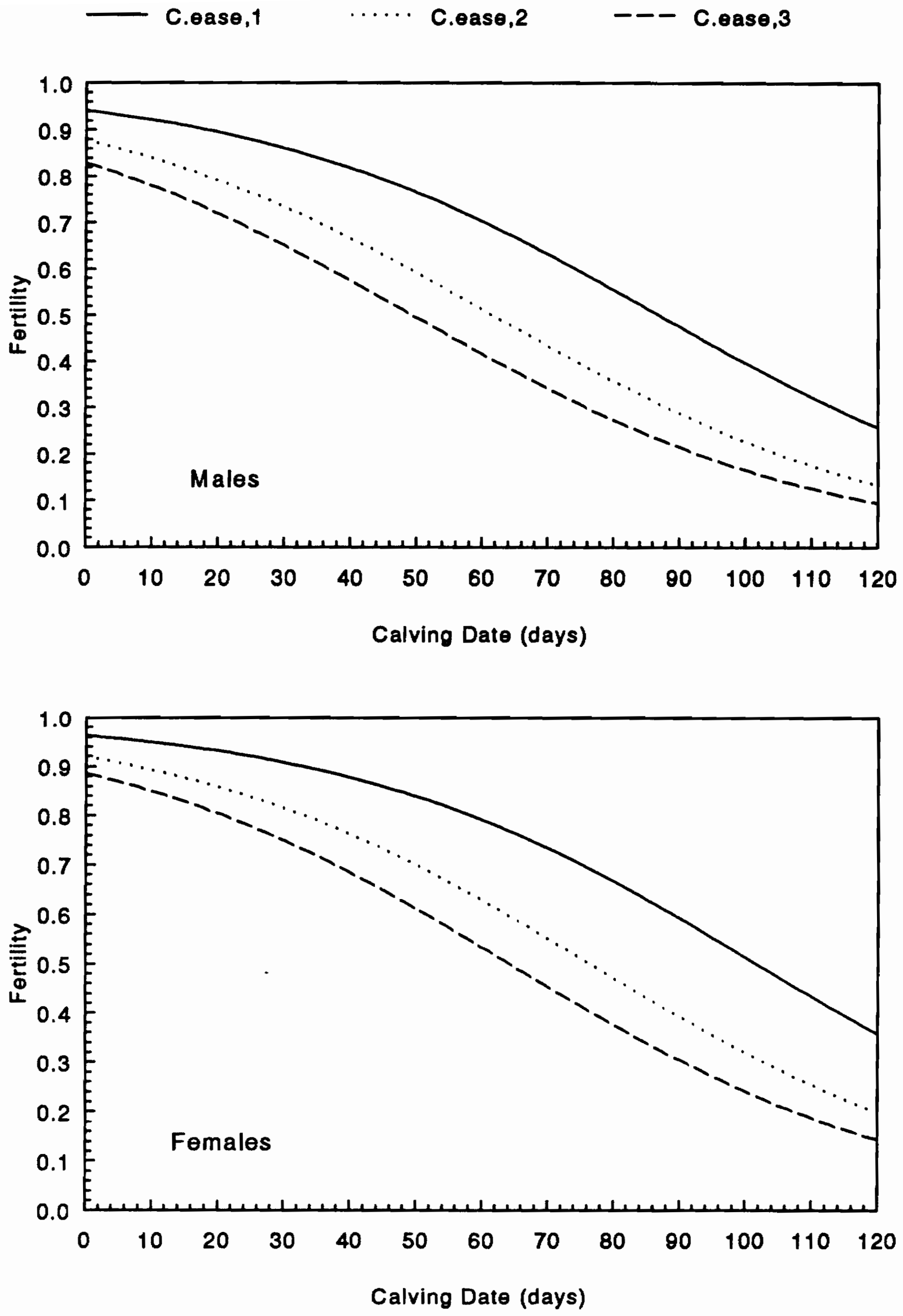


Figure 3. Regression in Angus females of fertility in the second breeding season on calving date and the effects of sex of the calf and calving ease in the first parturition.

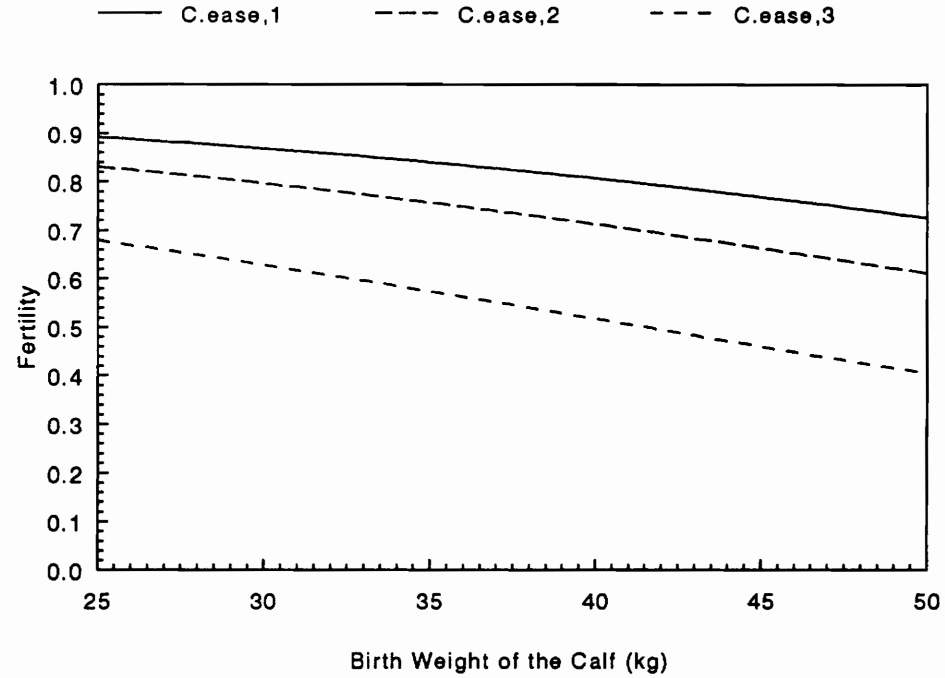


Figure 4. Regression in Simmental females of fertility in the second breeding season on birth weight of the calf and the effect of calving ease score in the first parturition.

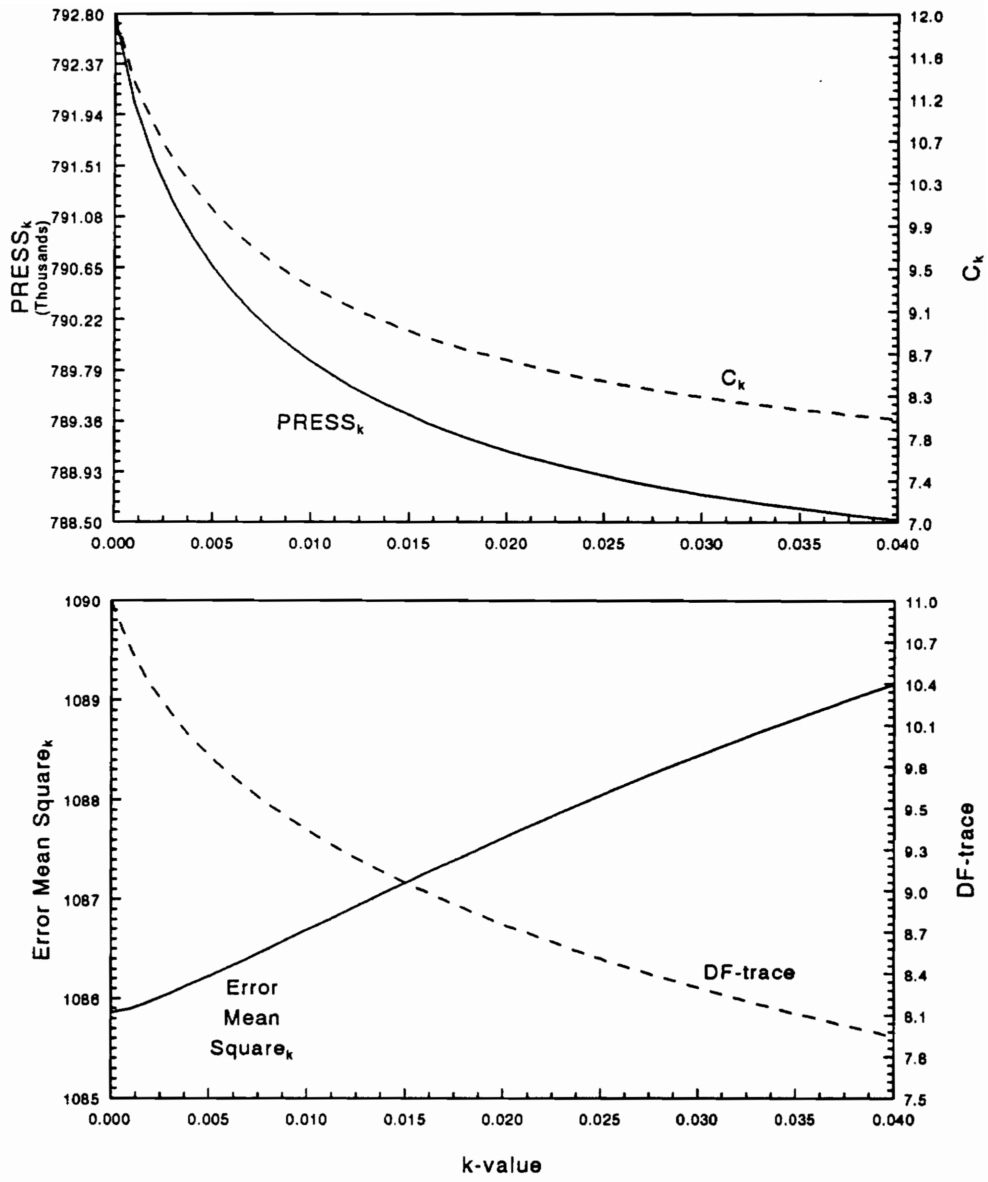


Figure 5. PRESS$_k$, C_k, error mean square$_k$ and DF-trace statistics in ridge regression of weaning weight of first calves on calfhood traits of Angus females, according to different values of k.

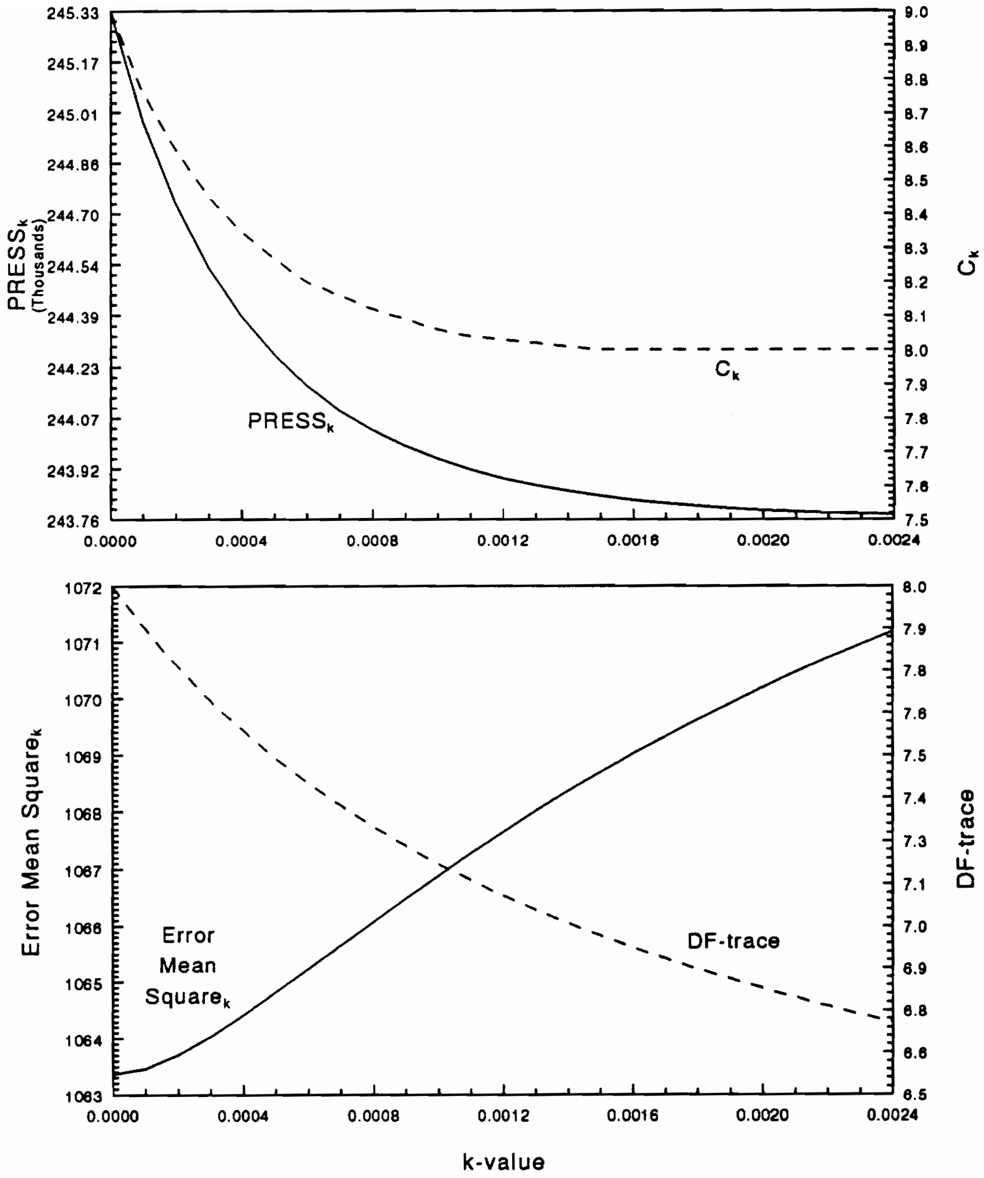


Figure 6. PRESS$_k$, C$_k$, error mean square$_k$ and DF-trace statistics in ridge regression of weaning weight of first calves on calfhood traits of Simmental females, according to different values of k.

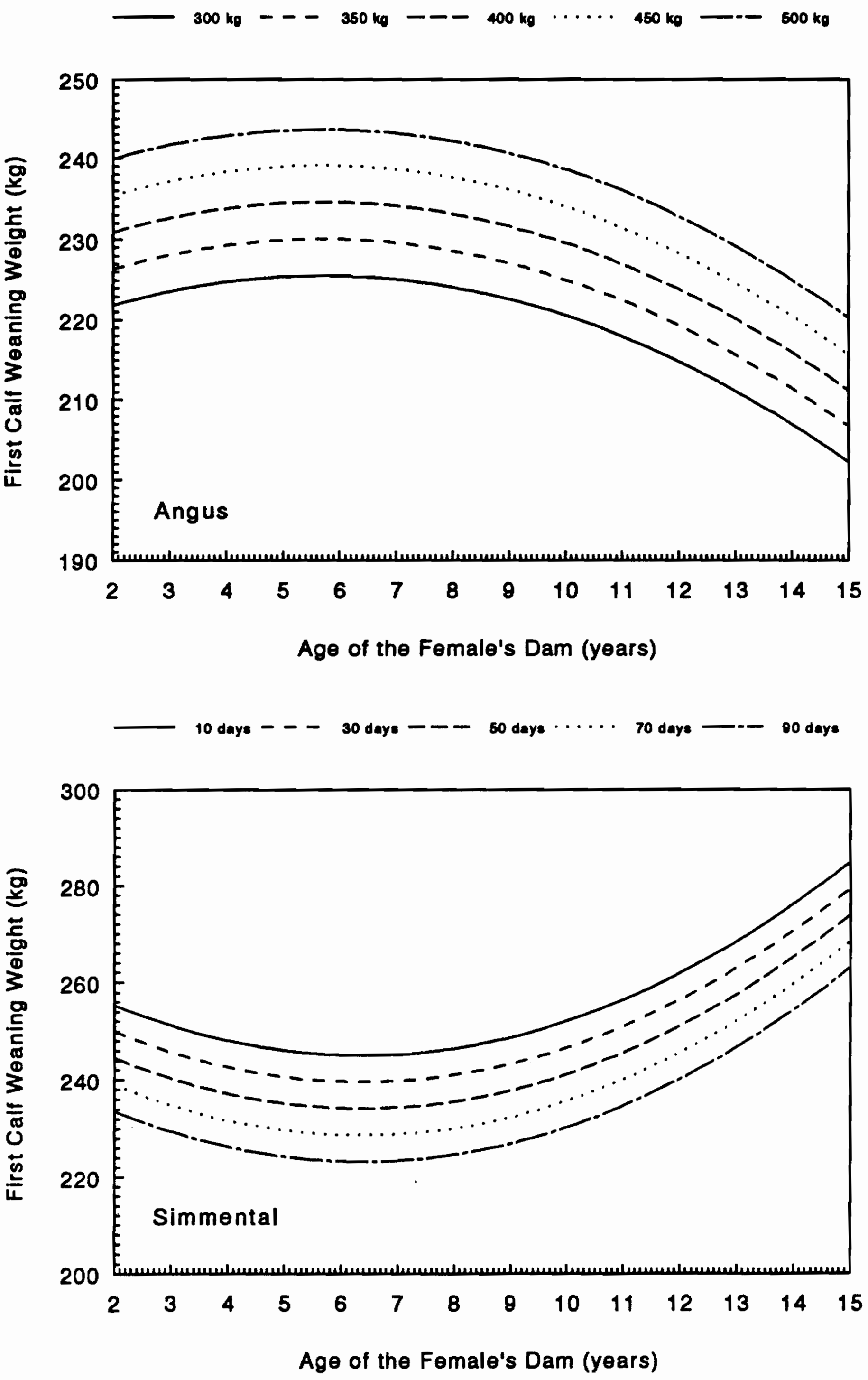


Figure 7. Regression of weaning weight of first calves of Angus and Simmental females on age of their dams and on their own yearling weight (Angus) or their own birth date (Simmental).

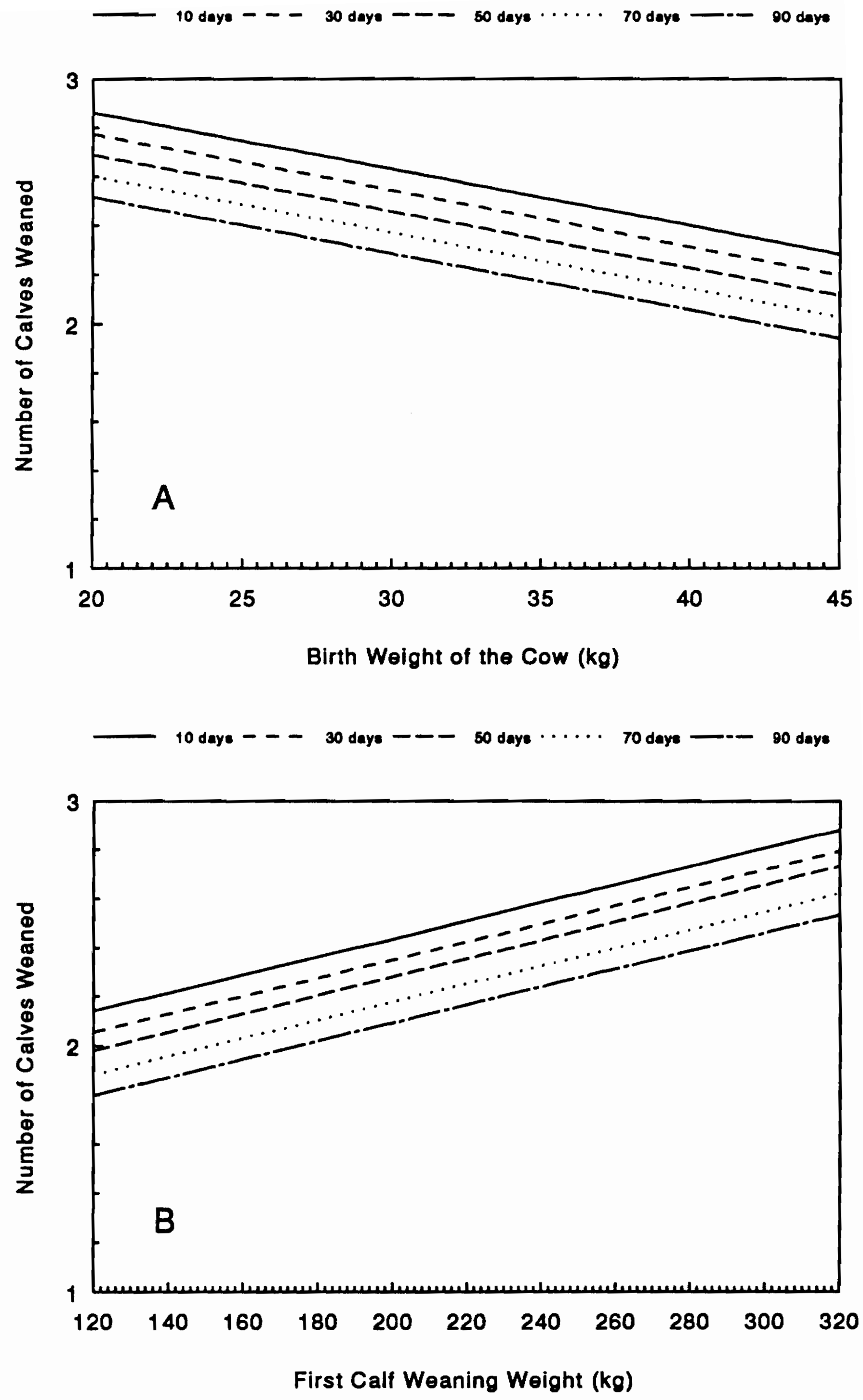


Figure 8. Regression of number of calves weaned in the first three years of production of Angus females on birth weight of the cow (A) and weaning weight of the first calf (B), the cow's own birth date and for first calf calving ease equals 1.

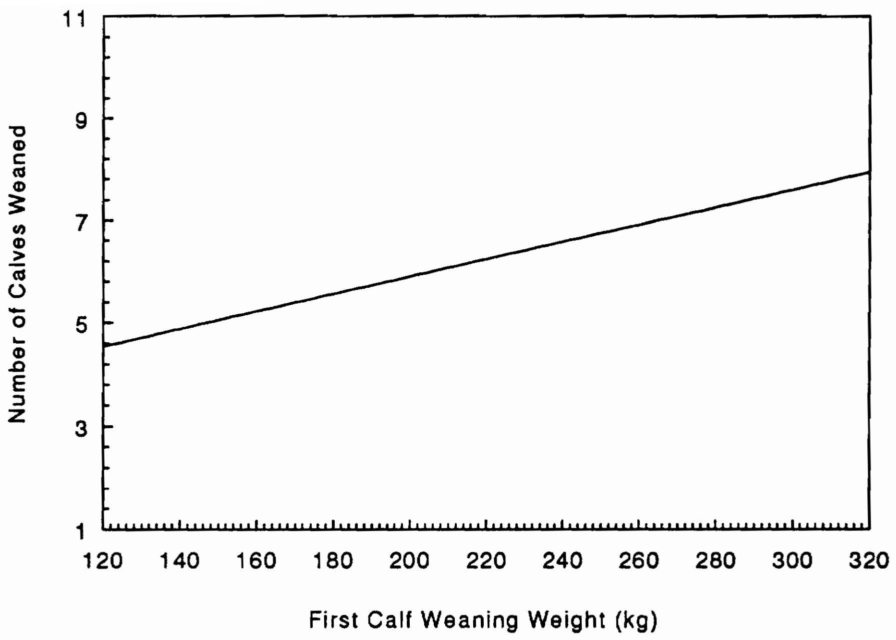


Figure 9. Regression of number of calves weaned in eleven years of production of Angus females on weaning weight of the first calf.

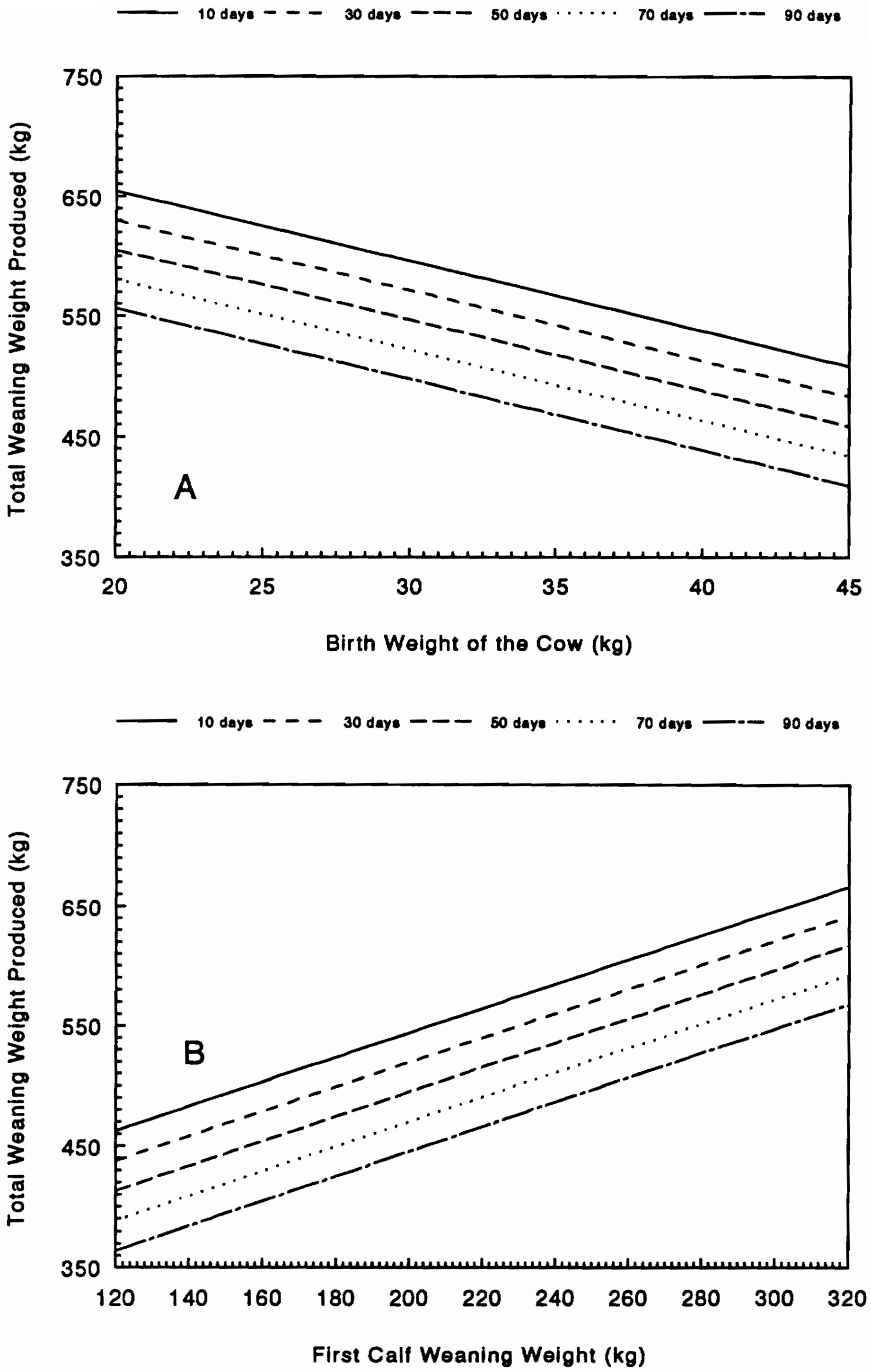


Figure 10. Regression of total weaning weight produced in the first three years of production of Angus females on birth weight of the cow (A) and weaning weight of the first calf (B), the cow's own birth date and for first calf equal 1 (male).

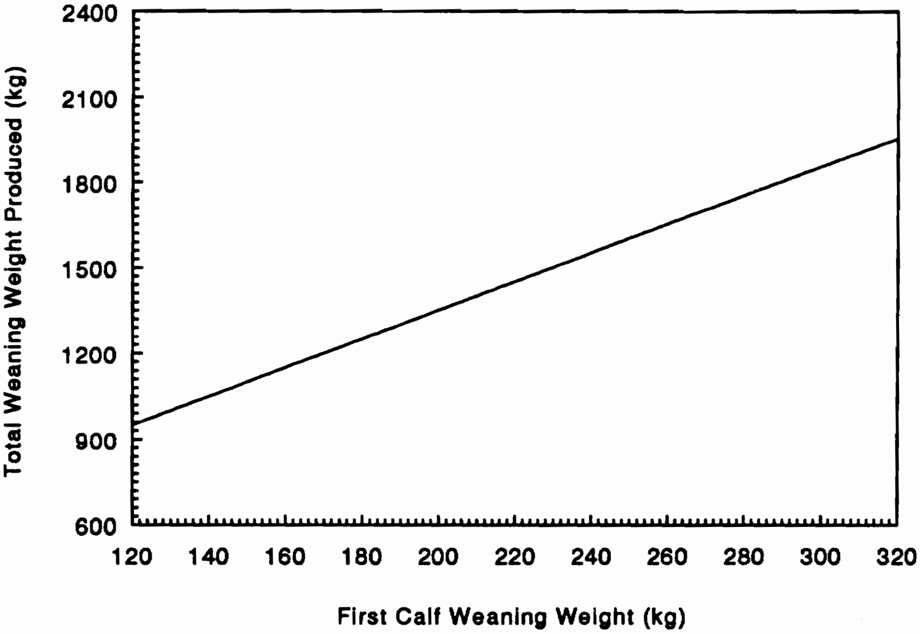
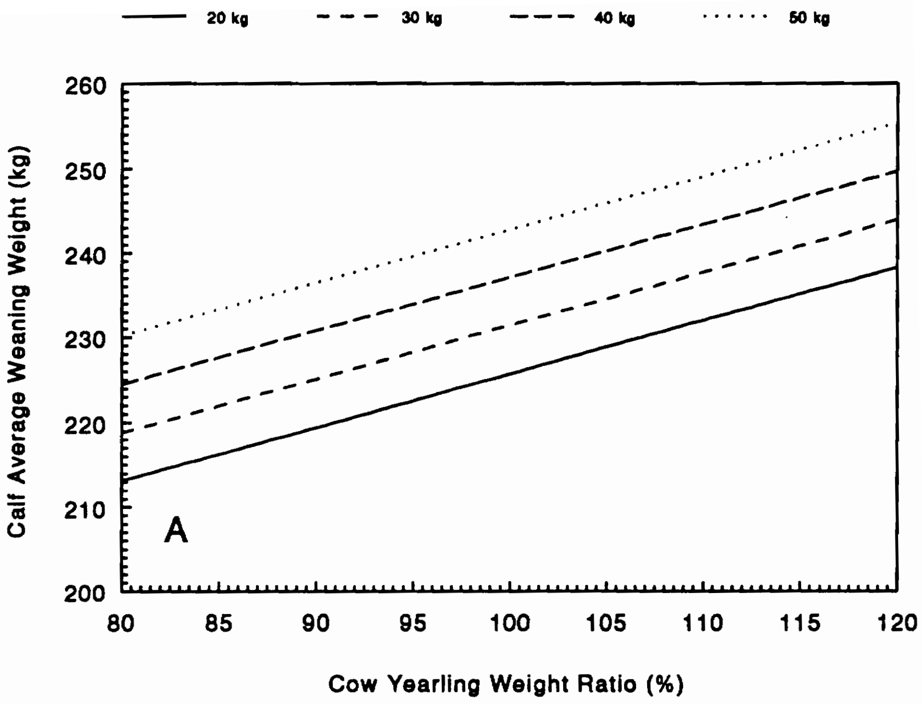


Figure 11. Regression of total weaning weight produced in eleven years of production of Angus females on weaning weight of the first calf.



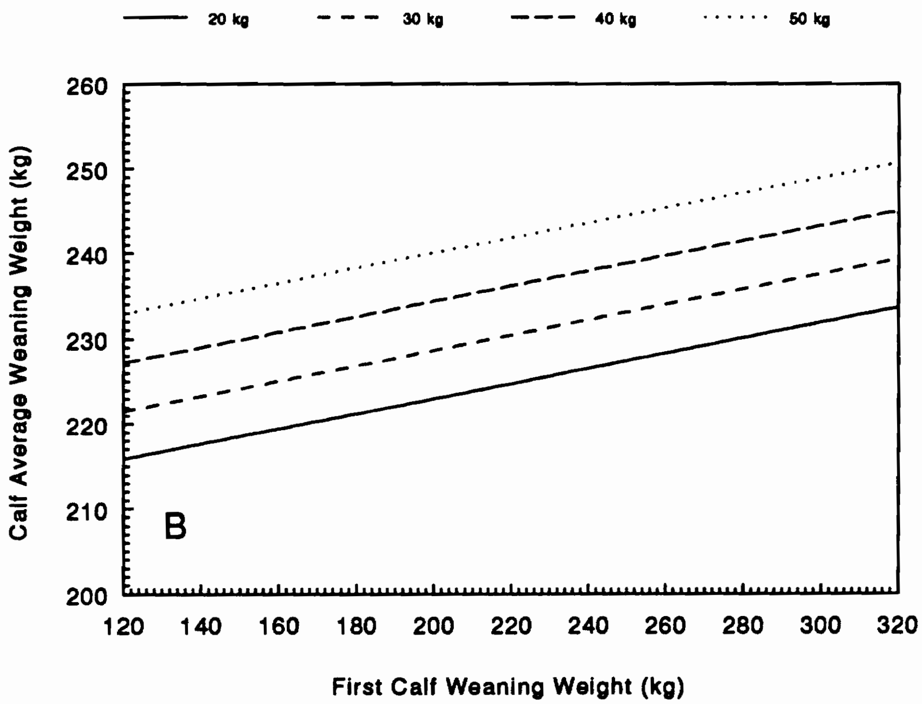


Figure 12. Regression of average weaning weight of calves produced in the first three years of production of Angus females on yearling weight ratio of the cow (A), first calf weaning weight (B) and according to birth weight of the first calf.

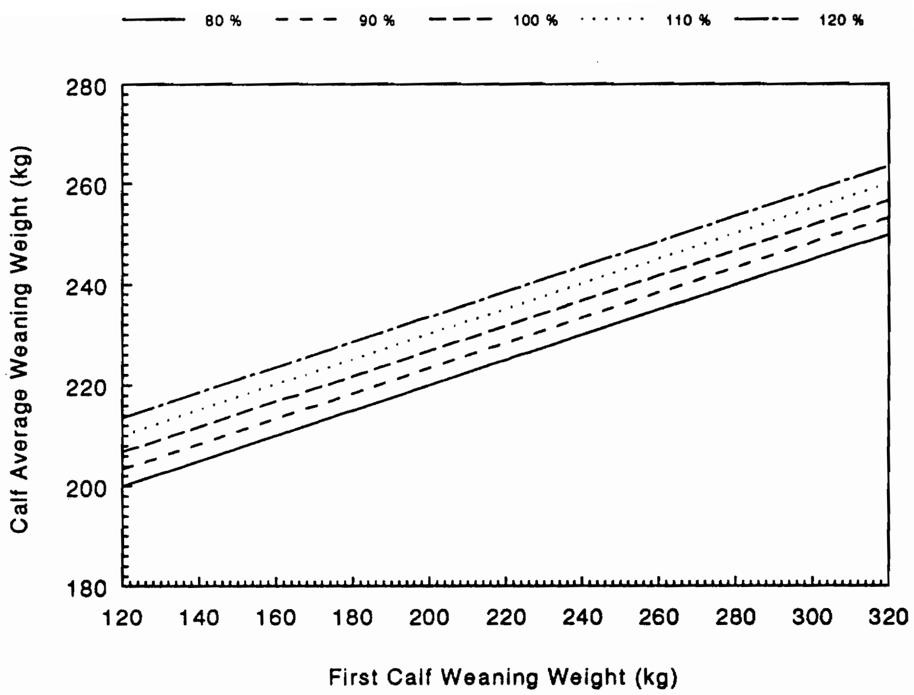


Figure 13. Regression of average weaning weight of calves produced in eleven years of production of Angus females on their own yearling weight ratio and on weaning weight of their first calves.

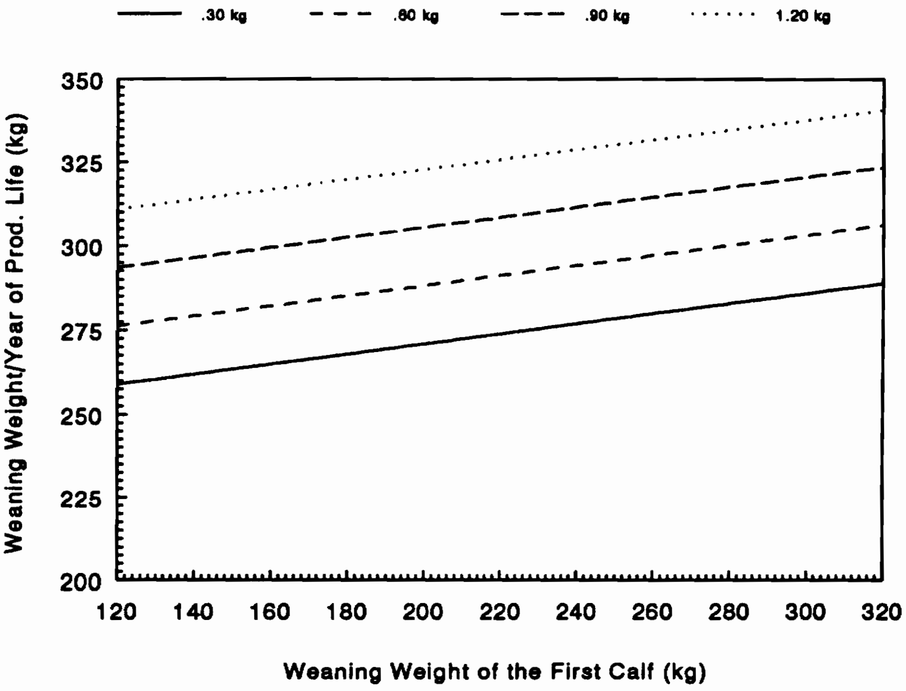


Figure 14. Regression of average weaning weight of calves per year of productive life in the first three years of production of Angus females on their own weaning-yearling average daily gain and on weaning weight of their first calves.

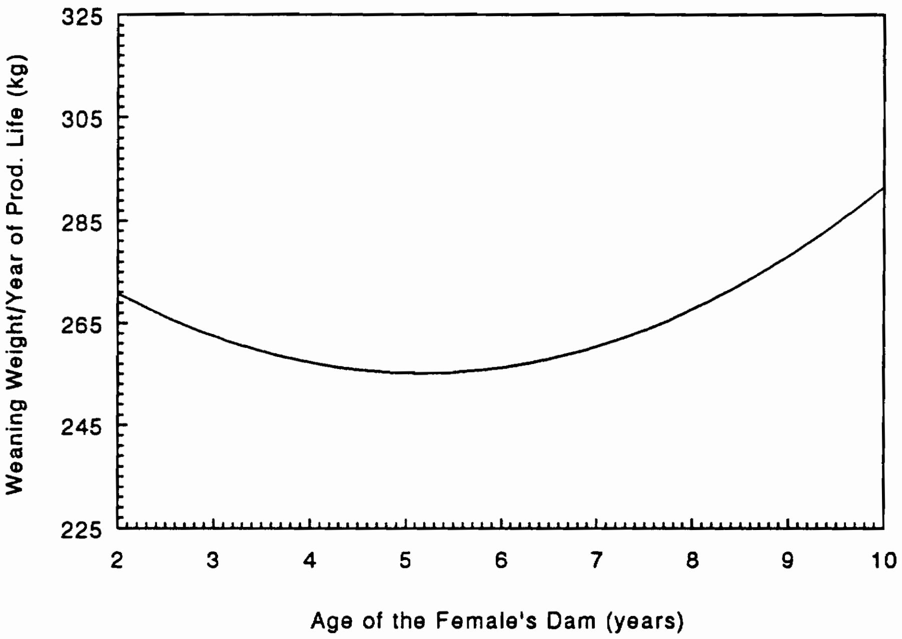


Figure 15. Regression of average weaning weight of calves per year of productive life in eleven years of production of Angus females on the age of their dams.

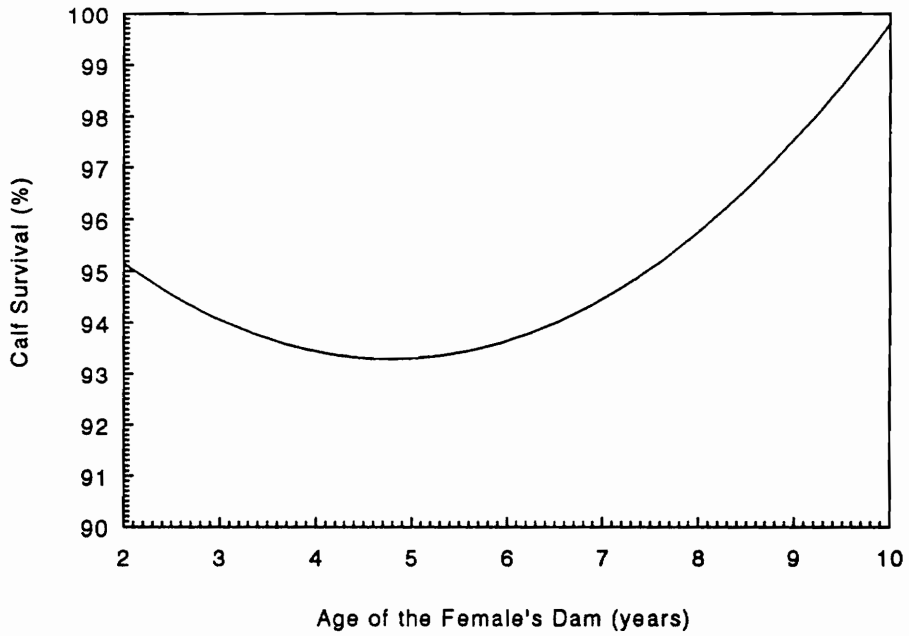


Figure 16. Regression of survival of calves from birth to weaning age in the first three years of production of Angus females on age of their dams.

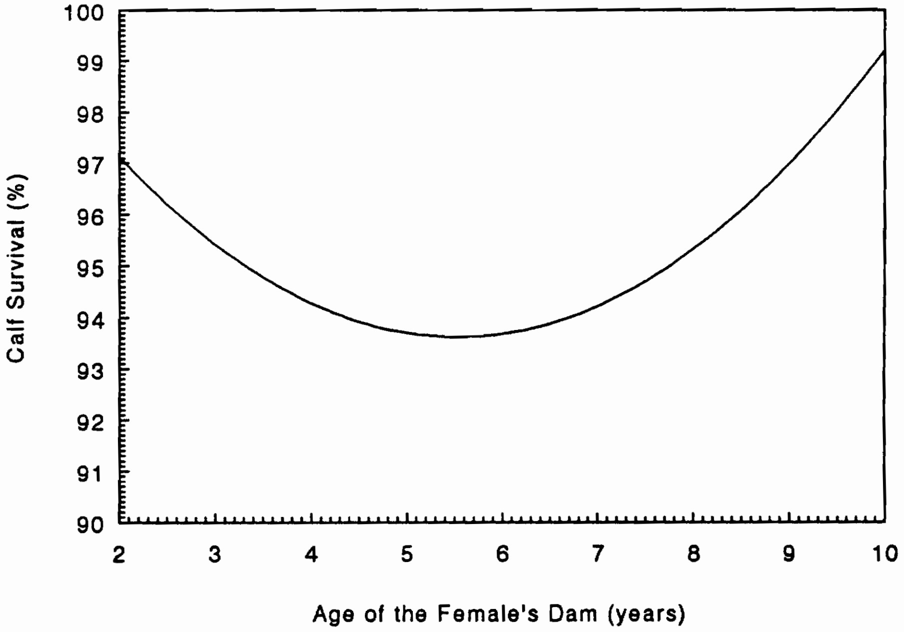


Figure 17. Regression of survival of calves from birth to weaning age in eleven years of production of Angus females on the age of their dams.

Vita

The author was born in Belo Horizonte, State of Minas Gerais, Brazil, on November 1, 1954. He received his D.V.M. in 1977 and his Master of Science in 1982, both degrees from the Federal University of Minas Gerais, Brazil. Since March 1982, he has been employed as an Associate Professor at the Animal Science Department of the Veterinary School of the same University. He entered Virginia Tech in August 1988, and received his Ph.D. in July 1992.