

Effect of Maternal Nutrition on Calf Health and Growth

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■ Take Home Messages

- ▶ Maternal under- and over-nutrition can restrict nutrient supply to the fetus
- ▶ Altered maternal nutrition during the first trimester primarily impacts animal metabolism with long-term implications for progeny energy balance and body composition
- ▶ Altered maternal nutrition during the last trimester primarily impacts the extent of fetal growth, affecting birth weights and having potential implications for long-term growth and body composition
- ▶ Early post-natal nutrition impacts progeny development and can ameliorate or exacerbate fetal programming

■ What is Developmental Programming?

In livestock, just as in humans, there is increasing evidence that production characteristics in livestock may be affected by maternal diet (Wu et al., 2006). This so-called metabolic or developmental “programming” of postnatal growth occurs during certain windows of growth characterized by plasticity of metabolic regulatory systems, namely in utero or shortly after birth. Compromised fetal or neonatal growth in livestock has been shown to lead to increased neonatal morbidity and mortality, slow postnatal growth, increased fat deposition, insulin resistance, and dysfunction of specific organs, including the ovaries, testes, mammary gland, liver, and small intestine (Wu et al., 2006). Thus, it is likely that the cow of today, with high milk yield but also reproductive and metabolic challenges, is not only a consequence of genetic selection, but also the result of the way her dam was fed and the way she was fed early after birth.

The concept that postnatal growth and production is sensitive to direct and indirect effects of maternal nutrition was first proposed by Dr. Barker based on epidemiological studies investigating low nutrient intake by pregnant mothers

experienced during the 1944 Dutch Famine of World War II and the resulting long-term health implication of their children. The hypothesis suggests that if intrauterine conditions are poor (e.g., poor nutrition), then the fetus becomes adapted through altered gene expression to maximize the uptake and utilization of the nutrients available. Such adaptations cause the progeny to exhibit a competitive advantage if exposed to a similarly poor environment in adulthood. However, favorable postnatal conditions can challenge the individual's homeostatic mechanisms and lead to development of deleterious metabolic conditions.

Developmental programming in mammals occurs through epigenetic changes during periods of developmental plasticity (Wu et al., 2006). Epigenetic modifications do not alter the DNA sequence, rather the chromatin structure is changed through histone acetylation or DNA methylation. As a result gene expression is altered and can be passed on to more than one succeeding generation.

■ Practical Relevance in Livestock

Within livestock production systems, there is real potential for ruminants to undergo periods of under-nutrition or over-nutrition (overfeeding) during gestation. Reduced maternal nutrient supply to the fetus can result from environmental extremes or from physiological extremes such as high milk output, metabolic disorders, multiple births, or continued growth of the dam, as is the case with peripubertal mothers. Typical management of livestock may also influence nutrient supply, such as extensive grazing or situations where animals are grouped and fed based on average body weight – where below average body weight animals are overfed and above average body weight animals are underfed. While growth (2 yr old cows) and milk production of the dam have clear implications for development of the fetus (Banos et al., 2007), diet during pregnancy is the primary modifiable factor that has a substantial influence on body condition and energy status of the dam as well as viability and body composition of newborns. Under-nutrition during the first half of gestation may not impact birth weights, but has been demonstrated to impact metabolic function of sheep and cattle offspring that results in altered production and body composition later in life (Ford et al., 2007; Long et al., 2010c). Under-nutrition during the last third of pregnancy will decrease birth weights with a potential negative impact on long-term growth and body composition of the progeny (Greenwood et al., 2010; Underwood et al., 2010). Over-nutrition can also restrict placental and fetal development, resulting in decreased birth weights, post-natal growth, and altered body composition (Caton et al., 2007).

■ Fetal Development

As the growth trajectories for different tissues vary, each tissue is susceptible to environmental conditions at different periods. Thus, to understand the implications of maternal nutrition on fetal development, one must understand fetal development first. Development of the fetus through gestation was summarized by Funston et al. (2010). Growth and development of the animal begins with fertilization of the egg within the dam's reproductive tract. The embryo attaches to the uterus beginning on day 19, and around day 25, placentation, an intricate cellular interface between the cow and the calf, begins. By day 42 the embryo has fully attached to the uterus of the cow. A heartbeat is detected by 20 to 22 days of gestation and by day 25 limb buds begin to develop along with the liver, pancreas, lungs, thyroid, brain, and kidneys. If the fetus is female, the first discernible structures destined to become the udder are evident around day 30. If the fetus is male, testicular development initiates at day 45, or if female, ovarian development initiates between 50 to 60 days. Prenatal muscle development occurs during the embryonic and fetal stage in two phases: primary myogenesis, which occurs from day 30 to 90, and secondary myogenesis, which starts at day 90 (Brameld et al., 2010). In cattle, abdominal fat appears in fetuses at day 80, followed by subcutaneous and intermuscular fat from day 180 onwards, while intramuscular fat is dissectible only after birth (Vernon, 1986). Increases in mass of tissues occur during the second and primarily third trimesters.

■ Maternal Environment Effect On Growth and Body Composition

Periconception

Developmental programming of offspring can begin as early as the peri-conceptual period. The peri-conceptual period typically coincides with peak lactation in a mature cow and with development of peripubertal dams. Thus, the embryo must compete for nutrients with the cow's nutrient demands for lactation and the peripubertal animal's demands for growth. In sheep, oocyte quality does not appear to be impacted by nutritional status of the ewe; however, inadequate (50-60% of requirements) or excess energy reduced successful fertilizations and produced embryos with decreased cleavage rates compared with adequate energy (Grazul-Bilska et al., 2006). Under-nutrition during the peri-conceptual period also impacts long-term performance of the progeny as Nordby et al. (1987) demonstrated that lambs of ewes fed at 70% of nutritional requirements from 30 days prior to mating until 100 days of pregnancy had higher neonatal mortality rates, were lighter at birth and grew more slowly after weaning than those fed at 100% of estimated requirements. These observations suggest nutritional status of ewes during the peri-conceptual period is highly important to fertility and that some fetal

programming may actually begin in the oocyte before mating occurs. For cows, the effect of peri-conceptual nutrition on offspring is less clear. Positive, negative, or no effects of plane of nutrition (high vs. low energy diets) on oocyte quality, fertilization rate, and early embryonic development have been reported (reviewed in Caton et al., 2007).

Early Gestation

The placenta plays a major role in the regulation of fetal growth. Establishment of functional fetal and uteroplacental circulation is one of the earliest events during embryonic and placental development (Funston et al., 2010). It has been shown that the large increase in transplacental exchange, which supports the exponential increase in fetal growth during the last one-half of gestation, depends primarily on the dramatic growth of the uteroplacental vascular beds during the first one-half of pregnancy (Funston et al., 2010). In beef cattle, under-nutrition of ~75% of recommended allowance during early stages of pregnancy compromises placental angiogenesis, cotyledon weight, and thus, fetal development (Zhu et al., 2007). Fetuses that were nutrient restricted during the first trimester were similar in weight near term to unrestricted fetuses after dams were put on a common nutrient sufficient diet (Zhu et al., 2007). However, the uterine environment during the first trimester can have a significant impact on development of homeostatic mechanisms in the liver and pancreas with an impact on capacity of the progeny to utilize and metabolize nutrients (Symonds et al., 2010).

Glucose is the primary source of energy for the fetus and energy and nitrogen requirements of the fetus are met almost entirely by placental uptake of glucose and amino acids from maternal blood. One of the primary effects of maternal nutrient restriction is a reduction in plasma concentrations of major regulators of glucose homeostasis such as cortisol, thyroid hormones, and insulin (Symonds et al., 2010). These adaptations ensure that the maternal plasma glucose concentration is maintained and, thus, fetal growth is not compromised. However, the endocrine sensitivities of a large number of fetal organs are reset. Specifically, glucocorticoid action is enhanced in fetuses of restricted ewes (Whorwood et al., 2001; Gardner et al., 2006). When raised under conditions of adequate nutrition during postnatal life, animals with enhanced glucocorticoid action exhibit increased lipid accumulation and insulin resistance (Symonds et al., 2010). Previous studies in the sheep have demonstrated that an extended period of maternal nutrient restriction during the first half of gestation results in relatively normal birth weights, but leads to increases in the length and thinness of the neonate, increases in adiposity, and suppressed glucose tolerance (Whorwood et al., 2001; Ford et al., 2007). Ford et al. (2007) demonstrated that early fetal restriction in sheep can cause increased carcass fatness in male progeny at 280 days of age. Long et al. (2012) reported that a 30% nutrient restriction during early gestation in cattle

did not affect birth, weaning, or yearling slaughter weights, however fat cell size was increased and muscle size was decreased at slaughter after 1 year of age. Altered endocrine sensitivity of the liver and pancreas in conjunction with increased adiposity in a lactating dairy cow as a result of fetal programming could potentially have a significant impact on her ability to mobilize body fat after parturition and influence the incidence of metabolic disorders.

Late Gestation

During the second trimester the fetus continues to develop and grow, but it will only reach about 25% of the size it will be at birth (Symonds et al., 2010). The majority of fetal development has already occurred by the beginning of the final trimester, however, 75% of fetal growth (increase in tissue size) occurs during this phase, thus energy demand by the gravid uterus is greatest during the last trimester (reviewed in Caton et al., 2007).

Energy deficiency (70% of recommendations) in primiparous beef cows during the last 100 days of pregnancy in beef cattle was reported to decrease calf birth weight, weaning weight, and delayed age at puberty of the progeny compared to heifers from dams adequately fed during the last 100 d (Corah et al., 1975). Furthermore, Corah et al. (1975) observed that progeny born to energy restricted cows had increased rates of morbidity and mortality. Greenwood et al. (2010) reported that post-natal growth of cattle was inhibited by in utero energy restriction, but body composition was not altered. In contrast, Underwood et al. (2010) observed that nutrient restriction from mid to late gestation increased postnatal weight gain and decreased body fat.

In sheep Gardner et al. (2005) observed that a 50% restriction in energy from 110 days of gestation to parturition did not impact birth weights but reduced glucose tolerance and caused insulin resistance in lamb progeny. As a result, adiposity was increased in lamb progeny carcasses at 1 year of age. However, Greenwood et al. (2010) reported that birth weights in sheep are generally decreased by nutrient restriction during the last trimester and that reductions in postnatal growth and alterations to body composition may or may not persist through 1 year of age depending on the adequacy of postnatal diets. When ewes are undernourished during lactation, growth restriction of progeny persists, but when ewes are adequately nourished during lactation, growth restriction of progeny does not persist. Thus, it appears that direct prenatal effects on capacity for growth of the progeny are ameliorated or exacerbated depending upon the postnatal environment into which they are born (Greenwood et al., 2010).

As lactation and gestation progress in the cow, she moves from a negative to a positive energy balance. Excess energy during this period has the potential to increase glucose supply to the fetus and lead to increased risk of glucose

intolerance and obesity in the offspring. Long et al. (2010a) observed decreased glucose effectiveness and insulin sensitivity, increased appetite and gain, increased carcass adiposity, and increased weight at 19 months of age in progeny from gestating ewes fed 150% of energy requirements to an obese body mass index. Swanson et al., (2008) demonstrated that feeding 140% of nutritional requirements to growing ewes from day 50 of pregnancy to parturition resulted in decreased birth weights.

Studies investigating protein supplementation of cows during late gestation have reported long-term impacts on their progeny as well. In a recent review, Vonnahme and Lemley (2012) reported that providing protein supplementation to cows beginning on day 190 of gestation resulted in a doubling of uterine blood flow when compared with non-supplemented cows. The increased uterine blood flow and nutrient transfer to the fetus, in turn, may increase progeny performance. For example, gestating ewes fed a diet high in urea had progeny who went on to exhibit increased rate of metabolism and growth compared to progeny from those ewes not supplemented with urea (McEvoy et al., 1997). In addition, singleton fetuses from ewes consuming a high-protein diet during late gestation were heavier on day 130 of gestation compared with fetuses from ewes consuming a low-protein diet, with no differences in placental weight (reviewed in Vonnahme and Lemley, 2012). Although protein restriction late (last 50 d) in fetal development did not decrease fetal growth, postnatal growth and pregnancy rates were increased in female progeny (Vonnahme and Lemley, 2012) and slaughter weights and fat deposition in male progeny after 15 months of age were increased. However, protein over-nutrition may have a negative effect on progeny performance, as Sletmoen-Olsen et al. (2000) indicated that high levels of metabolizable protein supplementation to mature beef cows reduced birth weights relative to controls fed at their protein requirement.

■ Maternal Environment Effect On Growth and Reproduction

While it has been demonstrated that body fat in heifers is not the sole regulator of puberty onset, the hormones and metabolites associated with increased adiposity, such as increased insulin and insulin-like growth hormone, do play an important role in puberty attainment in cattle (Yelich et al., 1995). It has been demonstrated that nutrient restriction in the second trimester in cows produced female progeny with a reduced number of follicles (Mossa et al., 2013) and that nutrient restriction in the third trimester in cows produced female progeny that conceived later in their first breeding (Cushman et al., 2012) compared to female progeny from adequately fed dams. Furthermore, Long et al. (2010b) reported that ewes born to dams that were nutrient restricted during the second trimester gave fewer births to a lamb during their first parturition. With regard to maternal protein and reproductive

development of the female progeny, maternal protein supplementation during late gestation has been shown to increase the probability of female progeny reaching puberty prior to the first year of breeding, to increase pregnancy rates during their first year of breeding, and to calve earlier during their first year of calving (Funston et al., 2010).

■ Source of Energy

Removing starch from corn creates a feed (distillers grains with solubles - DGS) with a unique set of characteristics, in that calories are almost equally provided from fat, which is highly unsaturated, fiber, and protein. A high percentage of these nutrients bypass ruminal fermentation and have the potential to influence fetal growth and milk production. Furthermore, other nutrients, such as minerals, are concentrated approximately 3-fold in DGS compared to corn. Distillers grains are used primarily as a protein source for cattle because of the increased concentration of protein in DGS compared with corn. However, increased competition for corn has increased the use of DGS as an *energy* source in beef cattle rations, resulting in diets that exceed protein requirements. Research we have conducted at Purdue (Gunn, 2013), as well as research conducted by Radunz et al. (2010) has demonstrated that when dried DGS is fed to gestating (third trimester) and lactating beef cows as an energy source, increased progeny birth weights result compared to beef cows fed hay-based or corn-based diets with similar energy concentrations. However, problems with dystocia have been observed (Gunn, 2013). Progeny from DGS fed cows have not differed in blood glucose or insulin concentrations, glucose clearance, morbidity, or immunoglobulin concentrations (Radunz et al. 2012; Gunn, 2013). The effect of maternal DGS on postnatal progeny weight gain has been variable. In male progeny fed in the feedlot, weaning and yearling weights did not differ (Radunz et al. 2012; Gunn et al., 2013), however, female progeny from DGS treated dams tended to be heavier throughout the developmental post-weaning period and had greater conception rates to timed AI than female progeny from corn silage/hay treated dams (Gunn, 2013).

■ Neonatal Period

The first weeks of life for a neonate seem to also have long-lasting consequences on the physiological function of the animal. In beef cows, Freetly et al. (2000) demonstrated that effects of variable nutrition during mid and/or late pregnancy on weight at birth are overcome when adequate, high quality postnatal nutrition is available, and resulted in no differences in calf body weights at 58 days of age. Research conducted at Purdue University (Shee, 2013) has demonstrated that feeding DGS to cows from calving to mid lactation (129 days postpartum) increased male progeny gain and weight at weaning (219 days postpartum) compared to male progeny from cows fed a

corn silage based diet. The diets were isocaloric, but differed in fat and protein content. As a result, milk composition of the cows was altered and may have been responsible for changes in growth. Feeding DGS to cows from calving to mid lactation did not affect milk production, but decreased milk fat and protein, increased the percentage of long-chain, monounsaturated and polyunsaturated fatty acids in milk, including CLA, and decreased the percentage of medium-chain and saturated fatty acids (Shee, 2013). Specific fatty acids and level of unsaturation of the fatty acids in maternal milk can impact growth of progeny. In rats, maternal consumption of a highly unsaturated or highly saturated fatty acid diet results in lower birth weights and decreased postnatal weight gain (Siemelink et al., 2002). Shee (2013) observed that the weight advantage for male progeny whose dams were fed DGS was not maintained through slaughter; however, intramuscular fat content was decreased in the male progeny of DGS fed cows, indicating that maternal DGS can impact progeny body composition.

■ Conclusion

Unfortunately, there is a lack of studies in dairy cattle that demonstrate direct effects of maternal nutrition on postnatal performance of offspring. However, numerous studies in beef cattle and sheep demonstrate that both energy and protein (inadequate or excess) can affect long-term productivity of progeny. Thus, management of the cow herd not only has consequences for cow productivity but also for productivity of the next generation of cows. Fortunately, management of the neonatal calf can ameliorate many of the negative consequences of poor fetal nutrition. Data is lacking on the effect of specific nutrients (fatty acids, amino acids, vitamins, and minerals) on long-term performance of offspring and further research is needed to determine these effects and understand the underlying mechanisms.

■ References

- Banos, G., S. Brotherstone, and M. P. Coffey. 2007. Prenatal maternal effects on body condition score, female fertility, and milk yield of dairy cows. *J. Dairy Sci.* 90:3490–3499.
- Brameld, J. M., P. L. Greenwood, and A. W. Bell. 2010. Biological mechanisms of fetal development relating to postnatal growth, efficiency and carcass characteristics in ruminants. Pp. 93-119. In: *Managing the prenatal environment to enhance livestock productivity*. Eds. P. L. Greenwood, A. W. Bell, P. E. Vercoe, and G. J. Viljoen. Springer, The Netherlands.

- Caton, J.S., A.T. Grazul-Bilska, K.A. Vonnahme, J.S. Luther, G.P. Lardy, C.J. Hammer, D.A. Redmer, and L.P. Reynolds. 2007. Nutritional management during gestation: impacts on lifelong performance. Proc. 18th Annual Florida Ruminant Nutrition Symposium. Pages 1-20. Gainesville, FL.
- Corah, L. R., T. G. Dunn, and C. C. Kaltenbach. 1975. Influence of prepartum nutrition on the reproductive performance of beef females and the performance of their progeny. *J. Anim. Sci.* 41:819-824.
- Cushman, R. A., A. K. McNeel, and H. C. Freetly. 2012. The impact of cow nutrient status during the second and third trimester on development of the reproductive axis and fertility of daughters. *J. Anim. Sci.* 90(E-Suppl. 1): (Abstr.).
- Ford, S. P., B. W. Hess, M. M. Schwope, M. J. Nijland, J. S. Gilbert, K. A. Vonnahme, W. J. Means, H. Han, and P. W. Nathanielsz. 2007. Maternal undernutrition during early to mid-gestation in the ewe results in altered growth, adiposity, and glucose tolerance in male offspring. *J. Anim. Sci.* 85:1285-1294.
- Freetly, H. C., C. L. Ferrell, and T. G. Jenkins. 2000. Timing of realimentation of mature cows that were feed-restricted during pregnancy influences calf birth weights and growth and rates. *J. Anim. Sci.* 78:2790-2796.
- Funston, R. N., D. M. Larson, and K. A. Vonnahme. 2010. Effects of maternal nutrition on conceptus growth and offspring performance: Implications for beef cattle production. *J. Anim. Sci.* 88(E Suppl.):E205-E215.
- Gardner, D. S., K. Tingey, B. W. M. Van Bon, S. E. Ozanne, V. Wilson, J. Dandrea, D. H. Keisler, T. Stephenson, and M. E. Symonds. 2005. Programming of glucose-insulin metabolism in adult sheep after maternal undernutrition. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 289:R947-R954.
- Gardner D. S., B. W. Van Bon, J. Dandrea, P. J. Goddard, S. F. May, V. Wilson, T. Stephenson, and M. E. Symonds. 2006. Effect of periconceptual undernutrition and gender on hypothalamic-pituitary-adrenal axis function in young adult sheep. *J. Endocrinol.* 190:203-212.
- Grazul-Bilska, A.T., D. Pant, J.S. Luther, P.P. Borowicz, C. Navanukraw, J.S. Caton, M.A. Ward, D.A. Redmer, and L.P. Reynolds. 2006. Pregnancy rates and gravid uterine parameters in single, twin, and triplet pregnancies in naturally bred ewes after transfer of in vitro produced embryos. *Anim. Reprod. Sci.* 92(3-4):263-283.
- Greenwood, P. L., A. M. Thompson and S. P. Ford. 2010. Postnatal consequences of the maternal environment and of growth during prenatal life for productivity of ruminants. In *Managing the Prenatal Environment to Enhance Livestock Productivity*. Pages 3-36. P. L. Greenwood, A. W. Bell, P. E. Vercoe and G. J. Viljoen, eds. Springer, Dordrecht, The Netherlands.
- Gunn, P. J. 2013. Inclusion of dried distiller's grains with solubles in beef cow diets and impact on reproduction and subsequent development of progeny. PhD Dissertation. Purdue University, West Lafayette.

- Long, N. M., C. B. Tousley, K. R. Underwood, S. I. Paisley, W. J. Means, B. W. Hess, M. Du, and S. P. Ford. 2012. Effects of early- to mid-gestational undernutrition with or without protein supplementation on offspring growth, carcass characteristics, and adipocyte size in beef cattle. *J. Anim. Sci.* 90:197-206.
- Long, N. M., L. A. George, A. B. Uthlaut, D. T. Smith, M. J. Nijland, P. W. Nathanielsz, and S. P. Ford. 2010a. Maternal obesity and increased nutrient intake before and during gestation in the ewe results in altered growth, adiposity, and glucose tolerance in adult offspring. *J Anim Sci* 88:3546-3553.
- Long, N. M., M. J. Nijland, P. W. Nathanielsz, and S. P. Ford. 2010b. The impact of early to mid-gestational nutrient restriction on female offspring fertility and hypothalamic-pituitary-adrenal axis response to stress. *J. Anim. Sci.* 88:2029–2037.
- Long, N. M., M. J. Prado-Cooper, C. R. Krehbiel, U. DeSilva, and R. P. Wettermann. 2010c. Effects of nutrient restriction of bovine dams during early-gestation on postnatal growth, carcass and organ characteristics, and gene expression in adipose tissue and muscle. *J. Anim. Sci.* 88:3251-3261.
- McEvoy, T. G., J.J. Robinson, R.P. Aitken, P.A. Findley and I.S. Robertson. 1997. Dietary excesses of urea influence the viability and metabolism of preimplantation sheep embryos and may affect fetal growth among survivors, *Anim. Reprod. Sci.* 47:71–9.
- Mossa, F., F. Carter, S. W. Walsh, D. A. Kenny, G. W. Smith, J. L. H. Ireland, T. B. Hildebrandt, P. Lonergan, J. J. Ireland, and A. C. O. Evans. 2013. Maternal undernutrition in cows impairs ovarian and cardiovascular systems in their offspring. *Biol. Reprod.* 88:92, 1-9.
- Nordby, D.J., R.A. Field, M.L. Riley, and C.J. Kercher. 1987. Effects of maternal undernutrition during early pregnancy on growth, muscle cellularity, fiber type and carcass composition in lambs. *J. Anim. Sci.* 64:1419–1427.
- Radunz, A. E., F. L. Fluharty, M. L. Day, H. N. Zerby, and S. C. Loerch. 2010. Parturition dietary energy source fed to beef cows: I. Effects on pre- and postpartum cow performance. *J. Anim. Sci.* 88: 2717-2728.
- Radunz, A. E., F. L. Fluharty, A. E. Relling, T. L. Felix, L. M. Shoup, H. N. Zerby, and S. C. Loerch. 2012. Parturition dietary energy source fed to beef cows: II. Effects on progeny postnatal growth, glucose tolerance, and carcass composition. *J. Anim. Sci.* 90:4962-4974.
- Shee, C.N. 2013. Inclusion of ethanol co-products in beef cow diets: Impact on cow performance and developmental programming of the progeny. PhD Dissertation. Purdue University, West Lafayette.
- Siemelink, M., A. Verhoef, J. A. M. A. Dormans, P. N. Span, and A. H. Piersma. 2002. Dietary fatty acid composition during pregnancy and lactation in the rat programs growth and glucose metabolism in the offspring. *Diabetol.* 45:1397-1403.

- Sletmoen-Olson, K. E., J. S. Caton, K. C. Olson, D. A. Redmer, J. D. Kirsch, and L. P. Reynolds. 2000. Undegraded intake protein supplementation: II. Effects on plasma hormone and metabolite concentrations in periparturient beef cows fed low-quality hay during gestation and lactation. *J. Anim. Sci.* 78:456-463.
- Swanson, T. J., C. J. Hammer, J. S. Luther, D. B. Carlson, J. B. Taylor, D. A. Redmer, T. L. Neville, J. J. Reed, L. P. Reynolds, J. S. Caton and K. A. Vonnahme. 2008. Effects of gestational plane of nutrition and selenium supplementation on mammary development and colostrum quality in pregnant ewe lambs. *J. Anim. Sci.* 86(9):2415-23.
- Symonds, M.E., S.P. Sebert, and H. Budge. 2010. Nutritional regulation of fetal growth and implications for productive life in ruminants. *Animal.* 4(7):1075-1083.
- Underwood, K. R., J. F. Tong, P. L. Price, A. J. Roberts, E. E. Grings, B. W. Hess, W. J. Means, and M. Du. 2010. Nutrition during mid to late gestation affects growth, adipose tissue deposition, and tenderness in cross-bred beef steers. *Meat Sci.* 86:588-593.
- Vernon, R.G. 1986. The growth and metabolism of adipocytes. In *Control and Manipulation of Animal Growth* (ed. PJ Buttery, NB Haynes and DB Lindsay), pp. 67–83. Butterworths, London, UK.
- Vonnahme, K.A., and C.O. Lemley. 2012. Programming the offspring through altered uteroplacental hemodynamics: how maternal environment impacts uterine and umbilical blood flow in cattle, sheep, and pigs. *Repro. Fert. Dev.* 24:97-104
- Whorwood, C.B, K.M. Firth, H. Budge and M.E. Symonds. 2001. Maternal undernutrition during early to midgestation programs tissue-specific alterations in the expression of the glucocorticoid receptor, 11 β -hydroxysteroid dehydrogenase isoforms, and type 1 angiotensin II receptor in neonatal sheep. *Endocrinology.* 142:2854-2864.
- Wu, G., F. W. Bazer, J. M. Wallace, and T. E. Spencer. 2006. Board-Invited Review: Intrauterine growth retardation: Implications for the animal sciences. *J. Anim. Sci.* 84:2316-2337.
- Yelich, J. V. et al. 1995. Effects of growth rate on carcass composition and lipid partitioning at puberty and growth-hormone, insulin-like growth-factor 1, insulin, and metabolites before puberty in beef heifers. *J. Anim. Sci.* 73: 2390-2405.
- Zhu, M. J., M. Du, B. W. Hess, W. J. Means, P. W. Nathanielsz, and S. P. Ford. 2007. Maternal nutrient restriction upregulates growth signaling pathways in the cotyledonary artery of cow placentomes. *Placenta* 28:361-368.



