PREDICTION OF DIET QUALITY PARAMETERS OF ROCKY MOUNTAIN ELK VIA NEAR INFRARED REFLECTANCE SPECTROSCOPY (NIRS) FECAL PROFILING

A Dissertation

by

MARVIN SCOTT KEATING

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2005

Major Subject: Rangeland Ecology and Management

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ABSTRACT

Prediction of Diet Quality Parameters of Rocky Mountain Elk via
Near Infrared Reflectance Spectroscopy (NIRS) Fecal Profiling. (May 2005)
Marvin Scott Keating, B.S., Texas A&M University;
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The objective of this experiment was to determine the validity of predicting the diet quality of Rocky Mountain Elk (*Cervus elaphus nelsoni*) by exposing a dried fecal sample to light energy (a spectrophotometer). The resulting spectra measured were then compared to the known wet chemistry of the diet to arrive at an equation for forecasting the crude protein (CP) and digestible organic matter (DOM) ingested by the elk. Forages were gathered from western ranges and blended to simulate plant species ingested representing various elk diet qualities at different seasons of the year. Feeding trials were begun during the summer of 1999 using the USDA Forest Service Starkey Unit's herd of tame elk in northeast Oregon. Additional feeding trials were conducted at Center, Texas and College Station, Texas in the spring of 2000 and the summers of 2000 and 2001, respectively. In all feeding trials, 1 elk was fed 1 diet of known quality, *ad libitum*, for 8 days with fecal specimens collected on day 7 and day 8 for spectral scanning. Results indicate acceptable predictability (R^2 = 0.95, SEC = 1.13 for CP, R^2 = 0.80, SEC=1.73 for DOM) in forecasting the diet quality of elk, and thus it is concluded that NIRS is a valuable management tool in monitoring the well-being of captive and free-ranging elk.

DEDICATION

This dissertation if dedicated to my family members, past and present, to Carolyn, Pat, and Robin who made me want to be better, and to the many friends of my Texas A&M family, past and present.

ACKNOWLEDGMENTS

I give all things to the glory of my Lord and Savior Jesus Christ who enabled me to complete the requirements for this degree. All things are accomplished by Him and through Him.

Special thanks are in order to my advisor and committee chair, Dr. Jerry W. Stuth, for his guidance through this program. Dr. Stuth is certainly the most dedicated and brightest research scientist I have ever known. All graduate committee members, Mr. Wayne Hamilton, Dr. Richard Conner, Dr. Jim Jensen, and Dr. Neal Wilkins, have made much appreciated contributions to my growth during this Ph.D. program. It has been my honor to perform various field studies with all of you. In addition, the staff of the Grazingland Animal Nutrition Laboratory (GAN Lab) at Texas A&M University were just irreplaceable in getting the elk equation completed. To Kris Banak and the dozens of student workers I extend my sincere appreciation. Nothing would have been completed without the help of Doug Tolleson and the unselfish donation of his time and patience. You are my true heroes. Austin Blaney was always on hand to grind the many tons of forages or hammer nails in the construction of the elk feeding facility that we built. And to my friends Jim and Blanton Beard of Greenbranch Deer Farm, who loaned me the use of their elk to complete these elk feeding trials, thank you. You were an answered prayer.

As my elk feeding trials began, several key people were pivotal in the Oregon portion of the research trials. Dr. John Cook (the true "Elk Whisperer") of the National Council for Air and Stream Improvement (N.C.A.S.I.) bottle-raised and trained all the tame elk and built the research facilities at Boise Cascade Corporation's Kamela, Ore., research site and provided needed information on the handling and care of each of these very special elk. Each one has a name and a special personality. The USDA Forest Service provided the trailer at the top of the Blue Mountains near Kamela, Ore., where I lived during the summer of 1999. Dr. Bruce Johnson and the Oregon Department of Fish and Wildlife provided use of forage dryers at their Range and Forest Science

Laboratory at LaGrande, Ore., for curing the many tons of clipped forage needed to conduct these feeding trials.

The Curtis Martin family of North Powder, Ore., took me in and treated me like a family member, and provided several much-needed forage collection sites on their ranches as well. The help of Dr. Dennis Sheehy and Mr. Pete Shroeder with forage collection was also appreciated.

To the USDA/GIT people, thank you for partially funding this research. You have taken part in improving the technology for managing the plant/animal interactions of the Rocky Mountain elk in their native habitat of the western United States.

My appreciation goes out to the late Dr. E. J. Dysterhuis who first gave me the interest and the beginning of a career and an unending love for our natural resources. To my friend and outdoor mentor, the late Perry Wilson, thanks for making me to just want to be better. You will be with me always; I will never forget you. I will never forget any of you.

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CHAPTER I

INTRODUCTION

In recent years, developments in near infrared reflectance spectroscopy (NIRS) have proven that prediction of diet quality of free-ranging ruminants on range and forest lands through analysis of fecal samples is feasible (Brooks et al. 1984, Leite and Stuth 1995, Lyons and Stuth 1992, Whitley 1996, Showers 1997, Coates 1998, Ossiya 1999). The high degree of predictability of known diets under free-ranging conditions, coupled with the low cost and quick turn-around time of the results qualify NIRS as a high priority tool for evaluating forage diets consumed by Rocky Mountain Elk (*Cervus elaphus nelsoni*). Land practices such as fire, grazing, logging, seeding, or fertilization create diverse nutritional environments for elk (Peek 1986).

Research work in NIRS to date has been focused on free-ranging herbivores such as cattle (*Bos* spp.), goats (*Capra* spp.), sheep (*Orvis* spp.), and white-tailed deer (*Odocoileus virginianus*). Prediction of dietary crude protein (CP) and digestible organic matter (DOM) of these free-ranging herbivores can be made via NIRS fecal profiling with a degree of precision equal to that of standard wet chemistry diet analysis (Gill 1983, Lyons and Stuth 1992, Leite and Stuth 1995, Coates 1998, Ossiya 1999, Showers 1997, Whitley 1996). Brooks et al. (1984) suggested that NIRS analysis of fecal samples could be useful in providing crude protein and fiber concentrations in the diets of elk. Since that time, however, few studies have been done to establish NIRS as a viable method of analyzing the CP and DOM content of forage ingested by wild ungulates via fecal analysis. Certainly, no definitive work has been done with elk to establish stable NIRS calibration equations capable of predicting dietary CP and DOM for free-ranging elk over a wide range of forages. Knowledge of what composes elk diets is necessary for the development of NIRS equations for CP and DOM. In addition to diet preference, forages representing different seasons of the year and geographic areas are needed to increase the robustness of the calibration equation.

This dissertation follows the style and format of the Journal of Range Management.

The forage selected by herbivores is influenced by such things as the herbivore species, mixture of species on offer, location of water, the topography of the landscape, season of the year, migration patterns, weather, and predators (Senft et al. 1987). Since both domestic livestock and wild ungulates forage to maximize energy (Stuth 1991) problems can be anticipated with inter-species competition on common range at given times of the year. The game animals, however, use the more rugged and inaccessible areas where livestock use is limited (Miller and Krueger 1976, Sheehy and Vavra 1996, Stuth and Winward 1977, Yeo et al. 1993). Anderson and Scherzinger (1975) found that grazing cattle actually improved the elk range as long as care was given to removing the cattle before the end of the growing season. Holechek et al. (1995) noted, however, that forage competition is more of a problem between cattle and elk than between cattle and either deer or pronghorns. Elk have rumen-reticulum volume, rumen fauna, and digestion capabilities (at least for cellulose) that are more akin to those of cattle than other North American deer species (Leege and Nelson 1982).

Rowland (1983) found that forage quality was more variable than was diet quality, indicating the ability of elk to maintain relatively constant diet quality when confronted with large fluctuations in forage quality. Therefore, season of the year probably has more impact on the nutritional quality of elk foraging than any other single factor in their herbivory habits (Leslie et al. 1984). Results from Cook (1996) confirm the importance of nutrition in late summer and fall for growth of elk calves, suggesting a mechanism linking diet quality during this season to winter survival, and demonstrating the importance of evaluating forage quality for reliable assessment of habitat quality on elk summer and autumn ranges. Table 1 is a representative summary by researcher and region of forage choices made by elk at various seasons of the year.

A recent survey revealed that elk herd managers view continued habitat conservation as vital to a healthy elk herd (RMEF 1997). These wildlife managers listed domestic livestock forage competition, ecological succession, and habitat preservation as the pressing issues affecting future elk herd management. Development of NIRS technology to predict forage quality being consumed could aid both the elk and their

habitat. This study is designed to provide resource managers a tool to monitor the nutritional well-being of free-ranging elk herds and support their decision-making process relative to habitat and species interaction.

Objectives

The primary objectives of this research were to develop diet assembly/feeding protocols representing a broad range of crude protein and digestible organic matter for Rocky Mountain elk and to determine how fecal NIRS profiling technology could be applied to a landscape issue regarding elk nutrition and habitat relationships.

CHAPTER II
LITERATURE REVIEW

Population History

Distribution of elk (*Cervus elaphus*) in the 1500's was widely scattered across what is now the United States with the exception of the extreme southern states, approaching 10 million animals. The 6 subspecies of elk generally accepted to have inhabited North America in the 1500's appear in Table 2. Two of the subspecies are believed to be extinct (*C.e. canadensis* and *C.e. merriami*), 3 subspecies exist only in very small populations (*C.e. nannodes, C.e. manitobensis, C.e. roosevelti*), leaving 1 subspecies (*C.e. nelsoni*) that makes up the great majority of the approximately 1 million head of the elk population today (Bryant and Maser 1982, RMEF 1997). Extent of the population 400 years ago included both forested mountains and open plains of North America (Mitchell et al. 1977). Primarily, disappearance of animal numbers has been from the undisturbed prairie or parkland ecotones that have a prevailing grass-forb composition (Bubenik 1982). Elk populations circa 1922 were estimated to be only 90,000 free-ranging animals, 40,000 of which were located within the boundaries of Yellowstone National Park. In addition, today's elk are mostly confined to the mountainous, more inaccessible regions of the western United States and Canada. As a result, the foraging habits of the free-ranging elk have changed rather dramatically over time, and remain extremely variable from one location to another depending on forage availability (Leege and Nelson 1982, Skovlin 1982). Reasons for this change in herbivory can largely be explained by civilization and man's encroachment into elk habitat. Many researchers have reported on the conflict between elk and man's various species of domestic livestock (Holechek et al. 1995, Lyon 1979, Morgantini and Hudson 1979). Other research, however, has demonstrated livestock grazing in an area may force indigenous animals to use marginal habitats (Yeo et al. 1993).

As might be expected, each domestic grazing system varies somewhat in its influence on wildlife. Each may increase or decrease the abundance of food and quality

of cover for wildlife, or simply affect the social interactions between wildlife and livestock (Robinson and Bolen 1989). Elk preferred allotments managed with a deferred-rotational system in Oregon because the deferred plan, rather than season-long grazing, reduced the grazing disturbance of cattle even though there was no direct competition for forage (Skovlin et al. 1976). Holechek et al. (1982) summarized their review of grazing and wildlife relationships with the caution that the balance between defoliation and recovery must be assessed for any grazing system. Because plant productivity on western ranges varies with precipitation, the amount of forage utilized each year is not as important as the amount of vegetation left at the end of the grazing period.

Anderson and Sherzinger (1975) described a grazing plan for cattle that improved the quality of winter forage for elk. Cattle grazed the vegetation in late spring and early summer, but they were removed before the end of the growing season. This strategy allowed time for the plants to regrow and cure as forage of high nutritional quality. Without cattle, the ungrazed vegetation remained fibrous and of low quality. Because cattle stimulated the regrowth of forage later used by elk, the winter elk population increased from 320 animals to 1,190 animals in the study area in the 10-year period after the grazing plan was implemented.

Social Structure

Elk have developed a high degree of sociability, which is a common behavior pattern among ungulates of open landscapes. Social classes are composed of year groups with common features that are at similar stages of physical, physiological, and behavioral maturation. There is no abrupt transition between classes (Bubenik 1982). Bubenik (1982) partitions the social classes of elk as follows:

> l) Calves include all individuals up to the age of 12 months after which maternal care is no longer necessary. Through delayed maturation due to malnutrition and/or social distress, calf age can be extended to 24 months (Selye 1974).

2) Juveniles included 1- to 3-year old animals. Juveniles in elk are neither sexually, physically, nor behaviorally mature.

3) Prime and Senior include all animals older than 5 years. Franklin et al. (1975) consider 4 years as the transition year of maturing for bulls. Maturation in cows is marked by their first pregnancy, which occurs as 3-year olds (Flook 1970). In well-organized populations, bulls cannot compete for the highest social ranks before the age of 7 years (Clutton-Brock et al. 1979).

Digestive Physiology

Digestion in mammalian herbivores is generally a 2-stage process of fermentation and enzymatic digestion. On the basis of digestive anatomy and function, herbivores are divided into 2 main groups. Those in which forage is subjected to fermentation before enzymatic digestion are generally referred to as ruminants or foregut fermenters. In the second group, food is first digested enzymatically and then subjected to fermentation further along the tract (Van Hoven and Boomker 1985). Elk belong to the group known as foregut fermenters.

Free-ranging ruminants show various degrees of specialization and adaptation in their digestive physiology through evolutionary trends enabling them to favor specific food selection (Hofmann 1988). This physiology permits ruminant feeding types to be classified into 3 categories based on their diet selection and digestive physiology differences: 1) concentrate selectors, choosing fruit and dicotyledonous foliage, 2) grass/roughage selectors, choosing monocotyledonous plants, and 3) intermediate selectors, choosing both monocotyledonous and dicotyledonous plants at times in their diets depending on species availability (Hofmann 1989). In general, almost all small ruminants are concentrate-selector feeders while large ruminants are bulk- and roughage-eaters (Van Soest 1994).

The 4 chambers of the ruminant stomach are the rumen, reticulum, omasum, and abomasum (Ullrey 1980). The rumen is a large, thin-walled, sac-like structure lined with papillae. The papillae increase the absorptive surface area from 16- to 38-fold relative to the theoretically non-papillated rumen wall (Hoppe et al. 1977). A myriad of microorganisms, predominantly bacteria in the concentration of 10^{10} to 10^{11} cells g^{-1} of rumen contents, protozoa, and anaerobic fungi, depend on the animal to provide the physiological conditions necessary for their existence. In turn, these microorganisms are essential for digestion and fermentation of the large amounts of fibrous feeds, which the ruminant consumes, but otherwise cannot efficiently utilize (Yokoyama and Johnson 1988).

Finer food particles pass into the reticulum, which has a honeycombed, reticulated epithelium. The rumen and reticulum, often called a single organ (reticulorumen), are separated by the reticuloruminal fold. Since the separation is only partial, free exchange of contents is still possible, and it is in these 2 sacs that the major portion of fermentative activity and absorption of nutrients occurs. The reticular fold is an important sorting device for heavier matter that has sunk to the bottom of the rumen (Van Soest 1994).

The omasum is a finely partitioned, weir-like structure that 1) separates the highly acidic abomasal contents from the fermenting contents of the rumen-reticulum, 2) provides for the passage of smaller feed particles into the abomasum while retaining less digested, larger particles in the rumen-reticulum, and 3) absorbs water and soluble food and microbial products (Prins and Geelen 1971, Prins et al. 1972). The relative size of the omasum varies among species, but it is generally smaller and less functional in concentrate selectors (Van Soest 1994). Small concentrate-selector ruminants are intolerant of high-fiber diets, which, if imposed, lead to impaction of the omasum (Hofmann 1989).

Microbial cells, small food particles, and previously non-absorbed metabolites pass into the abomasum, or true stomach, for enzymatic and acid hydrolysis (Robbins 1993). Ingesta flow in ruminants requires a more or less continuous secretion of gastric

juice, in contrast with nonruminant species, in which entrance of ingesta to the abomasum is intermittent. The presence of volatile fatty acids (VFAs) and lactic acid stimulates gastric secretions and contraction in the organ. Peptic digestion in ruminants includes the digestion of microbial cells that arrive from the rumen in a virtually living state. Acid and pepsin are accompanied by lysozyme secretions that lyse the bacteria and thus speed digestion of microbial protein (Van Soest 1994). McBee et al. (1969) estimated 57.5 to 66.9 billion bacteria g^{-1} of rumen contents in 4 Yellowstone elk. *Bacterioides succinogenes* and *Bacterioides ruminicola* comprised 48% of the bacteria. *Butyrivibrio spp.* made up the major portion of the remaining 52%.

Many species of microbes require specific plant constituents such as cellulose, hemicellulose, starch, sugars, lipids, and proteins to use as a source of energy. Some survive using fermentation products produced by other microbes. The numbers and species composition of the rumen organisms depend on the amount and kind of food ingested by the ruminant and the rate of passage through its digestive system. In turn, the amount and kind of food that a ruminant can effectively digest depends on numbers and species composition of the rumen microbial community (Bruggeman et al. 1972, Cook 2002). Rapid changes in diets, particularly from highly fibrous diets (roughages) to those high in energy and low in fiber (concentrates), can induce changes in the rumen environment that in turn may drastically alter the species composition of microbes. Such changes can make the animal sick and can even be fatal, but are usually problematic only for animals fed processed diets containing higher levels of rapidly fermentable carbohydrates than would be found in native forages.

Total digestive retention times vary widely among ruminants. Using 3 forms of alfalfa (pelleted, cubed, and baled), Dean et al. (1980) measured retention times in elk. Excretion of 90% of the marker used served as the mark of retention time. Feed particle size differed in pelleted, cubed, and baled alfalfa. Pelleted hay was finely ground before being pressed into pellets, cubed hay was partially chopped during the process of compressing cubes, and baled hay was generally in the long form. On the pelleted diet, the retention time was 68 hours for yearlings and 80 hours for adult animals while the

baled diet gave retention times of 120 and 140 hours for yearlings and adults, respectively.

Evolution of the forestomach fermentation process has allowed elk to meet their energy requirements from previously non-digestible plant fiber (Flatt and Schneider 1975, Robbins 1993). Equally important was the capability to conserve and synthesize microbial protein from non-protein nitrogen, to synthesize vitamins, and to detoxify many secondary plant compounds anterior to the normal site of host enzymatic digestion and absorption (Austin et al. 1989). The benefits of forestomach fermentation, however, are balanced somewhat by a reduced rate of food passage and microbial losses of easily digestible plant cellular contents (Merchen 1988).

More time is spent chewing during rumination than during eating. The amount of time spent ruminating is influenced by the nature of the diet and appears to be proportional to the cell wall content in coarse forages. Ruminants may spend 10 to 11 hours daily ruminating if foods are high in structural tissues, which can be a factor in limiting the amount of food an animal eats each day. Feeding concentrates or finely ground or pelleted hay in the diet may greatly reduce rumination time. Rumination time appears to be induced by sensors in the rumen wall, which is innervated principally by the dorsal trunk of the vagus nerve. Rumination can be stimulated by tactile means or by presence of coarse material; hence, the literature on ruminant nutrition uses the term "scratch factor" to describe the dietary characteristic which is probably responsible for inducing normal rumination. Lack of stimulation may be responsible for the low level of rumination in animals on concentrate and pelleted diets (Van Soest 1994).

The ability to regurgitate and masticate food has survival benefits for the animal. Ruminants can quickly fill their rumen with food and spend more time bedded while processing their food (ruminating) in areas protected from predators or harsh weather. Muscles in the rumen and reticulum contract and relax throughout the day, which mixes the ingesta and prevents clogging in the rumen. Large, coarse materials float and are regurgitated from the rumen and rechewed while the finer, more dense particles are passed out. Non-ruminant digestive systems are unable to digest and acquire energy

from cellulose because it is impervious to normal acid/pepsin digestion (Ferrell 1988). The rumen-reticulum provide a fermentation vat of relatively constant temperature and pH for a variety of anaerobic bacteria, fungi, and protozoa (Van Soest 1994).

Generally, grinding forage increases their rate of passage. Concentrates, which usually have smaller particle sizes than forages, are associated with faster passage. Ingestion of large quantities of concentrates providing a source of rapidly fermentable carbohydrates can result in a rapid proliferation of lactic acid-producing bacteria, mostly commonly *Streptococcus bovis*, causing tissue damage to the rumen epithelial cells (Owens and Goetsch 1988). Lactic acid has been noted to reduce rumen pH values from a norm of 6.5 to a much more acidic 5.5 in just 90 minutes (Robbins 1993). Church and Hines (1978) even noted mild damage in the form of hemorrhagic and edematous papillae on the rumen walls of 7 Roosevelt elk fed alfalfa hay and a small amount of native browse.

The morphology of forages affects the prehension and selection of the food ingested. If the ingestion rate is slow, fermentation is continuous and there are no peaks in acid production. Rapid eating allows more material to be fermented simultaneously, resulting in a more synchronized peaking of fermentation and an acid production that must be balanced by buffering mechanisms, the most important of which is ensalivation (Holleman et al. 1979, Van Soest 1994). About 70% of the water entering the rumen comes from salivary secretion (Church 1988).

Of the 3 ruminant forage classifications, grass/roughage feeders and intermediate (mixed) feeders have rumen-reticulum volumes that are 53% and 22% greater, respectively, than those of concentrate selectors. Browsers, however, can have a smaller rumen so that leaves can be digested and passed faster than grasses (Robbins 1993). Browsers also have a less complex, more open omasum than either grazers or intermediate feeders that is less of an impediment to particle flow (Baker et al. 1994, Spalinger et al. 1986).

Foraging Habits

Researchers have determined foraging habits of large herbivores follow rather organized ecological hierarchies, making forage selections at the individual plant feeding stations located within a plant community/soil plant association, within a landscape system, and all within a regional ecosystem (Bailey et al. 1996, Stuth 1991). All large herbivores make spatial changes of foraging activity based upon moving from an area of discomfort where physiological needs are not being met with regards to forage availability, safety from predators, thermal compatibility, and proximity to water, to an area of preference that satisfies their physiological needs. During bouts of feeding, an elk circulates through its home range making decisions about where and what it eats. Vegetation assemblages typically are distributed heterogeneously across landscapes due to effects of soil type, land management, topography, soil moisture, forest canopy cover, and snow. Elk generally would be expected to select those patches that would allow them to consume nutrients at the highest rate (Langvatn and Hanley 1993) and remain in a patch until nutrient intake rates began to decline, because movement among patches increases energy expenditure. Therefore, elk should theoretically allocate time within patches and time traveling between patches so as to maximize energy intake and minimize energy expenditure (Jiang and Hudson 1993). Studies of elk during summer in Idaho and Montana suggest that elk select sites with relatively abundant succulent forbs and shrubs, particularly in late summer (Edge et al. 1988, Irwin and Peek 1983).

Intake rates (g min^{-1}) of elk within a patch are a function of the plants the elk will consume, bite size, cropping rate, amount of time required to bite the plant and prepare the forage for swallowing, and the extent of physical obstructions, such as woody material associated with the forage (Gross et al. 1993). Greater intake rates have been reported for elk on cured pastures than on lush green pastures, apparently due to greater water content of lush vegetation and a greater tendency of less fibrous feeds to break at the point clipped by incisors rather than at ground level (Hudson and Watkins 1986).

Elk do certainly fit the description of intermediate feeders, grazing grasses and grass-likes first and then making best use of the browse and forbs presented to them in

accordance with season, availability, and competition from other herbivores (Holechek et al. 1995, Miller et al. 1981). Elk often choose to leave a place of environmental and elemental discomfort in favor of a place of protection from the elements, predators, or pressure from man, and thus are readily willing to change their diet quickly to accommodate their circumstance of physical comfort or safety (Morgantini and Hudson 1985, Parker and Robbins 1984).

Geist (1982) reports that opportunism should express itself as migration between seasonal home ranges, following sprouting vegetation from the lowlands to alpine habitats, and from southern exposures to northern ones, from the open to the closed canopy, or along retreating waterlines of annually flooded or marshy areas. Opportunism results in elk taking advantage of locally abundant food sources brought about by a variety of changing ecological and climatic factors (Geist 1982, Irwin and Peek 1983, Robbins et al. 1979, Thorliefson et al. 1998, Thorne et al. 1976, Westra and Hudson 1981). Hudson and Haigh (2002) concluded that elk are marvelously adapted generalists with a well-developed capacity to adjust physically, physiologically and behaviorally to a variety of habitats and disturbances, and their adaptability will continue to be tested in their ever-changing and increasingly artificial environment.

Intake and Energy Expenditures of Elk Compared to Other Ungulates

Foraging is the dominant activity of free-ranging ungulates. Wild ungulates typically devote 40 to 60% of each day to finding and consuming food (Collins et al. 1978). Several studies have indicated that elk can consume as much as 20 g min^{-1} on a dry matter (DM) basis if forage is abundant (Collins and Urness 1983, Hudson and Watkins 1986, Wickstrom et al. 1984). Wickstrom et al. (1984) measured the energetic cost of grazing in the Blue Mountains of northeastern Oregon using indirect calorimetry with a tracheotomized elk and found the cost of eating herbaceous forage averaged 0.32 kcal $kg^{-0.75}$ $hour^{-1}$, an energetic increment of 26% over standing costs. Forage intake was also quantified by Wickstrom et al. (1984) using esophageal fistulated mule deer and elk. Asymptotic grass intake rates were 2.22 and 14.04 g DM min^{-1} for deer

and elk, respectively. Consumption rate and bite size were greater in shrub-forb communities than on grass pastures of comparable biomass. Biting rate ranged from 15 to 60 bites min^{-1} and was inversely related to bite size. Rate of foraging decreased exponentially with increasing forage availability. This research was conducted on bottle-raised elk and mule deer, which were habituated to the experimental protocol.

Total energy expenditure by elk while consuming grasses and/or forbs of 1.55 kcal kg $BW^{-0.75}$ $hour^{-1}$ has been documented by Jiang and Hudson (1992). The cost of grazing, part from energy expenses to maintain posture, averaged 0.32 kcal kg $BW^{-0.75}$ $hour^{-1}$ (Jiang and Hudson 1992). No difference was observed in the energy expenditure of consuming grasses alone (mean = 0.31 kcal kg $BW^{-0.75}$ $hour^{-1}$) versus forbs alone (mean = 0.27 kcal kg $BW^{-0.75}$ $hour^{-1}$) (Jiang and Hudson 1992). Grazing costs reported for domestic sheep and cattle (0.54 and 0.67 kcal kg $BW^{-0.75}$ $hour^{-1}$, respectively, above the cost of standing) were higher than those costs observed for elk (Graham 1964, Holmes et al. 1978). Eating costs per unit time were lower for elk than for other ungulates. The expenditure expressed as an increment above standing (26%) falls between values reported for bighorn sheep (32%) and moose calves (20%) (Chappel and Hudson 1978, Renecker et al. 1978).

Grass consumption rates have been reported at 2.22 and 14.04 g DM min^{-1} for mule deer and elk, respectively (Wickstrom et al. 1984). Maximum grass intakes for domestic livestock ranges from 4.8 g min^{-1} to 18.0 g min^{-1} in cattle (Allden and Whittaker 1970, Chacon and Stobbs 1976). Forage intake was more rapid when animals were consuming browse alone (mean = 5.63 for deer and 13.41 g DM min^{-1} for elk). Peak intake was 0.43 g DM kg $BW^{-0.75}$ min^{-1} for deer and 0.47 g DM kg $BW^{-0.75}$ min^{-1} for elk (Wickstrom et al. 1984).

Mean bite size was reported consistently greater in the conifer understory communities for both deer and elk, at 180 and 498 mg DM $bite^{-1}$, respectively (Wickstrom et al. 1984). This compares similarly with those values reported by others, 400 to 600 mg DM $bite^{-1}$ for elk (Collins et al. 1978) and 154 to 440 mg DM $bite^{-1}$ for mule deer (Deschamp 1977). Elk bite size ranged from 540 to 1,740 mg DM $bite^{-1}$ when

consuming browse. Thorne et al. (1976) fed a variety of diets to 46 cow elk throughout 3 winter-spring periods until parturition. Cows fed 17.5 to 19.4 g kg $BW^{-0.75}$ of hay and concentrates were able to maintain or slightly increase their weights. CP of these diets ranged from 8 to 14%. Like domestic cattle, elk apparently require less total feed when concentrates are included in their diet (Howery and Pfister 1990). Bulls have been reported to consume 1.4 times as much as cows (Murie 1951).

Jiang and Hudson (1994) used non-lactating female elk averaging 234 kg body weight fed 3 different diets to compare intake estimates using both the single marker and the bite count method. Intakes from the single marker method were calculated as follows:

$$DMI = 100 - 2.4Dfec / Dig\%$$

where DMI = dry matter intake, Dfec is the dried fecal output (g $hour^{-1}$), and Dig% = the percent dry matter digestibility (DMD) of the forage. DMI by the bite count method was calculated as follows:

$$DMI = BR \times BS \times AT \times FR$$

where BR = the bite rate (bites min^{-1}), BS is bite size (g min^{-1}) in dry matter, AT is active time (min day^{-1}), and FR is the ratio of foraging time to activity time. Results of daily DMIs were: 1) herbage-fed penned elk in January, 3.37 kg day^{-1}, 2) barley/alfalfa pellet-fed penned elk in February, 3.05 kg day^{-1}, and 3) aspen/parkland pastured elk in May, 7.60 kg day^{-1}.

Factors Affecting Intake and Nutrition

Voluntary intake varies with forage quality, body, condition, physiological status, and season. On medium quality forage, nonpregnant and nonlactating elk consume over 4,000 g DM day^{-1}, or approximately 2% of their body weight. Young animals and those

recovering from periods of nutritional stress have higher relative levels of consumption (Hudson and White 1985).

Estimates of daily forage intake rates of free-ranging cow elk are found in Table 3. DMI rates were estimated by month to correlate to physiological state of the cow. Estimates were based on data collected on mature lactating cows (Robbins et al. 1981) and nonpregnant, nonlactating 2- to 4- year old cows (Cook 2002). As expected, peak intake parallels peak forage production months while least intake parallels months of least available forage resources. Forage intake estimates are modified by the effects of photoperiod, environmental factors, state of physiological production, season, and mating behavior.

For free-ranging elk, there is little published data on exact DMI and estimates of captive research elk vary greatly. For example, estimates of winter DMI of calves range from 35 g kg $BW^{-0.75}$ (Jiang and Hudson 1994) to 50 g kg $BW^{-0.75}$ (Cook 2002). DMI in May ranges from 65 g kg $BW^{-0.75}$ in pregnant cows (Robbins et al. 1981) to 154 g kg $BW^{-0.75}$ in subadult nonpregnant cows (Jiang and Hudson 1994) compared with 100 g kg $BW^{-0.75}$ used in Table 3.

Two of the most critical requirements of any herbivore are CP and energy, normally captured by determination of DOM. Next to water (Church and Pond 1982, Cullison and Lowery 1987), energy and protein are the most essential nutrients required in the largest quantity in the diet (Thorliefson et al. 1998). Protein is required by rumen microorganisms to unlock energy by fermentation of cellulose (Robbins 1993). Protein and energy, then, are closely linked. Energy is required for all bodily functions including maintenance, growth, reproduction, antler growth, and activity. Energy requirements of elk are commonly expressed as metabolizable energy (ME), which quantifies the amount of energy available to the tissues after subtracting energy losses in digestion and metabolic conversions (Harris 1970). ME units are expressed in kilocalories (kcal) or megacalories (Mcal).

Effects of Photoperiod

Most mammalian species express seasonal rhythms. This seasonality is particularly evident in deer that have evolved in temperate zones where synchrony of metabolic and reproductive events with matching seasonal forage supplies has powerful influence on survival (Haigh and Hudson 1993). These seasonal rhythms (photoperiod) are under endocrinological control with melatonin being the best-understood and key mediator (Reiter 1991). The rhythms cause DMI to vary several fold depending on forage quality and availability (Hudson and Haigh 2002). A spring-summer increase in voluntary intake and an autumn increase in lipogenesis occur in elk, regardless of body condition. This is followed by a lipolytic period during the winter when there is a reduction in voluntary intake, even in captive animals supplied with ample feed. Metabolic rates are also lower in elk and this may be accompanied by a reduction in body temperature. In most cases these responses are induced by photoperiod and will occur regardless of body composition, nutrient availability, or ambient temperature. The magnitude of response, however, is influenced by these factors (Parker and Robbins 1984). The animal will, therefore, expect to lose weight during winter and then gain weight back in the spring in synchrony with the available vegetation (Price and White 1985).

As a validation of the photoperiod impact on DMI, Jiang and Hudson (1994) conducted research trials with 6 elk fed a high quality alfalfa-barley pelletized feed and 6 elk grazed on native pastures and supplemented with alfalfa hay in western Canada during winter, spring, and summer. No difference was found in winter DMI of the 2 feeding regimes, indicating an agreement that low intake in winter is not due to diet quality. Voluntary DMI in this same study increased concomitantly with the availability of natural pasture in spring and summer.

Working with red deer, Heydon et al. (1995) concluded that melatonin overrides both the effects of nutrition and lactation on DMI. Daily herbage intake was measured at 17-day intervals between July and October using lactating and nonlactating females with 1 g subcutaneous melatonin implants. The melatonin-treated group exhibited

significantly lower intakes than the non-treated group. Suttie and Simpson (1985), also working with red deer, noted forage intakes to be reduced in November in response to endogenous cycles due to photoperiod.

Effects of Environmental Conditions

Elk are one of the largest and best insulated of all the free-ranging ungulates. Although calves have lower critical temperatures of –20°C when bedded, it rises to –5°C when they are standing or active. Protected from wind, adults are very resistant to temperatures as low as –25°C. Pauls et al. (1981) performed research on tethered elk during November, December, and January in central Alberta, Canada and reported that air temperatures from –25°C to 8°C did not affect the metabolic rate of adult elk. Despite cold climates, elk seem only to require shelter from wind and long-wave radiation (Parker and Robbins 1984). Critical to their thermoregulation is staying dry during extreme cold. Healthy adults are more resistant to cold than are juveniles, seniors, or any animal in weakened condition, such as mature bulls in post-rut recovery.

Although allowances for activity on pasture has received little study, research data on both red deer and elk suggest that the energy cost of walking on a hard horizontal surface is similar to that of domestic animals, which is about 10.9 kcal kg^{-1} km^{-1} irrespective of the animal's traveling speed. On inclined surfaces this value increases about tenfold per unit of elevation (Brockway and Gessaman 1977, Gates and Hudson 1979b). Specific energy costs are listed under Energy Requirements discussed later in this paper.

Effects of State of Production

Females near parturition may consume 1.5 times as much as a maintenance diet for nonbreeding animals, increasing to 2 times as much during lactation (Haigh and Hudson 1993). Despite rapid growth of the fetus in the third trimester of pregnancy, intakes remain low (40 to 65 g kg $BW^{-0.75}$ day^{-1}) but increase sharply to approximately

100 g kg $BW^{-0.75}$ day^{-1} during lactation. This exceeds DMI of dry cows by more than 50% (Haigh and Hudson 1993).

ME requirements for liveweight gain of elk range from 6 kcal g $BW^{-0.75}$ gain in winter to almost 10 kcal g $BW^{-0.75}$ gain in summer (Jiang and Hudson 1994). Research on red deer in New Zealand determined a value of 8.8 kcal g $BW^{-0.75}$ gain for 6- to 18-month-old stags and 13 kcal g $BW^{-0.75}$ gain for hinds (Fennessy et al. 1981, Suttie et al. 1987). Seasonal energy requirements of red deer and elk differ mainly in scale. There is an important reproductive difference between the 2 species (both classified as *Cervus elaphus*) in gestation. Elk gestate 255 days, red deer 230 days. Because of this gestation difference, red deer rut several weeks later than elk and as a result, generally go into the winter in poorer condition than elk and require more energy. Elk are usually able to recover some of their post-rut weight loss before winter solstice. An adult elk female requires almost 9.56 Mcal ME day^{-1} for much of the year, but this is almost doubled by demands of lactation. A yearly energy budget expression for female elk is approximately 4,421 Mcal $year^{-1}$, which is very similar for adult males (Haigh and Hudson 1993).

Effects of Social Behavior

Dry matter intake of elk bulls during the fall rutting season range from less than 20 g kg $BW^{-0.75}$ day^{-1} during the rut to more than 100 g kg $BW^{-0.75}$ day^{-1} in early summer. In summer with abundant forage and relatively low foraging costs, rapid passage of digesta enables elk to somewhat relieve the constraint of digestive capacity on DMI (Hudson and Haigh 2002). Seasons of the North generate great forage abundance and scarcity which gives the bull elk an opportunity to store energy and nutrients during the seasons of abundance for use during seasons of scarcity. Such nutrient storage allows the bulls to endure the high energy costs associated with rutting (Geist 2002).

Animals of either gender may register varied DMI rates based on feeding competition from other animals. Galbraith et al. (1998) noted lower intake rates under

group feeding situations compared to being individually fed with voluntary DMI of 86 g $kg^{-0.75}$ when fed in groups compared to DMI of 78 to 90 g $kg^{-0.75}$ when fed individually. Jiang and Hudson (1992) observed DMI during February/March in north central Alberta, Canada, of 52 g $kg^{-0.75}$.

Nutrition of Elk

General Nutritional Requirements

Nutrient requirements of elk vary with season, age, and sex (Ammann et al. 1973, Robbins et al. 1979, Thorliefson et al. 1998, Thorne et al. 1976, Westra and Hudson 1981). Rowland (1983) noted while observing winter diets of elk in New Mexico that forage quality was more variable than was diet quality, indicating the ability of elk to maintain relatively constant diet quality when confronted with large fluctuations in forage quality. In addition, the availability, palatability, and nutritive value of forage species vary both temporally and spatially. Acetic, propionic, and butyric acids are the principal VFAs found in elk rumen contents (Leege and Nelson 1982) and their ratios to each other very closely approximate those ratios of the domestic bovine herbivore (Holechek et al. 1995, Leege and Nelson 1982). Molar ratios of the VFAs acetate, propionate, and butyrate are generally 65:24:10, respectively, for roughage diets (Owens and Goetsch 1988).

Seasonal Effect on Qualitative Intake – Western U.S. Scenario

Winter (December, January, February). December marks the initiation of harsh conditions on most elk ranges; however, with deepening snow and storms elk do not seem to suffer. Food is still plentiful on ranges that are not overstocked. The winter diet of grass and browse (Baker and Hobbs 1982, Irwin et al. 1993, Johnson 1998) dominate the diet and preference is given to green foliage (Murie 1951). Plants such as Quaking Aspen, Mountain Mahogany, and Four-Winged Saltbush are readily consumed due to their soft bark and underlying green cambium layer (Keating et al. 2001). Garrison and Hayes (1960) report the 3 most important plants of the winter diet to be Ceanothus

Snowbush, Curl-leaf Mountain Mahogany, and Antelope Bitterbrush. Elk are able to forage under the snow as they routinely paw down to depths of 76 cm (Murie 1951) and will begin to migrate to regions of lesser snow depth as snow deepens beyond 76 cm (Adams 1982), although the scientific literature reports elk migrations under a variety of snow depth conditions from region to region and from year to year, depicted in Table 4 (Adams 1982, Collins et al. 1978, Wickstrom et al. 1984). Adams (1982) also reports that if the right combination of food, water, and shelter is found in an area, elk will remain there year-round. Since elk are generally found in mountainous regions they are able to move vertically to different areas in response to seasonal changes in vegetation (Harper et al. 1967).

Some researchers (Collins et al. 1978, Wickstrom et al. 1984) have reported intake rates in elk begin to decrease when forage drops below 1,000 kg ha^{-1}, although this is totally grazing-dependent on associated forages available, as evidenced by a foraging intake study done with 160 kg elk calves having a limiting threshold of 1,500 kg ha^{-1} (Wickstrom et al. 1984). Craighead et al. (1972) noted that elk in Yellowstone National Park spend less time feeding during the day in winter than during any other season. The efficient animal will minimize time and energy expenditures for food gathering while maximizing digestible energy intake. Foraging efficiency decreases as the animal is forced to expend more time and energy acquiring necessary food. When food availability becomes so low that requirements cannot be met because continued foraging would simply increase requirements faster than intake, elk reduce foraging effort to conserve body reserves (Robbins 1993). Other research confirms the fibrous foods consumed in winter require more rumination than the succulent foods of summer (Gates and Hudson 1979a, Renecker and Hudson 1989).

February is the most critical month for elk survival (Murie 1951), as preferred and desirable forages have been depleted. Calf mortality is the highest of the population classes (Boyce 1989). Elk will seek sedges and grass-likes during winter, where available, after selectively grazing grasses and are subsequently forced on to coarser forages such as Cattails, Rabbitbrush, Douglass Fir, and Lodgepole Pine in the

mountainous winter range of the Rocky Mountains (Murie 1951). Research in western Canada has shown that even the sedge meadows drop to about 7% CP and about 45% dry matter digestibility (DMD) (Hudson and White 1985). Elk are more susceptible to ticks and other diseases due to their weaker state of nutrition and suppression of immune responses.

Spring (March, April, May). Forage availability begins to improve slightly in March with the advent of new forage growth and snow melt in most elk ranges of the western U.S. Dried grasses combined with browse comprise the forage supply. April usually marks the end of winter's grip on elk as snow melts further and elk scatter across the hillsides in pursuit of tender, green forage (Keating 1999, Leege and Nelson 1982, Skovlin and Vavra 1979, Thorliefson et al. 1998) while still consuming plant leaf material the melting snow has left exposed.

May marks a steady transition into abundant green forage as elk begin to migrate to higher elevations seeking the early green growth of the sedges or browse leaves (Kufeld 1973). Leege and Nelson (1982) confirm that by early May elk are feeding almost exclusively on young leafy forages. Protein contents of 20% and DMDs of 65 to 70% are easily reached in most ecosystems (Hudson and White 1985). Elk spend the next 6 to 8 weeks gradually drifting to higher elevations, and shifting locations from south- and west-facing slopes to north- and east-facing slopes, following the "green line" of lush green growth.

Summer (June, July, August). The onset of June brings the heaviest volume of high quality forages of the year. Forage quality is the highest of the year during June and July; photoperiod the longest, and DMI the highest. The process of lipogenesis matches this surge in vegetation quality as well as the greater nutritional need of the females during lactation (Leege and Nelson 1982, Thorliefson et al. 1998). Calving begins about June 1 in most regions (Robbins 1993). The degree of nutritional hardship experienced by elk in winter is largely determined by foraging conditions of late summer and fall.

Their inability to lay down sufficient body fat reserves at this time of year cannot be compensated during winter (Cook 1996).

Fall (September, October, November). Breeding is generally considered to begin in early September (Leege and Nelson 1982). There is little change in diet composition in early fall from that of late summer except that vegetation is beginning to mature and dry up and elk are losing their opportunity to pick anything green wherever they graze. Elk become more selective in their foraging by seeking plants of less maturity. Plant species offering the highest bulk density of unmixed green foliage with the highest nutrient concentration and lowest content of secondary compounds, such as phenolic acids, has the greatest probability of being grazed (Stuth 1991). Wider variation is now seen in quality of plants within the same species depending on the resources available to that plant (Arnold 1981, Provenza 1995). Plants of a given species may be passed up at 1 feeding station because they have dried up while the same plant species is readily grazed at another feeding station where it has been exposed to different resources and remains greener and more tender (Skovlin and Vavra 1979, Thorliefson et al. 1998). September is the time of the rut when the bulls begin to exhaust their stored resources of body energy and may go weeks at a time with negligible forage intake (Geist 1982, Leege and Nelson 1982).

October is a month of climatic transition in most of the elk ranges and foraging is concentrated on grazing whatever forages are green. Grasses and grass-likes are now consumed readily on the slopes where they can be found (Johnson 1998). The rut is waning and the bulls are beginning to forage once again (Geist 1982).

Winter begins to impact elk in November, stimulating migration to lower altitudes (Adams 1982, Murie 1951). Browse consumption begins to increase during this period. Plants with higher tannin and soluble polyphenols such as Rabbitbrush and Big Sagebrush, which have been objectionable species all year for grazing elk, are now readily grazed (Garrison and Hayes 1960, Leege and Nelson 1982, Skovlin 1982). Higher phenolic acid content rendered these plants objectionable in spring and summer

months compared to other available forages (Thorliefson et al. 1998). Secondary plant compounds such as soluble phenols, alkaloids, and terpenoids represent protective evolutionary defensive mechanisms in plant anti-herbivory strategy (Robbins 1993).

Whatever the season of the year, elk will make forage selections in the grasses and grass-like category first (Hobbs et al. 1981, Kufeld 1973, Wydeven and Dahlgren 1983). Secondly, elk choose forages in the forb strata when grass availability is limited (Leslie et al. 1979, Leslie et al. 1984, Wydeven and Dahlgren 1983). At any time consumption of grasses, grass-likes, and forbs are limited, forage selection shifts to browse (Skovlin and Vavra 1979). Preferences will always focus on the physiological state of young, tender, green, and fastest growing forages (Thorliefson et al. 1998).

Nutrient Intake

Protein Requirements

Arriving at estimates of protein requirements is more difficult than arriving at energy requirements because dietary protein use depends on its amino acid composition, relationships between protein usability and energy intake, and total food intake (Robbins 1993).

Metabolic fecal protein is roughly a constant function of food intake and about 33 g kg^{-1} DMI (Mould and Robbins 1981, NRC 1985). Calculating fecal protein losses requires estimates of amount of feed consumed. Urinary endogenous and dermal losses can be estimated based on body weight. Daily CP needed for maintenance can be estimated using the following formula (NRC 1984):

$$CP_m = [33I + (2.75W^{0.5}) + (0.2W^{0.6})] / (TD \times BV)$$

where CP_m = protein required for maintenance (in g), I = daily food intake on a dry matter basis (in kg day^{-1}), 33I = estimated endogenous fecal loss, $2.75W^{0.5}$ = estimated urinary losses based on body weight (W), $0.2W^{0.6}$ = estimated dermal losses based on

body weight (W), TD = true protein digestibility (assumed 0.9) and BV = biological value of protein (assumed 0.65).

Cook (2002) reported daily protein requirements for an adult cow elk weighing 236 kg (Table 5). Daily food intake was estimated by Robbins et al. (1981) based on intake levels reported for mature pregnant and lactating captive elk. These elk consumed 60, 68, 88, and 131 g of forage kg $BW^{-0.75}$ day^{-1} during winter, the last 2 months of gestation (April and May), the first month of lactation and the second 2 months of lactation (July and August), respectively. Intake of 110, 90, and 60 g of forage kg $BW^{-0.75}$ day^{-1} during September, October and November, and December, respectively was assumed. On the basis of these seasonal intakes, a 236 kg elk has to consume a low in winter of 284 g day^{-1} of protein and a high in summer of 526 g day^{-1} of protein to meet maintenance requirements.

Protein Requirements for Gestation

Total protein deposited in the fetal body during the last 3 to 4 months of gestation can be estimated using the equation presented for cattle by Prior and Laster (1979):

$$TP_g = \{0.000586e^{[(0.0589t/GR)-0.00009334(t/GR)^2]}\}BWR$$

where TP_g = total protein in fetus in grams (dry matter basis), e = exponential function, t = day of gestation, GR = gestation length ratio (256/290 = 0.91) to adjust for shorter gestation length in elk compared with cattle and BWR = birth weight ratio (18/36 = 0.50) to adjust for smaller birth weight of elk calves (assumes 36 kg birth weight for cattle). TP_g was adjusted up by 5% to account for non-fetal products of placental and uterine tissue. From TP_g, an equation was developed to predict the amount of protein required for fetal growth each day and to convert this to estimates of CP requirement for gestation (CP_g):

$$CP_g = 0.01267e^{(0.07072t-0.00016133t^2)} / (TD \times BV)$$

where e = exponential function, t = day of gestation, TD = true digestibility and BV = biological value.

Daily protein accretion for pregnancy maximizes at 30 g day^{-1} in late gestation resulting in CP consumption of 50 g day^{-1}. Daily rate of protein accretion declines slightly during the last 2 to 3 weeks of gestation (Cook 2002).

Protein Requirements for Lactation

Although feed intake is not greatly stimulated by pregnancy, intake during lactation increases about 2-fold. Although feed intake and milk yield are correlated in the long term, peak feed intake lags behind peak milk yield by about 2 weeks (Robbins et al. 1981).

Daily CP requirements for lactation can be estimated with the following equation (Cook 2002, Robbins et al. 1981):

$$CP_1 = (MY \times PC) / (TD \times BV)$$

where CP_1 = crude protein for lactation (g day^{-1}), MY = milk yield (g day^{-1}, wet weight basis), PC = protein content of milk (averages 6.2%), TD = true digestibility coefficient (0.90) and BV = biological value coefficient (0.65). CP requirements for lactation peak at 450 g day^{-1} 3 to 4 weeks postpartum and decline to approximately 150 g day^{-1} 3 to 4 months postpartum. CP requirements for early lactation (450 g day^{-1}) are approximately 9x higher than late gestation (50 g day^{-1}) while requirements for late lactation (150 g day^{-1}) are approximately 3x higher than late gestation.

Crude Protein Requirements of Winter Stasis

Most free-ranging *Cervids* in northern latitudes are characterized by winter weight stasis followed by compensatory summer growth or weight gain due to increased forage availability and increased DMI by the animal. The animal's performance and well-being can be described by how accurately it falls within each window of this weight

gain/loss scenario as defined by the appropriate spatial parameters (Haigh and Hudson 1993).

Summer and fall protein requirements to replace body weight lost during winter depend on the amount of weight lost in winter and the protein content of that lost weight. According to Torbit et al. (1985), and assuming a protein-to-fat catabolism ratio of 40:60, a cow losing 25% of her body weight would have to replace 10.5 kg of protein and a cow losing 10% of her body weight would have to replace 4.2 kg of protein. Assuming a seasonal weight gain period distributed from May to mid-October, 165 days of weight gaining requires a daily CP intake of 108.8 and 43.5 g day^{-1} for 25% and 10% winter body weight loss scenarios, respectively.

Energy Requirements

Energy requirements of all *Cervidae* species follow a seasonal pattern related in proportion to photoperiod (Haigh and Hudson 1993, Houston 1982, Robbins 1993). Elk reduce their basal metabolic rate by 40 to 60% during winter and thereby reduce their energy requirements and their daily forage intake (Thorliefson et al. 1998). Table 6 provides an estimated daily activity pattern calculated by Craighead et al. (1972) and energy expenditure rates compiled by Moen (1973) for a 236 kg cow elk. There is difficulty in attempting to measure the many diverse variables of energy and protein requirements of animals, especially free-ranging wild animals and so there is some disagreement and expected diversity in the measured results which are reported. Daily CP and energy requirements reported by Thorliefson et al. (1998) are broken down by stages of maintenance and production in Table 7.

Energy Requirements for Gestation

The greater energy requirements for pregnant cows are due to the accumulation of energy contained in the tissues of the growing fetus. Accretion of fetal tissues occurs slowly during the first 150 days of gestation and increases thereafter for the 105 or so

remaining days. Cook (2002) estimates elk energy requirements for pregnancy by an adaptation of an equation developed for bovine species (NRC 1984):

$$Q_{ne} = PW(0.0149 - 0.0000407t/GT)e^{[0.05883t-0.00008804(t/GR)^2]}$$

where Q_{ne} = net energy (kcal day^{-1}) required for pregnancy, PW = average elk calf weight at parturition (18 kg), e = exponential function, t = elk gestation time in days and GT = ratio of elk-cattle gestation time (256/280 days = 0.91). Estimates of daily ME requirements of mature pregnant or lactating cow elk according to Cook (2002) appear in Table 8.

Energy Requirements for Lactation

Energy needs for lactating dams is greater than for pregnancy. Price and White (1985) report a lactating dam's energy requirements to be about 4x higher for lactation than for pregnancy. The costs of lactation include the energy contained in milk less the energetic costs of energy conversion from the dam. This efficiency rate averages about 65% in wild ruminants (Price and White 1985). Energy costs of lactation are calculated as the product of milk yield and energy content of milk (Cook 2002):

$$Q_{el} = [(MY)(EC)] / 0.65$$

where Q_{el} = energy (kcal day^{-1}) required for lactation, MY = milk yield (g day^{-1}), EC = energy content of milk (kcal g^{-1}) and is based on caloric values of 9.25, 5.85 and 3.69 kcal g^{-1} of fat, protein and lactose, respectively (Robbins et al. 1981) and 0.65 = efficiency of ME conversion.

Robbins et al. (1981) presents 2 equations for milk yield: 1) increasing milk yield from 1 to 25 days postpartum, and 2) decreasing milk yield for 26 to 80 days postpartum:

$$1)\ MY = 3055.5 + 50.1t$$

$$2)\ MY = 55.789e^{(-0.0125t)}$$

where MY = milk yield (g day^{-1}), e = exponential function, and t = number of days postpartum. Cook (2002) reports daily ME requirements 30 to 40 days postpartum at 7,000 kcal and a decline to 3,200 kcal at 120 days postpartum.

Energy Requirements of Winter Stasis

Body tissue lost during winter must be replaced during spring through fall for the animal to maintain itself year to year. Kozak et al. (1995) found substantial winter weight losses to result in reduced milk yields the following summer. Jiang and Hudson (1992) estimated that 9.31 kcal ME are required per gram of gain in large, subadult cow elk. A 236 kg cow elk losing 10% of her weight during winter would require 219,480 kcal ME to replace the lost body tissue. A 236 kg cow elk losing 25% of her weight during an atypically harsh winter would require 549,290 kcal ME, or about 3,330 kcal day^{-1} (spread over 165 days), or about 55 kcal kg BW^{-1} day^{-1} to replace her lost body tissue. Assuming weight gain to occur between April and early November and excluding June to mid-July as peak lactation, elk have 165 days at their disposal for weight gain. Recovery from severe winter weight losses threatens animal survival.

Principles of Near Infrared Reflectance Spectroscopy (NIRS)

The word "spectroscopy" is derived from the Latin root *spectrum* (appearance, image) and the Greek root *skopia* (to view), which is rather descriptive of the spectroscopic measurement itself: to view a light image coming from a specimen (Miller 2001). Recent studies have indicated reliability in using NIRS to predict diet quality of various classes of free-ranging ruminants in diverse forage environments via fecal scanning (Brooks et al. 1984, Coleman et al. 1989, Leite and Stuth 1995, Lyons and Stuth 1992, Ossiya 1999, Showers 1997, Stuth et al. 1989, Stuth et al. 1999, Whitley 1996).

The basis for using NIRS for determining diet quality is the use of a monochromatic light source (a spectrophotometer) to irradiate a substance's molecules (dried fecal material) and its chemical bonds (Ossiya 1999, Showers 1997). The composition and behavior of all plant and animal materials are direct consequences of their chemical makeup (Windham et al. 1989). The chief components of all natural substances are proteins, nonfibrous carbohydrates, moisture, minerals, and vitamins. Protein, carbohydrates, and fats are complex compounds composed of simpler compounds such as amino acids, monosaccharide and disaccharide sugars, fatty acids, and glycerol. Their spatial arrangement and electrostatic and covalent bonding capacity interact to create a wide array of chemical and physicochemical properties. All organic matter consists of atoms, mainly carbon, oxygen, hydrogen, nitrogen, phosphorous, and sulphur. These atoms combine by covalent and electrovalent bonds to form molecules.

The molecules are constantly in motion and vibrate at frequencies corresponding to wavelengths in the infrared region of the electromagnetic spectrum. NIRS affords a method for the translation of these vibrations into simple, very rapid, and non-polluting analytical data (Murray and Williams 1987, Williams 1987a). The fact that each of the major chemical components of a sample has near infrared absorption properties, combined with the radiation-scattering properties of the sample, determines the diffuse reflectance of a sample. Therefore, the near infrared diffuse reflectance signal contains information about the composition of the sample.

The near infrared region is generally defined as comprising the wavelengths from 700 to 3,000 nanometers (nm); however, most of the near infrared reflectance quantitative analysis work is done in the range of 1,200 to 2,500 nm. Norris (1989b) states that the absorption bands on wavelengths below 1,200 nm are so weak that quantitative measurements by reflectance are difficult, and the absorption bands on wavelengths above 2,500 nm are so strong that quantitative measurements are also difficult. As a result, the most functional region is from 1,200 to 2,500 nm.

According to (Norris 1989a) the NIRS method of analyzing fecal or forage material has 4 advantages: 1) speed, 2) simplicity of sample preparation, 3) multiplicity

of analyses with one operation, and 4) nonconsumption of the sample so that it can be used for other procedures. Sample preparation consists of creating homogeneous particles by grinding to achieve a size range of 100 to 500 ? m. The homogeneously prepared sample is placed in a cup and is ready for measurement. Many constituents are measured at the same time by making measurements at many wavelengths. The method requires no reagents that are polluting and characterizes the entire sample rather than specific components of interest (Deaville and Flinn 2000). The main disadvantages of NIRS are the instrument requirements, dependence on calibration procedure, complexity in the choice of data treatment, and the lack of sensitivity for constituents in relatively low concentrations (Norris 1989a). Once the equipment has been acquired and an appropriate calibration procedure developed, however, subsequent purchase of expensive reagents and glassware is not required.

When molecules are irradiated with an external source of energy they acquire the potential for energy changes and motion. The main types of molecular motion are caused by rotational and vibrational energy transitions. Vibrational motion is created by movements of the atoms toward and away from each other in a manner similar to a continuously oscillating spring. Rotational motion is created by rotation about the molecular axes. Vibrational spectra appear as bands and represent characteristic wavelengths from their specific generic chemistry. There are 2 main modes of molecular vibrations, stretching and bending. Stretching is the movement along the axes of bonds while bending involves changes in bond angles between atoms (Murray and Williams 1987).

Molecules result from the combination of covalent and electrovalent bonding of atoms present in all organic matter as elemental carbon, oxygen, hydrogen, nitrogen, and minor amounts of other elements. The molecules are in constant motion and vibrate at frequencies corresponding to wavelengths in the infrared spectrum in accordance with the nature of the bonds, the electrostatic charges of the atoms, and the molecules themselves (Murray and Williams 1987).

Multi-term linear regression is used in the development of calibration equations to isolate effects of a single absorber and normalize the baseline (Hruschka 1987). Optical data generated from fecal scans are the dependent variables and diet chemistry values are the independent variables (Williams 1987b). In Figure 2 wavelength is plotted in nm on the x axis and the y axis expresses the mathematical inverse logarithm of the portion of light reflected (log 1/R). Absorbance spectra are a measure of how much light is absorbed by a sample. For most samples, absorbance is linearly related to the concentration of the substance. The software calculates using the following equation:

$$A_\lambda = -\log 10\ (S_\lambda - D_\lambda / R_\lambda - D_\lambda)$$

where S is the sample intensity at wavelength λ, D is the dark density at wavelength λ, and R is the reference intensity at wavelength λ. Absorbance can be expressed as proportional to the concentration of the substance interacting with the light, known as Beer's Law (ISI 1992).

Wavelengths are selected using the modified stepwise regression approach (Westerhaus 1989a). One wavelength for every 10 samples is recommended as maximum terms allowable for an equation (ISI 1992). Calibrations using fewer wavelengths perform most effectively (Shenk and Westerhaus 1990, Williams 1987b).

Agricultural Use of NIRS

Near infrared reflectance spectroscopy has a long history of being used in determining quality components of agricultural food products (Rubenthaler and Bruinsma 1978, Stermer et al. 1977, Williams 1975). NIRS had been used widely in grains to predict moisture, protein, and oil (Pierce et al. 1996, Shenk et al. 1991). NIRS has been used in prediction of soil parameters such as clay content, cation exchange capacity, base saturation, and soil pH (Foley et al. 1998, Stenberg et al. 1995). Moron and Cozzolino (2002) used NIRS to determine soil organic carbon, total N and pH and then later to determine texture, Fe, Zn, and Cu in soil material (Moron and Cozzolino

2003). NIRS has proven to be a valuable tool for forage quality analysis research and is an established tool for predicting nutrient levels across a wide array of forage types (Bengtsson and Larsson 1984, Bolster et al. 1996, Burdick et al. 1981, Lippke et al. 1989, Roberts et al. 2003, Stuth et al. 2003). The use of NIRS in the analysis of highly fibrous feeds is different than that of grains because the components of the plant matrix are more complex and involve numerous discrete interactions (Barton and Kays 2001). NIRS methodology has been used in examining fecal material of livestock to predict such diet quality parameters as CP and digestibility (Coates 1998, Gibbs et al. 2002, Krachounov et al. 2000, Leite and Stuth 1995, Li 2004, Lyons and Stuth 1992, Ossiya 1999, Whitley 1996). With wildlife, NIRS has also proven useful as a management tool in predicting their nutritional well-being (Brooks et al. 1984, Dorgeloh et al. 1998, Gallagher 1990, Keating et al. 2001, Lister et al. 1997, Showers 1997). One of the greatest hindrances in using NIRS for monitoring wildlife has been the complexity involved with the development of calibration equations. Once equation development is accomplished, use of NIRS as a wildlife management tool has the added advantage of being non-invasive and low stress for the particular animal species. A key for equation development is incorporating a diverse group of plant species and functional group profiles to insure a spatial and temporal robustness useful in predicting animal performance (Stuth 2004).

Use of NIRS in Prediction of Animal Performance

The use of proximate analysis of forages has for years been the benchmark in ranking forage value. Nutritive value of forages is estimated based on chemical constituents such as CP, which is usually considered to be nitrogen x 6.25, and some form of fiber evaluation such as crude fiber (CF), neutral detergent fiber (NDF), or acid detergent fiber (ADF). Although fiber is not a true nutrient, knowledge of fiber content of ingested forage is useful in determining the animal's ability to biologically transition the forage for its own use. Bertrand (2001) demonstrated success in fiber prediction in The Netherlands using NIRS. Berardo et al. (1997) achieved a coefficient of

determination (R^2) of 0.95 in prediction of NDF and ADF while working with *Cajanas cajan* (pigeon pea) and Mizuno et al. (1997) report R^2 of 0.97 and 0.96, respectively, in prediction of NDF and ADF in temperate grasses and legumes. Stuth et al. (2003) state the ability of NIRS to predict fiber content of forages is due to variations in CH and OH bonds in the range of 300 to 800 g kg^{-1} DM. Strong relationships (R^2 values above 0.95 with standard errors well within lab errors) have been reported for total nitrogen or CP. Strong –N–H absorptions are the primary cause for these good relationships. The high concentrations of N, which in forages and feeds can range from 30 to 500 g kg^{-1}, is also another contributing factor (Roberts et al. 2003).

NIRS has proven the ability to predict the CP and digestibility for livestock and wildlife via fecal profiling (Flinn and Downes 1996, Showers 1997).

Use of NIRS to Predict Diet Quality of Livestock

The GAN Lab at Texas A&M University has produced a lengthy record of successful NIRS predictive equations for CP and DOM for various species of livestock (Table 9). Lyons and Stuth (1992) first worked with esophageal fistulated steers in Texas reporting R^2 of 0.92 and standard error for calibration (SEC) of 0.89 for CP and R^2 0.80, SEC 1.75 for DOM. Also working in Texas with goats, Leite and Stuth (1995) reported values of R^2 0.94, SEC 1.12 for CP and R^2 0.93, SEC 2.02 for DOM. Ossiya (1999) formed predictive cattle equations in sub-Saharan Africa with R^2 0.88, SEC 0.85 for CP and R^2 0.83, SEC 3.39 for DOM. Awuma (2003) expanded the cattle, sheep, and goat predictive equations in Africa to generate R^2 0.95, SEC 0.87 for CP and R^2 0.90, SEC 3.02 for DOM in cattle; R^2 0.97, SEC 0.78 for CP and R^2 0.94, SEC 2.26 for DOM in sheep; and R^2 0.97, SEC 0.79 for CP and R^2 0.95, SEC 2.86 for DOM in goats. Japanese experiments with dairy cattle (Purnomoadi et al. 1998) have yielded R^2 0.98 for CP. Australian studies (Coates 1998) have contrasted stall feeding versus esophageal grazing trials in cattle, finding better calibration statistics with the stall-fed animals. Recent work by Gibbs et al. (2002) expanded the realm of NIRS beyond forages to

include a dietary concentrate supplement with very favorable calibration statistics of R^2 0.99, SEC 1.28 for CP and R^2 0.87, SEC 2.63 for DOM in cattle.

Use of NIRS to Predict Diet Quality of Wildlife

The nutritional well-being of wildlife has received a breakthrough in recent years beginning with initial work in elk by Brooks et al. (1984). Using a limited number of samples, this study revealed the potential NIRS held for predicting wildlife diets with R^2 0.99, SEC 0.88 for CP and R^2 0.80 and SEC 0.68 for DMD. Showers (1997) generated a calibration equation working with tame white-tailed deer. Calibration statistics recorded were R^2 0.94, SEC 0.70 for CP and R^2 0.89, SEC 2.64 for DOM. Working with both tame and free-ranging Rocky Mountain elk, Keating et al. (2001) generated a calibration equation that yielded R^2 0.95, SEC 1.13 for CP and R^2 0.80, SEC 1.73 for DOM. These recent studies demonstrate the feasibility of using fecal NIRS profiling for predicting the nutritional status of wildlife, and thus have management implications for habitat.

Additional Animal Applications Using Fecal NIRS

Fecal NIRS has been used successfully to determine gender and species differences between cattle and sheep. Tolleson et al. (2001) found that a pooled discriminant NIRS equation (R^2 0.6984, SEC 0.2743) correctly identified 82% of females and 74% of males using white-tailed deer (*Odecoileus virginianus*), fallow deer (*Dama dama*), red deer (*Cervus elaphus*), and African elephants (*Loxodonta africana*). Calibration statistics for livestock and wildlife can be seen in Table 22. This data gives high possibilities of using this non-invasive method as a management tool with wildlife.

Studies have been conducted (Tolleson et al. 2000) to determine the ability of fecal NIRS to detect dietary tannin concentration in wild ungulate (white-tailed deer) diets. Since fecal nitrogen is the most often used indicator of diet quality in both wild (Brooks et al. 1984, Gallagher 1990, Cook et al. 1994, Showers 1997, Keating et al. 2001) and domestic (Lyons and Stuth 1992, Leite and Stuth 1995, Whitley 1996, Coates

1998, Ossiya 1999, Gibbs et al. 2002, Awuma 2003) animals, the development of a rapid and non-invasive index for determining tannin levels can greatly enhance nutritional management of all ungulates. This work was conducted with a small sample set, but results indicate the ability of NIRS to discriminate between diets differing in tannin concentration and to quantify those tannin concentrations. Further conclusions were made that development of a robust tannin predictive equation will depend upon the collection of a calibration set rich in diversity of both tannin quantity and source.

Godfrey et al. (2001) used fecal NIRS to correctly identify 47/50 pregnant and 19/25 non-pregnant ewes. The use of NIRS as a non-invasive tool for determining gestation status of ungulates has positive potential in production agriculture. In wild ungulates, the economic and physiological cost benefits of identifying pregnancy without handling stress are substantial and may be the only practical method of determining gestation in free-ranging wild ungulates.

Unique fecal chemistry resulting from differences in parasite burden can also be detected by NIRS. A recent study (Tolleson et al. 2000) used fecal specimens of cattle to determine the presence and parasite burden of Lone Star (*Amblyomma americanum*), Gulf Coast (*A. maculatum*), and Cayenne (*A. cajennense*) ticks. A second experiment used horses in determining the presence of stomach bots (*Gasterophilus intestinalis*). Visual inspection of the near infrared reflectance (NIR) fecal spectra of the three-dimensional graphics in the WinISI® version 1.5e software successfully segregated animals with parasite loads. NIRS holds economic potential for both domestic and wild ungulates in the management of internal and external parasites.

Ecological Applications of NIRS

The potential application of NIRS to aspects of ecological research is great, particularly in plant/herbivore dynamics. Table 23 lists some studies performed using NIRS to evaluate and predict variables of terrestrial forage quality. While the benefits of NIRS have long been known among agricultural scientists, there has been little use of this method by ecologists (Foley et al. 1998). Woolnough and Foley (2002) were able to

analyze 120 to 140 ground plant samples daily in duplicate for 8 nutritional attributes in their study of the northern hairy-nosed wombat *(Lasiorhinus krefftii*), a large, endangered Australian range herbivore, thus resulting in reduced laboratory time and associated costs. By using NIRS the researcher can rapidly analyze large numbers of samples with limited reduction of precision, thereby enabling large-scale applications that may have previously been impeded by time and costs.

CHAPTER III
DEVELOPMENT OF CALIBRATION EQUATION

Introduction

Near infrared reflectance spectroscopy is a rapid and non-invasive analytical technique based on the unique absorption and reflectance of monochromatic light in the wavelength range of 700 to 2,500 nm by chemical bonds primarily involving nitrogen, carbon, hydrogen and oxygen. Research in NIRS to date has focused on several species of free-ranging herbivores listed in Table 10. Prediction of dietary CP and DOM of these free-ranging herbivores can be accomplished through NIRS fecal profiling with a degree of precision equal to that of standard chemical diet analysis (Coates 1998, Leite and Stuth 1995, Lyons and Stuth 1992). Brooks et al. (1984) first suggested that NIRS analysis of fecal samples could be useful in providing CP and fiber concentrations in the diets of elk. Since that time, however, few studies have been conducted to establish NIRS as a viable method of analyzing the CP and DOM content of forage ingested by wild ungulates via fecal analysis (Dorgeloh et al. 1998, Showers 1997). Certainly, no definitive work has been conducted with elk to establish stable NIRS calibration equations capable of predicting dietary CP and DOM for free-ranging elk over a wide range of forages.

Knowledge of what composes elk diet composition is necessary for the development of NIRS equations for CP and DOM. Rowland (1983) found that forage quality was more variable than was diet quality, indicating the ability of elk to maintain relatively constant diet quality when confronted with large fluctuations in forage quality. Therefore, season of the year probably has more impact on the nutritional quality of elk foraging than any other single factor in their herbivory habits (Leslie et al. 1984). Results from Cook (1996) confirm the importance of nutrition in late summer and fall for growth of elk calves, suggesting a mechanism linking diet quality during this season to winter survival and demonstrating the importance of evaluating forage quality for reliable assessment of habitat quality on elk summer and autumn ranges.

A recent survey revealed that elk herd managers view continued habitat conservation as vital to a healthy elk herd (RMEF 1997). These wildlife managers listed domestic livestock forage competition, ecological succession, and habitat preservation as the pressing issues affecting future elk herd management. The objective of this experiment was to develop NIRS predictive equations to provide wildlife managers an improved monitoring system for detecting dietary CP and DOM of free-ranging elk in their native habitat.

Materials and Methods

Forage Identification

Forages collected for this study were chosen on the basis of their proportional quantity in elk diets as derived from current literature (Garrison and Hays 1960). Selection of forage species was further referenced with current taxonomic literature for the collection areas (Garrison and Hays 1960, Hatch et al. 1990, Hitchcock 1971, Hitchcock and Cronquist 1991, Johnson 1998, Weber 1976). Forages were collected (Table 11) in Oregon during the summer of 1999 from the public lands of the Wallowa-Whitman National Forest, public roadside areas, and private ranches. Forages were collected in altitudes up to 2,500 m elevation in December 2000 from the San Luis Valley of Colorado. In Texas, collections were made in all seasons from private ranches, public roadsides and from Texas A&M University's natural resource areas near campus. In all collection sites, care was given to harvest only the plant parts judged to be consumed by elk among a wide array of environmental conditions.

Diet Blending

A concerted effort was made to simulate diets encountered by elk in their respective geographic region and within the seasonal plant community variation of that region. On occasion, diets were blended with high phenol content plants from a season when free-ranging elk would normally avoid consuming them. Pre-formulated diets were hand mixed. The completed pre-mixed diets were stored in burlap bags off the

barn floor to allow air to move freely and to reduce mold contamination. Effort was given to blending diets to a single homogeneous particle length to reduce animal selection or rejection of specific plant species. A wood chipper was used in processing forages to result in plant parts ranging l5 to 50 mm in length. Diets were designed to have 5 combinations of forage components using a gradient from 3 to 27% CP. Within each CP category, e.g. 7%, an array of species composition would be assembled to reflect the different ways a 7% CP diet could be constructed. The associated DOM values of the diet were accepted as derived from this ration construction process. Tables 12, 13, 14, 15, and 16 list the diets by category and illustrate the geographic and seasonal variability of the overall diets. Upper and lower CP values for Oregon and Texas diets appear in Table 17. The Infrasoft International software program (ISI 1992) allows for detailed 3-dimensional search of diet distribution to avoid major gaps in the calibration set (Fig. 1). Each elk was fed an exclusive and specific diet of known content for a period of 8 days.

Study Area and Treatments

This study was conducted at 3 locations. The first was on The Timberland Elk Research Unit in Kamela, Oregon, located in northeast Oregon approximately 40 km northwest of LaGrande. Using 18 head of the USDA Starkey Unit's tame elk herd (Table 18) maintained by the National Council for Air and Stream Improvement (N.C.A.S.I.), feeding trials were undertaken in June, July and August 1999.

Social behavior of the elk was carefully observed and recorded daily throughout the feeding trials on the animal's individual feeding page. Feed offered and the remaining orts were weighed and recorded each day. Feeding was done 2x daily from 5:00 a.m. until 10:00 a.m. and 2:00 p.m. until 7:00 p.m. in individual wooden feeding stalls 4.57 m wide x 7.32 m long with a wooden floor slotted to allow urine to pass through but not fecal material. Animals were separated according to lactation and released into common dry lots of 0.41 or 0.82 ha, accordingly, behind a 7.32 m game-proof fence. Fresh, clean water was provided. Animals had no opportunity to consume

forages outside the feeding trial pens. Low quality diets were fed first with a spacing of approximately 2 weeks with medium quality feeds provided in between to allow time for animal recovery while consuming a high maintenance diet of forages native to the area. This practice was ceased when diet CP values were greater than 7%.

Two commercial elk production facilities in Texas served for the other study sites during the spring and summer of 2000 and the summer of 2001. Feeding trials were conducted in a manner consistent with the Oregon feeding trials except that Texas animals were confined 24 hours and were fed in pens 2.0 m x 3.05 m with solid walls 2.3 m in height. All pens were covered and had a floor of hard surface road base material. Animals had 24-hour access to water. Feed distribution, fecal collection, and diet grab sampling procedures were consistent with the Oregon feeding trials.

Diet and Fecal Sampling Procedures

Fecal NIRS equations depend on a calibration set of known diet chemistry:fecal spectrum pairs. Fecal samples were swept away and discarded from day 1 through day 6. A representative sampling of the feces was collected without contamination from soil or animal hair on day 7 and day 8, labeled in plastic bags with animal, date, and diet number. After storage at –20ºC, fecal samples were sent to the GAN Lab at Texas A&M University for NIRS scanning. A random grab sample of the diet at 5 strategic points in each feed bunk ration was collected on day 7 and day 8, placed in sealed bags, labeled as above and stored until chemical analysis. Since the animals rarely consumed the entire feed offering, the chemical analysis of the feed actually consumed was derived by factoring out the orts in accordance with the following formula:

$$Y = (x_1 - ax_2) / b \quad (1)$$

where x_1 is the nutrient level of the diet, a is that percent of the diet refused, x_2 is the nutrient concentration of those orts, and b is the percent of the diet calculated by subtracting a from 100. In cases where the nutrient level of the diet was higher than the

nutrient level of the orts, the portion consumed was higher than the nutrient level of the diet. Conversely, if the nutrient level for the orts was higher than the portion consumed, the consumed portion had a lower nutrient level than the diet.

Crude Protein (CP)

Diet samples (rations) were prepared for wet chemistry analysis by drying the samples at 60ºC for 48 hours and grinding through a cyclone mill to pass a 1-mm screen. Nitrogen was analyzed by the automated combustion method to determine total nitrogen of the diet material (Sweeney 1989). The method has a detection limit of 0.10% nitrogen (dry sample basis) and is generally reproducible to within ±0.5%.

Digestibile Organic Matter (DOM)

Digestibility of the diet samples (in triplicate) was determined by in sacco Ankom filter bags (45 x 39.5 cm zippered nylon) technique (Komarek et al. 1994), followed by a 1-hour neutral detergent fiber analysis (Van Soest and Wine 1967) using Ankom fiber analyzer. The 48-hour in situ fermentation replaced the in vitro fermentation (Tilly and Terry 1963) and was consistent with the procedures of Awuma (2003). Four standards of known in vivo organic matter digestiblility (IVOMD) were also included in each in vitro treatment in triplicate. Three were bovine in vivo standards from the GAN Lab and 1 was an elk standard supplied by Dr. Dan Baker, Colorado Division of Wildlife (Baker and Hobbs 1987). Bovine in vivo standards were alfalfa (*Medicago sativa* L.) hay, 76.2% IVOMD, kleingrass (*Panicum coloratum* L.) hay, 64.9% IVOMD, wheat (*Triticum aestivum* L.) straw, 54.8% IVOMD, and a low quality grass/shrub forage in vivo elk standard of 50.8% IVOMD.

Forty-eight hour in vitro values were corrected to in vivo values using least squares regression. Known in vivo values were then regressed on the correction factors to develop a regression equation for calculating time-in-bath correction factor (TIBCF). In vitro values were corrected according to TIBCF and those corrected values were then divided into known in vivo values in developing in vivo correction factors (IVCF) for

each standard. The adjusted in vitro values were then regressed on the IVCF. Unknown samples in each in vitro run were corrected using regression equations for TIBCF and IVCF. Corrected IVOMD of each sample was converted to DOM by multiplying IVOMD by percent organic matter of the ration.

Near Infrared Reflectance Spectroscopy (NIRS)

Each ground fecal sample was dried for 12 hours in a forced-air oven at 60ºC prior to analysis by NIRS. Samples were packed tightly into quartz crystal lens cups for scanning with a Foss 6500® scanning monochrometer, with reflectance readings captured in the range of 1,100 to 2,498 nm at 2 nm intervals. The average spectra for the calibration set are displayed in Figure 2. NIRS is concerned with the light scattering (diffuse reflectance) properties of a material and its relationship with absorption (Birth and Hecht 1987). A high log (1/R) value indicates less reflected radiation or more absorbed by the sample at that wavelength (Hruschka 1987). Calibration equations were developed using multiple stepwise regression in WinISI® version 1.5e. The spectra number was used throughout analysis as the key identifying reference number for the diet:fecal pairing.

Results

General Equation Selection Criteria

The goal of the calibration procedure is to find the best fitting equation for the samples in the calibration set (Westerhaus 1989b). Calibration equations were examined using assorted combinations of day-7, day-8, and cross matches of day-7 diet:day-8 fecal pairs and were developed using day-7 fecal samples that represented 117 diets. Abrams (1989) states that the population to be represented by the calibration set may be either finite or infinite. A finite population has defined boundaries which limit the population to a specific number, whereas an infinite population has no such defined boundaries. Infinite populations may not always be represented by the calibration data set. Selected samples from a population may be either structured or random. Structured sampling is

based on some prior knowledge about the population, in this case elk, and our desire to test a pre-determined range of nutrient intake levels for the calibration data set. Random selection in this case would have resulted in bias so that the calibration set would not have represented the nutrient intake level of the elk population. The critical point about calibration sample selection is that the samples chosen represent the range of characteristics (chemical, physical, and botanical) present in the population. It is thus important to the robustness of the equation to not extrapolate beyond the range of available information.

Multi-term linear regression is used in calibration development to isolate effects of a single absorber/reflector and normalize the baseline (Hruschka 1987). The spectral data generated by the fecal scans represent the dependent variables and the laboratory chemistry values represent the independent variables (Williams 1987b). Wavelengths are selected using the modified stepwise approach (Westerhaus 1989b). The first term is simply the best fitting wavelength. The second term is then fixed, and an attempt is made to find a term that fits better than the original term. Then each term is rejected one at a time as an attempt is made to find a better set of terms.

Multiple iterations of NIRS predictive equations were performed and evaluated by considering SEC, R^2, wavelength frequency, F-statistic, and the biological interpretation of its wavelengths. The evaluation of these regression statistics and interpretation of the equation's most important wavelengths all contribute to determining the stability of the equation.

Selection of CP Equation

Using all classes of elk in the 117 individual feeding trials resulted in a CP calibration equation with a SEC 1.13 and R^2 0.95 (Table 19) with a math treatment of 2,4,4,1, with 2 being the derivative function, 4 the gap between points used to calculate the derivative, 4 the segment length over which the above function was smoothed, and 1 the segment length over which the smooth function was subjected to a second smooth. Two iterations were conducted through the data set to eliminate outliers. A parameter of

1.25 was set for the T value to arrive at an optimum predictive equation, which resulted in a final CP equation being built with 74 of the 117 observations. T values reflect the relationship between lab values and the spectra data (Martens and Naes 1987). Given the high individual variation in animal behavior and multiple locations of the studies, a more strict T value was chosen to insure that diet:fecal pairs were matched to the highest degree possible. The SEC was acceptable at approximately 2x the Standard Error of Lab (SEL) range (Hruschka 1987) of 0.4 to 0.6.

While partial least squares (PLS) regression is often used on large and evenly distributed data sets, this study achieved superior performance using the stepwise analysis, given the non-homogenous nature of the mixed rations. Other first-generation fecal NIRS based calibrations equations for wildlife species produced from the GAN Lab have experienced more stable calibration equations using the stepwise analysis method on the smaller data sets lacking more uniform histograms (Stuth 2004). Histograms of laboratory values for CP and DOM of elk diets can be seen in Figure 3. Statistical analysis using PLS regression resulted in the following: R^2 0.89, SEC 1.45, standard error of cross-validation (SECV) 1.49 for CP using the same T and H values and the same math treatment as the stepwise analysis.

Westerhaus (1989b) states that SEC describes how well the calibration samples were fit to the reference values. If the NIRS measurements and calibration process were error free, SEC would equal the laboratory repeatability error of the calibrated variable (Hruschka 1987). In practice, however, NIRS data are measured with error and the calibration process is imperfect. SEC is representative of a progressive accumulation of all sources of error including sampling error, orts, lab error, and processing error.

In order to determine if the calibration equation has a biological basis for predicting a given dietary component from an indirect measure, it is important to examine the most dominant wavelength as indicated by the largest F value. While SEC measures the accuracy of the equation, the value of F is an indicator of strength of accuracy when unknown samples are measured (Mark 1992). Chemical bonds most likely to exhibit absorbencies in the near infrared region are oxygen, carbon, nitrogen,

and hydrogen, with hydrogen being the most important (Murray and Williams 1987). The dominant wavelength for the CP equation (Table 19) is 2,004 nm, F value 285.9. This wavelength is associated with nitrites, carbonyl bonds, –OH phenol bonds, =CO terminal bonds, NH_2 groups, –SH groups, –OH terminal bonds, and =NH amines + imide bonds. Since there is agreement in the literature (Shenk et al. 1992) that protein bonds are represented at wavelengths either slightly higher (2,055 to 2,336 nm) or slightly lower (1,680 to 1,940 nm) than our best CP wavelength, we hypothesize that the slight deviation is accounted for by the high woody plant diets containing phenol compounds which are indicative of high tannin levels. Tannins are a chemically diverse group of water-soluble phenolics which bind proteins to form soluble or insoluble complexes (Bate-Smith and Swain 1962, Hagerman 1989, Driedeger and Hatfield 1972). Tannins are widespread among dicotyledonous forbs, shrubs, and trees (Haslam 1979, Robbins et al. 1991, Robbins et al. 1987a, Robbins 1987b, Mehansho 1987) and are ingested by many herbivorous mammals, including elk.

Selection of DOM Equation

The best predictive equation for DOM using stepwise regression had an SEC 1.73 with R^2 0.80 (Table 19) meeting the equation selection criteria of 1,4,4,1-math treatment. Using a T value of 1.25, 79 diet:fecal pairs were selected. PLS regression analysis for DOM only produced an R^2 of 0.38 with an SEC and SECV of 2.08 and 2.17, respectively. The standard error for laboratory (SEL) for DOM was 1.27 and easily meets the criteria for acceptance of the SEC values of 2x SEL for the chosen calibration equation. The dominant wavelength was 2,332 nm, F value 190.1, corresponding to the combination of bonds in C–H stretching and methylene groups.

As with CP bonds, the DOM bonds listed in Table 19 were compared for their biological agreement before selecting the final calibration equation. The predominant DOM wavelength corresponded to $–CH_3$ groups, –CH aliphatic bonds, –CH vibrations, $=CH_2$ groups, –CH aromatic bonds, and –CH protein bonds, all well within the acceptable fiber absorption wavelengths (Shenk et al. 1992).

Statistical Outliers

Detection of statistical outliers is an important process in equation calibration development. Outliers may be the most informative samples in a data set or they could be just common errors (Martens and Martens 2001). Two general categories of outliers are encountered in the development of NIRS calibration equations: 1) spectral and 2) reference:spectral outliers. For most agricultural products, spectral outliers are considered to be those samples whose spectrum is greater than 3 standard deviations away from the mean spectrum in a calibration set. Work by Walker et al. (2000) indicates that 3 standard deviation units may be too restrictive for fecal NIRS. In our experience with fecal NIRS, we have found that using a criterion of up to 8 standard deviation units results in calibrations which include more samples, thus more spectral diversity, and still yields acceptable predictive equations (Stuth 2004). Reference:spectral outliers are those in which there is a large difference between the reference values of a sample and the reference values of spectrally similar samples (Martens and Naes 1987). Errors in the chemical data can be caused by transcription, lab technique, sampling, or in the case of this experiment, animal behavior. These can occur on either the reference or the spectral side of the process.

We found that 63% of the CP outliers and 56% of the DOM outliers could be accounted for by animals fed diets having either greater than 15% woody species and/or greater than 15% concentrates. Further, we found that while elk in the Oregon trials represented 31% of the diet:fecal pairs, they accounted for 42% of the CP outliers and 54% of the DOM outliers.

We found no clear outlier relationship linked to males, females, or juveniles. There was also no clear outlier relationship between lactating and non-lactating females, or between Texas and Oregon feeding trials. It appears the statistical outliers in this study are best accounted for by animal behavioral issues, reflecting differential adaptability of individuals in these confined feeding trials. Our data examination did not clearly support further conclusions.

Validation

Due to logistics (cost and animal availability) encountered in obtaining an independent validation set, cross-validation (Martens and Martens 2001) was employed in this study. Briefly, cross-validation involves removing a certain portion of samples from the calibration set, and then predicting them with the equation developed using the remaining samples. This process can be repeated up to n-1 times for a particular calibration and is a standard feature of the WinISI® software. The SECV as reported in this study was derived from 4 cross-validation iterations.

SECV for CP was 1.17 (SEC = 1.13) and SECV for DOM was 1.80 (SEC = 1.73), the close range indicating agreement in the precision of predictability. Studies reported by other researchers rarely approach values closer than those observed here (Awuma 2003, Leite and Stuth 1995, Li 2004, Lyons and Stuth 1992, Ossiya 1999, Showers 1997, Whitley 1996).

Discussion and Conclusions

Since there are no appreciable differences in outliers between CP and DOM, and DOM is well within acceptable tolerances, we consider the slightly higher SEC for CP to be an inherent attribute of this study. Given that PLS regression gave poorer statistical performance than stepwise multiple regression, we suspect that the CP equation will require a calibration set with greater diversity of forage types with more continuous gradation of values, e.g. more samples and greater variability of constituents and nutrient composition. Further, behavioral characteristics of wild ungulates in feeding trials appears to have a more profound effect on CP than DOM, requiring greater care to evaluate animal behavior prior to including in confined feeding trials.

Results for the CP and DOM equations are comparable to earlier research on indirect measurement of diet quality with NIRS fecal scans of other ruminant species (Awuma 2003, Coates 1998, Gibbs et al. 2002, Leite and Stuth 1995, Li 2004, Lyons and Stuth 1992). NIRS, as indicated in this study and supported by other studies, is an effective means to monitor the diet quality and nutritional well-being of free-ranging elk.

Although the study utilized 115 species of forages from diverse functional groups and geography consumed by elk in various seasons by diverse age and gender groups of animals over a 3-year period, robustness of the equation would be greatly improved by expanding the number of viable diet:fecal pairs. Those organizations focusing on the nutritional well-being of elk would benefit greatly with an expanded calibration equation.

CHAPTER IV
MANAGEMENT IMPLICATIONS

Introduction

Fecal NIRS is described primarily as a decision support tool through the ability to capture relevant quantitative information on dietary nutritional status and growth performance of grazing ungulates as well as through an improved knowledge and understanding of the nutritional aspects and complexities of rangeland systems. The technology lends itself to commercial application because of the simplicity of sampling and analytical procedures, the rapid turn-around between sampling and availability of results, the range of attributes that can be predicted from a single analysis, and low cost compared with conventional laboratory analysis. The attribute being determined can be estimated from the NIR spectrum of the substance being analyzed. These estimates are based on calibration equations developed by relating attribute value as determined by a primary analytical technique to NIR spectra of a large and diverse set of samples known as a calibration set (Coates 2000). With wildlife or any ungulate with a well-developed flight response, there is the added benefit of remaining non-invasive to the animal and thus further reducing physiological costs to the animal and economic costs to the producer.

Fecal Chemical Indices to Predict Diet Quality

The near infrared spectra depend on the number and type of C–H, N–H, and O–H bonds in the material being analyzed. The spectral features are then combined with reliable compositional analysis of the material in a predictive statistical model (Foley et al. 1998). This multivariate statistical model (referred to as an equation) and having the ability to describe the relationship between the NIR spectral absorbencies of the animal's fecal material and the chemical composition of CP and/or DOM ingested is then used to predict the composition of new or unknown samples that are part of the

same population (Lyons 1990, Lyons and Stuth 1992, Lyons et al. 1995, Shenk and Westerhaus 1993, Leite and Stuth 1995, Ossiya 1999, Awuma 2003).

The GAN Lab and the researchers of Texas A&M University and the co-workers of Dr. Jerry Stuth have pioneered the use of NIRS equations in domestic cattle, sheep and goats (Lyons and Stuth 1992, Leite and Stuth 1995, Whitley 1996, Ossiya 1999, Awuma 2003, Li 2004) and wild ungulates using white-tailed deer and elk (Gallagher 1990, Showers 1997, Keating et al. 2001). In recent years, calibration equations have been developed by Australian scientists also using domestic cattle (Coates 1998, Gibbs et al. 2002) and African scientists using antelope and elephants (Lister et al. 1997, Dorgeloh et al. 1998). Awuma (2003) successfully expanded the present NIRS equation for cattle, sheep, and goats in sub-Saharan Africa and correlated those NIRS equations with geostatistics to add another management tool in predicting diet quality in that African ecosystem. NIRS has also been used as a non-invasive tool in monitoring the nutritional well-being of endangered animals (Woolnough and Foley 2002).

Prediction of diet quality from fecal samples means that the actual diet chosen by the animal is evaluated and not the diet a researcher has formulated. All elk fecal samples received by the GAN Lab from March 1997 through September 2002 were predicted using our new elk equation and appear in Table 20. Spectral stability was assessed by the occurrence of global H statistical outliers (starring), which indicate distance from the mean value of the calibration set for NIRS-predicted values of unknown samples and give indication to the spectral stability of the equation in regard to the samples of interest. This computer-generated algorithm is expressed as the Mahalanobis distance and is defined by a distance measure based on a set of multivariate data used to describe that data and whose Euclidean length varies according to the direction in space in which it is being measured (Mahalanobis 1930). The equivalent Euclidean length is large in dimensional direction where the data are spread out and small in dimensional direction where the data are compact (Mark 2001). One star indicates a spectrum is 3x the average distance in the calibration set from the mean, and 2 stars indicate a spectrum is 4x the average distance from the mean (ISI 1992). Of the

179 elk samples received from 1997 to 2002, there were 52 samples with 1 star and 0 samples with 2 stars. Sorted by region in Table 21, elk samples north of 41° 45' Lat had 14% starring while elk samples south of 41° 45' Lat had 37% starring. These results suggest that predictions with the new elk equation are more reliable in habitats of the most northern latitudes and further suggest expansion of the calibration equation should focus efforts on increasing the dietary spectra of the most southern latitudes.

Supplemental Feeding, Free-Ranging Elk

Supplemental feeding of free-ranging elk has been controversial for the entire century in North America. Elk may be fed supplementally during winter to prevent malnutrition losses, substitute for inadequate habitat, prevent damage to vegetation and crops, or to retain animals in areas where they may be readily observed (Craighead et al. 1973, Peek et al. 2002). Leopold (1933) pointed out that keeping things wild is the business of wildlife management. Dasmann (1964) discussed the predilection of humans to provide food for wildlife throughout history and did not consider supplemental feeding to be a substitute for habitat restoration. However, as habitats continue to fragment and diminish, supplemental feeding may be the only recourse to sustaining elk and other ungulates where demand is high (Ozoga and Verme 1982). Concentrating elk on feeding grounds has long provided social and economic benefits to communities that have capitalized on elk viewing as a recreational opportunity. In 2000, 924,000 people visited the National Elk Refuge in Jackson, Wyoming (Wolfe et al. 2002). Smith and Robbins (1994) found the fidelity of elk to summer ranges in the Yellowstone National Park area of Wyoming to be 98%, and fidelity to winter ranges on the National Elk Refuge to be 97%.

The usefulness of NIRS evaluation of elk fecal material in prediction of diet quality remains prominent on concentrated wintering grounds. The majority of elk populations spend summers on lands managed mostly by the U.S. Forest Service. In winter, when these elk move to lower elevations, a growing number of herds find winter ranges converted to agricultural, residential, and urban land uses. In these locations, the

future existence of elk populations may depend on refuge areas or winter feeding grounds (Wolfe et al. 2002).

Figure 4 is designed to illustrate the CP predictive capability of the new NIRS elk equation over the cattle predictive equation as it was applied to elk. Figure 5 represents the new NIRS elk equation capability for predicting DOM as compared with the cattle equation used for years. These two figures represent 179 elk fecal samples received from 1997 through 2002 at the GAN Lab. The elk equation tends to predict higher values on the upper end and lower values on the lower end of the CP and DOM ranges than did elk predicted with the cattle equation.

Figure 6 and Figure 7 track the fluctuation in CP and DOM dietary parameters of elk, respectively, over an 18-month time frame from the HH ranch at Socorro, New Mexico. Estimated requirements for CP and DOM are adaptations from Leege and Nelson (1982), Haigh and Hudson (1993), Thorliefson et al. (1998), and Cook (2002). Having the nutritionally deficient periods defined in an ecosystem reveals those temporal requirements of supplemental feeding. When compared to estimated nutritional needs, determination can be made to quantify the nutritional deficits and permits the elk herd manager to be proactive in corrective management measures (Keating 1999).

NIRS can also be useful in determining where CP and DOM deficiencies occur in the elk's home range. Having knowledge of the nutritionally deficient areas can aid the landscape manager in selecting areas for improved management, such as prescribed burns (Skovlin et al. 2002).

Supplemental Feeding, Captive Elk

Farming of privately owned elk is well established in Canada and the United States. Canada raises approximately 46,000 elk per year on 1,800 farms, and the United States accounts for approximately 18,753 elk on 555 farms. The elk industry in the Unites States is worth approximately $500 million per year according to the North American Elk Breeders Association. Regulations vary by U.S. state or Canadian province, but typically require that individual elk be identified and tested for disease

whenever change of ownership or location occurs (Peek et al. 2002). Some of the major issues involved with elk farming are disease control, contamination/dilution of the native gene pool via escaped farmed elk, and collection of native wild stock by game ranchers.

The nutritional needs of captive elk are somewhat modified as their range parameters become defined by game-proof fencing. Elk no longer have the option of migrating freely between landscapes in search of food resources to meet the nutritional needs of their various physiological production stages.

CHAPTER V
GENERAL CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A current calibration equation was developed to predict the diet quality of Rocky Mountain elk to better serve the decision making of elk herd and landscape managers throughout the intermountain west and southwestern United States. Forages numbering 115 species indigenous to elk habitat were included in feeding trials spanning 3 years in Oregon and Texas. This is a first-generation NIRS equation with R^2 0.95, SEC 1.13 for CP and R^2 0.80, SEC 1.73 for DOM. We found the degree of spectral agreement and stability here to be encouraging considering the limited number of diets utilized in establishing the calibration set.

When applied to 179 random elk fecal samples collected by the GAN Lab over the period from 1997 to 2002, we found acceptable predictive performance with the new elk calibration equation. Cross validation statistics have also shown the elk equation to have high predictive capability of the diet quality of elk on the western range (SECV 1.17 for CP, SECV 1.80 for DOM). The close range between SEC and SECV validates the precision of predictability.

Optimum statistical analysis was accomplished using stepwise multiple regression rather than partial least squares. Stepwise multiple regression has a record of superior performance on data sets that are non-homogenous in nature, such as those encountered in many studies with wildlife. Since there are no appreciable differences in outliers between CP and DOM, and DOM is well within tolerances, we consider the slightly higher SEC for CP to be an inherent attribute of this study. Further, behavioral characteristics of wild ungulate in feeding trials appear to have a more profound effect on CP than on DOM.

Results for the CP and DOM equations are comparable to earlier research on indirect measurement of diet quality with NIRS fecal scans of other ruminant species (Awuma 2003, Coates 1998, Gibbs et al. 2002, Leite and Stuth 1995, Li 2004, Lyons

and Stuth 1992). NIRS, as indicated in this study and supported by other studies, is an effective means to monitor the diet quality and nutritional well-being of free-ranging elk. Although the study utilized a broad variety of forages from diverse functional groups consumed by elk in various seasons by diverse age and gender groups of animals over a 3-year period, robustness of the equation would be greatly improved by expanding the number of viable diet:fecal pairs. Those organizations focusing on the nutritional well-being of elk would benefit greatly with an expanded calibration equation.

Recommendations

- More feeding trials should be carried out with elk using an even expanded variety of forages which are collected during the seasons in which an elk actually consumes those forages, e.g., Rabbitbrush is high in phenol compounds and should not be collected during the growing season and fed in research feeding trials. Elk are documented to consume this plant, but only during winter when polyphenols have descended from the viable plant tissues.
- All feeding trials using wild ungulates should be conducted with tame individuals of the species in quiet, low-stress environments.
- Feeding trials should be conducted with physiologically mature animals, either females or altered males. Male specimens should be avoided whenever possible.
- Non-lactating female specimens are much easier to handle than lactating specimens and should be favored unless specific lactation data is needed.
- Further investigate the future possibilities of using NIRS as another management tool used in solution of the ongoing ecological puzzle and improving our stewardship of our natural resources.

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APPENDIX A

TABLES

Table 1. Representative summary of forage choices made by elk.

Researchers	Region	Habit	Fall	Winter	Spring	Summer
Leslie et al. 1984	Western Washington	Grass	15%	10%	13%	16%
		Forbs	22%	31%	57%	60%
		Browse	64%	55%	24%	16%
Leslie et al. 1984	Western Washington	Grass	26%	7%	13%	-
		Forbs	26%	32%	68%	-
		Browse	44%	56%	13%	-
Hobbs et al. 1981	North central Colorado	Grass	-	61%	-	-
		Forbs	-	6%	-	-
		Browse	-	32%	-	-
Hobbs et al. 1981	North central Colorado	Grass	-	50%	-	-
		Forbs	-	6%	-	-
		Browse	-	44%	-	-
Wydeven and Dahlgren 1983	Central Montana	Grass	34%	42%	73%	78%
		Forbs	61%	56%	25%	12%
		Browse	5%	2%	2%	11%
Miller et al. 1981	Northeastern Oregon	Grass	-	-	52%	-
		Forbs	-	-	38%	-
		Browse	-	-	10%	-
Kufeld 1973	Montana	Grass	-	84%	-	-
		Forbs	-	8%	-	-
		Browse	-	9%	-	-
Rowland 1983	New Mexico	Grass	-	52%	-	-
		Forbs	-	5%	-	-
		Browse	-	41%	-	-

Table 2. Six subspecies of elk that inhabitated North America in the 1500's.

Scientific Name	Common Name
Cervus elaphus nelsoni	Rocky Mountain elk
Cervus elaphus roosevelti	Roosevelt elk
Cervus elaphus manitobensis	Manitoban elk
Cervus elaphus nannodes	Tule elk
Cervus elaphus canadensis (extinct)	Eastern elk
Cervus elaphus merriami (extinct)	Merriam elk

Table 3. Estimates of daily food intake rates of cow elk[1].

Month of Year	Intake (g kg $BW^{-0.75}$)	Status of Cows
November-March	60	Adult pregnant cows
	62-85	2- and 3-year-old cows[2]
April	68	Adult pregnant cows
	64-72	2- and 3-year-old cows[2]
	93	2-year-old compensating cows[2]
May	68	Adult pregnant cows
	72-77	2- and 3-year old cows[2]
	101	2-year-old compensating cows[2]
June	88	Adult lactating cows
	78-80	3- and 4-year-old cows[2]
	104-106	3- and 4-year-old compensating cows[2]
July-August	125	Adult lactating cows
	75-82	3- and 4-year-old cows[2]
	99-104	3- and 4-year-old compensating cows[2]
September	120	Adult lactating cows
	79	3-year-old cows[2]
	96-111	2- and 3-year-old compensating cows[2]
October	100	Adult lactating cows
	70	3-year-old cows[2]
	82-87	2- and 3-year-old compensating cows[2]

[1]Adapted from Robbins et al. 1981 and Cook 2002.
[2]Cows fed a high quality *ad libitum* diet.

Table 4. Summary of snow depth conditions causing elk migrations.

Region	Snow Depth (cm)	Researcher
Montana	102 (adults)	Gaffney 1941
Montana	76 (calves)	Gaffney 1941
Washington	157	Schwartz and Mitchell 1945
Michigan	46	Moran 1973
Montana	61	Martinka 1976
Idaho	53	Leege and Hickey 1977

Table 5. Estimated daily protein requirements (dry matter basis) for maintenance of a 236 kg adult cow elk[1].

Period	Food Intake (g kg $BW^{-0.75}$)	Total Food Intake (kg day^{-1})	Protein Lost (g day^{-1})	Total (g day^{-1})	$BW^{-0.75}$ (g day^{-1})
December-March	60	3.61	166.6	284.8	4.73
April-May	68	4.09	182.5	312.0	5.18
June	88	5.30	222.4	380.2	6.31
July-August	131	7.89	307.9	526.3	8.74
September	110	6.62	266.0	454.8	7.55
October-November	80	4.82	206.6	353.2	5.87

[1]Cook 2002

Table 6. Estimated daily activity pattern[1] and energy expenditure rates[2] by seasons for a 236-kilogram cow elk.

	Daily Activity										
	Foraging		Bedding		Traveling		Standing		Ruminating		
Season	Hours	Kilo-calories	Hours	Kilo-calories	Hours	Kilo-calories	Hours	Kilo-calories	Hours	Kilo-calories	SMR plus activity
Winter	9.2	1,172	13.5	0	0.9	301	0.4	7	6	340	6,035
Spring	13.0	1,657	9.6	0	1.1	368	0.3	5	6	340	6,585
Summer	9.7	1,236	9.8	0	3.1	1,036	1.3	23	6	340	6,850
Fall	12.7	1,618	9.8	0	0.8	267	0.7	12	6	340	6,452

[1]Craighead et al. 1972.
[2]Moen 1973.

Table 7. Daily crude protein and energy requirements for maintenance and production[1].

	Crude Protein	Energy DE (Mcal kg^{-1})
Maintenance	7-10%	2.3
Production:		
Antler Growth	16%	2.4
Growth, 3-6 months	18-20%	3.0
Growth, 6-9 months	16-18%	2.8
Growth, 9-18 months	12-14%	2.6
Gestation, 12-24 weeks	14-16%	2.5
Gestation, 24-36 weeks	12-14%	2.6
Lactation, 0-6 weeks	14-16%	2.8
Lactation, 6-12 weeks	12-14%	2.7

[1]Thorleifson et al. 1998

Table 8. Estimates of daily metabolizable energy requirements of mature pregnant or lactating female elk/red deer.

Species	Maintenance[1]	Mid-Gestation[2]	Late Gestation[3]	Early-Mid Lactation[4]	Mid-late Lactation[5]	Source
Elk	165	165	170	300	265	Cook 2002
Elk	145	150	195	285	285	Haigh and Hudson 1993
Elk		132	149	250	250	Robbins et al. 1981[6]
Elk	132					Jiang and Hudson 1992[7]
Elk	168					Cook 2002[8]
Elk	173					Hobbs et al. 1982
Red deer	136					Kay and Staines 1981

[1] Early winter before gestation energy demands begin
[2] February and March (calving June 1 assumed)
[3] April and May (calving June 1 assumed)
[4] June and July (calving June 1 assumed)
[5] August and September (calving June 1 assumed)
[6] Adapted by Cook 2002
[7] Study used penned subadult non-gravid cows averaging 234 kg
[8] Study used penned 3-year-old non-gravid cows averaging 200 kg

Table 9. List of GAN Lab studies reporting prediction of diet quality in livestock and wildlife via near infrared reflectance spectroscopy of feces.

Species	Reference	Publication
Cattle	Lyons and Stuth 1992	J. Range Manage.
	Awuma 2003	Ph.D. Diss., Texas A&M Univ.
Sheep	Awuma 2003	Ph.D. Diss., Texas A&M Univ.
	Li 2004	M.S. Thesis, Texas A&M Univ.
Goats	Leite and Stuth 1995	Sm. Rumn. Res.
	Awuma 2003	Ph.D. Diss., Texas A&M Univ.
Deer	Gallagher 1990	M.S. Thesis, Texas A&M Univ.
	Showers 1997	M.S. Thesis, Texas A&M Univ.
Elk	Keating et al. 2001	Proc., Tex. Chapt., Wildl. Soc.

Table 10. List of studies reporting prediction of diet quality in livestock and wildlife via near infrared reflectance spectroscopy of feces.

Species	Reference	Publication
Cattle	Lyons and Stuth 1992	J. Range Manage.
	Purnomoadi et al. 1998	Anim. Sci. Tech.
	Coates 1998	CSIRO Rpt.
	Gibbs et al. 2002	Proc., Australian NIRS Natl. Conf.
	Awuma 2003	Ph.D. Diss., Texas A&M Univ.
Sheep	Krachounov et al. 2000	Zhivotnov'Dni Nauki
	Awuma 2003	Ph.D. Diss., Texas A&M Univ.
	Li 2004	M.S. Thesis, Texas A&M Univ.
Goats	Leite and Stuth 1995	Sm. Rumn. Res.
	Awuma 2003	Ph.D. Diss., Texas A&M Univ.
Deer	Gallagher 1990	Ph.D. Diss., Texas A&M Univ.
	Showers 1997	M.S. Thesis, Texas A&M Univ.
Elk	Brooks et al. 1984	J. Wildl. Manage.
	Keating et al. 2001	Proc., Tex. Chapt., Wildl. Soc.
Roan Antelope	Dorgeloh et al. 1998	S. Afr. J. Wildl. Res.
Elephant	Lister et al. 1997	J. Near Infrared Spectrosc.
	Greyling 2002	Ph.D. Diss., Univ. Witwatersrand

Table 11. Forages used by functional group.

Grasses/grass-likes

Idaho Fescue straw (*Festuca idahoensis* Elmer)
Western fescue (*Festuca occidentalis* Hook.)
Green Fescue (*Fesctuca viridula* Vasey)
Sheep Fescue (*Festuca thurberi* Vasey)
Kentucky Bluegrass (*Poa pratensis* L.)
Wheeler's Bluegrass (*Poa nervosa* (Hook.) Vasey)
Sandberg's Bluegrass (*Poa sandbergii* Vasey)
Canada Bluegrass (*Poa compressa* L.)
Orchardgrass (*Dactylis glomerata* L.)
Timothy (*Phleum pretense* L.)
Cheatgrass (*Bromus tectorum* Spenner)
Mountain Brome (*Bromus carinatus* Hook and Arn.)
Japanese Brome (*Bromus japonicus* Thunb.)
Columbia Brome (*Bromus vulgaris* (Hook.) Shear)
Prairie Junegrass (*Koeleria cristata* (L.) Pers.)
Barley (*Hordeum vulgare* L.)
Oats (*Avena sativa* L.)
Wheat (*Triticum aestivum* L.)
Tufted Hairgrass (*Deschampsia caespitosa* (L.) Beauv.)
Bearded Wheatgrass (*Agropyron caninum* (L.) Beauv.)
Western Wheatgrass (*Agropyron smithii* Rydb.)
Slender Wheatgrass (*Agropyron trachycaulum* (Link) Malte)
Purple Reedgrass (*Calamagrostis purpurascens* R. Br.)
Pinegrass (*Calamagrostis rubescens* Buckl.)
Northern Reedgrass (*Calamagrostis inexpansa* A. Gray)
Mat Muhly (*Muhlenbergia richardsonis* (Trin.) Rydb.)
Nebraska Sedge (*Carex nebraskensis* Dewey)
Bluebunch Wheatgrass (*Agropyron spicatum* (Pursh) Scribn. and Smith)
Sedge (*Carex spp.* L.)
Baltic Rush (*Juncus balticus* Willd.)
Ryegrass (*Lolium perenne* L.)
Rescue Grass (*Bromus unioloides* Kunth in H.B.K.)
Little Barley (*Hordeum pusillum* Nutt.)
Bahiagrass (*Paspalum notatum* Flugge)
Common Bermudagrass (*Cynodon dactylon* (L.) Pers.)
Switchgrass (*Panicum virgatum* L.)
Bushy Beardgrass (*Andropogon glomeratus* (Walt.) B.S.P.)
Elk Sedge (*Carex geyeri* Boott)
Arundo (*Arundo donax* L.)
Common Rush (*Juncus effusus* L.)
Ryegrass/Wheat Green Chop (*Lolium perenne* L./*Triticum aestivum* L.)

Table 11 (Continued).

Forbs

Alfalfa (*Medicago sativa* L.)
Cow Peas (*Vigna unguiculata* L.)
Big Head Clover (*Trifolium macrocephalum* Pursh)
Falseflax (*Camelina sativa* (L.) Crantz)
Fanweed (*Thlaspi arvense* L.)
Checker-mallow (*Sidalcea spp.* Gray)
Prairie Sage (*Artemisia ludoviciana* Nutt.)
Blue Flag (*Iris missouriensis* Nutt.)
Shrubby Cinquefoil (*Potentilla fruticosa* L.)
False Hellebore (*Veratrum spp.* L.)
Yarrow (*Achillea lanulosa* (Nutt.) Piper)
Monkshood (*Aconitum columbianum* Nutt.)
Marshmarigold (*Caltha leptosepala* DC.)
Starflower *(Lithofragma parviflora* (Hook.) Nutt.)
Grass-of-parnassus (*Parnassia fimbriata* Konig.)
Rosecrown (*Sedum rhodanthum* Gray)
Shootingstar (*Dodecantheon pauciflorum* (Durand) Green)
Green Gentian (*Frasera speciosa* Dougl.)
Heartleaf Arnica (*Arnica cordifolia* Hook.)
Elephanthead (*Pedicularis groenlandica* Retz.)
Horse Hair Lichens (*Bryoria glabra* (Mot.) Brodo & D. Hawksw.)
Wolf Lichens (*Letharia vulpina* (L.) Hue)
Forked Tube Lichens (*Hypogymnia inshaugii* Krog)
Cattails (*Typha latifolia* L.)

Browse

Grand Fir (*Abies grandis* (Dougl.) Forbes)
Western Juniper *(Juniperus occidentalis* Hook.)
Rocky Mountain Juniper (*Juniperus scopulorum* Sarg.)
Lodgepole Pine (*Pinus contorta var. latifolia* Engelm.)
Ponderosa Pine Duff (*Pinus ponderosa var. ponderosa* Dougl.)
Curl-Leaf Mountain Mahogany (*Cercocarpus ledifolius* Nutt.)
True Mountain Mahogany (*Cercocarpus montanus* Raf.)
Rocky Mountain maple (*Acer glabrum* Torr.)
Big Mountain Sagebrush (*Artemisia tridentata var vaseyana* Nutt.)
Big Sagebrush (*Artemisia tridentata* Nutt.)
Stiff Sagebrush (*Artemisia rigida* (Nutt.) Gray)
Antelope Bitterbrush (*Pursia tridentata* (Pursh) DC)
Gray Rabbitbrush (*Chrysothamnus nauseosus* (Pall.) Britt.)
Scoular's Willow (*Salix scouleriana* Barratt)
Black Willow (*Salix nigra* Marsh.)
Winterfat (*Ceratoides lanata* (Pursh) Howell)
Mountain Snowberry (*Symphoricarpos oreophilus* Gray)

Table 11 (Continued).

Browse (Continued)

Common Snowberry (*Symphoricarpos albus* (L.) Blake)
Big Huckleberry (*Vaccinium membranaceum* Dougl.)
Bearberry (*Arctostaphylos uva-ursi* (L.) Spreng.)
Redosier Dogwood (*Cornus stolonifera* Michx.)
Douglass Fir (*Pseudotsuga menziesii* var. *glauca* (Mirbel) Franco)
Tamarack (*Larix occidentalis* Nutt.)
Oceanspray (*Holodiscus discolor* (Pursh) Maxim)
Ceanothus Snowbrush (*Ceanothus velutinus* Dougl.)
Greasewood (*Sarcobatus vermiculatus* (Hook.) Torr.)
Four Winged Saltbush (*Atriplex canescens* (Pursh) Nutt.)
Quaking Aspen (*Populus tremuloides* Michx.)
Pinon Pine (*Pinus edulis* Engelm.)
Sassafras (*Sassafras albidum* (Nutt.) Nees)
Liveoak (*Quercus virginiana* Mill.)

Mast, Whole Grains, and By-products

Acorns, Liveoak (*Quercus virginiana* Mill.)
Corn Silage (*Zea mays* L.)
Beet Pulp Shredds (*Beta vulgaris* L.)
Beet Pulp Pellets (*Beta vulgaris* L.)
Corn Distillers' Grains (*Zea mays* L.)
Brewers' Grains (*Hordeum spp.* L.)
Whole Cottonseed (*Gossypium hirsutum* L.)
Cottonseed Meal (*Gossypium hirsutum* L.)
Wet Potato Waste (*Solanum spp.* L.)
Dried Potato Flakes (*Solanum spp.* L.)
Whole Barley (*Hordeum vulgare* L.)
Whole Corn (*Zea mays* L.)
Whole Oats (*Avena sativa* L.)
Whole Wheat (*Triticum aestivum* L.)
Grass Screening Pellets *(Poa spp.* L./*Festuca spp.* L./*Bromus spp.* L./*Agropyron spp.* Gaertn.)

Table 12. Example of 4 very low CP Diets, 4-7%.

Plant Species	Diet			
	#2	#3	#19	#35
Alfalfa Hay	-	-	-	50.0%
Oregon Wheat Hay	-	-	-	50.0%
Oregon Prairie Meadow Hay	-	-	25.0%	-
Mountain Brome Hay	-	-	25.0%	-
Barley Hay	-	-	-	-
Western Juniper	20.0%	-	10.0%	-
Whole Oats	-	-	40.0%	-
Rocky Mountain Juniper	-	10.0%	-	-
Big Mountain Sagebrush	-	4.0%	-	-
Antelope Bitterbrush	-	10.0%	-	-
Ponderosa Pine Duff	5.0%	-	-	-
Pinon Pine	-	-	-	-
Green Rabbitbrush	15.0%	15.0%	-	-
Serviceberry	-	11.0%	-	-
Chokecherry	10.0%	-	-	-
Western Wheatgrass/Bluegrass Hay	50.0%	-	-	-
Bluegrass Straw	-	50.0%	-	-
Oregon Wheat Hay #14	-	-	-	-
	100.0%	100.0%	100.0%	100.0%

Table 13. Example of 4 low CP Diets, 7-10%.

Plant Species	Diet			
	#7	#14	#46	#124
Alfalfa Hay	80.0%	-	-	33.7%
Orchardgrass Hay	-	25.0%	-	9.3%
Quaking Aspen	-	-	10.0%	2.5%
Ryegrass Hay	-	-	25.0%	5.3%
Barley Hay	-	-	-	3.3%
Colorado Mountain Meadow Hay #16	-	-	45.0%	10.7%
Western Juniper	15.0%	-	-	-
Pinon Pine	-	-	10.0%	2.5%
Green Rabbitbrush	5.0%	-	-	-
Oregon Prairie Meadow Hay #7	-	25.0%	-	-
Rolled Barley	-	50.0%	-	-
Liveoak Acorns	-	-	10.0%	2.5%
Willow Baccharis	-	-	-	9.2%
Oregon Wheat Hay #14	-	-	-	21.0%
	100.0%	100.0%	100.0%	100.0%

Table 14. Example of 4 Medium CP Diets, 10-14%.

Plant Species	Diet			
	#8	#79	#34	#123
Alfalfa Hay	80.0%	11.7%	50.0%	37.5%
Orchardgrass Hay	-	11.7%	-	-
Curl Leaf Mountain Mahogany	16.0%	-	-	-
True Mountain Mahogany	-	-	-	5.0%
Quaking Aspen	-	-	-	5.0%
Beet Pulp	-	11.7%	-	-
Bearberry	2.0%	-	-	-
Redosier Dogwood	2.0%	-	-	-
Whole Cottonseed	-	11.7%	-	-
Ryegrass Hay	-	-	-	-
Dried Corn Silage	-	53.2%	-	-
Barley Hay	-	-	50.0%	25.0%
Johnsongrass	-	-	-	12.5%
Oregon Mountain Meadow Hay	-	-	-	12.5%
41% Cottonseed Meal	-	-	-	2.5%
	100.0%	100.0%	100.0%	100.0%

Table 15. Example of 4 High CP Diets, 14-18%.

Plant Species	Diet			
	#135	#67	#80	#104
Alfalfa Hay	50.3%	26.0%	-	100%
Ryegrass Hay	6.6%	35.5%	35.7%	-
Ryegrass/Wheat Green Chop	2.4%	12.5%	-	-
Dried Brewers' Grain	4.6%	-	17.4%	-
Whole Cottonseed	4.7%	26.0%	17.4%	-
Fescue Hay	-	-	29.5%	-
18% Dairy Pellet	31.4%	-	-	-
	100.0%	100.0%	100.0%	100.0%

Table 16. Example of 4 Very High CP Diets, >18%.

Plant Species	Diet			
	#131	#93	#90	#43
Alfalfa Hay	31.3%	24.2%	42.2%	15.0%
English Pea Leafs	-	36.1%	57.8%	-
Mountain Meadow Hay	-	-	-	75.0%
Cottonseed Meal	-	-	-	10.0%
Pea Hay	-	19.9%	-	-
Dried Brewers' Grain	4.6%	9.9%	-	-
Whole Cottonseed	29.7%	9.9%	-	-
20% Protein Deer Pellet	25.0%	-	-	-
Ryegrass Hay	9.4%	-	-	-
	100.0%	100.0%	100.0%	100.0%

Table 17. Range of crude protein (CP) and digestible organic matter (DOM) values fed to elk in diet chemistry:fecal spectra calibration trials.

	CP (%)			DOM (%)		
Trial	Min	Max	Mean	Min	Max	Mean
Total	3.90	27.00	12.35	37.42	74.03	62.19
Oregon	3.90	18.96	10.42	37.42	74.03	60.03
Texas	6.39	27.00	13.21	45.02	71.99	63.15

Table 18. Age, sex, and physiology classes of elk used, by location, in diet chemistry:fecal spectra calibration trials.

Class		Location			Feeding Trials
Sex	Age/Physiology	Kamela, Ore.	Center, Tex.	College Station, Tex.	N
F	Mature, lactating	7	-	-	14
	Mature, non-lactating	11	3	1	35
	Juvenile, < 2 yrs	2	5	5	33
M	Mature, >7 yrs	-	-	1	4
	Mature, 2-7 yrs	-	-	1	4
	Juvenile, < 2 yrs	-	-	5	27
Totals		20	8	13	117

Table 19. Prediction equation selected to predict dietary CP and DOM of elk.

	Math Treatment	SEC	R^2	Associated Chemical Bonds in Dominant Wavelength	F Value
CP	2,4,4,1	1.13	0.95	Nitrites, carbonyl bond, –OH phenol, =CO terminal, $–NH_2$ groups, –SH groups, –OH alcohols, =NH amines + imide	285.9
DOM	1,4,4,1	1.73	0.80	–CH aliphatic, $–CH_3$ groups, –CH vibrations, $=CH_2$ groups, –CH aromatic, –CH protein bonds, $=CH_2$ groups	190.1

Table 20. Prediction of elk fecal samples received 1997-2002.

Sample	CP	DOM	GH
75846	7.7	64.4	4.889*
75847	8.5	63.6	3.439*
75848	10.8	61.5	1.044
75849	6.8	62.0	3.438*
75850	6.8	61.3	2.320
75851	16.4	68.5	1.436
75852	10.1	62.2	1.603
75853	9.5	67.4	1.934
75854	10.5	62.0	3.086*
75855	11.0	60.1	3.523*
75856	7.1	62.6	5.099*
5153	7.6	60.1	3.623*
5154	7.8	60.1	1.037
5155	10.4	60.3	1.035
5156	7.5	57.9	0.883
5157	11.9	66.1	1.239
5158	7.7	60.2	1.155
5159	8.5	59.2	0.670
5160	9.9	60.7	1.592
5161	9.8	59.7	1.080
5162	10.0	61.1	1.007
5163	8.3	58.8	1.504
5164	11.1	54.1	4.084*
5165	9.9	60.9	0.973
5166	11.7	64.5	0.532
5167	6.8	60.8	1.581
5168	8.6	58.8	1.750
5169	12.2	66.1	1.101
5170	4.6	59.3	0.836
5171	7.0	58.5	0.848
5172	5.3	60.4	0.894
5173	11.3	64.7	0.719
5174	10.3	66.3	0.906
5175	7.3	61.7	0.824
5176	10.0	63.4	0.659
5177	11.4	67.3	0.632
5178	5.9	60.2	0.833
5179	6.5	60.5	0.658
5180	8.1	60.1	0.751
5181	12.5	65.9	0.924
5182	12.6	69.4	0.477
5183	7.8	62.9	0.644

Table 20. (Continued).

Sample	CP	DOM	GH
5184	11.2	66.0	0.357
5185	9.2	65.4	0.403
5186	4.9	59.2	0.888
5187	5.4	59.8	0.989
5188	5.2	60.3	0.730
5189	9.5	62.4	0.871
5190	7.5	64.0	0.459
5191	9.9	62.8	0.608
5192	7.1	59.7	1.473
5193	9.3	63.6	0.341
5194	9.1	64.8	1.123
5195	4.5	58.0	0.866
5196	5.8	59.8	0.633
5197	6.3	58.7	0.624
5198	11.5	62.9	0.481
5199	4.5	59.9	0.834
5200	8.9	64.7	0.731
5201	5.1	61.3	0.757
5202	10.4	66.6	0.391
5203	11.3	68.2	0.673
5204	9.4	67.3	0.489
5205	5.5	59.7	0.762
5206	6.3	60.1	0.939
5207	10.6	65.0	0.608
5208	6.1	59.0	1.114
5209	5.2	59.3	0.830
5210	11.0	66.2	0.592
5211	8.1	65.0	0.609
5212	10.6	66.8	0.582
5213	5.8	59.3	0.719
5214	5.7	60.0	0.572
5215	12.8	66.4	1.127
5216	6.9	60.4	0.728
71122	3.7	65.2	1.391
71123	4.4	64.8	1.459
71124	9.3	59.9	2.120
71125	7.3	63.6	1.098
71126	0.1	62.0	1.987
71127	10.1	62.8	0.396
71259	0.1	58.0	2.043
71265	10.4	63.4	0.686
71266	0.3	59.6	2.048

Table 20. (Continued).

Sample	CP	DOM	GH
80104	20.5	71.4	3.940*
80105	1.2	62.4	6.245*
80106	0.1	62.7	4.537*
80107	10.8	67.4	7.760*
80108	9.4	66.1	7.303*
80109	8.3	68.9	1.966
80110	5.4	63.3	2.620
80111	4.6	62.6	3.293*
80112	11.1	68.5	0.686
80113	14.7	76.6	0.648
80114	14.5	73.3	0.597
80115	14.8	73.6	3.599*
80116	3.3	60.1	2.638
80117	0.1	56.4	4.561*
80118	14.5	75.2	1.477
80119	16.7	79.6	0.770
80120	18.4	77.6	0.890
80121	15.3	79.8	1.903
80122	9.0	70.4	1.691
80123	8.2	74.9	1.579
80124	11.4	75.1	2.140
80125	5.4	69.3	2.057
80126	4.6	61.5	2.178
80127	4.2	62.1	3.234*
80128	6.7	66.6	3.101*
80129	5.1	59.0	7.460*
80130	3.1	54.5	3.379*
80131	8.6	51.8	8.642*
80132	9.3	69.6	1.857
80133	8.6	69.7	1.994
80134	16.5	71.2	1.508
80135	9.7	69.1	0.585
80136	20.5	82.2	9.964*
71093	23.5	74.6	6.360*
71094	20.9	75.8	2.863
71095	22.6	73.9	2.948
71096	24.6	76.3	5.167*
71097	19.8	75.0	4.525*
71099	14.2	53.5	3.337*
71100	13.7	67.5	13.199*
71101	5.8	68.1	1.637
71102	15.9	82.2	8.408*

Table 20. (Continued).

Sample	CP	DOM	GH
71103	7.5	67.0	3.204*
71104	4.8	58.0	4.155*
71105	14.6	64.0	0.686
71106	0.6	59.1	3.119*
71107	1.1	61.0	4.512*
71109	0.3	59.1	4.503*
71111	14.1	82.0	5.380*
71112	2.0	66.7	4.403*
71113	6.5	62.5	4.841*
71114	7.1	52.4	6.769*
71115	19.6	70.0	1.154
71116	1.8	61.8	2.640
71117	11.9	73.5	0.252
71118	9.9	63.1	8.940*
71119	2.9	57.5	3.340*
71120	1.3	65.5	2.864
71121	1.9	60.1	7.123*
71122	3.7	65.2	1.391
71123	4.4	64.8	1.459
71124	9.3	59.9	2.120
71125	7.3	63.6	1.098
71126	0.1	62.0	1.987
71127	10.1	62.8	0.396
71259	0.1	58.0	2.043
71265	10.4	63.4	0.686
71266	0.3	59.6	2.048
80104	20.5	71.4	3.940*
80105	1.2	62.4	6.245*
80106	0.1	62.7	4.537*
80107	10.8	67.4	7.760*
80108	9.4	66.1	7.303*
80109	8.3	68.9	1.966
80110	5.4	63.3	2.620
80111	4.6	62.6	3.293*
80112	11.1	68.5	0.686
80113	14.7	76.6	0.648
80114	14.5	73.3	0.597
80115	14.8	73.6	3.599*
80116	3.3	60.1	2.638
80117	0.1	56.4	4.561*
80118	14.5	75.2	1.477
80119	16.7	79.6	0.770

Table 20. (Continued).

Sample	CP	DOM	GH
80120	18.4	77.6	0.890
80121	15.3	79.8	1.903
80122	9.0	70.4	1.691
80123	8.2	74.9	1.579
80124	11.4	75.1	2.140
80125	5.4	69.3	2.057
80126	4.6	61.5	2.178
80127	4.2	62.1	3.234*
80128	6.7	66.6	3.101*
80129	5.1	59.0	7.460*
80130	3.1	54.5	3.379*
80131	8.6	51.8	8.642*
80132	9.3	69.6	1.857
80133	8.6	69.7	1.994
80134	16.5	71.2	1.508
80135	9.7	69.1	0.585
80136	20.5	82.2	9.964*
109	8.8	60.8	0.879
110	12.3	61.7	1.646
361	9.2	65.1	0.858
362	9.5	64.4	1.243
363	12.2	67.1	0.525
636	1.6	63.9	1.789
637	11.3	75.5	1.995
638	6.4	66.2	1.274
639	9.5	65.0	0.339
622	12.1	62.2	0.960
623	7.6	60.7	2.383
624	9.9	61.4	0.846
625	9.9	72.4	0.506
1197	1.2	62.2	2.294
1198	9.7	60.5	7.908*
1271	9.3	55.5	2.490
1893	1.1	59.0	2.695
1517	13.0	69.3	0.815
1518	9.7	65.7	0.610
1519	10.1	65.8	0.792
2654	15.5	71.2	2.877
2655	9.3	62.2	4.455*
2656	6.0	61.0	1.326
2657	19.6	73.2	2.087
2658	13.5	70.7	0.973

Table 20. (Continued).

Sample	CP	DOM	GH
2654	15.5	71.2	2.877
2655	9.3	62.2	4.455*
2656	6.0	61.0	1.326
2657	19.6	73.2	2.087
2658	13.5	70.7	0.973
1682	6.8	55.3	2.419
2073	10.1	58.4	5.417*
82012	19.5	88.3	1.272
82013	16.9	73.8	2.722
3597	18.6	84.5	1.152
3598	16.0	76.8	0.679
3599	18.9	79.3	1.812
3600	19.2	81.0	2.366
3601	12.9	79.9	1.494
3602	16.3	74.2	0.364
3013	15.2	70.8	0.666
3014	11.4	67.1	1.879
3015	13.2	66.0	0.971
3016	12.1	68.6	0.437
72873	15.9	74.5	0.640
3083	20.5	71.0	2.113
82983	9.8	69.8	0.838
82984	14.4	67.5	2.871
3509	17.9	71.9	1.406
3510	21.4	72.6	4.024*
4234	19.4	58.0	3.500*
4451	4.6	64.7	2.507
4452	8.0	63.4	2.544
4453	8.7	68.4	0.875
4454	6.4	64.5	1.225
4455	23.6	71.7	2.405
4456	26.0	69.4	3.550*
4457	26.3	70.8	5.580*
4458	4.1	64.0	4.847*
4459	6.0	65.7	6.635*
4860	17.1	63.7	1.425
6853	4.5	65.5	2.219
6854	4.7	64.5	3.180*
5187	27.2	70.0	3.957*
5188	2.0	62.1	8.230*
5189	6.3	64.2	4.094*
5190	0.6	60.1	4.021*

Table 20. (Continued).

Sample	CP	DOM	GH
5191	0.6	60.3	2.142
5192	3.4	60.8	2.380
5193	4.6	63.1	3.251*
5488	4.0	63.8	9.323*
5489	25.0	71.1	3.326*
5490	2.4	62.7	4.989*
5491	4.4	64.6	8.383*
5833	9.9	69.3	1.631
6686	13.0	69.1	0.252
7130	10.2	60.4	2.162
7131	11.9	61.8	1.762
8011	3.4	54.8	1.467
8012	10.9	66.9	8.682*

Table 21. Comparison of regional effectiveness of elk predictive equation.

Region	State	Habitat	Ratio and Percent of Sample Starring	
			By State	By Region
north of 41° 45' Lat	Alaska	native range / oat hay	0/6 -	9/64 14%
	Michigan	cool season grasses / legumes	0/3 -	
	Montana	native range / cool season grasses	2/4 50%	
	Oregon	native range	7/46 15%	
	South Dakota	native range	0/5 -	
south of 41° 45' Lat	Utah	man-derived rations	20/49 41%	43/115 37%
	Colorado	native range	0/3 -	
	Arizona	native range	13/28 46%	
	Missouri	clover / fescue / alfalfa / orchardgrass	4/7 57%	
	New Mexico	native range / alfalfa	6/28 21%	

Table 22. Calibration statistics for fecal profiling equations developed for livestock and wildlife[1].

		Crude Protein			Digestibility	
Reference	Species	R^2	SEC	Units	R^2	SEC
Brooks et al. 1984	Elk	0.99	0.88	In vivo DMD	0.80	0.68
Lyons and Stuth 1992	Cattle	0.64	0.88	In vitro DOM	0.69	1.66
Lyons and Stuth 1992	Cattle	0.92	0.89	In vitro DOM	0.80	1.75
Leite and Stuth 1995	Goats	0.94	1.12	In vitro DOM	0.93	2.02
Purnomoadi et al. 1998	Cattle	0.98	0.70	-	-	-
Showers 1997	Deer	0.94	0.70	In vitro DOM	0.89	2.64
Coates 1998	Cattle	0.99	0.54	In vitro DMD	0.89	2.50
Coates 1998	Cattle	-	-	In vitro DMD	0.97	2.20
Ossiya 1999	Cattle	0.88	0.85	In vitro DOM	0.83	3.39
Ossiya 1999	Cattle	-	-	In vitro DOM	0.89	1.82
Krachounov et al. 2000	Sheep	-	-	In vitro DMD	0.94	2.26
Gibbs et al. 2002	Cattle	0.99	1.28	In vitro DMD	0.87	2.63
Awuma 2003	Cattle	0.95	0.87	In vitro DOM	0.90	3.02
Awuma 2003	Sheep	0.97	0.78	In vitro DOM	0.94	2.26
Awuma 2003	Goats	0.97	0.79	In vitro DOM	0.95	2.86
Awuma 2003	Cattle	0.93	0.77	In vitro DOM	0.90	1.90
Awuma 2003	Goats	0.97	0.72	In vitro DOM	0.95	2.44
Keating et al. 2001	Elk	0.95	1.13	In vitro DOM	0.74	1.81

[1]Adapted from Stuth et al. 2003.

Table 23. Review of calibration statistics for research studies using NIRS to predict variable of terrestrial forage quality[1].

Forage Description, Country of Study	N		NDF		ADF		IVDMD		Reference
	R^2	SEC	R^2	SEC	R^2	SEC	R^2	SEC	
Cultivated crops, USA	0.99	0.74	0.98	2.39	0.96	1.56	-	-	Norris et al. 1976
Cultivated grain crops, USA	0.96	0.95	0.95	2.64	0.86	2.31	0.89	2.73	Shenk et al. 1979
Semi-arid rangeland grasses, forbs, and browse, USA	0.98	0.37	-	-	0.90	1.26	-	-	Ward et al. 1982
Temperate grasses and legumes, USA	1.00	0.03	1.00	0.09	1.00	0.36	1.00	0.73	Brooks et al. 1984
Semi-natural grasses and legumes, Spain	0.95	0.56	0.91	1.97	0.87	1.24	-	-	Garcia-Cuidad et al. 1993
Mature annual legumes, Australia	-	-	0.93	0.31	0.91	0.44	-	-	Kellaway and Stinson 1993
Trees and shrub foliage, France	0.98	0.11	0.99	1.36	0.97	1.85	0.99	1.51	Meuret et al. 1993
Grass silage, UK	-	-	-	-	-	-	0.82	2.35	Baker et al. 1994
Semi-arid rangeland grasses, Argentina	0.90	0.31	0.94	0.43	-	-	0.97	1.14	Rabotnikof et al. 1995
Semi-arid tropical savanna grasses, sedges and forbs, Australia	0.99	0.04	0.98	1.49	0.89	1.92	0.96	1.18	Woolnough and Foley 2002

[1]Adapted from Woolnough and Foley (2002)

APPENDIX B

FIGURES

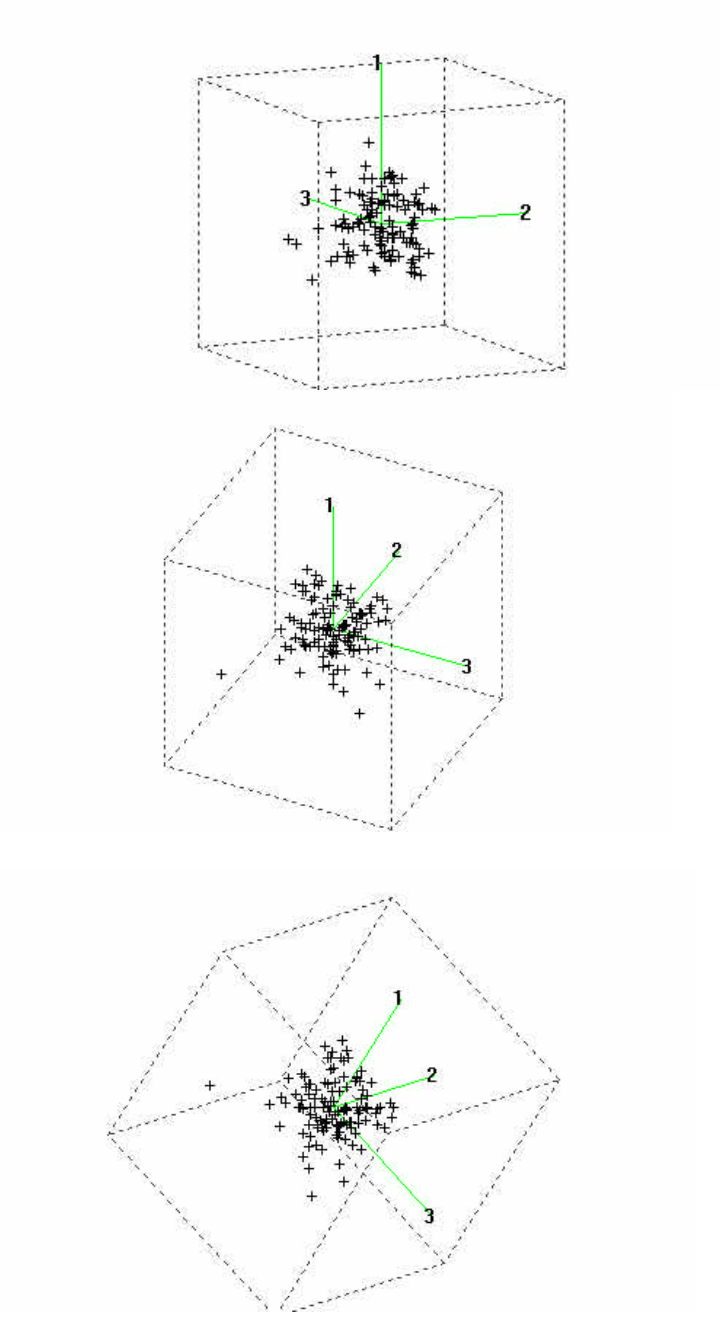

Fig. 1. 3-D representation of elk diets.

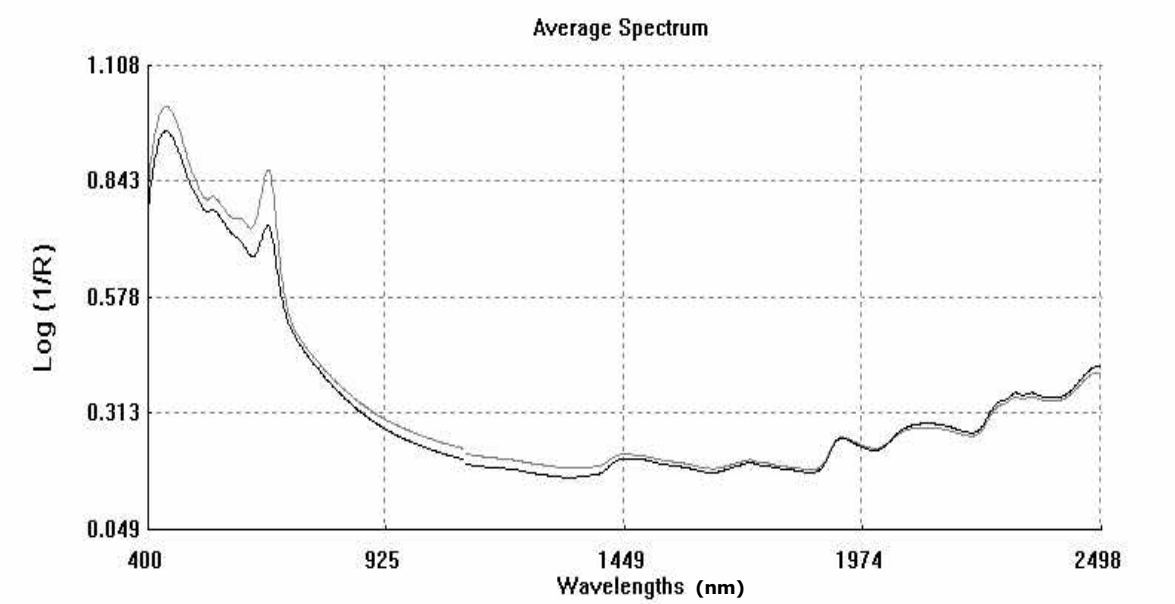

Fig. 2. Average spectra of calibration set.

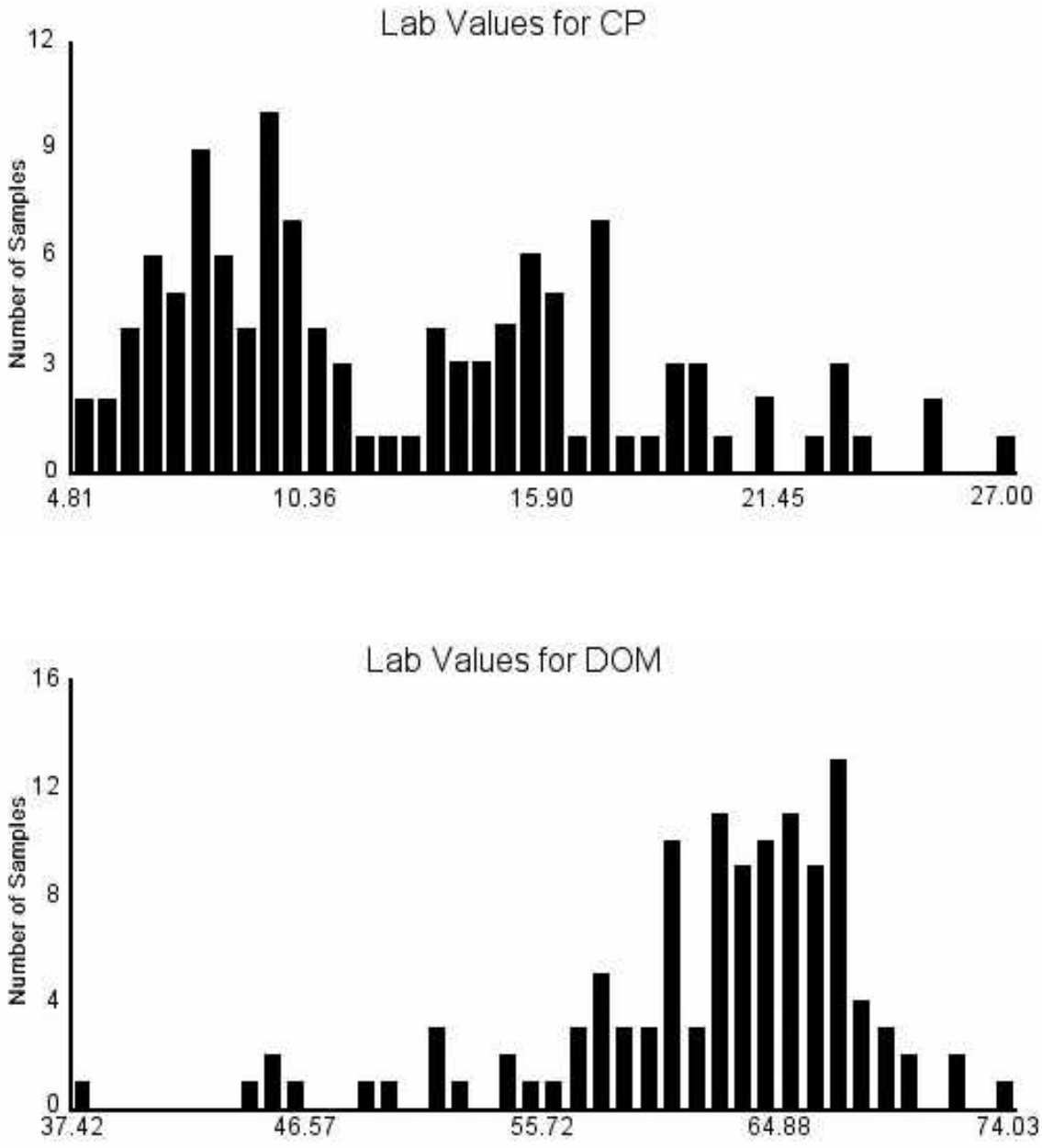

Fig. 3. Lab values for CP and DOM of elk diets.

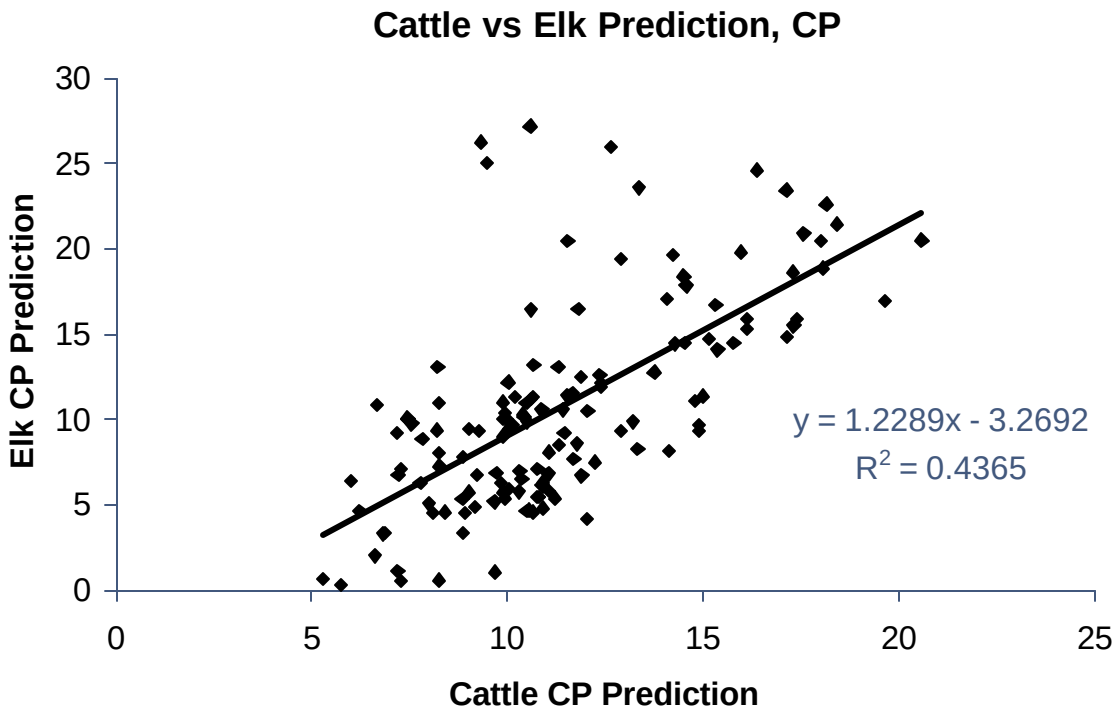

Fig. 4. Cattle vs. elk prediction, CP.

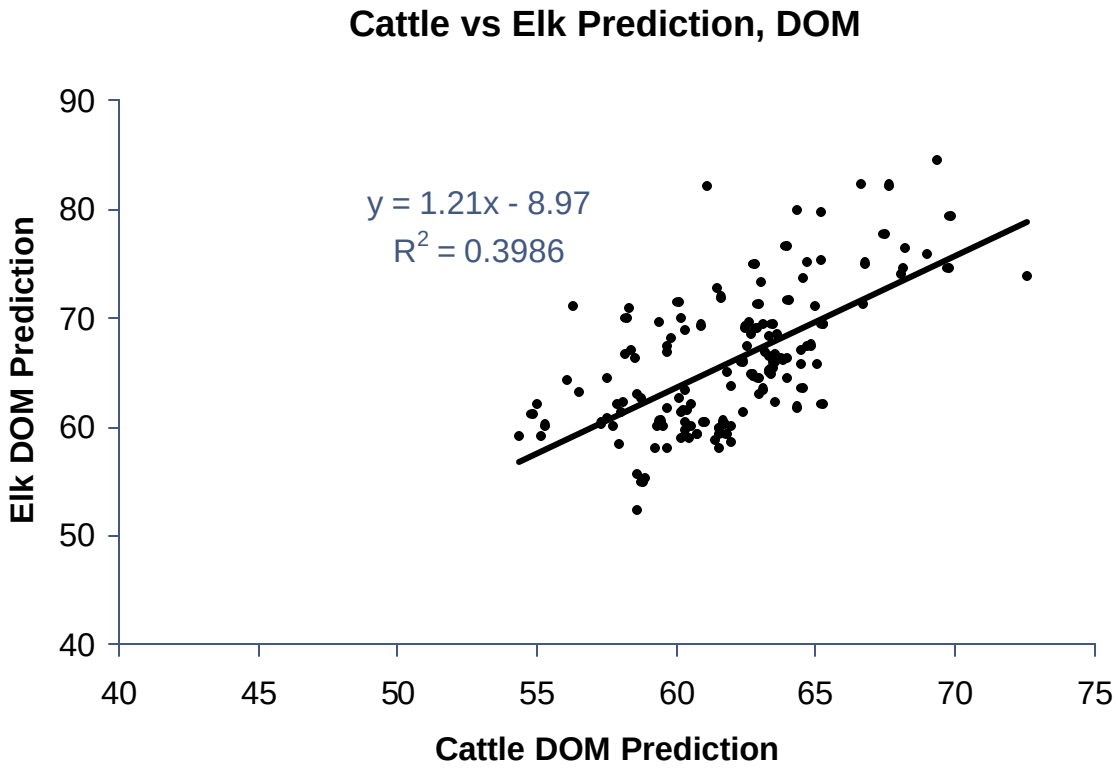

Fig. 5. Cattle vs. elk prediction, DOM.

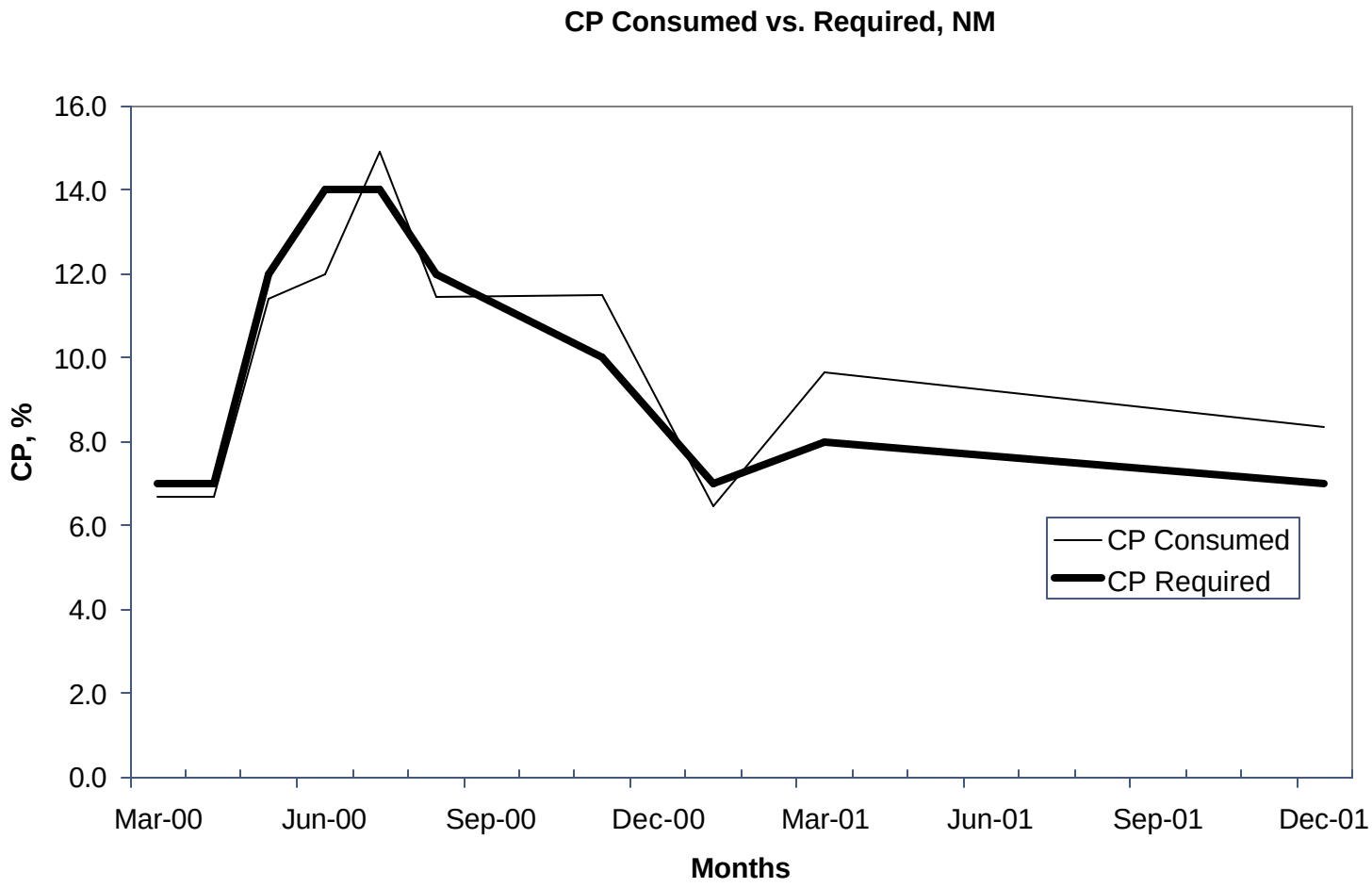

Fig. 6. Consumed CP vs. required CP in New Mexico.

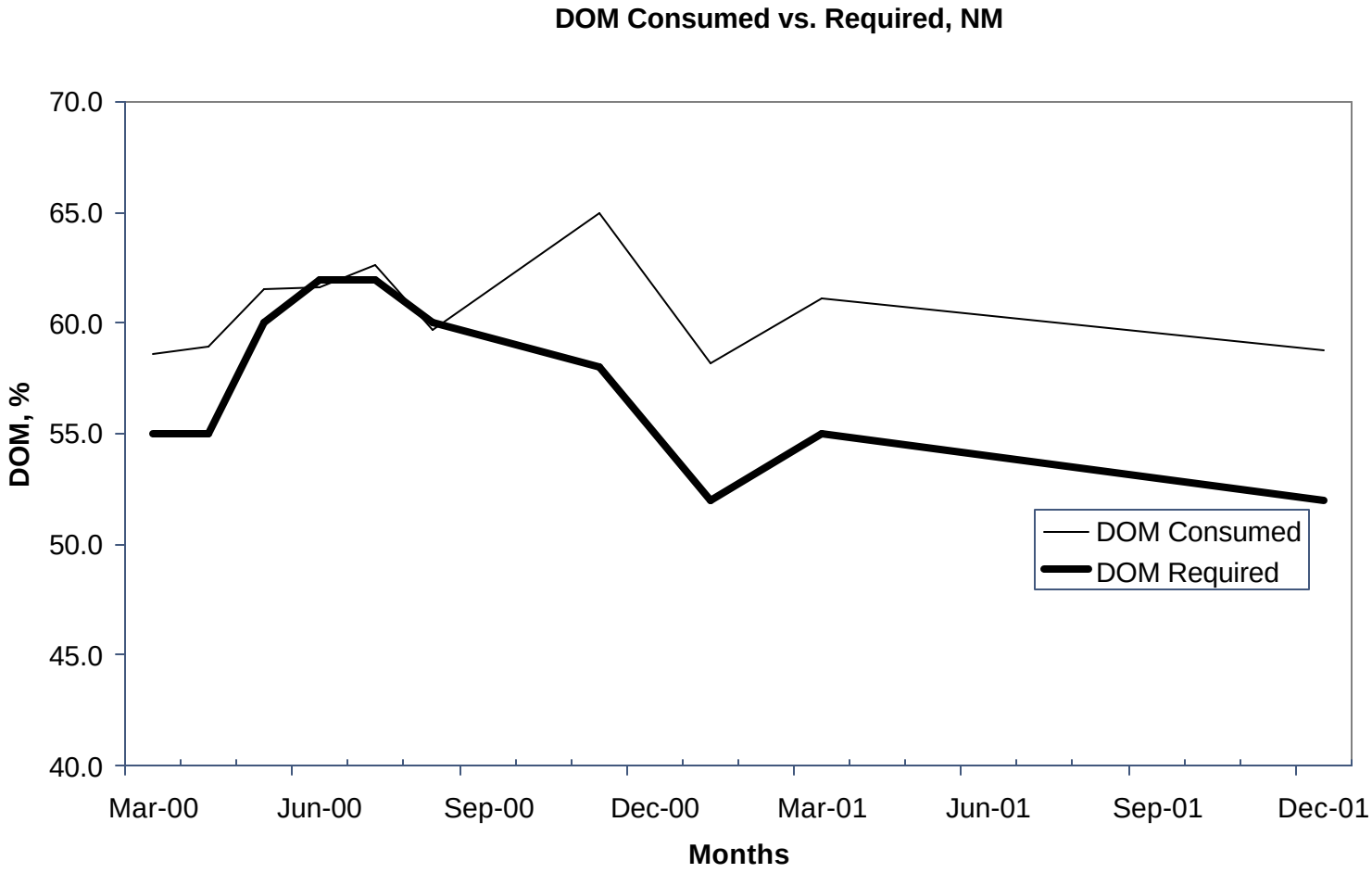

Fig. 7. Consumed DOM vs. required DOM in New Mexico.

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