# APPLICATION OF NIRS FECAL PROFILING AND GEOSTATISTICS TO PREDICT DIET QUALITY OF AFRICAN LIVESTOCK

A Dissertation

by

KOSI SEMEBIA AWUMA

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

December 2003

Major Subject: Rangeland Ecology and Management

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## ABSTRACT

Application of NIRS Fecal Profiling and Geostatistics to Predict Diet Quality of African Livestock. (December 2003)

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Near infrared reflectance spectroscopy (NIRS) and geostatistical techniques were used to predict diet quality of sub-Saharan African (SSA) livestock, and to create cokriged estimated diet quality maps for cattle across a landscape. Rations of native vegetation were stall-fed to cattle (*Bos indicus*), sheep (*Ovis aries*), and goats (*Capra hircus*) to generate diet-fecal pair data. Trials were conducted in Ethiopia, Kenya, Uganda, Tanzania, and Ghana. Historical data from Ethiopia, Nigeria, and Niger were included. Diet samples were analyzed for crude protein (CP%), and digestible organic matter (DOM%), while feces were scanned for NIR spectra. NIRS equations were developed from data using modified partial least square (MPLS) regression. Coefficients of determination ($R^2$) of CP for cattle, sheep, and goats were 0.92, 0.95, and 0.97, with corresponding standard errors of calibration (SEC) being 0.90, 0.79, and 0.80, respectively. Standard errors of cross validation (SECV) for CP were 1.12%, 1.08%, and 1.03% for cattle, sheep, and goats, respectively. $R^2$ and

SEC values for DOM were 0.88, 0.94, 0.94 and 2.82%, 1.68%, and 2.65%, for cattle, sheep, and goats, respectively. Corresponding SECV values for DOM were 3.26%, 2.07%, and 3.30%, respectively. The statistics reported were within the acceptable limits for NIRS calibrations. The results indicate that dietary CP and DOM of free-ranging SSA livestock can be predicted with the same precision as that of conventional wet chemistry methods.

The cattle equation was used to predict cattle fecal samples collected, from February to August 2000, from selected households located within the northern Ghana savanna. The predicted CP% and DOM% were used with Normalized Differential Vegetation Index (NDVI) data, and cokriging technique to create diet quality maps for March and July 2000 for the northern Ghana savanna. Cross validation results indicated a moderate capability of cokriging to estimate predicted CP% for March ($r^2$ = 0.687, SEp = 1.736) and July ($r^2$ = 0.513, SEp = 1.558). Cokriged-estimated DOM value for July was above average ($r^2$ = 0.584, SEp = 3.611), while March DOM% estimation was rather poor ($r^2$ = 0.132, SEp = 3.891). The techniques of cokriging and creation of diet quality maps were moderately successful in this study.

## DEDICATION

This dissertation is dedicated to two special groups of people, my parents and my nuclear family. To the memory of my father Togbe Origines Kofi Atta Awuma (Tsami Atta) who had gone to be with the Lord in March 1999, hence could not see the completion of this phase of my education. To my loving mother, Selestine who did not believe she would live to see to my Diploma, but God, the live giver, has kept her alive.

To my loving wife Jessie, who had to put up with an absentee husband for two years, and even while we were together had to live with my long hours of absence from the house. Finally, to my loving children, Sena, Ewoenam, Mautor, and Deladem, most of who had to endure my absence when they needed me most for the last five years. I love you all.

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# CHAPTER I

## INTRODUCTION

Ruminant livestock, referring mainly to cattle (*Bos indicus*), sheep (*Ovis aries*), and goats (*Capra hircus*), play an important role in the lives of human beings. Livestock provide essential proteins, minerals, vitamins, and micronutrients through meat and milk, draft power for farming and transportation, nutrients in the form of manure. Furthermore, livestock serve as sources of income, employment, and valuable foreign exchange earner for some countries. Additionally, in sub-Saharan Africa (SSA), livestock serve as wealth on hoof. Socially, livestock are used for many traditional functions such as payment of dowries, religious rite, and in certain cases livestock serve as a status symbol to their owners. Livestock's contribution to the national domestic product of the various countries within the sub-region is substantial. For example, in 1991 livestock products, excluding values for animal traction, transport, and manure, accounted for about 28 percent of the agricultural domestic product (GDP) of SSA (USDA 1993).

Consumption of protein from animal sources is essential for good growth since it compliments and corrects the amino acid deficiencies in the cereal-

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

based human diets thereby permitting total protein utilization (De Beer et al. 1994). However, on the average, only 10.5 g per head per day of protein from animal sources is consumed in SSA compared to 55.5 g per head per day in the developed world. The SSA protein consumption level is even below the average of 20.4 g per head per day for the entire developing world (FAO 2000).

Sub-Sahara Africa's population is said to be growing at the rate of 3.1 percent (Williams et al. 1995), and by World Bank estimates 1.3 billion people will be living in the region by 2025 (World Bank 1989). However per capita meat production from livestock has not kept pace with population growth from the early 1980s to mid 1990s (Delgado et al. 1999). Current meat and milk deficit is a feature of every zone in SSA (Mohammed-Saleem 1995) and will worsen in the future.

Livestock production in SSA is rangeland based depending largely on natural vegetation for most of the nutrients required by the livestock. The rangelands are vast in size, diverse in use, and traversing five agro-ecological zones namely: arid, semi-arid, highlands (montane), humid, and sub-humid (Attah-Krah 1989). SSA has been estimated to cover 13.4 million $km^2$ or about 60% of the continent (Dregne et al. 1991).

Climatic (rainfall especially) and edaphic factors (soil) are the determinants of vegetation types across the various ecological zones. Description of the effects of climatic in shaping vegetation in the zones is presented in Chapter III. In general, forest vegetation decreases with

decreasing rainfall from the humid to the arid zones while the grass component increases into the arid zones, though grass content of the arid areas are rather sparse due to low rainfall. Skerman and Riveros (1990) gave a detailed description of the dominant grass tribes and dominant grass associations of sub-Saharan Africa from the West through Central to East Africa. Briefly, the grazinglands of SSA are made up of dominant grass tribes of Andropogoneae, Aristideae, Arundiceae, Eragrostideae, Chlorideae and Paniceae. However, Andropogoneae and Paniceae are the most prevalent, while the presence of Eragrostideae is an indication of increasing aridity (Humphreys 1977).

Trees and shrubs are important components of the African rangelands, existing with grasses in various associations in relation to climate, giving vegetative description of the rangelands in terms of parklands, savannas, shrublands, thickets, and woodlands (Bailey 1998). Comprehensive documentation of browse species of importance to livestock in the SSA rangelands have been made by Audru (1980), Le Houérou (1980), Lamprey et al. (1980), and Toutain (1980). Foliage of trees and shrubs forms a significant component of the ruminant diet, either through *ad libitum* browsing or by lopping, particularly during the normal dry season and during severe drought period (Skerman et al. 1988, Harris 2000), and are even more valuable in the arid and semi-arid areas (Devendra 1989). The advantage of browse is in its ability to maintain its feeding value into the dry season, though most browse species contain anti-nutritive factors (phenolics, saponins, fluoroacetates, amino acid

derivatives), which adversely affect nutritive value especially as a sole diet (Kaitho 1997).

Livestock production systems in the tropics have been described generally as pastoral in which livestock is seen as an entity unrelated to other agricultural practices such as crop production. This approach is based on the degree of herd movement from highly nomadic through transhumance to agropastoralism (FAO 2001). However, Jahnke's (1982) classification of livestock production into pastoral–range livestock production system, crop-livestock production system of the lowlands, and crop-livestock production system of the highlands, based on farming systems approach of Ruthemberg (1980, cited by Jahnke 1982) seems most appropriate for SSA, since livestock production as a form of land use cannot be entirely separated from other forms of land use such as cropping. Nomadism (pastoral-range system) is the system of choice in the arid zones, areas too dry for cropping as in parts of West and East Africa. As rainfall regime improves crop-livestock system is practiced in the semi-arid zones with transhumance as the mode of livestock production. In sub-humid zones with better rainfall and longer growing period, crop-livestock production system is the agricultural practice of choice and the people involved are referred to as agro-pastoralists.

A major challenge to livestock production on rangelands is the fluctuating forage production in terms of both quantity and quality due to seasonal effects, recurrent drought (Coppock et al. 1986), and rampant bush fires. The nutrition

of the free-ranging livestock therefore suffers greatly leading to perpetual low levels of production that is compounded by catastrophic losses due to periods of extended drought

Nutritional intervention is a means of reducing nutritional stress on livestock during seasonal period of low range forage production in both quality and quantity such as winter in temperate climates, dry season in the tropics as well as periods of severe drought. In developed countries, intervention comes in the form of protein supplementation such as soybean meal, cottonseed or high legume hay to maintain or increase production. In contrast, supplementation in SSA comes in the form of crop residues (Dibissa and Peters 1999, Harris 2000). Cereal (maize, millet, sorghum, and rice) stovers and straws, legume (cowpea and peanut) haulms are the main crop residues used in the semi-arid and the sub-humid zones. These crop residues are either grazed on the crop fields or fed from storage (Schiere and Kater 2001). The purpose is to maintain body condition of the animals rather than production during the adverse seasonal periods. Nutritional mitigation thus practiced, in the form of opportunistic use of crop residues, is rather generally offered too late and in limited quantities. There is limited use of cottonseed products and wheat/corn bran concentrates. A rapid assessment method to observe the trend in the nutritional status of the free-ranging animal long before emaciation becomes visible is needed. The method should be accessible, low cost, reliable, and easy to manage by pastoralists, as well as being compatible with extension methods.

Productivity of grazing livestock is determined by the quantity and quality of forage eaten, and where quantity is not a limiting factor, diet quality becomes the over-riding determinant of animal productivity (Lyons 1990, Coates 1998). Methods previously used in diet quality determination have been characterized by relatively low precision, high labor demand, and high sensitivity to bias (Langlands 1974). Techniques such as hand plucking of forage to mimic diets ingested by the free-ranging animals, generally under estimate diet quality and are highly variable (Erasmus et al. 1978), since diets selected by the free-ranging animals are usually higher in nutrient content than the available forage (Coleman and Barth 1973). The use of esophageal fistulated animals as a means of determining the diet quality of the grazing animals have been found to be critically dependent on sampling site selection (Erasmus et al. 1978). These techniques employ the method of wet chemistry analysis to determine the quality of the diet of the animal. The wet chemistry method is dependent on chemical reagents, glassware, and suitable laboratory facilities. The cost of establishing and running such laboratories is high, and the limited ability to use surgically altered esophageal fistulated animals have limited the wide use of these techniques in determining the diet quality of grazing animals in the free-ranging setting.

Nutritional recommendations for ruminant livestock (ARC 1980, NRC 1987) based on wet chemistry analysis, have been useful in determining the nutritional well-being of livestock under intensive management systems on tame

pasture, but found to be unsatisfactory in determining the nutritional status of animals under free-ranging conditions (Tuah 1989, SCA 1990).

Monitoring the body condition score (BCS) or the degree of fatness of an animal relative to the traditional stress period such as dry season, and the onset of breeding season has also been used as a measure of the nutritional well being of the grazing animal (Corah 1989, Keown 1991, Encinias and Lardy 2000). BCS, though important, is actually an indication of past nutrition (Lyons 1990, Encinias and Lardy 2000), therefore to rely on body condition as a means of determining current nutritional status of the free-ranging animals could lead to disastrous consequences. Because of the delay in expression of physical signs of nutritional stress, timely application of corrective measures in form of nutrient supplements would be impossible.

Forage digestibility and crude protein (CP) or nitrogen (N) status of the diet have been identified as being highly related to forage intake and productivity of the grazing animals (Coates 1998). Ability to predict these dietary attributes adequately will be of tremendous boost to the livestock sector, especially under free-ranging conditions where accurate diet quality determination is rather difficult due to spatial heterogeneity of the range quality imposed by various environmental factors such as rainfall, temperature, watering point location, and by selective grazing. The inadequacy of previous technologies in determining the nutritional status of the free-ranging livestock has led to the search for other technologies, such as the near infrared reflectance spectroscopy (NIRS). The

NIRS technology detects fecal by-products of digestion and metabolism as they relate to dietary CP and digestible organic matter (DOM) of the animal (Stuth et al. 2003b, Roberts et al. 2003). Several studies have indicated the usefulness of fecal NIRS as a tool for nutritional profiling (monitoring diet quality at short interval) of free-ranging animals to the same degree of accuracy as conventional wet chemistry analysis (Lyons and Stuth 1992, Leite and Stuth 1995, Whitley 1996, Showers 1997, Coates 1998, 1999, Ossiya 1999). Recently, Gibbs et al. (2002) developed calibration equations capable of predicting dietary digestibility and crude protein content of cattle fed supplements in Queensland with similar precision as obtained by previous researchers. From the above, NIRS has performed well as a nutritional profiling technique, however there is the need to explore methods of reflecting predicted CP% and DOM% over large regions of the world. The development community is also requiring mechanisms to estimate spatial patterns of diet quality to allow large scale assessment of animal populations. Emerging geostatistical techniques that can be used to link a sparse sampling of point-based CP and DOM values (%) with pervasive satellite based Normalized Differential Vegetation Index (NDVI) greenness data may offer new opportunities in achieving this goal.

The overall goal of this research was to use fecal NIRS techniques to derive predictive equations for assessing the diet quality of free-ranging sub-Saharan African (SSA) livestock via fecal NIRS profiling, and to use these predicted values in conjunction with goestatistics to explore the feasibility to

create interpolated diet-quality maps using the northern savanna zone of Ghana as a test bed. The specific objectives were:

- To develop enhanced fecal NIRS prediction equations capable of predicting diet quality of free-ranging livestock (cattle, sheep, and goats) within the five major agro-ecological zones of SSA.
- Determine if diet-quality maps could provide viable diet quality assessment at the landscape scale.

# CHAPTER II

# LITERATURE REVIEW

Ruminant livestock require nutrients such as carbohydrates and fats to provide energy, proteins for tissue building and repairs, mineral and vitamins for the regulation of body functions, and water for the maintenance of normal tissue functions (McDowell 1985b, Van Soest 1994). Van Soest (1994) indicated that energy and protein are often the most limiting factors for ruminants. In the grazing environment, these requirements are mainly met from ingesting available range forage resources.

## Factors Affecting Forage Quality in SSA Rangelands

In SSA, ruminants obtain majority, if not all, of their nutrients from the diverse natural plant communities in the rangelands of the region. Forage production of these rangelands is closely related to climate and soil (Crowder and Chheda 1982, Wilson 1982, Atta-Krah 1989), and within the climatic factors precipitation is the most determinant factor since temperature and light are less likely to be limiting for growth of plants in the region (Crowder and Chheda 1982). The same climatic and edaphic factors affect the nutritive quality of the range forages. In addition, Van Soest (1994) observed that forage quality varies tremendously with the season, the age of the plant, and the portion of the plant eaten. Wilson (1982) reported that high growth temperatures, which are responsible for accelerated stem development and maturation in plants, cause a substantial decrease in the digestibility of grasses and a similar but smaller

effect on legumes. Furthermore, severe droughts are detrimental to herbage quality.

Tropical forage species are characterized by $C_4$ grasses, and $C_3$ shrubs and legumes (Humphreys 1977, Van Soest 1994). The grasses posses the $C_4$ dicarboxylic acid photosynthetic pathway, which are more efficient at converting solar radiation into dry matter production than the $C_3$ phosphoglyceric acid pathway of temperate species, and are therefore characterized by higher efficiency of nitrogen utilization and higher growth rates compared to temperate species (Humphreys 1977, Norton 1982, Jones and Wilson 1987). The rapid growth rates of grasses within the region enable most grass species to grow fast, mature quickly, and become lignified mid-way into the rainy season. Grass quality therefore declines though quantity may still be high prior to the onset of the dry season. Forage quality, especially in the case of grasses, follow the same cyclical pattern defined by seasonal rainfall. For example, Fianu et al. (1972) reported that the natural grasslands of Ghana would have crude protein content of about 14% from the beginning of the rainy season falling to about 2% or less at the end of the dry season, using a total biomass clipping method. The high lignification, low soluble carbohydrate, and high cell wall contents as well as higher neutral detergent fiber (NDF) as compared to temperate species result in low forage quality, and low forage intake below the optimal level for the $C_4$ grasses within the region (Van Soest 1994).

Since most SSA rangelands do not benefit from use of fertilizer, and rely on inherent soil fertility, the nutritive value of the range forages will therefore depend on the fertility of the soil. For example, Minson (1990) indicated that the protein content and the level of phosphorus in tropical grasses would depend on the level of available nitrogen and phosphorus in the soil.

Nutritive quality differences exist between plants, among plants of the same species and within species. As plants age, nutritive value generally declines as a result of lignification and a decreased proportion of leaves to stems (Holechek et al. 1998, Van Soest 1994). Tropical grasses have been described as inherently of low in nutritive quality compared to temperate grasses (McDowell 1985a). On the contrary, tropical legumes do not decline in nutritive value as rapidly with age as those of tropical grasses (Stobbs 1975). Similarly, in comparison with tropical grasses, browses have a distinct advantage, being superior in nutritional value particularly during the dry season (Le Houérou 1980, Kaitho 1997). Holechek et al. (1998) also observed that leaves of forbs and shrubs are generally higher in nitrogen (N) than leaves of grasses, and stems at comparative stages of growth. Grazing livestock consume different parts of plant species encountered, namely, leaves, stem, twigs, bark, flowers, fruits, and seeds (Le Houérou 1980). In general, leaves of grasses, forbs, and shrubs are much higher in protein and digestible nutrients than stems (Holechek et al. 1998), and leaves are also higher in quality than the plant as a whole (Stoddard et al. 1975). Fruits are rich in easily digestible nutrients and have highly

nutritious cell contents and would be considered to be equal to or higher in quality than leaves, thus are considered as concentrates (Hoffman 1988, Van Soest 1994).

Tree and shrub fodders are important sources of supplementary protein, vitamins, and minerals for livestock grazing poor quality SSA range grasses (Le Houérou 1980, Topps 1992, Hove et al. 2001) or crop residues (Reed et al. 1990) during the dry season. Topps (1992) reported that most fodder from legume based trees and shrubs have medium to high content of CP (range 120-289 g $kg^{-1}$ DM). The significance of browse on forage intake in cattle has been estimated to range from 5% at the beginning to 45% at the end of the dry season (Le Houérou 1980, FAO 1986). Similarly, Mnene (1985) reported that browse formed 4-34% of the diet of cattle on *Commiphora* savanna rangeland of Kenya, though the browse composition of the diet varied with bush level, herbage level, and season. Various proportions of browse have been reported in the diet of African livestock. In northern Nigeria, nomadic Fulani cattle were reported to spend 5% of their feeding time on browse during the wet season and 15-20% during the dry season (de Leeuw 1975, cited by Le Houerou 1980). Field (1979) working in Kenya reported that perennial woody plants comprised 33% of the diet of sheep and 52% of the diet of goats. The fruits of some browse trees are also a good source of feed and protein. For example, the Maasai pastoralist of Kenya usually feed their livestock on ripe *Acacia tortilis* pods during the dry season, and pods were found to make up about 50% of the

total daily intake of the small ruminants (de Leeuw et al. 1986, cited by Atta-Krah 1989).

Generally, most browse species contain high concentrations of proteins (Kaitho 1997), and remain relatively constant throughout the year (Le Houérou 1990). The degradability of the protein, as estimated by *in sacco* method, varied considerably with regard to tannin content, with low or no tannin containing browse species exhibiting high protein degradability, whereas most tannin containing species showed low protein degradability (Kaitho 1997). Atta-Krah (1989), and Kaitho (1997) indicated that the anti-nutritive factors such as phenolics, saponins, fluoroacetates, alkaloids, and amino acid derivates contained in most browse species adversely affect nutritive values, palatability and metabolism. Of greater importance are complex phenolic compounds, which appear to be a major constraint on the use of legume shrubs and trees for animal fodder because of adverse effects of phenolic compounds on intake, digestibility, nitrogen availability, and animal's metabolism (Topps 1992, Leng 1997, Nantoume 1999). Phenolics are abundant in tropical woody species and frequently occur at levels of 10-20% leaf dry matter in tropical shrubs (Lowry 1989). Tannins are classified into two chemically distinct groups: hydrolyzable tannins (gallotannins and ellagitannins), polyesters of gallic acid and other phenolic acids derived from it, with sugar (normally glucose). These are readily hydrolyzed by acid. The second group, condensed tannins (flavolans) are polymers of catechins, which are flavonoid phenols and are relatively stable

(Leng 1997). Condensed tannins may be less harmful than hydolyzable tannins since they do not depolymerize and are not absorbed (Topps 1992). Though few cases of mortality has been reported, Topps (1992) observed that phenolics, with a few exceptions, have low mammalian toxicity but most of them show broad-spectrum anti-microbial activity which reduces fermentation rates in the rumen, and binds protein. Nantoume (1999) in a study on effects of guajillo (*Acacia berlandieri*) on goats observed that increasing dietary levels of guajillo resulted in decreased balance in energy and nitrogen available to the animal due to increasing levels of acidic detergent fiber nitrogen (ADF-N), and tannins in guajillo.

## Diet Selection and Forage Preference Under Free-ranging Conditions

The grazing animal is said to possess a unique prehensile morphology to gather and process food in a digestive system adapted to the primary food groups ingested (Stuth 1991, Holechek et al. 1998). Stuth (1991), further described the grazing process of food gathering as a hierarchical system of diet selection (from the landscape level through plant community, patch, feeding station to the individual plant) interacting with the animal's physiological needs (water, thermal balance, food, etc.) resulting in a unique pattern of use across a given landscape.

Factors that affect or influence diet selection of the grazing livestock can be broadly grouped as animal, plant, and environmental. Hanley (1982) stated

that body size, size of the digestive system relative to body weight, type of digestive system, and mouth size and shape are primary factors determining forage selection by different range animals. The grazing livestock have therefore being divided into three groups based on their foraging habits, namely grazers, browsers, and intermediate feeders (Holechek 1984). The grazing cattle have a characteristic of wrapping their tongue around herbage and pulling rather than biting cleanly, walking slowly forward, moving their head from side to side to take mouthfuls while on the move (Forbes 1995). The much larger buccal/oral cavities of cattle enable formation of a bolus of diet prior to swallowing hence grasses with high canopy bulk density of green material are more profitable to them (Stuth 1991). In addition, Demment and Van Soest (1981) observed that cattle have higher dry matter requirements, lower nutrient requirement, less precise prehensile organs, and larger rumen volume: body volume ratio than goats. Cattle are therefore mainly grazers with grasses forming dominant component of their diets. Cattle consume some browse only after severe restrictions in dry matter intake due to marginal availability of grasses (Launchbaugh et al. 1990), and forbs when temporal flushes of desirable species occur (Stuth 1991). Goats, being browsers and with smaller mouthparts, are able to select leaves and twigs within shrubby thorns with ease. Stuth (1991) observed that goats show high preference for browse regardless of availability and only increase grass in their diets relative to its availability as the composition of browse and to lesser extent forbs decline. Sheep on the other

hand are intermediate feeders (Holechek et al. 1998), and have the forbs-food group as their principal dietary group though they have a rumen: body ratio similar to cattle (Demment and Van Soest 1981; Hanley 1982). With a much smaller body size, sheep require higher nutrient concentration in their diet than cattle. Compared to cattle, sheep utilize browse more readily but generally browse species do not form the major portion of their diet unless grass and forbs are in limited supply (Stuth 1991).

Selection of forage presumes morphological and nutritive differentiation in plants. The differentiation in plants is influenced by the individual plant species, number of plant species available, the environment for growth, and the age and maturity of the forage (Van Soest 1994). Animals are continually making choices among plants at feeding station level. The kind of plant chosen is largely related to the animal, the relative abundance of alternative food sources or forage diversity (Van Soest 1994), and the complexity of the landscape relative to the water and thermal needs of the animal (Stuth 1991). SSA range forages which are often composed of mixed species and are in a mature state for the greater part of the year offer the grazing animals a range of expression for selection in terms of choice of leaves, stems, and plant species of disparate quality or palatability (Van Soest 1994). Stuth (1991) indicated that the physical presentation of green leaf blade relative to its pattern of senescence and culm development would influence diet selection. Hence, grasses with rapid culm development (determinant growth) and a strong midrib leaf structure will be

selected less frequently if allowed to develop long-standing senesced leaf material. Since there are differences in the degree of sheath development and angle of growth of tillers, cattle with less selective prehensile organ have a much harder time than sheep in selecting short or decumbent species.

Leaf size and distribution will influence diet selection and intake especially in plants with highly lignified stems, since the grazing animal will have to select each leaf and avoid stem, random biting will be discouraged and intake may be reduced (van Soest 1994). Browse presents itself in many forms: deciduous or evergreen, spineless or spiny, single leaves or compound leaves, short or tall, single stemmed or multi-stemmed. Browse preferring livestock have adapted prehensile and digestive organs enabling utilization of these species to an extent that height, spininess, and secondary compounds are the principal plant characteristics that affect their selection (Cooper and Owen-Smith 1986). Spininess and height may not be too much of a factor for goats in SSA. Goats are dexterous in picking leaves from among thorny branches of leguminous shrubs and even on occasion could be found climbing small trees to feed (Van Soest 1994). Goats use different browsing tactics to consume herbage from browse plants with different deterrent structures. For example, Zimmerman (2002) observed that goats use more lip bites to obtain herbage from highly thorny plants, but adopt jaw bites on less or non-thorny plant species.

Seasonal diet availability equally influence diet selection of the grazing animals. Migongo-Bake and Hansen (1987) working in semiarid rangelands of

northern Kenya found the browse component of the diet of cattle to be higher in green (wet) season, when the browse shoots were most abundant and easier to harvest, than in the dry season. Mnene (1985) observed that cattle selected more grass in a high herbage paddocks and during the dry season, but browse component in the diet increased as grass consumption declined under low herbage level and during the wet season. On the contrary, Kibet (1984), observed that cattle diets were dominated by grass and grass-like species irrespective of season and preference was in the order of grass, followed by forbs, and browse being the least selected. Sheep, as intermediate feeders, were observed to increase their browse intake during both the very dry season (July-September) and the very green (wet) season (October-December) due to relative abundance (Migongo-Bake and Hansen 1987). The authors observed goats to browse relatively more during the driest season.

**Conventional Methods of Determining Diet Nutritive Quality**

Forage nutritive quality can be determined by sampling the forage consumed by the target animal and determining such factors as composition, digestibility and intake (Van Soest 1994). One method of obtaining forage that mimics animal selectivity is through clipping. The selective hand clipping is useful for surveying mixed vegetation, including browse, and is in some ways less labor-intensive than other procedures (Van Soest 1994). Because of selective grazing, animals with esophageal or rumen fistulas have been widely

used in recent years to obtain forage samples for chemical analysis (Holechek et al. 1982c).

Fistulation techniques are rather intrusive to the animal (Van Soest 1994) and several factors limit the precision with which fistula forage samples represent the chemical composition of the diet. For example, samples obtained by either esophageal fistula or rumen emptying are contaminated with saliva, which contains both mineral and organic compounds, hence chemical composition of the forage samples would not exactly reflect that of the forage eaten (Van Soest 1994). However, Holechek et al. (1982c) suggested that presenting the data on ash free basis could ameliorate the problem; all the same the fistula samples cannot be used for phosphorus (P) determination due to the salivary contamination. While the fistulation procedure requires considerable expertise and expensive, the fistulae require constant care, and maintenance (Van Soest 1994). Furthermore, the use of fistulated animals is mostly limited to research applications, and will have no wide application in extensive rangeland situations as pertains in SSA.

Wet chemistry, the most often used analytical procedure, though can provide accurate analysis of nutritive value of forage species especially in the case of samples obtained from fistulated animals has limitations as well. The turn around time reduces the reliability of the method (Norris et al. 1976). Furthermore, the wet chemistry analysis is dependent on expensive chemical reagents and suitable laboratory facilities, thus the cost of setting up, and

operating wet chemistry laboratories in SSA preclude the use of the method in extensive rangeland situations in SSA.

## Fecal Indices for Estimating Diet Quality

Intake and diet nutritive quality determinations of the free-ranging ruminant remain some of the most difficult aspects of range nutrition, since the conventional methods are limited by high labor demand and relatively low precision under range conditions (Holechek et al. 1982c, Holloway et al. 1981). Diverse plant communities, changing topography, and large seasonal and yearly variations in quantity and quality of the available forage, complicate the nutrition of the free-ranging animal (Wofford et al. 1985). Additionally, selectivity of the grazing ruminants greatly complicates the ability to obtain samples of grazed forage (Theurer et al. 1976). The search for an easy and cost effective technique with the potential for application under range conditions has led to the development of the fecal indices of diet quality. Holloway et al. (1981) submitted that fecal index technique is the only technique with the potential for evaluating the nutritional status of grazing animal under extensive pasture conditions. Fecal indicators found to have such potential include fecal nitrogen (FN) concentration (Holechek et al. 1982c, Squires and Siebert 1983, Leite and Stuth 1990); total fecal nitrogen output (Stallcup et al. 1975); and total fecal output (Holechek et al. 1985). Other indirect methods such as lignin-ratio technique (Wallace and Van Dyne 1970), and fecal 2, 6-diaminopimelic acid (DAPA) (Hodgman et al.1996) have been used. However, the FN index method has

been the most commonly used (Wallace and Van Dyne 1970, Langlands 1974, Cordova et al. 1978, Van Soest 1994). Subsequent discussion is restricted to FN index technique. The index procedures generally relate level of intake, digestibility or CP to some component in the feces through a regression equation (Cordova et al. 1978)

Fecal N index technique was developed through Lancaster's (1949) observation of a strong relationship between digestibility of diet and the N percent in the feces. Reliability of fecal indices for monitoring nutritional status of the range animal has been rather a controversial subject (Hobbs 1987, Leslie and Starkey 1987). The physiological basis for the FN indices is that feces contain undigested fractions of the diet consumed in addition to metabolic excretions (Van Soest 1994). The metabolic excretions are mainly microbial matter and small amount of endogenous secretions emanating from digestive tract cells and digestive secretions (Van Soest 1994). FN therefore represents a combination of unabsorbed dietary nitrogen (DN), undigested microbial N, and endogenous N (Robbins 1983) diluted by undigested dietary dry matter and endogenous material (Leslie and Starkey 1987). Mason (1969) reported that nearly all nitrogen in ruminant feces is of microbial origin and very little comes from the diet ingested. In support, (Van Soest 1994) indicating that bacterial matter contributes more than 80% of the total fecal nitrogen, while Mason (1969) stated that microbial matter concentrations in ruminant feces increases with increasing diet quality. Microbial matter concentrations hence fecal N therefore

would appear to be a good indicator of nutritional well being of the grazing animal. However, the value of fecal indices as a good indicator lies in their predictive ability. In this regard, Nunez-Hernandez et al. (1992) and Hodgman et al. (1996) observed that the fecal indices acting as the independent variable should account for not less than 80% ($R^2$ = 0.80) of the variations in the dependent variable, the dietary variable. Furthermore, the equation should not be use to predict samples outside the range within which the equation has been developed (Hodgman et al. 1996).

Fecal N% and dietary N% were found to be correlated (Holechek et al. 19982b, Nunez- Hernandez et al. 1992), but the relationship is not predictive of diet quality. Robbins (1983), and Hobbs (1987) therefore suggested that FN content should be used only as a general indicator of protein intake, and not as a predictor of dietary nutrient levels in animals. In support, Arthun et al. (1982), Leite and Stuth (1990), Nunez-Hernandez et al. (1992), and Wehausen (1996) did not find any strong relation between FN% and dietary N% of ruminant livestock. Arthun et al. (1982) observed that FN was less effective in accounting for variations in forage CP% ($R^2$ = 0.66), while Leite and Stuth (1990) reported a low $R^2$ of 0.59 between total N concentration (%N in fecal OM) and dietary N % for cattle grazing mixed post oak savanna in Texas. Nunez-Hernandez et al. (1992) reported that FN had low correlation with diet CP% and regressions varied greatly with type of feed for both cattle and goats. Thus Nunez-Hernandez et al. (1992) and Leite and Stuth (1990) were of the opinion that FN

percent lacks reliability for monitoring trend in nutritional status of a particular ruminant on the same range if their diet showed major shifts in botanical composition. The above findings suggest that there is no predictive relationship between fecal N concentration and diet N concentration that has any quantitative value to predicting nutritional status of ruminants.

## Principles of NIRS Technology

The near infrared reflectance spectroscopy (NIRS) method of analysis is an instrumental based method for rapidly, and reproducibly measuring the chemical composition of samples with minimal sample preparation (Norris 1989a). The method has the advantage of speed, simplicity of sample preparation, multiplicity of analyses with one operation, and nonconsumption of the sample (Norris 1989a). The method requires no reagents hence non-polluting, and characterizes the entire sample of interest rather than specific component of interest (Deaville and Flynn 2000). The main disadvantages of the NIRS method are instrumentation 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). However, once the equipment has been acquired and an appropriate calibration procedure developed, subsequent purchase of expensive reagents and glassware are not required.

Near infrared reflectance spectroscopy is a physical, and analytical method based on the absorbance of light in wavelength regions that relate to

chemical components within a substance (Deaville and Flynn 2000). The physical basis of NIRS is the irradiation of molecules of a substance with monochromatic light from an external source in which varying proportions of light energy are absorbed by, reflected by, or transmitted through the substance (Birth and Hecht 1987). The molecules therefore acquire the potential for energy changes. Molecules result from the combination by covalent and electrovalent bonding of atoms present in all organic matter mainly as carbon, oxygen, hydrogen, nitrogen, phosphorus, and sulfur, with minor amounts of other elements. These molecules are in constant motion vibrating at frequencies corresponding to wavelengths in the infrared region of the electromagnetic spectrum, due to nature of the bonds, the electrostatic charges on the atoms, and the molecules themselves (Murray and Williams 1987). However, each bond vibrates at a given frequency that is specific to its chemical group and the energy of an incident radiation can only be absorbed when the frequency of the light is the same as the natural frequency of the molecular bond (Bertrand 2001). Stretching and bending are the two main modes of molecular vibrations. Stretching is movement along the axes of bonds, so that the distance between atoms changes rhythmically, while bending vibrations may involve changes in bond angles between atoms, or movement of groups of atoms with respect to the rest of the molecule without movement of the atoms in the group with respect each other. Only vibrations that result in rhythmic changes in the

dipole movement of a molecule can cause absorbance in the infrared region (Murray and Williams 1987).

Ideally the absorption spectrum should be the output of instrumentation. However, most instruments measure the radiation that is not absorbed (Birth and Hecht 1987). According to Murray and Williams (1987) intensity of absorption can be described in terms of transmittance (*T*)

$$T = I/I_o \qquad (1)$$

Where *I* is the intensity of energy emerging from, and $I_o$ the energy incident on the sample. But Beer/Lambert law indicates that the concentration of an absorber is directly proportional to *A*, the sample absorbance (Birth and Hecht 1987).

$$A = \log (I_o/I) \qquad (2)$$

Thus for absorption spectra, the intensity can be expressed by Beer/Lambert law (Murray and Williams 1987) as:

$$\log (I_o/I) = \log (1/T) = kcl = A \qquad (3)$$

However, in the field of NIRS, reflectance (R) is analogous to transmittance, equation (3) can thus be expressed in terms of R as:

$$\log (1/R) = kcl = A \qquad (4)$$

***k*** is the molecular absorption coefficient (molecular extinction) and is characteristic of each molecular species.

***c*** is the concentration of the absorbing molecules

***l*** is the path length of the irradiating energy through the sample.

Equation (4) can be written in more familiar form as:

$$A = \log (1/R) \qquad (5)$$

The NIR spectrometer actually collects spectra on a sample in the form of log (1/R); the spectra are then stored in a microcomputer interface. There is an almost linear relationship between absorbance and concentration, provided Beer's law is upheld and no association occurs between absorbing molecules (Murray and Williams 1987). However, Shenk et al. (1992) indicated that there is no definitive theory on diffuse reflectance. A higher log (1/R) value is an indication that more radiation has been absorbed (less reflected) by the sample at that wavelength (Hruschka 1987).

An NIR absorption band is produced when NIR radiation at a specific frequency vibrates at the same frequency as a molecular bond in the sample. Since the amount of absorption that takes place differs at different wave points, an undulating pattern known as spectrum is created in the shape of "peaks and valleys." This shape is characteristic of all the absorbing molecules present in the sample (Murray and Williams 1987). The highest absorption in the band is referred to as an absorption peak (Shenk et al. 1992). The shape of the spectral trace is affected by several factors including the composition of the molecules, the presence and magnitude of the dipoles, the interaction between the molecules, the resolution capability of the spectrometer, and the efficiency of the detector at different wavelengths (Murray and Williams 1987).

The NIR spectra region is a domain of harmonic and combination bands (Bertrand 2001). The major bands in this region are second and third harmonics of fundamental O-H, C-H, and N-H stretching vibrations found in the mid-infrared region (Shenk et al. 1992). The chemical groups responsible for spectral absorption in the NIR region are mainly in the form of X-H, where X corresponds to carbon, oxygen, or nitrogen atoms (Bertrand 2001, Shenk et al. 1992). Shenk et al. (1992) further reported the presence of other important functional groups such as carbonyl, carbon-to-oxygen stretching vibrations, and metal halides. Information on the structural or "skeletal" bending and distortion within a molecule occur at higher wavelengths.

Generally, the near infrared region is defined as comprising the wavelengths from 700-3000 nm (Hruschka 1987, Norris 1989b). However the wavelengths in the region of 1100 to 2500 nm are used in most diffuse reflectance analysis (Hruschka 1987, Murray and Williams 1987).

## Calibration Equation Development

Near infrared spectra contain relevant information on the physical and biological characteristics of the measured samples. However, such information is hidden in the spectra, and requires some effort to be properly extracted. To properly extra this information requires calibration process relating the spectra data to a reference data set using chemometrical procedures (Bertrand 2001). Chemometrics refers to the use of mathematics, statistics, and computer science methods for improving the extraction of useful information from chemical

measurement data (Geladi 1995). Shenk and Westerhaus (1996) described calibration as a process of creating a spectro-chemical prediction model. The purpose therefore would be to relate the concentration of some analyte found in a sample by reference laboratory methods to the spectral data collected from that sample (Workman 1992). The ultimate objective of developing calibration model is to obtain a predictive equation that can be subsequently used to determine the constituent of interest using NIRS alone thereby bypassing the laboratory method.

The calibration process begins with obtaining a sample set of interest, such as cereal grains, forage or feces. The sample set selected must meet certain criteria. Component concentration within the samples set should include a complete range of interest as well as being fairly distributed. The even concentration distribution allows the model to minimize the residuals at the extremes and at the center with relatively equal weighting. Furthermore, the sample set should be representative of type of samples to be analyzed in the general analysis procedure in the future (Workman 1992). Workman (1992) listed several common sources of error in NIR calibration. Among the critical ones are the particle size of samples, moisture (O-H stretch) content, and temperature at which spectra were obtained. Laboratory processing through drying, grinding, and drying temperature of the calibration sample set for NIRS, as well as ambient temperature at which NIRS samples were prepared should be consistent with the method to be used in routine analysis. Drying and

grinding procedures are very important since water is a strong absorber in the NIR region and sample particle size also affects the shape of the spectrum (Workman 1992, Stuth et al. 2003b). Temperature also affects the shape of the spectra shifting the expression of absorption peaks and possibly altering the interpretation of a spectrum (Stuth et al. 2003b).

The spectra and the laboratory reference data thus acquired are matched and stored as the calibration file. Mathematical and statistical procedures are then performed on the calibration file, and the calibration file is taken through several pretreatment steps. Such procedures as the use of repeatability files, standard normal variate (SNV)-detrend, multiplicative scatter correction, and derivatization are used to account for such common errors as residual moisture in samples, light scatter and path length variations (Deaville and Flynn 2000). SNV scales each spectrum to have a standard deviation of 1.0 to help reduce the particle effects, while detrend removes the linear and quadratic curvature of each spectrum (ISI 2002). Derivative math treatments are essential for resolving band overlap and baseline drift errors (Williams 1987, Workman 1992). The first-, and second-order derivatives of log (1/R) math treatments are the most common forms in which spectra of agricultural products are displayed; third-, and fourth-order derivatives are possible but are rarely used to interpret spectra meaningfully due to mathematical artifacts such as false valleys and side lobe bands exhibited in fourth-order (Shenk et al. 1992). Furthermore, third and fourth order calibration equations cannot be transferred from one NIRS machine

to another (Stuth, personal communication). The second-order derivative calculation results in a spectral pattern display of absorption peaks pointing down rather than up, thereby giving it the advantage of generating fewer, if any, false peaks in the negative direction. In this form the spectra is easier to interpret since band intensity and peak location are maintained with those in the log (1/R) spectra pattern, and apparent band resolution is equally enhanced (Shenk et al. 1992). Several multivariate regression statistical procedures such as stepwise multiple regression (SMR) using individual wavelengths, partial least square (PLS) (Workman 1992, Bertrand 2001, Stuth et al. 2003b) or principal component analysis (PCA) (Workman 1992, Bertrand 2001) using the full spectrum have been developed and applied to spectral data. Stepwise multiple regression, probably the simplest and most often used technique has a problem of allowing intercorrelation (multi-collinearity) between spectral data, which is avoided by principal component and partial least square analyses. Partial least square is said to be the more preferred analysis since it uses reference data as well as spectral data to derive the predictions (Deaville and Flynn 2000).

Once the calibration equation has been developed the best equation selection and validation would be based on the following parameters; standard error of calibration (SEC), standard error of laboratory (SEL), coefficient of determination ($R^2$), standard error of cross validation (SECV), F-statistic, wavelength coefficient magnitude**,** examination of wavelengths to determine biological significant of their associated chemical bonds, and finally the

geographical robustness of the equation (Westerhaus 1987, Shenk and Westerhaus 1996).

## Agricultural Applications of NIRS

Near infrared reflectance spectroscopy (NIRS) has a long history of use in direct quality determining of agricultural produce for quality control, breeding, and nutritive value evaluation purposes. NIRS has been used widely in determining constituents such as moisture, protein, and oil in grains, an area in which the application has received wide use (Pierce et al. 1996). NIRS has also been used to predict a wide range of forage quality parameters such as dry matter (DM), CP and digestibility with superior predictions of nutritive values than chemical analysis or bioassays (Holechek et al. 1982b, Barber et al. 1990, Flinn and Downes 1996, Adesogan et al. 1998). The technique has also been upheld as a cost saving method over traditional method as well as having great predictive potential in routine analysis of soil parameters such as clay content, cation exchange capacity, base saturation, and pH (Stenberg 1995, Foley et al. 1998), organic carbon, total N, and pH (Moron and Cozzolino 2002), texture, Fe, Zn, and Cu (Moron and Cozzolino 2003). The technology has been used in predicting the diet quality of grazing livestock and wildlife via fecal analysis (Lyons and Stuth 1992, Leite and Stuth 1995, Whitley 1996, Showers 1997, Coates 1998, Ossiya 1999, Gibbs et al. 2002, Krachounov and Kirilov 2000, Li et al. 2004). Subsequent discussions will be limited to the direct and indirect

agricultural applications of NIRS in relation to forage and diet evaluation of the ruminant livestock.

**Direct Application**

NIRS has been used to successfully predict the botanical composition of grass-legume mixtures clipped from field plots (Coleman and Shenk 1990), and from esophageal extrusa samples, though NIRS could not quantify adequately the minor component from the extrusa (Volesky and Coleman 1996). Thus, Volesky and Coleman (1996) concluded that the NIRS offers an acceptable precision and accuracy in the predicting major components of forage, and that the method is practical and efficient because of the reduction in the number of sample that would have to be microhistologically analyzed. Smart et al. (1998) used the technique to successfully predict leaf:stem ratios in monocultures of big bluestem (*Andropogon gerardii* Vitman) and switchgrass (*Panicum virgatum* L.) but not in smooth bromegrass (*Bromus inermis* Leyss).

Nutritive value of forages is often estimated on the basis of their chemical constituents such as nitrogen (N) or crude protein (CP) measured usually as (N x 6.25), crude fiber (CF), neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL). NIRS has been applied in predicting these constituents with high degree of accuracy in most instances (Holechek et al. 1982a, Park et al. 1983, Marten and Windham 1989, Mizuno et al. 1990, Berardo et al. 1997). Coefficients of determination ($R^2$) values of 0.93 or greater with standard errors well within laboratory errors have been obtained in

prediction of CP in forages (Marten and Windham 1989, Mizuno et al. 1990, Berardo et al. 1997, Lindgren 1998). The relatively strong NH absorptions in the NIR region are the primary reasons for these good relationships. Furthermore the high concentration of CP, which in forages and feeds can range from 30 to 500 g $kg^{-1}$ DM is a contributing factor (Roberts et al. 2003).

Fiber constituent comes next to nitrogen components in chemical analysis of forages /crop residues. NDF and ADF are the most common forms in which fiber is reported. Fiber as well as digestibility though not true nutrients but rather properties of forages have been predicted with NIRS with considerable success (Flinn and Downes 1996, Bertrand 2001). 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 (Stuth et al. 2003b). For example, Berardo et al. (1997) working in Zimbabwe obtained $R^2$ of 0.95 and above for NDF, ADF and ADL in pigeon pea [*Cajanus cajan* (L.) Huth], while Mizuno et al. (1997) reported $R^2$ of 0.97, 0.96, and 0.90 for NDF and ADF and ADL respectively for temperate grasses and legumes. Cosgrove et al. (1994) reported $R^2$ of 0.97 for NDF of extrusa samples from steers grazing temperate pasture grasses and there was no difference in value for ash corrected NDF.

Livestock performance is the best index of feed quality especially under controlled environments. However, public outcry against animal experimentation, the high cost, and labor-intensive nature limit such experimentations. Therefore, animal performance is usually estimated from less

animal-based techniques or indirect methods. For example, the two-stage *in vitro* technique of Tilley and Terry (1963) has been acclaimed as the most useful method for predicting digestibility *in vivo* (De Boever et al. 1988). The indirect methods lack ease and rapidity of estimation, a situation that seems to be resolved by the advent of NIRS technology. Norris et al. (1976) reported the first successful prediction of digestibility, dry matter intake, and digestible energy intake of grass and legume forages fed to sheep, since then NIRS method has been widely used for forage quality testing. Marten and Windham (1989) observed NIRS to be generally accurate for forage evaluation in crop management, physiology, genetic, and breeding research programs. The authors further indicated that the NIRS method is faster, and quite reliable for evaluation of feeding value attributes of forages and other feedstuff provided the proper procedures are followed. Lippke et al. (1989) recorded high correlation between NIRS predicted and validated dry matter digestibility (DDM) of several grass hays, dry organic matter intake (DOMI), and average daily weight gain (ADG) of coastal bermudagrass. NIRS has been used to predict organic matter digestibility (OMD) of fresh grass, hay, and grass silage successfully (Biston et al. 1989). Coefficients of determination ($R^2$) reported in these studies were 0.92, 0.95 and 0.89, respectively. Coefficient of prediction was equally high, above 0.90 except in silage 0.77, while standard error of prediction (SEP) ranged from 1.6 to 2.2 g $kg^{-1}$.

Baker and Barnes (1990) reported the development of NIRS predictive equations for *in vivo* digestibility of organic matter in the dry matter (DOMD) for grass silage and cereal straws with an acceptable accuracy and precision. The equations were capable of being used over several seasons thereby eliminating seasonal variation that affected NIRS predicted data. The coefficient of determination ($R^2$), and corresponding SEC for grass silage and cereal straws were 0.81, 2.77% and 0.78, 2.94%, respectively. In a similar experiment to compare the different methods of OMD of grass silage determination used by government advisory bodies across UK and Ireland, Barber et al. (1990) reported that NIRS gave the best single predictive equation using multiple regression ($R^2$ = 0.85, SEC = 0.025 g $kg^{-1}$). The next best technique, *in vitro* organic matter digestibility gave a single regression line ($R^2$ = 0.74, RSD = 0.032 g $kg^{-1}$) for all silages populations (RSD = residual standard deviation). NIRS also gave the best prediction of the OMD of a blind test population of grass silages. In furtherance to Barber et al.'s work, Baker et al. (1994) obtained the highest predictive ability for OMD using the second derivative modified partial least square regression (MPLS) in combination with scatter correction and noise repeatability procedures. The best calibration equation of Baker et al. (1994) did not distinguish between grass silages made in clamps or as big bales wrapped in plastics. The best equation of Baker et al. (1994) had $R^2$ = 0.89, SEC = 2.09% with validation statistics of $R^2$ = 0.82 and SEP = 2.35%. Park et al. (1997) came to a firm conclusion that NIRS is most accurate for predicting *in*

*vivo* OMD and voluntary intake of grass silage by cattle and sheep. Calibration statistics obtained on 136 samples were $R^2$ = 0.94, SEC = 1.64 g $kg^{-1}$ for *in vivo* OMD and $R^2$ = 0.90 and SEC = 3.43 g $kg^{-1}$ for voluntary intake using MPLS regression in both cases. On whole crop wheat silage, Adesogan et al. (1998) found NIRS to be most promising in predicting *in vivo* DOMD of the silage.

On wet forage analysis, Gordon et al. (1998) and Park et al. (1998) demonstrated that NIRS could be used to predict, with most accuracy, *in vivo* OMD of undried grass silages. Park et al. (1998) further indicated that the technique could also be used to provide accurate predictions of other digestibility parameters such as dry matter, nitrogen, and NDF in undried grass silage.

**Indirect Fecal NIRS Analysis to Predict Livestock Diet Quality**

Fecal monitoring with the NIRS was reported as a potentially useful tool in assessing the diet quality of free-ranging herbivores (Brooks et al. 1984, Coleman et al. 1989, Stuth et al. 1989). Lyons and Stuth (1992) predicted dietary CP and digestible organic matter (DOM) of free ranging cattle with indirect fecal NIRS analysis to a degree of precision equivalent to conventional laboratory diet analysis. The authors developed calibration equations for CP and DOM for cattle grazing two different rangelands with a diverse plant composition. Calibration statistics of $R^2$ and SEC reported were 0.92, 0.89% for CP and 0.80, 1.66% for DOM. The corresponding validation statistics, coefficient of determination for validation ($r^2$) and standard error of validation corrected for bias (SEV (C)) were 0.93, 0.86% for CP and 0.80, 1.65% for DOM.

The calibration and validation values were comparable to the standard error of laboratory (SEL) of 0.44% for CP and 1.68% for DOM. In the same experiment, the authors observed that physiological state of the animals did not affect the NIRS calibration and predictions.

Whitley (1996) successfully developed NIRS calibration equation to predict fractional protein utilization in cattle for warm season, but the cool season equation was not very successful. Warm-season calibration statistics obtained for degradable intake protein (DIP), digestible undegraded protein (DUP), and indigestible intake protein (IIP) were SEC 0.96%, 0.36%, and 0.25%, respectively, while $R^2$ were 0.81, 0.94, and 0.97, respectively.

Coates (1998) examined the applicability of fecal NIRS technology under tropical Australian conditions, and observed that fecal NIRS could predict accurately the diet quality of cattle under grazed and stall-fed conditions as well as $C_3$ / $C_4$ composition of the diet of the grazing cattle. Samples derived from grazed pastures used in the calibration set were diverse as to quality, source, location, season, and year. Calibration statistics reported for dietary N were $R^2$ = 0.94, SEC = 0.133% from extrusa samples under grazed conditions, while stall-fed statistics were $R^2$ =0.99, SEC = 0.087%. *In vivo* DDM calibration statistics in Coates' studies were $R^2$ = 0.89, SEC = 0.025%. The stall-fed calibration statistics were better than those obtained from esophageal extrusa samples under grazing conditions. Coates (1998) suggested that the difference in results could be due to the greater accuracy in the derivation of reference

values from stall experiments. Surprisingly, Coates (1998) observed that *in vivo* DMD was poorly correlated with *in vitro* dry matter digestibility (IVDMD) using pepsin-cellulase technique, concluding that IVDMD analysis may not be accurate for estimates *in vivo* DMD for tropical forages as suggested in literature. Coates (1998) observed that fecal NIRS is potentially a good predictor of digestible dry matter intake (DDMI) in tropical forages, though Lyons and Stuth (1992) reported on the contrary. Further work by Coates (1999) was an indicative proof that NIRS could be used satisfactorily to track temporal changes in diet composition and nutritive value of grazing livestock. NIRS technology therefore has the potential to substantially improve the interpretation of experimental results, the understanding of grazing systems, and the development of relationship between animal performance and diet quality. Recently, Gibbs et al. (2002) developed fecal NIRS calibration equations to predict dietary CP% and DMD% of Australian range cattle fed supplements. Calibration statistics reported were $R^2$ of 0.99 for CP and 0.87-0.93% for DMD with corresponding SEC of 1.28 and 2.38-2.63 %, respectively.

Purnomoadi et al. (1996, 1997), working with dairy cattle in Japan, investigated the applicability of NIRS to predict the chemical composition of feces, and to estimate the digestibility and energy value of the diets indirectly or in a secondary mode by lignin indicator method. Chemical analysis of the lignin indicator was determined by both conventional laboratory procedure (Purnomoadi et al. 1996), and by NIRS prediction, then separate calibration

equations were developed for both feed and fecal samples. These equations were the used to predict the lignin concentrations in the diets. Purnomoadi et al. (1996) reported high correlation coefficients between lignin indicator laboratory (LIGLab) and lignin indicator NIRS (LIGNIRS) values for CP, dry matter (DM) organic matter (OM), acid detergent fiber (ADF), crude fiber (CF), lignin, ether extract (EE) and energy. On comparison, Purnomoadi et al. (1996) observed that *in vivo* digestibility values for DM, OM, CP, ADF, CF, EE were similar to those obtained through LIGLab and LIGNIRS, respectively. The authors therefore concluded that digestibility estimation using lignin determined by NIRS, as an indicator was useful for the routine evaluation of nutritive values of diets because the procedure is simple, fast, and accurate.

In sub-Saharan Africa, Stuth (1999) tested the USA equation (Stuth et al. 1999) on fecal material obtained from cattle grazing *Acacia senegal* and *Commiphera sp* savanna rangeland in Kenya, *Acacia sp*./*Panicum maximum* rangelands in southwestern Uganda, *Acacia tortillas*/*Pennisetum sp*. savanna in Ethiopia. The results indicated that the USA equation has a potential to predict diets in these tropical regions (Stuth 1999). However Ossiya (1999) and Awuma (unpublished data) observed that the USA equation could not predict some of the West African samples effectively. The weak prediction in Ossiya and Awuma's studies could be due to differences in species diversity and chemistry, and metabolic end products of feces from West Africa. Ossiya (1999) developed calibration equations for cattle and sheep form historical diet-fecal pair samples

from International Livestock Research Institute (ILRI) regional centers in Ethiopia, Nigeria, and Niger. Calibration results for combined location data reported were, for cattle $R^2$ = 0.95, SEC = 1.04% for CP, and $R^2$ = 0.91, SEC = 3.39% for DOM. In the case of sheep $R^2$ = 0.87, SEC = 1.46% for CP, and $R^2$ = 0.89, SEC = 3.21% for DOM were calibration statistics reported.

Further fecal NIRS studies in sheep were conducted by Krachounov and Kirilov (2000) in Bulgaria, and Li et al. (2004) in College Station, Texas. Krachounov and Kirilov (2000) developed a calibration equation for predicting *in vivo* DMD for sheep based on an array of stall-fed forages (n = 119) in Germany and Bulgaria. Calibration statistics obtained were $R^2$ = 0.94, SEC = 2.26%. Li et al. (2004) reported the following calibration statistics for sheep, $R^2$ of 0.95 and 0.80 for CP and DOM, respectively. The corresponding SECs were 1.08% and 1.51% for CP and DOM, respectively. Furthermore Li et al. (2004) observed that individual animal variation accounted for about 25-30% of the measurement error in the experiment.

Lyons and Stuth (1992) observed that fecal profiling equation developed for cattle could not work satisfactorily on goats, an indication that goats have different fecal biochemistry from that of cattle, hence the need for a separate equation for goats. Leite and Stuth (1995) therefore developed calibration equations for predicting the CP and DOM content of diets of free-ranging goats. The coefficient of determination ($R^2$) for CP and DOM were 0.94 and 0.93, the corresponding SEC were 1.12% for CP and 2.02% for DOM.

NIRS research has been extended into the wildlife sector as well; studies carried out by Brooks et al. (1984) on elk, Gallagher (1990) and Showers (1997) on white-tailed deer are discussed. Brooks et al. (1984) developed calibration equation to predict dietary CP and DMD of captive elk. The calibration was deemed successful though samples used were small (n = 36). Calibration statistics reported were $R^2$ of 0.99 and 0.88 for CP and DMD, respectively while corresponding SEC were 0.50% and 2.20% for CP and DMD, respectively.

Gallagher (1990) reported $R^2$ of 0.86 and 0.76, respectively, for CP and DMD with corresponding SEC values of 1.37% and 6.7% for CP and DMD, respectively, for captive white-tailed deer fed on natural forage and pelleted diets. Showers (1997) successfully developed a calibration equation for predicting the diet quality (CP, DOM, and P) of white-tailed deer with high degree of success in a validation trail. The calibration statistics reported were $R^2$ 0.94 for CP, 0.89 for DOM, and 0.94 for phosphorus (P). Corresponding SEC values were 0.70% for CP, 2.64% for DOM, and 0.02% for P. These studies demonstrated the feasibility of using NIRS profiling to predict the nutritional status of wildlife.

NIRS has been used to directly determine tannin concentrations in forages (Windham et al. 1988, Roberts et al. 1993, Goodchild et al. 1998). The feasibility of using fecal NIRS to indirectly predict dietary tannin content has been explored. Ossiya (1999) developed fecal NIRS calibration equation for predicting dietary tannin content in diet of sheep though only a moderate

success was attained in the validation trail. Calibration statistics were $R^2$ = 0.91, SEC = 9.02 g $kg^{-1}$, and validation $R^2$ = 0.61, SEP = 57.79 g $kg^{-1}$.

To translate the NIRS diet quality prediction into a more meaningful analysis, the Nutritional Balance Analyzer (NUTBAL) decision support system was developed to assist the user in obtaining nutritional balance report of the grazing livestock (Stuth et al. 1999). The NUTBAL system is a computerized decision aid that offers a mechanism to capture the complexity of the diet, the physiology of the animal, and the environment to predict the nutritional well being of domesticated ruminant livestock. The parameters considered in the NUTBAL system are the general characteristics (i.e., breed, class, age, body condition, physiological stage) of the animal, environmental condition (i.e., terrain, temperature, humidity, wind speed, and sunshine hours), forage conditions (i.e., standing crop or grazing pressure), other feedstuff on offer and the use of metabolic modifiers. When the NIRS predicted data are entered, the NUTBAL system produces a nutritional balance report of crude protein and net energy for maintenance or gain of the animal, and it predicts weight gain/loss. In addition the system helps to determine the amount of least-cost feedstuff necessary to correct any nutritional deficiency detected (Stuth and Lyons 1995)

The Ranching System Group, in the Department of Rangeland Ecology and Management, Texas A&M University, has deployed the NIRS/NUTBAL nutritional management system program in the USA since 1994. Currently, over 1,400 ranchers from 42 states are using the system (Stuth et al. 1999).

Preliminary tests with NIRS fecal profiling were conducted in East Africa (Stuth 1997). Further, implementation has been initiated in the Horn of Africa in association with the USAID Global Livestock Collaborative Research Support Program (GL-CRSP) subproject focused on livestock early warning system, in East Africa and the Crisis Mitigation Program, at ILRI, Ethiopia (GL-CRSP 2000).

## The Use of Normalized Differential Vegetation Index (NDVI) and Geostatistical Techniques in Range Diet Quality Mapping

Geostatistics is a branch of applied statistics that focuses on the detection, modeling, and estimation of spatial data (Rossi et al. 1992), accounting for spatial and temporal dependence of phenomena, which has not been the case with conventional statistical methods (Rossi et al. 1992). Tools such as variograms are used to model spatial dependency or variability in an observation, while kriging and cokriging are used to estimate observations in unrecorded location thus enabling the observations to be mapped (Rossi et al. 1992). Kriging is an optimal technique for linear unbiased estimation (Webster et al. 1989). As an interpolation method, ordinary kriging can provide estimates for unknown points by using the weighted linear average of the available samples (Rossi et al. 1994). Kriging is often described as the Best Linear Unbiased Estimator (B.L.U.E.) (Isaaks and Srivastava 1989). It is “best” because the variance of the errors is minimized, linear because the estimates are weighted linear combinations of the sample data, and unbiased in that the

average error is equal to zero (Isaaks and Srivastava 1989). Cokriging, which is an improvement on ordinary kriging, involves the use of a secondary variable (covariate) that is cross-correlated with the primary variable of interest. The secondary variable is usually the one most frequently and regularly sampled thus allowing estimation of unknown points using both variables. The use of covariate minimizes the error variance of the estimation (Isaaks and Srivastava 1989). The fundamental basis for using cokriging in estimating properties of natural resources at the ground level is that soil, vegetation, and radiation from the natural resources are spatially correlated, both to themselves (autocorrelated) and to one another (cross-correlated) (Myers 1982, Journel 1989, Bian and Walsh 1993). Consequently such parameters can be estimated form local (e.g., point) data

Remotely sensed data can be analyzed to provide measurements of features or phenomena on the surface of the earth using several techniques such as Normalized Differential Vegetation Index (NDVI). NDVI is a plant tissue condition index calculated from reflectance values in the red and near-infrared bands obtained from National Oceanographic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellites (Aronoff 1989), and processed by the Global Inventory Monitoring and Modeling Studies (GIMMS) at NASA. NDVI data for Africa is available to the public at the Africa Data Dissemination Service (ADDS) website maintained by the United

States Geological Services (USGS) Earth Resources Observation Systems (EROS) data center (http://edcintl.cr.usgs.gov/adds/adds.html).

Kriging and cokriging are statistical techniques that can be utilized when measurements are made at scattered points. Furthermore, when the forms of semivariogram, and cross-semivariogram are known, it is possible to estimate the concentrations of the variable at any unsampled location by kriging and cokriging techniques (Chang et al. 1998). Semivariogram is a function that relates semivariance (or dissimilarity) of data points to the distance that separates them. The graphical representation of semivariogram can be used to provide a picture of the spatial correlation of the data points with their neighbors (Johnson et al. 2001). Chang et al. (1998) demonstrated that the use of kriging and cokriging would allow for reduction in sampling density to as much as 50% of the original without lost of spatial information in a long term monitoring program of the fate and effects of contamination within the environment. Geostatistical estimators such as indicator kriging and ordinary kriging can be useful in remote sensing by estimating values for missing pixels. Rossi et al. (1994) used indicator kriging to interpolate pixels obscured by clouds and cloud shadows in a Landsat Thematic Mapper (LTM) image of pasture areas in Ciapas, Mexico without lost of spatial information. However, the authors cautioned that the application of indicator kriging in other missing data problem for remotely sensed images will depend on the amount and spatial pattern of the obscured pixels and the success of the spatial continuity mode used.

Cokiging has been use with NOAA AVHRR NDVI or greenness index to estimate total forage availability (kg $ha^{-1}$) from values simulated by PHYGROW (Phytomass Growth Simulator) (Rowan 1995) model for 30 pastoral households in southern Kenya (Angerer et al. 2001), and in pastoral areas of five countries in the Horn of Africa (Stuth et al. 2003a) successfully. The results of the cokriged output in each case were used to create surface maps within which areas of drought in 2002 were successfully identified (Angerer et al. 2001, Stuth et al. 2003a). Likewise cokriging, NDVI data, CP and DOM values derived from geo-referenced fecal NIRS scans have been used to interpolate point-based CP and DOM data with promising results in East Africa (GL-CRSP 2000). However the use of cokriging, NDVI data, and NIRS predicted CP and DOM to map out diet quality patterns in a grazing environment is an entirely new field being explored.

# CHAPTER III

# DEVELOPMENT OF ENHANCED FECAL NIRS CALIBRATION EQUATIONS TO PREDICT DIET QUALITY OF FREE-RANGING LIVESTOCK IN SUB-SAHARAN AFRICA

## Introduction

Livestock rearing is a way of life for the majority of the rural people in sub-Saharan Africa (SSA), yet some form of meat and milk deficit occurs across these vast tracts of rangeland despite the large animal population within the region. The fact remains that the livestock production systems of SSA are beset with numerous problems (Chapter I), prominent among them are the nutrition of the animals and a means of monitoring the nutritional well being of the free-ranging livestock. Recent studies have conclusively proved the suitability of fecal NIRS as a tool for nutritional profiling of the diet quality of the free-ranging livestock. Fecal NIRS calibration equations have been developed for predicting the CP and DOM of free-ranging cattle (Lyons and Stuth 1992, Coates 1998, Gibbs et al. 2002), for sheep (Krachounov and Kirilov 2000, Li et al. 2004, abstracts), for goats (Leite and Stuth 1995), for deer (Showers 1997), and for donkeys (Kidane and Stuth 2004). Ossiya (1999) demonstrated that the technique could be applied in Africa for cattle and sheep, and further investigated the suitability of NIRS fecal profiling to determine condensed tannin concentration of diets consumed by sheep using diet-fecal pair data. Gibbs et al. (2002) established that fecal NIRS calibration equations could be designed to

predict dietary digestibility and CP content for cattle fed concentrate supplements. The degree of accuracy (i.e. standard error of calibration, SEC) in all cases was equivalent to those obtainable using the conventional wet chemistry analysis under controlled feeding conditions. NIRS fecal profiling technology is eventually cheaper, reliable, easy to manage, and allows profiling of animals in pastoral setting, a criteria for application in agricultural extension methods. Stuth et al. (2003b) established that nutritional monitoring system via fecal analysis could be integrated with nutritional management system to provide needed information necessary for least cost feed interventions to be provided before emaciation becomes externally visible in the animal. Furthermore, used in conjunction with early warning weather system, the nutritional profiling technique could provide indicators for trends in possible weight loss due to inadequacy of feed in which case animals could be disposed off before catastrophic losses occur due to severe drought or moved to areas with better forage conditions (Stuth et al. 2003a).

Given the need for improved technology to assess the nutritional status of livestock in SSA, this study seeks to demonstrate that fecal NIRS profiling can reliably predict crude protein (CP%) and digestible organic matter (DOM%) for cattle, sheep, and goats across the expanse of SSA.

## Study Area Description

The data for the study were collected from seven countries within sub-Saharan Africa. The seven countries represent the five agro-ecological zones,

which stretch across sub-Saharan Africa from the Atlantic to the Indian Ocean. Highlands are represented by Debre Zeit, Ethiopia; humid zone by Ibadan, Nigeria, and Mpwapwa, Tanzania; sub-humid zone by Kiboko, Kenya, Mbarara, Uganda, and northern savanna of Ghana; semi-arid and arid zones by Bundu, Sadore, and Toukounous in Niger and Adami Tulu, Ethiopia (Fig. 1). Agro-ecological classification is based on rainfall, the length of the growing period (LPG), and altitude as it affects temperature. The LPG refers to the period in days during the year when rain-fed available moisture supply is greater than half the potential evapo-transpiration (PET) (Seré et al. 1996). The agro-ecological zones are therefore demarcated into: arid with less than 75 days LPG; semi-arid with LPG ranging from 75 to 180 days; sub-humid with LPG range of 180-270 days; and humid with LPG greater than 270 days (Seré et al. 1996). Highland areas are defined by mean monthly temperatures of less than 20° C during the growing season due to the effect of altitude on climate (Jahnke 1982, Seré et al. 1996).

Debre-Zeit, representing highland sites in this study is located at 1,850 m above sea level with temperature ranging from 5°-34° C and an average annual rainfall of 713 mm. Humid zone is characterized by mean annual rainfall of greater than 1,200 mm with usually high relative humidity and temperature. The natural vegetation is tall, closed forest which may be evergreen or semi-deciduous growing in soils that include Oxisols, Ultisols, and Alfisols (Blair-Rains 1986). The subhumid zone lies within 600-1,200 mm rainfall isohytes with

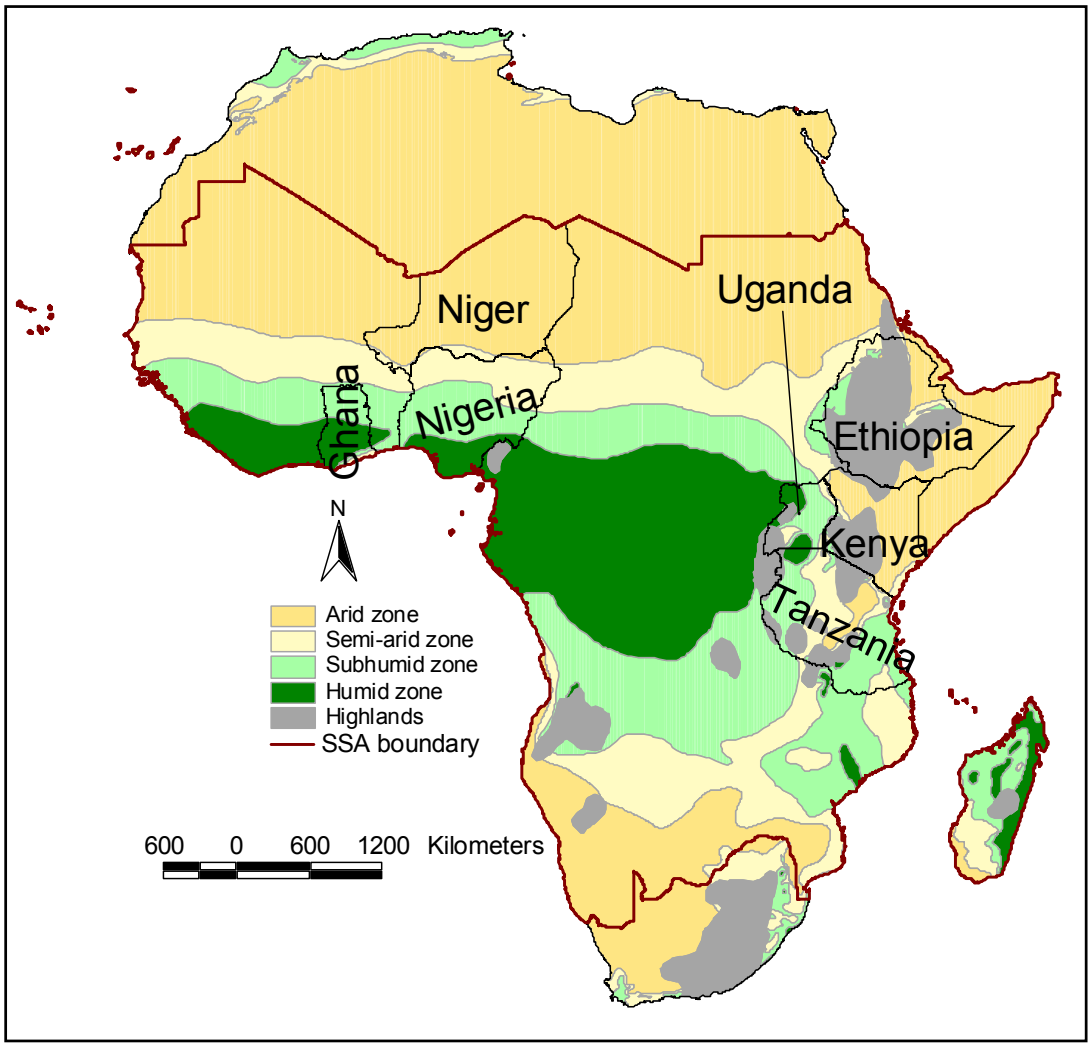


Fig. 1. Afro-ecological zones of Africa with superimposed SSA countries from which diet-fecal pair data were generated.

Alfisols and tropepts soil types occurring widely (Blair-Rains 1986). The natural vegetation is a medium-height or low woodland with understory shrubs, and a ground cover of medium to tall perennial grasses. Low rainfall and long dry season are the mark of the semi-arid zones, with mean annual rainfall ranging from 400-600 mm. Characteristic soil series are sandy (Aridisols) and tropepts. The natural vegetation is mainly open grassland with scattered trees (Blair-Rains 1986). The arid zone receives less than 400 mm mean annual rainfall. The soils are mainly sandy (Aridisols), weakly differentiated and low in plant nutrients. Vegetation consists of scattered shrubs in a sparse cover of mainly annual grasses (Blair-Rains 1986). In all the zones, livestock production is rangeland based with crop residues forming components of the diet of the animals.

## Methodology

### Data Sources

To develop fecal NIRS profiling system, a calibration equation must be developed based on pairing fecal NIRS spectra with known diet qualities, i.e. diet-fecal pairs. Data on diet-fecal pairs used in this study came from three sources. The first group came from trials involving cattle, sheep, and goats fed hand formulated rations of native vegetation in studies conducted by the Livestock Early Warning System (LEWS) project in Ethiopia, Kenya, Uganda, and Tanzania. LEWS is part of the larger Global Livestock Collaborative Research Program (GL-CRSP), a USAID funded program (Stuth et al. 2003a).

The second source of data came from feeding trials conducted in Ghana. Finally, historical diet-fecal pair data generated from 1992–1997 from ILRI research centers in Ethiopia, Nigeria, and Niger (Ossiya 1999) were included. The first two trials were specifically designed to generate diet-fecal pair data for developing fecal NIRS calibration equations.

All fecal samples generated in these studies were dried in forced-air oven at 60° C for 48 hrs to thoroughly dry, and pulverized. About 20g sub-samples of diet and matching fecal samples were sealed in ziplock or other plastic sampling bags and shipped from the various location in SSA to SteriGenics irradiation facility (APHIS approved) in New Jersey. At SteriGenics the samples were exposed to two, 3-MRAD doses, and transferred to the Grazingland Animal Nutrition Laboratory (GANLAB) at Texas A&M University (TAMU), College Station, Texas, for further analysis. APHIS refers to Animal and Plant Health Inspection Services of USDA.

**Generating Ghana Component of Diet-Fecal Pair Data**

In order to generate the Ghana component of diet-fecal data, a series of rations of diverse forage types (Table 1) were hand formulated and stall-fed to young animals. Number of forage species per ration ranged from 4 to 14 and the rations were designed to contain CP contents in the range of 4 to 15% for cattle, sheep, and goats, respectively. The rations per species of livestock were grouped into CP ranges such as low (4.8-8.9%), moderate (9.0-11.9%), and high (12.0-15.0%) respectively. The compositions of the rations are shown in

Appendix Tables 1 (a-d), 2 (a-d), and 3 (a-d) for cattle, sheep, and goats respectively.

Feeding trials were conducted in April and September 2000, representing the dry and wet seasons, respectively. Twelve individual pens (stalls) measuring 2.4 x 1.3 x 1.75 m were constructed in the cattle shed. The lambing and kidding pens were used for the sheep and goats trials. The pens were subdivided into 2.6 x 1.0 m sizes to create 12 individual pens per animal species. The sheep pens had concrete floor while the goat pens had split wooden floors. Woven local mats were therefore placed on the floors of the goat pens to prevent the feces from falling through the wooden splits. Wooden feed troughs were provided in each pen. Galvanized watering troughs were provided in the cattle and sheep pens, while locally produced earthenware pots were provided in the goat pens. Intact young males of cattle (10), sheep (10), and goats (11) within 12 and 24 months of age were used for the trial. The animals were weighed and dewormed. The average weights of the individual animals were cattle 115 kg, sheep 24.5 kg, and goats 12.4 kg. The young bulls were mainly West African shorthorns (WAS) breeds, while the young rams and billies were of the Sahelian breeds.

Pen and ration allocation for each individual were done randomly by animal kind. Each trial was completed in 10 days. The first 7 days served as ration acclimation period, and days 8, 9, and 10 served as fecal collection days.

Table1: List of forage resources used in the Ghana feeding trial.

**Grasses (Monocots)**

Gamba grass (*Andropogon gayanus* Kunth.)

Gamba grass (*Andropogon tectorum* Kunth.)

Bracchiaria (*Brachiaria deflexa* Stapf.)

Brachiaria (*Brachiaria lata* Stapf.)

Buffel grass (*Pennisetum ciliare* L.)

Bermudagrass (*Cynodon dactylon*, (L) Pers.)

Crow's foot grass (*Eluesine indica* (L) Gaertn.)

Spear grass (*Heteropogon contortus* (L) Beauv.)

Jargua grass (*Hyparrhenia rufa* (Nees) Stapf.)

Paspalum (*Paspalum orbicluare* L.)

Paspalum (*Paspalum scrobiculatum* L.)

Elephant grass (*Pennisetum voilaceum* (*Fresen*)

Rottboellia (*Rottboellia cochichinensis* (Clayton)

Setaria (*Setaria barbata*)

**Cereal Crop Residues**

Maize stover (*Zea mays* L.)

Rice straw (*Oriza sativa* L.) (untreated)

Rice straw (urea treated)

**Leguminous Crop Residues**

Cowpea (*Vigna unguiculata* L.) vines hay (haulms)

Peanut (*Aracis hypogaea* L.) vine hay (haulms)

Pigeon pea [*Cajanus cajan* (L.) Huth] husk

Whole cottonseed (*Gossypium spp*.)

Table 1: Continued.

| **Browse Species** | **Non-leguminous Browse Species** |
|---|---|
| **Leguminous** | Securinega (*Securinega virosa*) |
| Afzelia (*Afzelia African***)** | Tephrosia (Tephrosia *bracteolate*) |
| Lebbeck (*Albizzia lebbeck* (L) Benth.) | Ficus (*Ficus gnaphalocarpa)* |
| Faedherbia (*Faedherbia albida* (Del) A. Chev.) | |
| Stylo (*Stylosanthes scabra* (Vog) cv verano | |
| Pigeon pea (*Cajanus cajan* (L) Millsp.) | |
| **Non-leguminous Browse Species** | |
| Anogeissus (*Anogeissus leiocarpus*) | |
| Silk cotton tree (*Ceiba pentandra*) | |
| Dry-zone Mahogany (*Khaya senegalensis*) | |
| Shea butter leaves (*Vitellaria paradoxa*) | |
| Pterocarpus (*Pterocarpus irrenaceus*) | |

Water and mineral block were provided *ad libitum* per animal, though clean water was provided each morning and refreshed at subsequent feeding time. Rations were fed twice daily: morning (0700-0900 hours) and afternoon (1400 to 1600 hours). Cattle and sheep were fed at 3% of their liveweight, while goats received rations at 4% of their liveweight. At each feeding time, each animal received one half of the calculated ration per day in the morning. Rations provided during afternoon feeding were adjusted according to an animal's consumption pattern. Before dusk, each day, (1800-1900 hours) animals were observed to ensure that each animal had been fed and watered. Each morning the orts were removed weighed out and added on top of current morning's ration allocation. The idea was to promote total consumption of the experimental diet as possible. By day 4 a clear pattern of what each animal was consuming emerged. Day 1 protocol was followed through to day 6. On day 7 all orts were discarded after weighting. Fresh ration assigned to each experimental animal were given according to requirement. This protocol was following through to day 10. Rations were sampled from each burlap sack into ziplock bags on days 5, 8, and 9, labeled accordingly and stored in Styrofoam ice chests in a cold room. After the feeding trials, days 5, 8, and 9 samples of each diet were composited, subsampled and labeled with respective ration numbers. Fecal samples per individual animal were collected on days 8, 9, and 10 according to ration, properly labeled with the ration number and date of collection. All feed and fecal samples were stored in ziplock polyethylene bags and stored in a cold room.

Fecal and corresponding diet samples generated were treated in the same manner as described above prior to shipment.

## Laboratory Analysis

### Crude Protein Determination

Diet samples were ground to pass through 2-mm sieve using a Wiley mill. Five-gram duplicate samples of each ground diet samples were put into individually labeled coin envelopes. One set of the duplicate diet sample were analyzed for CP content by micro-Kjeldahl procedure (AOAC 1995) using Hach System (Hach Co 1990) at the Soil, Water and Forage Testing Laboratory, Texas A&M University.

### DOM Determination

Digestible organic matter (DOM) of the diet samples was determined by 48-hr *in situ* rumen fermentation, using Ankom filter bag technique (Komarek et al. 1994), followed by 1-hr neutral detergent fiber (NDF) analysis (Van Soest and Wine 1967) using Ankom fiber analyzer. The 48-hr *in situ* fermentation replaced the *in vitro* fermentation of Tilley and Terry (1963).

Triplicates of 0.5 g each of diet samples were weighed into Ankom *in situ* rumen filter bags. Bags were labeled to correspond with individual diets, heat-sealed, and 20 bags containing diet samples were randomly placed in a nylon mesh-bag. Each (nylon) mesh-bag measures 45 by 39.5 cm with a nylon zipped input and output opening. Similar protocol was used to weigh out the 3 standards of known *in vivo* DOM. Two samples of each standard were placed in

each mesh-bag resulting in 26 sample bags per mesh-bag. The standards with known *in vivo* digestibility (OMD) were alfalfa (*Medicago sativa* L.) hay 76.26%, kleingrass (*Panicum coloratum* L.) hay 64.98%, and wheat (*Triticum aestivum* L.) straw 54.81%. The mesh-bags were suspended on 4 stainless steel hooks with about a meter nylon ropes in the rumen of fistulated steers for 48-hrs. The steers were grazing coastal bermudagrass (*Cynodon dactylon* (L.) Pers.) pastures in July 2001. The stainless steel hooks serve a second purpose of weighing down the mesh-bags in the rumen. Mesh-bags were removed from the rumen after 48-hrs, given an initial rinse with tap water to remove excess rumen contents and transferred to the laboratory.

In the laboratory, individual sample bags were washed with tap water followed by distilled water, gently squeezed to remove excess water and spread out to on sieve trays to drain. The samples were then digested with 2 liters of NDF solution for 1-hr in Ankom fiber analyzer according to Van Soest and Wine (1967) procedure. The NDF solution was drained out after the period and the samples agitated in the analyzer 4 times with 200 ml each of boiling distilled water. Samples were then removed from the analyzer, soaked in acetone for 2- to 3-minutes and the spread out to dry. The digested samples were oven-dried at 105° C and weighed. The digested samples were ashed at 500° C for 4.5-hrs in a muffle furnace to determine ash content. Prior to *in situ* fermentation, dry matter (DM%) and organic matter (OM%) were determined on each sample.

Forty-eight hour *in sacco*/1-hr NDF values, hitherto referred to as 48-*in vitro* values, were corrected to *in vivo* values using least square regression similar to method reported by Lyons (1990), Lyons and Stuth (1992), Leite and Stuth (1995), and Showers (1997). Standards were used to calculate a regression equation to correct 48-hr *in vitro* values of the standards to average asymptotic values. The average asymptotic value and the mean 48-hr in vitro of OMD value of each standard were used to calculate a correction factor for each standard. The known 48-hr *in vitro* OMD values were then regressed on the correction factor resulting in a regression equation that was used to calculate the time in bath correction factor (TIBCF) for the standards. Corrected TIB OMD for the standards were obtained as product of uncorrected TIB OMD and TIBCF. A further correction factor to adjust the 48-hr *in vitro* OMD values was calculated as a quotient of know *in vivo* OMD and TIBCF OMD for the standards. TIBCF OMD was then regressed on this factor to develop a regression equation for calculating *in vivo* correction factor (IVCF). The product of CTIB OMD and TICF resulted in *in vivo* corrected OMD. The unknown samples in the 48-hr *in vitro* run were corrected using the regression equations for TIBCF and IVCF. Corrected *in vivo* organic matter digestibility (IVCOMD) of each sample was then converted to DOM as the product of IVCOMD and the percent organic matter (OM) in each sample dry matter (DM). The final DOM value per sample was arrived at by computing the mean of any pairs of the resultant triplicate calculated DOM values with not more than two percentage points difference in

value, but where differences were greater than two percentage points the mean of all triplicate DOM values per sample were computed.

**Fecal Samples Preparation for Spectral Determination**

The pulverized fecal samples from the diet-fecal pair experiments were ground in Tecator cyclotec mill though a 1-mm screen to attain uniform particle size. Once grinding was completed the samples were stored in coin envelopes and oven dried at $60^{O}$ C overnight. The dried samples were put in ziplock polyethelene bags, sealed, and placed in a desiccator for a minimum of one hour to cool in order to stabilize the moisture content of the samples (Lyons 1990).

Samples removed from the desiccator were packed in quartz-windowed sample cups, placed in sample trays and stored in desiccator prior to scanning. Scanning was done using FOSS NIRSystems reflectance monochromator, Model 6500, equipped with three tilting filters and a spinning sample cup, that reads reflectance in the range of 1100-2500 nm at 2 nm intervals (Osborne and Fearn 1986, ISI 1992). NIR spectra thus obtained were stored in a microcomputer interfaced to the NIRS machine as log (1/R) values for the different wavelengths, using Infrasoft International (ISI) software NIRS 2, version 3.0 (ISI 1992). The Ghana diet-fecal pair experiment generated data set of 22 for cattle, and 23 for sheep and goats, respectively.

**Data Processing**

In the GANLAB, diet-fecal pair samples shipped from other SSA countries were processed between 1998-2000 to generate data for percent CP and DOM values for the respective livestock species. The LEWS project samples provided dietary wet chemistry and fecal spectral values for 88, 9, and 31 samples for cattle, sheep, and goat, respectively. Quantities of data generated from the ILRI source samples by Ossiya (1999) were 335, 368, and 240 for cattle, sheep, and goats, respectively.

Since the ILRI data were obtained from standard animal nutrition research, numerous replicated entries existed in the data set; similarly few replicates existed in the LEWS data. In order to identify the most appropriate samples for calibration equation development, the programs “CENTER and SELECT” (Shenk and Westerhaus (1991,1996) within the WINISI program suite were applied to the data. The programs rely on converting spectra to scores and measuring the distance between sample scores using Mahalanobis distance. The measured distance is referred to as the H-statistic. The ‘CENTER’ program develops a score-generating file (SGF) using principal component analysis, which is then used to compute the scores and measure the Mahalanobis distance from each sample to the average of the sample set. Samples with large H-statistic were flagged as potential candidates for elimination. SELECT measures the distance from each sample to every other sample, and this distance is used to define neighborhoods in the score space.

The purpose of SELECT is to identify one sample for every neighborhood. SELECT removes redundant samples from the sample data set (Shenk and Westerhaus 1996). The H-statistics for CENTER and SELECT are referred to as global-H (GH) and neighborhood-H (NH) respectively. In this study the GH and NH applied were 4.00 and 0.60 respectively. The procedure identified 86, 166, and 81 sample sizes for cattle, sheep, and goats, respectively as being most appropriate for inclusion in the calibration development. Finally, data sets from LEWS, Ghana, and ILRI were combined to create calibration data files specific to cattle, sheep, and goats, respectively.

## Calibration Equation Development Procedures

The development of an enhanced sub-Saharan African calibration equation is dependent on the inclusion of sufficient set of samples reflecting the diversity in terms of physical, chemical, and botanical composition of the target population. Calibration files with corresponding reference and spectra values consisted of 196, 198, and 135 sample sets for cattle, sheep, and goats, respectively. Calibration equation development involves regressing the reflectance data (log1/R spectra) on the reference (dietary wet chemistry) values, using different math treatments involving scatter correction-SNV (standard normal variant) and detrend, first or second derivatives of log (1/R), the gap, and degree of smoothing (Williams and Sobering 1996, ISI 2002). An example of first derivative math treatment of log (1/R) spectrum with corresponding wavelength range (1100-2500 nm) for a sample in cattle

calibration file is presented in Fig. 2. All equations were taken through two iterations to eliminate outliers (ISI 2002). Outliers result from poor fitting of laboratory data (t-outlier) or samples with spectra quite different from average spectrum (H-outliers) (Shenk and Westerhaus 1996). MPLS (modified partial least square) regression statistic was used in developing each equation.

Each math treatment resulted in a separate equation from which the best fitting equation was selected based on evaluation of the following criteria; standard error of calibration (SEC), standard error of laboratory determination (SEL), coefficient of determination ($R^2$) (Westerhaus 1989, Windham et al. 1989), standard error of cross validation (SECV) (ISI 2002), wavelength coefficient magnitude (Williams 1987), and examination of wavelengths to determine the biological significant of their associated bonds (Westerhaus 1989). Shenk and Westerhaus (1996) reported that SEC is an indication of how well the calculated regression line fits the reference values, and Westerhaus (1989) observed that lower SEC values are always the best choices. Therefore, the best choice calibration equations were the ones with the lowest SECs where dominant wavelengths made biological sense and over fitting did not occur.

Relatively severe critical t-values were applied to the equations to minimize the inter-lab errors given the diversity of laboratory sources for the data.

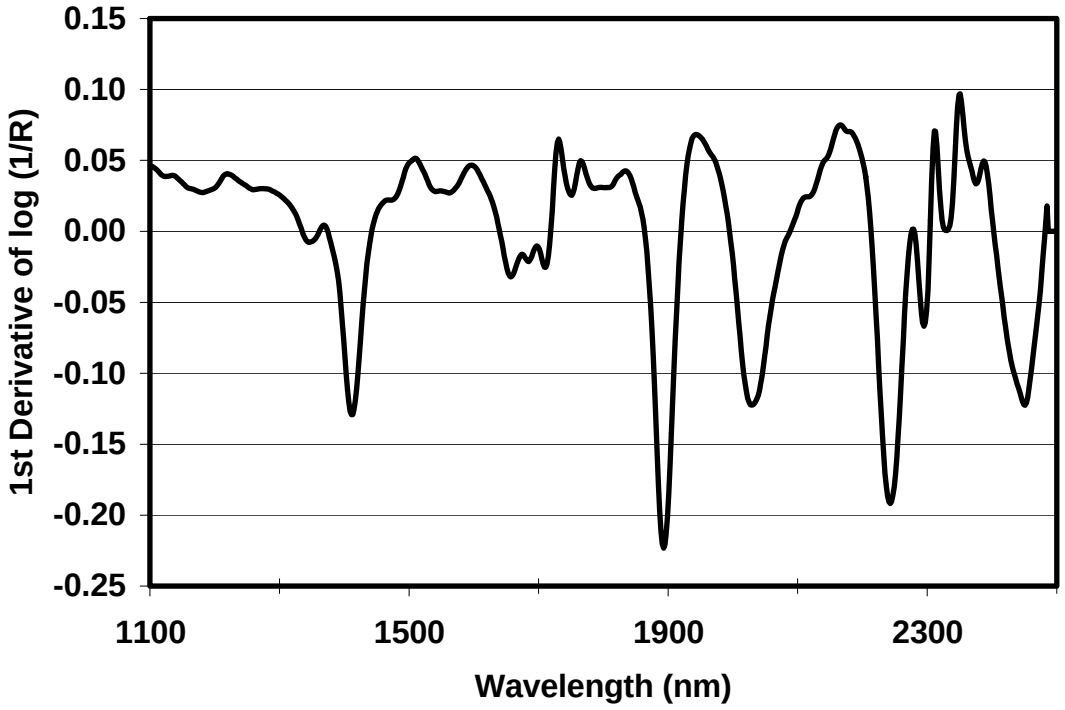


Fig. 2. First derivative math treatment of log (1/R) NIR spectrum of fecal sample indicating the absorption wavelength range.

Apart from CP equations for cattle and sheep that where developed with critical t-value of 1.65, the rest of the CP and DOM equations for cattle, sheep and goats were developed with critical t-value of 1.5

The ILRI source data came from three different laboratories with obvious different SELs, since SEL is the repeatability constant for wet chemistry analysis for a given constituent in a particular laboratory (Workman 1992). SEL is therefore laboratory specific. Including analyses done at Texas A&M on the LEWS and Ghana samples resulted in four different sources of SEL. Therefore to determine a final SEL for African equations, where data were available, a weighted average based on proportional number of samples contributed per laboratory to an equation from the different sources was used. SEL from GANLAB was used for cattle and in the case of DOM for sheep since SEL for 125 samples out of a total of 196 samples for cattle, and 167 out of 198 samples for sheep from ILR sources were not available.

## Results and Discussion

The range, mean, and standard deviation of laboratory CP and DOM values (%) for sample sets used in the calibration equation are presented for cattle, sheep, and goats, respectively (Table 2). The data range for each variable and species covered most of the reported ranges in diet quality reported in the literature for SSA.

**Cattle Calibration Equation**

The CP calibration equation was developed with a 156 sample-set, using 2, 8, 4, 1 second derivative math treatment. The first term (2) in the derivative math treatment indicates that second derivative math was applied to the equation; the second term (8) refers to the gap, which is the number of data points over which the derivative is calculated. The third and fourth terms refer to the smooth, the number of points to be averaged for data smoothing. The fourth term (second smooth) is never used thus usually set at 1 (ISI 2002). A relatively severe t-value was chosen given the diversity of laboratories sources for the data. The calibration statistics and the associated chemical bonds are presented in Table 3. The SEC of 0.90 falls within the recommended range of twice the SEL value (Westerhaus 1989) when considered in terms Texas A&M (TAMU) laboratory SEL of 0.50. Value for SEC reported here agrees with values reported by Lyons and Stuth (1992), Coates (1998), however the value was lower than those reported by Ossiya (1999), and Gibbs et al. (2002) (Table 4).

Coefficient of determination ($R^2$) of 0.92 recorded for CP in this study was the same as obtained by Lyons and Stuth (1992), (Table 4). Coates (1998), Ossiya (1999), and Gibbs et al. (2002) reported higher $R^2$ values in their respective studies on cattle, (Table 4). Shenk and Westerhaus (1996) indicated that an $R^2$ value greater than 0.90 is an indication of excellent quantitative information. Cross validation was performed to indicate the predictive capabilities of the CP

Table 2: Range, mean, and standard deviation (α = 0.05) for laboratory CP and DOM values (%) for African calibration sample sets.

| Livestock species | Constituent | Range | Mean | Standard Deviation |
|---|---|---|---|---|
| Cattle | CP | 2.88 – 19.09 | 8.11 | 3.23 |
| | DOM | 36.30 – 69.93 | 55.96 | 8.16 |
| Sheep | CP | 4.65 – 18.74 | 10.59 | 3.62 |
| | DOM | 37.39 – 68.12 | 51.28 | 7.24 |
| Goat | CP | 3.50 – 22.06 | 12.95 | 4.46 |
| | DOM | 25.57 – 66.57 | 44.81 | 11.35 |

equation and the SECV obtained was 1.12. Shenk and Westerhaus (1996) and ISI (2002) observed standard error of cross validation (SECV) to be the best single estimate of the prediction capability of an equation. Furthermore, SECV should be comparable to the experimental error (Shenk and Westerhaus 1996). SECV is usually slightly higher in value than SEC. One minus the variance ratio (1-VR) in cross validation statistics is equivalent to $R^2$ in the calibration, and the value obtained here was 0.87.

The two major wavelengths associated with the CP equation selected based on the equation wavelength coefficient magnitude (Williams 1987) were 1620 and 1124 nm, with 1620 nm being the first primary wavelength. Norris et al. (1976) and Windham et al. (1988) recommended the examination of only the two primary wavelengths in explaining the biological importance of the wavelengths selected by NIRS regression, however, Lyons and Stuth (1992) suggested the interpretation of only the primary wavelength. The biological significances of the two most important wavelengths are recorded in Table 3.

Both 1620 and 1124 nm wavelengths show strong representation of amides, amino acid groups, N-H bonds, carbonyl, carboxylic acid derivatives, and $CH_3$ group hence indicative of microbial activity (Merchen 1988, Van Soest 1994). The presence of allyl groups such as CH=CH2 and vinyl, and heterocyclic compounds (aromatic) such as pyridines, pyrimidines, quinolines, and benzene rings are indication of anti-quality factors in the diet.

Table 3: Cattle crude protein (CP%) calibration equation for sub-Sahara Africa.

| Equation | N | Math | SEC | $R^2$ | SECV | 1-VR |
|---|---|---|---|---|---|---|
| CP | 156 | 2, 8, 4, 1 | 0.90 | 0.92 | 1.12 | 0.87 |

| **Wavelength (mm)** | **Associated Chemical Bonds** (Described per Murray and Williams 1987) |
|---|---|
| 1620 | Amide II: N-H deformation coupled with C-H stretch, secondary amides especially peptides; Asymmetrical N-H stretch, all amino acids and hydrochlorides; N-H stretch, N-H bend, secondary amides, *cis* and *trans*; hydrogen bonding, peptide links, protein helices; C-H stretch, pyridines, pyrimidines, quinolines; C-H, C-H stretch, aromatics, $-CH=CH_2$, vinyl; C-O stretch, amino acid ionized carbonyls; C-O bending, $COO^-$ zwitterions; C=O stretch, urea, amide I, especially lower frequencies; O-H carboxylic acids; O-H stretch, intramolecular OH bonds, polymers; Benzene ring deformation, $NH_4$ +;Phosphates, $PO_2^-$, P=O hydrogen bonded. |
| 1124 | N-H stretch symmetrical, all amino acids and hydrochlorides; C-H stretch, $CH_3$ groups (A1); O-H stretch. carboxylic acid dimmers; O-H stretch, intramolecular OH bonds polymers. |

N – number of samples used in the calibration set.
SEC – standard error of calibration.
SECV – standard error of cross validation.
Math – derivative math treatment.
$R^2$ – coefficient of determination.
1-VR - 1 minus variance ratio.

Table 4: Comparison of calibration equation statistics for predicting dietary CP% and DOM% in ruminants.

| | | CP% | | DOM% | |
|---|---|---|---|---|---|
| **Author** | **Location** | **$R^2$** | **SEC** | **$R^2$** | **SEC** |
| | | **Cattle** | | | |
| Gibbs et al. (2002)[1] | Queensland | 0.99 | 1.28 | 0.87-0.92 | 2.38-2.6[1] |
| Coates (1998)[1] | Queensland | 0.94-0.99 | 0.54-0.83 | 0.80-0.97 | 2.2-3.3[1] |
| Ossiya (1999) | Africa | 0.95 | 1.04 | 0.91 | 3.39 |
| Lyons and Stuth (1992) | Texas | 0.92 | 0.89 | 0.80 | 1.66 |
| | | **Sheep** | | | |
| Ossiya (1998) | Africa | 0.87 | 1.46 | 0.89 | 3.21 |
| Krachounov and Kirilov (2000)[1] (Abstract). | Bulgaria | --- | --- | 0.94 | 2.26 |
| Li et al. (2004)[2] | Texas | 0.95 | 1.08 | 0.80 | 1.51 |

Table 4: Continued

| Author | Location | CP% | | DOM% | |
|---|---|---|---|---|---|
| | | $R^2$ | SEC | $R^2$ | SEC |
| | | **Goats** | | | |
| Leite and Stuth (1995) | Texas | 0.94 | 1.12 | 0.93 | 2.02 |
| | | **Wildlife** | | | |
| Showers (1997)[3] | Texas | 0.94 | 0.70 | 0.89 | 2.64 |
| Gallagher (1990)[3] | Texas | 0.86 | 1.37 | 0.76 | 6.7[1] |
| Brooks et al. (1984)[1,4] | Utah | 0.99 | 0.50 | 0.88 | 2.20[1] |

1-Values are for DMD (dry matter digestibility).

2-Abstract submitted to 57th Annual Meeting of Society of Range Management.

3-Study was on captive white-tailed deer.

4-Study was on captive elk.

The presence of O-H bonds denoting hydroxyl groups in both wavelengths further suggests the presence of anti-nutritive factors. Phosphorus could be source of phosphates, $PO_2^-$, and P=O bonds being detected, and these could be from animal sources. McDonald et al. (2002) reported that most organic compounds contain mineral elements; proteins contain mainly sulfur while phosphorus is found in carbohydrates and lipids. Furthermore, the authors indicated that potassium and silicon are major inorganic elements in plants, while calcium and phosphorus are the major inorganic components of animals.

The DOM calibration equation for cattle was developed with 137 sample set using first derivative math treatment of 1, 4, 4, 1. The calibration, and cross validation statistics, and description of chemical bonds associated with the equation wavelengths are presented in Table 5. SEC of 2.82 was deemed adequate, since it fell within twice the SEL range when compared with GANLAB SEL of 1.5 for DOM. SEC of 2.82 was higher than value reported for College Station-La Copita location (CSLC) by Lyons and Stuth (1992), but closer to the reported upper limit ranges of Coates (1998), and Gibbs et al. (2002), (Table 4). SEC for this study is however lower than value reported by Ossiya (1999), (Table 4). The $R^2$ of 0.88 obtained was higher than values reported by Lyons and Stuth (1992) though lower than values reported by Ossiya (1999), Coates (1998), and Gibbs et al. (2002) (Table 4). SECV of 3.26 obtained in this study is considered reasonable considering the fact that the difference between it and SEC is less than 0.5.

Table 5: Cattle *in vivo* corrected digestible organic matter (DOM%) calibration equation for sub-Sahara Africa.

| **Equation** | **N** | **Math** | **SEC** | **$R^2$** | **SECV** | **1-VR** |
|---|---|---|---|---|---|---|
| DOM | 137 | 1 4, 4, 1 | 2.82 | 0.88 | 3.26 | 0.84 |

| **Wavelength (mm)** | **Associated Chemical Bonds** (Described per Murray and Williams 1987) |
|---|---|
| 1836 | N-H stretch, symmetrical, all amino acids and hydrochlorides; unknown absorbers in most amino acids; C-O symmetrical vibrations zwitterions; C=O vibrations, open-chain acid anhydrides; C-H stretch aliphatic compounds; coupled C-O and O-H stretch, carboxylic acids; O-H deformation secondary alcohols; O-H stretch, intramolecular OH bonds, polymers; $-C(CH_3)_3$; CH deformation; C-H stretch, carbonyl compounds; -SH stretch (very weak); Phosphates, $PO_3$=; Phosphates, $PO_4$, all; Sulphates, $SO_4$=; Silicates. |
| 1852 | N-H stretch, symmetrical, all amino acids and hydrochlorides; unknown absorbers in most amino acids; C-N stretch, acrylamides, alkylamides primary-tertiary; cis secondary amides; C-O symmetrical vibrations zwitterions; C=O vibrations, open-chain acid anhydrides; C-H stretch aliphatic compounds; -CH-; CH deformation; coupled C-O and O-H stretch, carboxylic acids; O-H deformation secondary alcohols; O-H stretch, intramolecular OH bonds, polymers; CH deformation; C-H stretch, carbonyl compounds; -SH stretch (very weak); P-OH stretch; Phosphates, $PO_3$=; Phosphates, $PO_4$, all; Sulphates, $SO_4$=; Silicates. |

N – calibration set sample size. Math – derivative math treatment. SEC – standard error of calibration
$R^2$ – coefficient of determination. SECV – standard error of cross validation. 1-VR - 1 minus variance ratio.

The first and second best wavelengths, based on highest coefficient magnitudes, of 1836 and 1852 nm obtained for the cattle DOM fall within the same associated chemical bonds description of Murray and Williams (1987). Both wavelengths exhibited N-H, amino acids, primary to tertiary amides, carbonyl, and carboxyl absorption bonds indicating end products of protein degradation coming from microbial sources (Merchen 1988, Van Soest 1994). The presence of microbial N-compounds in the associated chemical bonds for DOM could be explained by the fact that total fecal organic matter fraction of feces is a composite of microbial cell wall from the rumen and microbial matter arising from both endogenous secretions and dietary carbohydrates that has escaped the upper digestive tract (Van Soest 1994). Since DOM is an indirect measurement of the digestible organic matter content of the diet, the presence of N-H bonds and amino acids should be expected. Acid anhydrides are derivatives of acids such as acetic, while C-O bonds are indicative of keto groups. Aldehydes are found in most sugars such as glucose, while keto group occur in fructose (Geissman 1977), thus indicative of carbohydrate digestion. Alcohol compounds are constituents of volatile oils of many plants (Geissman 1977), and account for most of the structure of lignin molecules (Harkin 1973). The presence of secondary alcohols therefore could be indicative of indigestible fraction of plant cell wall associated with carbohydrates. Secondary alcohols and hydroxyl bonds are also indicative of anti-quality factors. Absorption of aliphatic bonds could be associated with aliphatic amino acids such as glycine, valine,

alanine, leucine or isoleucine as speculated by (Showers 1997). The CP and DOM calibration results obtained in this study compared reasonably well with results from other researchers in different regions of the world, and considered capable of predicting dietary CP and DOM of free-ranging cattle in sub-Saharan Africa to an acceptable level of error.

**Sheep Calibration Equation**

The crude protein equation for sheep was developed with 158 samples in the calibration set using second derivative math treatment (2,4,4,1). Statistics for the calibration, cross validation, and description of the chemical bonds associated with selected wavelengths are presented in Table 6.

Calibration statistics obtained were SEC = 0.79, $R^2$ = 95 with corresponding SECV and 1-VR being 1.08 and 0.91, respectively. The current SEC value of 0.79 is lower than values reported for sheep (Ossiya 1999, Li et al. 2004), and values obtained for cattle (Lyons and Stuth 1992, Gibbs et al. 2002), but within the range reported by Coates (1998) (Table 4), hence the current SEC would indicate good predictive capability for sheep. A weighted average for SEL was 0.48, thus SEC was within recommended twice SEL values (Westerhaus 1989). $R^2$ of 0.95 obtained was the same as reported by Li et al. (2004) but greater than the value reported by Ossiya (1999), (Table 4). Compared to cattle results by other researchers, the $R^2$ obtained in this study was greater than value reported by Lyons and Stuth (1992) but lower than the upper range reported by Coates (1998), and Gibbs et al. (2002), (Table 4). SECV of 1.08

Table 6: Sheep crude protein (CP%) calibration equation for sub-Sahara Africa.

| Equation | N | Math | SEC | $R^2$ | SECV | 1-VR |
|---|---|---|---|---|---|---|
| CP | 158 | 2, 4, 4, 1 | 0.79 | 0.95 | 1.08 | 0.91 |

| **Wavelength (mm)** | **Associated Chemical Bonds** (Described per Murray and Williams 1987) |
|---|---|
| 1300 | N-H stretch, symmetrical, all amino acids and hydrochlorides; unknown absorbers in most amino acids; O-H stretch, intramolecular OH bonds, polymers; -SH stretch (very weak); P-OH stretching. |
| 1564. | Amide II: N-H deformation, coupled with C-H stretch; secondary amides especially peptide; N-H deformation, primary and secondary amides; $NH_3$ deformation, "amino acid I"; N=H stretch, unsaturated N compounds; N-H stretch, primary amides, bonded NH; H bonding, peptide links, protein helices; C-O stretch, COOH, amino acids; C=O stretch, urea, amide I especially lower frequencies; combination band ionized amino acids; C-O bending, $COO^-$ zwitterions; C-N stretch, -N=C=N-; -C=C- stretch, conjugated chains; benzene ring deformation; O-H stretch, intramolecular OH bonds, polymers; P=O free; Phosphates, $PO_2^-$; $NH_4$+. |

N – number of samples used in the calibration set.
SEC – standard error of calibration.
SECV – standard error of cross validation**.**
Math – derivative math treatment.
$R^2$ – coefficient of determination.
1-VR – 1 minus variance ratio

obtained exceeds SEC by only 0.29%, thus considered good according to standards suggested by Shenk and Westerhaus (1996), and ISI (2002).

Wavelengths selected for this equation were 1300 and 1564 nm. Both wavelengths exhibited absorptions in N-H and amino acid bonds, though the presence of chemical bonds associated with end products of protein digestion and metabolism was more prevalent in 1564 nm. The presence of N-H, amino acids, amide bonds and unsaturated N compounds agrees with Van Soest (1994) as explained in the case of cattle (Chapter III, p.70). Presence of –SH bonds, though weak could indicate proteins due to its sulfur element, which is an essential component of proteins. Absorption bonds of hydroxyl origin in both 1300 and 1564nm could represent OH bonds associated with certain amino acids or OH occurring on cellulose or other carbohydrates (Showers 1997). Carbon-carbon double bond is a center of non-saturation in a molecule, and compounds containing it are known as unsaturated compounds (Geissman 1977). The absorption of -C=C- and benzene ring, an aromatic compound, are further indication of anti-quality factors in the diet. Information available showed that sheep diets at some ILRI research centers contained high tannin bird-resistant sorghum crop residues, and tannin is a known anti-quality factor which could limit the utilization of available protein in the diet.

DOM calibration equation for sheep was developed with 146 samples in the sample set and a first derivative math treatment (1, 8, 4, 1). The calibration

and cross validation statistics, and the description of biological significance associated with the equation wavelengths are presented in Table 7.

The SEC of 1.68 for DOM was lower than the value reported by Ossiya (1999), and Krachounov and Kirilov (2000) but higher than value reported by Li et al. (2004) (Table 4). However, the current SEC is similar to value reported for cattle by Lyons and Stuth (1992) but lower than values reported by Coates (1998), and Gibbs et al. (2002) for cattle (Table 4). The $R^2$ value of 0.94 obtained is an indication of good relationship between fecal spectra and the laboratory reference value of the samples used. The $R^2$ reported in this study was similar or lower in value to those reported by (Krachounov and Kirilov 2000), Li et al. (2004), and Coates (1998) but higher than value reported by Ossiya (1999), and values reported for cattle (Lyons and Stuth 1992, Gibbs et al. 2002) (Table 4). The SEVC and 1-VR of 2.07 and 0.92, respectively were considered to be efficient to warrant the calibration equation for predictive purposes

Wavelengths associated with the sheep DOM equation were 1564 and 1788 nm. Both wavelengths exhibit absorption in amides, amino acid, N-H, carboxyl bonds. The presence of these compounds could be an indication of microbial cellular debris, keratinized tissues, and heat-damaged (Millard) proteins of dietary origin (Van Soest 1994). The explanation given for detection of microbial N-compounds in the associated chemical bonds for cattle DOM (Chapter IV, p.70) is equally applicable for Sheep DOM. The presence of carbonyl (C=O), keto (C-O) (McDonald et al. 2002), hydroxyl (O-H),

Table 7: Sheep *in vivo* corrected digestible organic matter (DOM%) calibration equation for sub-Sahara Africa.

| Equation | N | Math | SEC | $R^2$ | SECV | 1-VR |
|---|---|---|---|---|---|---|
| DOM | 146 | 1, 8, 4, 1 | 1.68 | 0.94 | 2.07 | 0.92 |

| **Wavelength (mm)** | **Associated Chemical Bonds** (Described per Murray and Williams 1987) |
|---|---|
| 1564 | Amide II: N-H deformation coupled with C-H stretch, secondary amides especially peptide, N-H deformation, primary and secondary amides, $NH_3$ deformation, “amino acid I”, N=H stretch, unsaturated N compounds, N-H stretch, primary amides, bonded NH, H bonding, peptide links, protein helices, C-O stretch, COOH, amino acids, C=O stretch, urea, amide I especially lower frequencies, combination band ionized amino acids, C-O bending, COO zwitterions, C-N stretch, unsaturated N compounds, -N=C=N-, -C=C- stretch, conjugated chains, benzene ring deformation, O-H stretch, intramolecular OH bonds, polymers, P=O free. Phosphates, $PO_2^-$; $NH_4$+. |
| 1788 | Amide IV: N-H bend, primary amides; N-H stretch, symmetrical, all amino acids and hydrochlorides; C-N stretch, amides with no N substitution; C-O symmetrical vibrations, zwitterions; C-H stretch, aliphatic compounds; carbonyl compounds; C-H in-phase deformation, CHO group; coupled C-O and O-H stretch, carboxylic acids; O-H stretch, intramolecular OH bonds, polymers; P=O hydrogen bonded; Phosphates, $PO_2^-$; $PO_3$ =, -SH stretch (very weak); Sulphates, $SO_4$ =. |

N – number of samples used in the calibration set.
SEC – standard error of calibration.
SECV – standard error of cross validation.
Math – derivative math treatment.
$R^2$ – coefficient of determination.
1-VR – 1 minus variance ratio

intramolecular O-H, functional groups and polymers are indicative of carbohydrate or cellulose digestion. The absorption of O-H bonds and COOH groups could be an indication of “non-core” lignin that acts as cross linkages between lignin and structural carbohydrates (Fahey and Berger 1988). The functional groups, aldehydes (CHO), C-O, O-H, and intramolecular O-H bonds present at 1788 nm are indicative of carbohydrate or cellulose digestion (Geisman 1977, Showers 1997). Osborne and Fearn (1986) indicated that all types of carbohydrates found in foods consist of C-H and O-H bonds.

Results obtained in the development of CP and DOM equations for Sheep satisfied all stated calibration criteria, and were comparable to or of lower error than calibration statistics obtained by other researchers. The equation development processes are therefore deemed successful, and the developed equations are capable of predicting the stated parameters of the diet quality of free-ranging sheep in sub-Saharan Africa.

**Goat Calibration Equation**

Goat CP calibration equation was developed with a 101 sample set using second derivative math treatment (2, 4, 4, 1). Calibration, cross validation statistics, and description of biological significance of the wavelengths associate with the equation are presented in Table 8.

The SEC of 0.80 was within the acceptable SEL limits of 0.50 for the TAMU laboratory. SEC obtained in this study was lower than the value reported for Spanish goats by Leite and Stuth (1995) (Table 4). Compared to results

obtained by other researchers, SEC in this study was higher than the value reported by Showers (1997), but lower than the value reported by Gallagher (1990) for captive white-tailed deer. In the case of captive elk, Brooks et al. (1984) observed a lower SEC than reported in this study (Table 4).

Coefficient of determination ($R^2$) of 0.97 obtained for CP was deemed excellent. Similar results though slightly lower, have been reported for other concentrate feeders such as goats (Leite and Stuth 1995), and white-tailed deer (Showers 1997, Gallagher 1990). However Brooks et al. (1984) recorded higher $R^2$ for captive elk (Table 4) using a smaller sample size and a narrow data range. Cross validation statistics obtained were SECV = 1.03 and 1-VR = 0.94. The cross validation statistics are considered good as well, according to Shenk and Westerhaus (1996), and ISI (2002).

Wavelengths selected for the equation were 1532 and 1188 nm at the first and second positions. The selected wavelengths in this study were different from 2305 and 2174 nm reported by (Leite and Stuth 1995) at first and second positions, respectively. These differences in wavelengths should be expected since no two fecal samples have exactly the same chemistry. Moreover, there were differences in the forage species used in the diets to arrive at respective calibration equations. Equally different were geographical locations and breeds, which could all be contributing factors. Both 1532 and 1188 nm exhibited N-H, N=H, amino acids, primary and secondary amides, C=O, $COO^-$ bonds among others denoting detection of keratinized tissues, microbial cellular debris, and

Table 8: Goat crude protein (CP%) calibration equation for sub-Sahara Africa.

| Equation | N | Math | SEC | $R^2$ | SECV | 1-VR |
|---|---|---|---|---|---|---|
| CP | 101 | 2, 4, 4, 1 | 0.80 | 0.97 | 1.03 | 0.94 |
| **Wavelength (mm)** | | **Associated Chemical Bonds** (Described per Murray and Williams 1987) | | | | |
| 1532. | | N-H stretch, symmetrical, all amino acids and hydrochlorides, N=H deformation, primary and secondary amides, N-H stretch, primary amides, bonded NH, N=H stretch, unsaturated N compounds, $NH_3$ deformation, "amino acid I" H bonding, peptide links, protein helices, C=O stretch, urea, amide I especially lower frequencies, $COO^-$ stretch, or combination band ionized amino acids, C=O stretch, alpha, beta, unsaturated ketones, C-N stretch, unsaturated N compounds, -C=C- stretch, non-conjugated chains, O-H stretch, internal OH bonds, single bridge, polymeric, O-H deformation, hydroxyl phosphates, $PO_2^-$, $NH_4$+. | | | | |
| 1188 | | N-H stretch, symmetrical, all amino acids and hydrochlorides, $COO^-$ stretch, or combination band, most amino acids; O-H stretch, intramolecular OH bonds, polymers; C-H stretch carbonyl compounds; -SH stretch (very weak). | | | | |

N – number of samples used in the calibration set.
SEC – standard error of calibration.
SECV – standard error of cross validation.
Math – derivative math treatment.
$R^2$ – coefficient of determination.
1-VR – 1 minus variance ratio

heat-damaged proteins of dietary origin (Van Soest 1994). Detection of ammonia and ammonium compounds in feces at 1532 nm could indicate low levels of carbohydrates available to rumen microorganisms, since low levels of carbohydrate in the rumen will limit utilization of ammonia (Johnson 1976). Ammonia may also result from either oxidative or non-oxidative deamination or transamination of amino acids at the tissue level. The excess ammonia is converted to urea for excretion (McDonald et al. 2002). The O-H and intramolecular OH absorption bonds shown in both 1532 and 1188 nm could represent OH bonds on carbohydrate compounds or associated with certain amino acids.

A sample size of 103 and a second derivative math treatment of 2, 4, 4, 1 were used to develop goat DOM calibration equation. The calibration, cross validation statistics, and chemical bonds associated with the selected wavelength are presented in Table 9. The precision of the calibration equation was within the acceptable limits for NIRS analysis

Standard error of calibration (SEC = 2.65) was higher than the value reported for Spanish goats (Leite and Stuth 1995), and for white-tailed deer (Brooks et al. 1984) but similar to the value reported for white-tailed deer (Showers 1997) (Table 4). The SEC reported for this study was within twice SEL of 1.5 for GANLAB.

The $R^2$ for DOM equation was 0.94, indicating good relationship between the sample spectra and laboratory reference value. The $R^2$ obtained in this

study was similar to the value reported for Spanish goats (Leite and Stuth 1995), but was higher than values reported for white-tailed deer (Showers 1997, Gallagher 1990), and for elk (Brooks et al. 1984) (Table 4). Cross validation statistics (SECV = 3.30 and 1-VR = 0.92) were considered satisfactory for predictive purposes.

Wavelengths selected for the DOM equation were 1836 and 1548 nm as the primary and secondary wavelengths, respectively. Wavelengths used in the equation development were different from those selected by Leite and Stuth (1995) and Showers (1997). Both wavelengths exhibited high concentrations of nitrogenous absorption bonds. The presence of N-H, N=H, amino acids, primary and secondary amides, C=O, $COO^{-}$, ammonia bonds among others could be explained by Van Soest's (1994) observation (chapter III, p.70). The absorption bonds of C-H present at 1834 nm are indicative of fiber (Clark and Lamb 1991). Detection of aliphatic compounds in feces may indicate decreased microbial activity in the rumen resulting from low production of volatile fatty acids (VFA) (Yokoyama and Johnson 1988). Structural bonds such as $–C(CH_3)_3$, which has an alkane base, are indicative of lignin, since alkanes are important constituent of lignins (Higuchi et al. 1967). The presence absorption bonds of alcohols and aromatic compounds of pyrimidine and quinoline ring deformations indicate detection of lignin as explained previously (Chapter III, p.73). Similarly, detection of inorganic bonds such as –SH, sulfates, phosphates, and silicate could be explained in the same manner as previously (Chapter III, p.77).

Table 9: Goat *in vivo* corrected digestible organic matter (DOM%) calibration equation for sub-Sahara Africa.

| **Equation** | **N** | **Math** | **SEC** | **$R^2$** | **SECV** | **1-VR** |
|---|---|---|---|---|---|---|
| DOM | 103 | 2, 4, 4, 1 | 2.65 | 0.94 | 3.30 | 0.92 |
| **Wavelength (mm)** | | **Associated Chemical Bonds** (Described per Murray and Williams 1987) | | | | |
| 1836 | | N-H stretch, symmetrical, all amino acids and hydrochlorides; unknown absorbers in most amino acids; C-O symmetrical vibrations zwitterions; C=O vibrations, open-chain acid anhydrides; C-H stretch aliphatic compounds; coupled C-O and O-H stretch, carboxylic acids; O-H deformation secondary alcohols; O-H stretch, intramolecular OH bonds, polymers; -$C(CH_3)_3$; CH deformation; C-H stretch, carbonyl compounds; -SH stretch (very weak); Phosphates, $PO_3$ =; Phosphates, $PO_4$, all; Sulphates, $SO_4$ =; Silicates. | | | | |
| 1548 | | N-H stretch, symmetrical, all amino acids and hydrochlorides; primary amides, bonded NH, N-H deformation, primary and secondary amines; $NH_3$ deformation, “amino acid I”, N=H stretch, unsaturated N compounds; N-H stretch, hydrogen bonding, peptide links, protein helices; C=O stretch, urea, amide I especially lower frequencies; α-β unsaturated ketones; $COO^-$ stretch, or combination band ionized amino acids; C-N stretch, unsaturated N compounds, -N=C=N-; -C=C- stretch, conjugated chains, O-H stretch internal OH bonds, single bridge, polymeric; Ring deformation, pyrimidines and quinolines; $NH_4$+; P=O free; Phosphates, $PO_2^-$. | | | | |

N – number of samples used in the calibration set.
SEC – standard error of calibration.
SECV – standard error of cross validation.
Math – derivative math treatment.
$R^2$ – coefficient of determination.
1-VR - 1 minus variance ratio.

## Summary and Conclusion

Enhanced NIRS calibration equations capable of predicting diet quality of free-ranging livestock (cattle, sheep, and goats) within five agro-ecological zones of sub-Saharan Africa (SSA) have been developed. The agro-ecological zones of interest were the highlands, humid, sub-humid, semi-arid and arid zones, respectively.

Data generated through diet-fecal pair feeding experiments in LEWS project countries (Ethiopia, Kenya, Uganda, and Tanzania), and Ghana were combined with historical diet-fecal data from some ILRI project centers (Ethiopia, Nigeria, and Niger) to create one calibration file for the equation development. Equations were developed for each livestock species (cattle, sheep, and goats), and the calibration statistics in terms of $R^2$, SEC, and SECV obtained in each case satisfied the requisite criteria for NIRS calibration development, as well having precision equivalent to those obtainable through conventional laboratory analysis. The calibration statistics for all species and diet attributes were better than reported by other researchers. The calibration equation development was therefore successful, and the equations could therefore be used to monitor diet quality of the free-ranging livestock under SSA conditions with success.

Fecal NIRS has proven to be a valuable managerial tool for monitoring nutritional quality of grazing livestock, thereby increasing efficiency, accuracy, reducing time, and labor inputs in the determination of nutritional quality of diets of free-ranging animals. The technology is even more appropriate for

application under SSA conditions where wet chemistry laboratories are rare, expensive to run, with services equally expensive and totally out of reach of the local livestock farmer or pastoralist.

The establishment of NIRS laboratories in Ethiopia, Kenya, Tanzania, and Uganda (East Africa) by GL-CRSP/LEWS is a step in the right direction. The SSA will be served better if African Governments work towards the expansion of NIRS technology to cover all strategic livestock raising countries in the west, central and south Africa. NIRS calibration files need to be upgraded regularly; hence there is more work to be done creating diet-fecal pair data from other strategic countries, in order to capture most of diverse forage species that exist within SSA. Given that increased diversity in the number and type of diet-fecal pairs used in a calibration increase predictive power, an international agreement between laboratories in Africa could ensure that all benefit from their respective work in each country. This strategy will enable the development of a more robust calibration equation for Africa.

# CHAPTER IV

# THE USE OF NDVI AND GEOSTATISTICAL TECHNIQUES IN MAPPING CATTLE DIET QUALITY IN THE NORTHERN SAVANNA ZONE OF GHANA

## Introduction

Despite the fact that approximately 50% of the total ruminant livestock population of the country is supported in the northern savanna zone, meat and milk output from these animals is low. Ruminant nutrition has been observed as one of the major constraints contributing to the low output from these animals. Ruminant livestock are reared solely on range resources with opportunistic inputs from crop residues, and agro-industrial by-products. The rapid growth rate of the range grasses coupled with long dry seasons ranging from 5 to 7 consecutive months of the year result in livestock being reared on poor quality herbage for greater part of any year. The resultant effect is the “saw-toothed” growth pattern (Skerman and Riveros 1990) of livestock within the zone.

There is a need to find solution to the perennial “saw-toothed” growth pattern of ruminant livestock in the zone and the country in general. A nutritional profiling technique, using fecal NIRS analysis, may offer a solution for monitoring individual herds. This technology currently allows assessment of herds at a given point in space. An emerging question that needs to be addressed is whether Normalized Differential Vegetation Index (NDVI) data and cokriging with known point diet quality parameters could be used to map diet quality over a region. Such maps would help in demarcating and identifying areas of

abundance and distress in forage quality. The information could be made available to Agricultural Extension Officers for use in planning livestock feed resource programs, in an advisory role to farmers on better feed resource conservation, and redirection of available feed resources to distressed area.

Cokriging, a geostatistical technique, and NDVI greenness data from National Oceanographic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) remotely sensed data have been used to successfully estimate PHYGROW simulated available forage (kg $ha^{-1}$), and create forage deviation surface maps for southern Kenya (Angerer et al. 2001, Stuth et al. 2003a). Promising results were also obtained in an initial study to create cokriged estimated CP% maps in Uganda using point based fecal samples and corresponding NDVI data (GL-CRSP 2002). Hence, the objective of this research is to determine if cokriging of NDVI imagery data with geo-referenced NIRS predicted CP and DOM values (%) could provide a viable monitoring tool for mapping diet quality of cattle across large landscapes.

## Site Description

The study was conducted in the northern (Guinea and Sudan) savanna agro-ecological zone of Ghana (Fig. 3). The zone lies between latitudes 8° to 11° 15' N and longitude 0° 30'E, 3° N, comprising three administrative regions of Ghana namely Northern (NR), Upper East (UE) and Upper West (UW).

The northern savanna accounts for 62.7 % of the total vegetation zones of the country, out of which Sudan savanna, occupying the northeastern most

part of the country, accounts for only 0.7% of the total northern savanna (MOA 1991). The area is typically a fire maintained climax community of broad-leaved deciduous trees, distributed in a continuous ground cover dominated by perennial bunch grasses of *Andropogon*, *Hyparrhenia*, and associated forbs (Rose Innes 1977). Skerman and Riveros (1990) described the vegetation of the area in general terms as mainly *Hyparrhenia*-dominated tree savanna ecosystems. The soils have predominantly light textured surface horizon, lateritic in nature, shallow, and frequently overlaying laterite hardpan (Rose Innes 1977); though sandy loams and loams are also present (MOA 1991). The zone experiences unimodal rainfall (Fig. 4) with a mean annual rainfall of 1,000-1,100 mm (MOA 1991).

## Methodology

### Outstation Fecal Sampling

In order to obtain predicted dietary CP and DOM values (%) for the free-ranging cattle, which formed the basis for creating the diet-quality maps for the zone, fortnightly (14 d) outstation fecal collection protocol was set up within the zone. Sixty-six households with livestock, distributed across the savanna zone, were randomly selected in 17 agricultural districts. Figure 3 provides a map of the sampling locations. Selection of the agricultural districts was made in collaboration with the Regional Animal Production Officers (RAO) and the

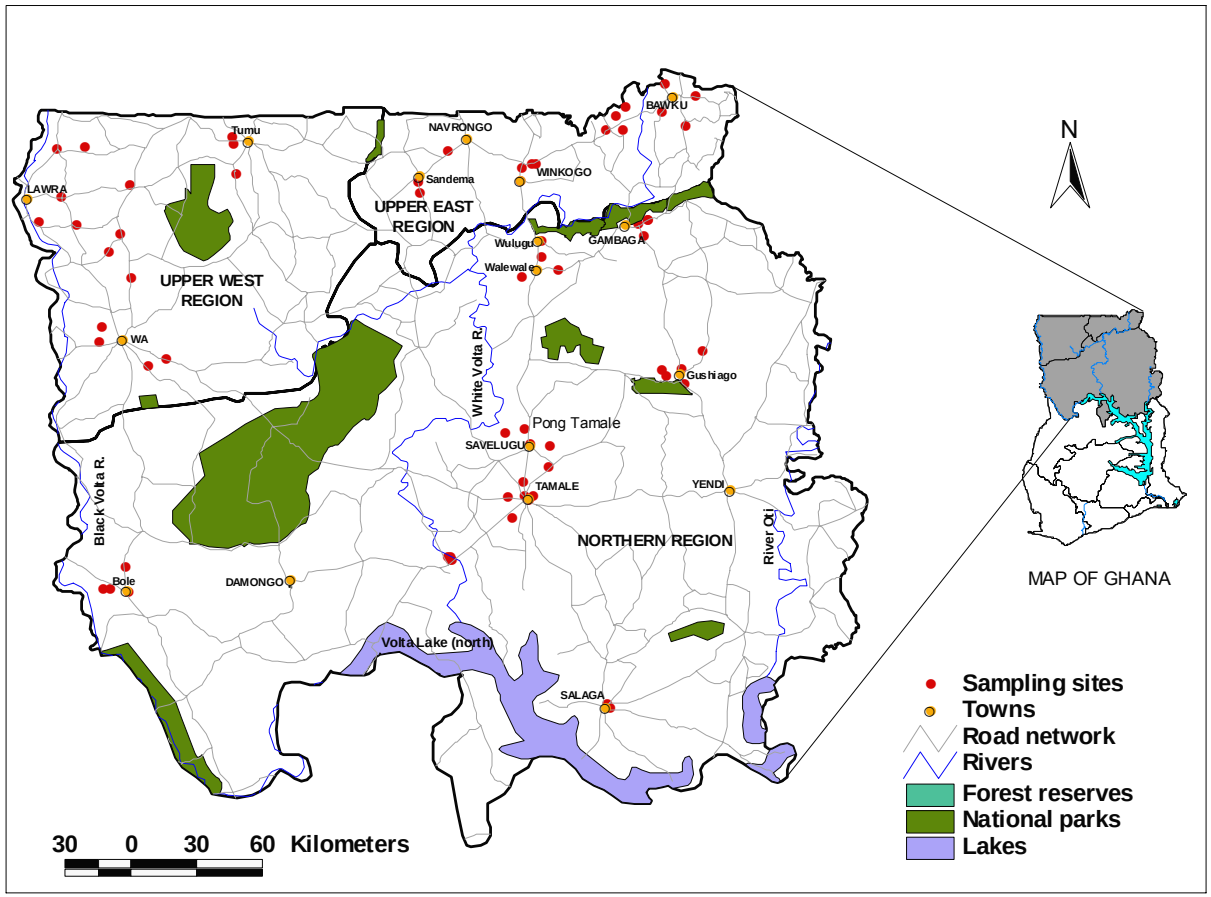


Fig. 3. Map of northern Ghana savanna zone indicating household fecal sampling sites.

District Directors of Agriculture, Ministry of Food and Agriculture (MOFA). The selection of a district and households within the district was random, though the following factors were considered; the importance of livestock in the locality, 1999 livestock census data for the area, accessibility of the area, nearness of the household within 5 km radius of major roads, and the previous cooperative experience MOFA staff had with the farmer. The geographical coordinates of the households were recorded with hand-held global position system (GPS) receiver.

In each of the three districts selected, the Agricultural Extension Agent (AEA) resident in the district and in direct contact with the farmers became the liaison between the farmers and researcher, and responsible for collecting and forwarding fecal samples to the regional contact personal at the Agricultural offices. The distribution of AEAs per region were as follows; Northern 8, Upper East 4, and Upper West 5. Each AEA had 3-4 sampling sites (households) to collect livestock feces. One-day training session was held for the AEAs per region, in selection, handling, preservation, and transportation of fecal materials to the central location. Each AEA was supplied with disposable hand gloves, ziplock polyethylene sample bags, self-adhesive labels, markers, ice packs, plastic spoons, and 8.8-liter cold boxes. The AEAs located at the regional centers served as coordinators. In the Northern regional fecal samples were forwarded directly to the project central location, Pong-Tamale.

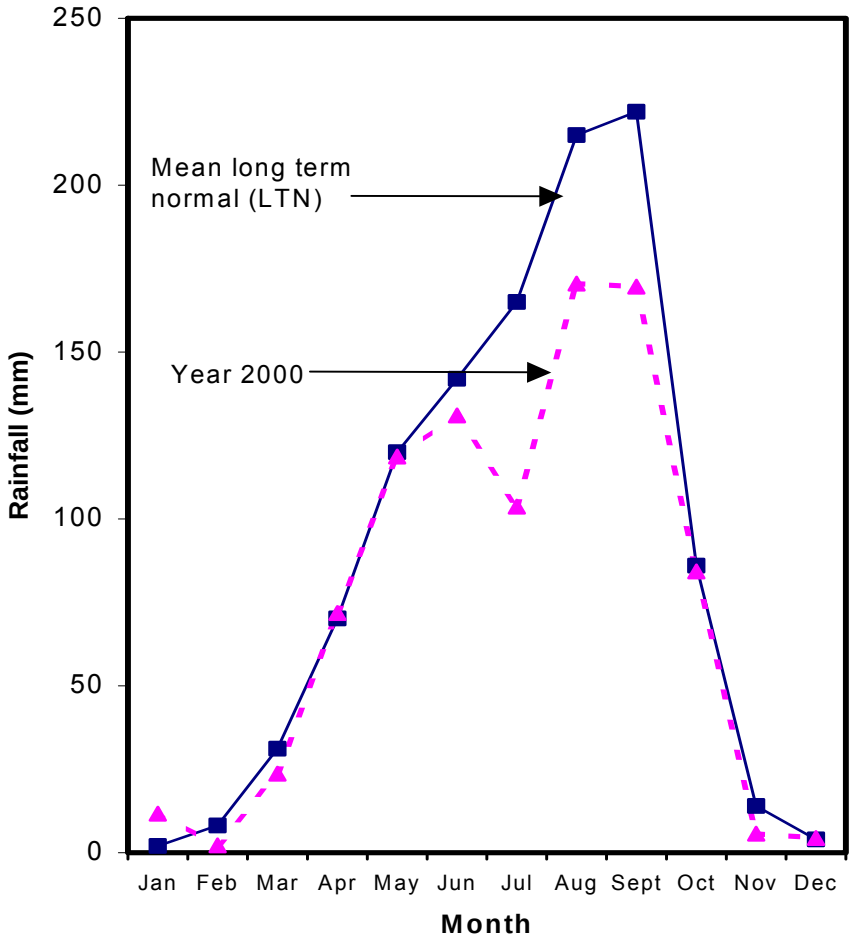


Fig.4. Mean monthly long term normal (LTN) and year 2000 rainfall pattern for all 66 sampling sites in the northern savanna zone of Ghana. (Sources: LTN – Collins et al. 2001; year 2000 rainfall, calculated from http://cnrit.tamu.edu/rsg/rainfall/rainfall.cgi).

Fecal collection was carried out every 14 days from cattle on a herd basis. For example, fecal samples were collected from fecal pats of an average of 10 animals randomly picked in the herd. The top of each fresh pat was scraped off and about two teaspoonfuls were taken and placed into the sampling bag. The same protocol was carried out for successive pats until an average of 10 obtained. The labeled zip-bagged samples were placed in the cold box, frozen ice packs placed on them followed by some old newspapers before replacing the lid. The samples were then sent to the central location for storage in either a freezer or cold room. The frozen fecal samples were packed into 30-liter styrofoam ice chests, labeled and sent by public transport to the central project location in Pong-Tamale. Each AEA had a motorcycle, thus upfront provision of an agreed fuel and incidental allowance enabled them to work unhindered to a reasonable degree. Prior arrangement was also made with Ghana Private Road Transportation Union (GPTRU) and Omnibus Service Authority (OSA) for the transportation of the samples from one destination to Pong-Tamale for a fee. The first batch of fecal samples was received from all locations in UE, UW and Tamale district of the Northern region in February 2002. Subsequently fecal samples were received fortnightly from all the 66 sampling sites from March to August 2002. Once fecal samples were received, they were stored in Veterinary Service Central Laboratory (MOFA) cold room in Pong-Tamale till processed. The outstation fecal samples were processed using the same procedures as described previously in Chapter III. These fecal

samples provided the data from which CP and DOM used for the diet quality mapping were predicted, using the equations developed for SSA (Chapter III). A spreadsheet was created matching each of the NIRS predicted CP and DOM values (%) with the sampling point decimal degrees of the X and Y coordinates (latitude and longitude) obtained with the GPS.

**Creation of Sampling Sites Grid-Codes**

Grid cells were created for Ghana in which the decimal degrees for each grid cell were converted to Albers Equal-Area (conic) projections for African, using ArcView GIS software (Version 3.3; Environmental Systems And Research Institute, Inc (ESRI), Redlands, CA.). Albers Equal-Area defines a geographic projection that preserves the correct area of a projection as on the sphere or ellipsoid (Clarke 1997). In addition, distortion in scale and shape vanishes along the two standard parallels. The standard parallel is a line along which the earth and the map match exactly, with the line coinciding with a parallel of latitude (Clarke 1997). Albers Equal-Area projection is used for conformity since NDVI data is already projected in Ablers. The procedure enables the creation of 8 x 8 km grids for the entire country with each grid cell having a centriod. A grid cell is rectangular building block that is filled with measured attribute table (Chrisman 1997), and it is the form in which raster data are organized. The grid cell determines the resolution of the data, and is organized in rows and columns (Clarke 1997). A centroid is a point location at the center of a feature used to represent that feature (Clarke 1997). The

creation of the grids results in each grid cell having a unique code usually referred to as grid-code. The 8 x 8 km dimension used is the standard range within which NDVI data is stored. The GPS readings for the sampling sites were converted to Albers Equal Area projection such that each sampling site fell within a grid and thus had a unique grid-code. The spreadsheets created per livestock species therefore had site ID (identity), unique grid-codes, X and Y coordinates, and CP and DOM values.

**Extracting NDVI Data**

NDVI data, which are usually recorded in dekads, were extracted in 8.0 km resolution format. A dekad is defined as a 10-day period, with three dekads in each month. Since fecal collections were carried out every 14 days, each collection period fell into a specific dekad. The various CP and DOM values (%) were therefore assigned to the first, second, or third dekads as regards the dekad within which the collection was made. The created diet-quality spreadsheet per livestock species therefore contained columns for site ID, grid-code, X and Y coordinates, CP and DOM values (%), dekad values. The excel spreadsheet was converted into database format (dbf) to enable NDVI extraction for the year 2000 using SAS program. The extracted NDVI file, either in database or Excel format, was imported into GS+ (Version 5.3.3) for the cokriging to be performed. GS+ is a Geostatistical software package developed for Environmental Sciences by Gamma Design Software (GDS), Plainwell, Michigan, USA.

**Cokriging Analysis**

In order to perform meaningful cokriging analysis, Pearson correlation analysis was used to determine the relationships between the predicted dietary CP, DOM and NDVI values in relation to dekads. Pearson correlation is a better determinant of relationship as regards cokriging than simple regression, since simple regression does not take into account the autocorrelation in a variable at a given pixel, likewise information in neighboring pixels is equally ignored (Dungan et al. 1994). A correlation coefficient of 0.5 or greater, and a sample size of 30 and above in any dekad are required for effective cokriging. Cokriging was performed using GS+ (Version 5.3.3). GS+ is a Geostatistical Analysis and Mapping program that enables quick and efficient measurement, and illustration of spatial relationships in geo-referenced data. The GS+ analyzes spatial data for autocorrelation and then uses the information to make optimal, statistically, and rigorous maps of the area sampled (GDS 2002)

The data file, in Excel format, was first sorted descending by the parameter to be cokriged. For example, if CP% in the first dekad of February 2000 was the primary variable for cokriging, the data were sorted by the CP%. File Import Command was used to load the data into the GS+ worksheet, followed by the setting of X and Y coordinates, primary variable (Z), and the covariate (Z2). The primary variable in this case was CP %, while the co-(secondary) variable referred to the corresponding dekadal NDVI values. Semivariance analysis was performed on both primary- and co-variables

separately. Semivariance is a measure of the degree of spatial dependence between samples (Dorsel and La Breche 2003). Semivariance analysis on both the primary- and co- variables enables the assessment of dissimilarity of data points to the spatial distance that separates them (Johnson et al. 2001). Semivarince analysis produces variograms, which provide information of spatial structure by describing how sample data were related to each other with different classes of separation distance and direction (Rossi et al. 1992). The same procedure was used to perform the semivariance analysis on the NDVI values (covariate, Z2).

Next, Cross-Semivariance Analysis was performed on the primary- and the co-variables (Z x Z2), measuring the joint variability between paired variables with respect to the separation distance. The cross-semivarince analysis created the cokriging model. In both the Semivariance and Cross-semivarince Analysis module, the following parameters were set; the Principal Axis (degrees N) at $0^{O}$, Offset tolerance (degrees) at $22.50^{O}$, Show model, and Show sample variance boxes were checked, while the default Active Lag Distances and Lag Class Distance Intervals were accepted. The Active Lag Distance describes the range over which semivariance should be calculated, while Lag Class Distance Interval defines how pairs of points will be grouped into lag classes (GDS 2002). For all variograms emanating from semivariance and cross semivariance analyses, the spherical models were chosen. The $r^2$ in each case should be 0.50 and above for an effective cokriging.

After evaluating the variograms, the spatial interpolation tools were selected and the required parameters set. The grid intervals for the X and Y coordinates were set to 8,000 m each, since NDVI data were extracted at a resolution of 8.0 km. Kriging methods adopted were Point kriging and Cokriging, and the cokriged data saved as ArcInfo ASCII grid for further processing.

To perform the semivariance analysis and interpolation for the corresponding dekadal DOM values, the same protocol and procedure, from data sorting in Excel to performing the interpolation in GS+ were used. The DOM values became the primary (Z) variable while the corresponding dekadal NDVI values became the covariate (Z2) variable. Furthermore, the same protocol and procedures were used to perform the cokriging for the other dekads, which had sample sizes of 30 and above, and showed a reasonable correlation between their respective primary- and co-variables.

**Creation of Diet Quality Maps in ArcView**

The interpolated data saved as ASCII (American Standard Code for Information Interchange) file, were converted to grids first, then to shapefiles to enable surface map to be created. Shapefiles are simple, non-topological format for storing geometric location and attribute information of geographic features (ESRI 2002a). The conversion of ASCII file to grid was performed with ASCII to Grid tool within ArcToolbox, an ArcInfo application toolbox that provides a rich and powerful set of geoprocessing functions for processing geographical data (ESRI 2002a).

Using ArcView 3.3 (ESRI 2002b), File Extensions such as GeoProcessing, and Spatial Analyst tools were activated. The GeoProcessing wizard provides the means of creating new data based on themes in a View, while the Spatial Analyst extension provides tools to create, query, analyze, and map cell-based raster data, and to integrate vector-raster analysis using feature-based, and grid-based themes (ESRI 2002b). In a new View, the grid data in raster format was loaded as Grid Source Data type and converted to shapefile using Convert to Shapefile module, and the shapefile added to the view. Subsequently Ghana centroid shapefile was added, and the diet quality parameter (e.g., CP%) in the cokriged shapefile was assigned by location to the Ghana centroid shapefile using the GeoProcessing wizard. Next, Ghana NDVI shapefile was added to the View as a theme. The NDVI shapefile represented the shapefile of the extracted NDVI data for the entire country, and contained, the polygon, gridcode, and unique ID. Both centroid and NDVI attribute tables were then joined by a common theme, gridcode.

After the “join” procedure, diet quality parameter (e.g. CP%) shapefile was highlighted in the View and the Legend Editor was used to select the best color combination that will make the differentiations in the map generated quite distinct. Graduated colors were chosen as the legend type, while parameter label (e.g., CP%) was chosen as the classification field. The graduated colors enabled identification of variations in the shapefiles corresponding to the changing pattern of the predicted diet quality parameter (e.g. CP%) being

mapped. A final map was produced using the Layout module in ArcView, and the map exported from ArcView as Placeable word metafile (WMF) file into MS Word document. The same procedures were used to create the CP and DOM maps for the other dekads.

## Results and Discussion

### Relationship Between Diet Quality Parameters and NDVI

Full compliment of data from the 66 sampling points could not be obtained in any sampling period (14 days) due to logistic and personnel problems. In addition fecal NIRS predicted CP and DOM values (%) with "Global H" values greater than 7 were rejected leading to a further reduction in the final data used in the cokriging.

Effective cokriging is contingent on a good relationship between the primary variate (diet quality parameter) and the covariate (NDVI). Usually a correlation coefficient (r) of 0.50 or higher, and a minimum sample size of 30 are required for effective cokriging. Therefore the relationship between NIRS predicted CP, DOM values (%) and NDVI over each dekad for cattle were studied, and the results presented as Pearson correlation (r) in Table 10.

The relationships between the predicted diet quality parameters and NDVI values were not consistent. The relationship between CP% and NDVI was positive in value from dekad 2 in February to dekad 3 in April, as well as in dekads 1 and 3 in May. Dekads 2 and 3 in February, and dekads 1 and 3 in April showed (r) values equal or greater than 0.50. The correlation (r) between

CP% and NDVI for the dekads from June to August were negative and below 0.50. DOM% was positively related with NDVI for the two dekads in February, and for all dekads in June and July. Apart from dekad 3 in May and dekads 1 and 3 in June in which r values for DOM% were greater than 0.50, r values for the rest of dekads sampled fell below 0.50.

Generally, positive relationships, though not strong in some cases, were observed between CP% and NDVI values during the months experiencing mean monthly rainfall of less than 75 mm (February to April), while a negative relationships between CP% and NDVI values were observed from months experiencing average monthly rainfall greater than 125 mm (Fig. 3) June to August. Dekadal relationships between DOM% and NDVI have been most inconsistent, however it appears where CP% relationship with NDVI was negative, DOM% relationship with NDVI was positive as observed in all dekads in June and July. August, which is one of the peak rainy months, produced rather poor relationship between predicted CP% and DOM% with NDVI for all its dekads. On the contrary moderate to high correlations between PHYGROW simulated forage production and NDVI (r = 0.60 to 0.86) were obtained for the majority of dekads analyzed (Angerer et al. 2001). The poor correlation obtained between fecal NIRS predicted dietary parameters and NDVI values compared to correlation obtained with forage production and NDVI could be explained by the fact that the correlation looked at the direct relationship between total forage production, while the correlation between diet quality

Table 10: Results of Pearson's correlation (r) analysis to determine the relationship between dekadal predicted diet quality parameters (CP & DOM) (primary variables) and NDVI (co-variable) for cattle.

| Diet quality and NDVI Dekad | Sample size | Correlation (r) CP | DOM |
|---|---|---|---|
| February, Dekad 2 | | 0.811 | 0.013 |
| February, Dekad 3 | | 0.779 | 0.414 |
| February Average | 34 | 0.772 | 0.218 |
| | | | |
| March, Dekad 1 | | 0.199 | 0.283 |
| March, Dekad 2 | | 0.114 | -0.143 |
| March, Dekad 3 | | 0.544 | 0.318 |
| March Average | 53 | 0.302 | 0.155 |
| | | | |
| April, Dekad 1 | | 0.823 | 0.360 |
| April, Dekad 2 | | 0.617 | -0.044 |
| April, Dekad 3 | | 0.870 | -0.333 |
| April Average | 51 | 0.655 | 0.107 |
| | | | |
| May, Dekad 1 | | 0.663 | -0.087 |
| May, Dekad 2 | | -0.007 | 0.044 |
| May, Dekad 3 | | 0.753 | 0.599 |
| May, Average | 35 | 0.653 | 0.304 |
| | | | |
| June, Dekad 1 | | -0.179 | 0.650 |
| June, Dekad 2 | | -0.329 | 0.034 |
| June, Dekad 3 | | -0.113 | 0.794 |
| June, Average | 45 | -0.491 | 0.635 |
| | | | |
| July, Dekad 1 | | -0.182 | 0.479 |
| July, Dekad 2 | | 0.495 | 0.177 |
| July, Dekad 3 | | -0.081 | 0.478 |
| July, Average | 59 | -0.587 | 0.465 |
| | | | |
| August, Dekad 1 | | -0.289 | -0.040 |
| August, Dekad 2 | | 0.078 | 0.370 |
| August, Dekad 3 | | -0.019 | -0.376 |
| August, Average | 60 | -0.100 | 0.190 |

parameter and NDVI is an indirect measurement of the quality of that portion of the forage consumed by the animal in relation to NDVI. Furthermore, NDVI is a measure of total greenness without discrimination between grazeable forage and tree canopy foliage.

**Mapping the Seasonal Changes in Cattle Diet Quality**

Data for the months of March (dry season) and July (wet season) were used for cokriging, and mapping of the cokriged estimated diet quality patterns for the year 2000. In order to depict diet quality changes in the dry and wet seasons of the year, the months of March and July with average data points greater than 30 were chosen. The coefficients of simple determination for semivariance analysis for the primary variables (CP and DOM) represented by Z, covariable (NDVI) represented by Z2, and their cross-semivariance (primary-x co- variable) denoted by Z x Z2 for March and July 2000 are presented in Table 11. The semivariance analysis for the covariate (NDVI) for both March and July were positive with $r^2$ in the range of 0.685-0.988. Semivariance analysis for CP% in March and DOM% in July were high with $r^2$ of 0.756 and 0.825 respectively, an indication that the semivariance analysis models for CP% and DOM% were able to explain the spatial variability in NIRS predicted CP% and DOM% for sampling sites across the landscape. On the other hand, semivariance analysis models for DOM% in March and CP% in July were poor with $r^2$ of 0.106 and 0.249, respectively, indicating that the semivariance analysis models for DOM% in March and CP% in July were unable to satisfactorily

explain the spatial variability in the NIRS predicted DOM% in March, and CP% in July for the sampling sites across the landscape. The cross-semivariance analysis model for the joint CP% and NDVI decreased from a moderate level ($r^2$ = 0.491) in March to a lower level ($r^2$ = 0.308) in July. On the contrary, cross-semivariance analysis model for the joint DOM% and NDVI remained high for March ($r^2$ = 0.692) and July ($r^2$ = 0.664). Since cross-semivarince analysis model determines the spatial relationship between the primary and secondary variables, the results show that the spatial relationship between CP% and NDVI fell from moderate values in March to low values in July, while DOM% relationship with NDVI remained high in both months. The drop in spatial relationship between CP% and NDVI values is in line with the observation that during periods of high rainfall or extended drought, correspondence between forage production and NDVI can be low (r <0.30) (Stuth et al. 2003a). A negative correspondence (r = -0.587) was actually recorded between CP% and NDVI in July. The DOM relationship with NDVI did not decline in value in July most probably because digestibility is a property rather than a constituent of feed (Flinn and Downes 1996)

The cokriged estimated CP% maps produced for March and July (Fig. 5) resulted in patterns depicting five CP ranges of 4-7%, 7-10%, 10-13%, 13-16%, and >16% respectively, with the lowest CP% range pattern occurring in the eastern portions of the zone. The range of 7-10% CP pattern mapped for Upper East Region (northeastern) portion of the zone in March was expected since this

Table 11: Coefficient of determination ($r^2$) for average values of CP% and DOM% (Z), NDVI (Z2), and cross-semivariate (Z x Z2) used in the cokriging for the months of March and July 2000

| **Season** | **Month** | **Parameter** | **$r^2$** |
|---|---|---|---|
| Dry | March | CP | 0.756 |
| | | NDVI | 0.988 |
| | | CP x NDVI | 0.491 |
| | | DOM | 0.106 |
| | | NDVI | 0.895 |
| | | DOM x NDVI | 0.692 |
| Wet | July | CP | 0.249 |
| | | NDVI | 0.658 |
| | | CP x NDVI | 0.308 |
| | | DOM | 0.825 |
| | | NDVI | 0.658 |
| | | DOM x NDVI | 0.664 |

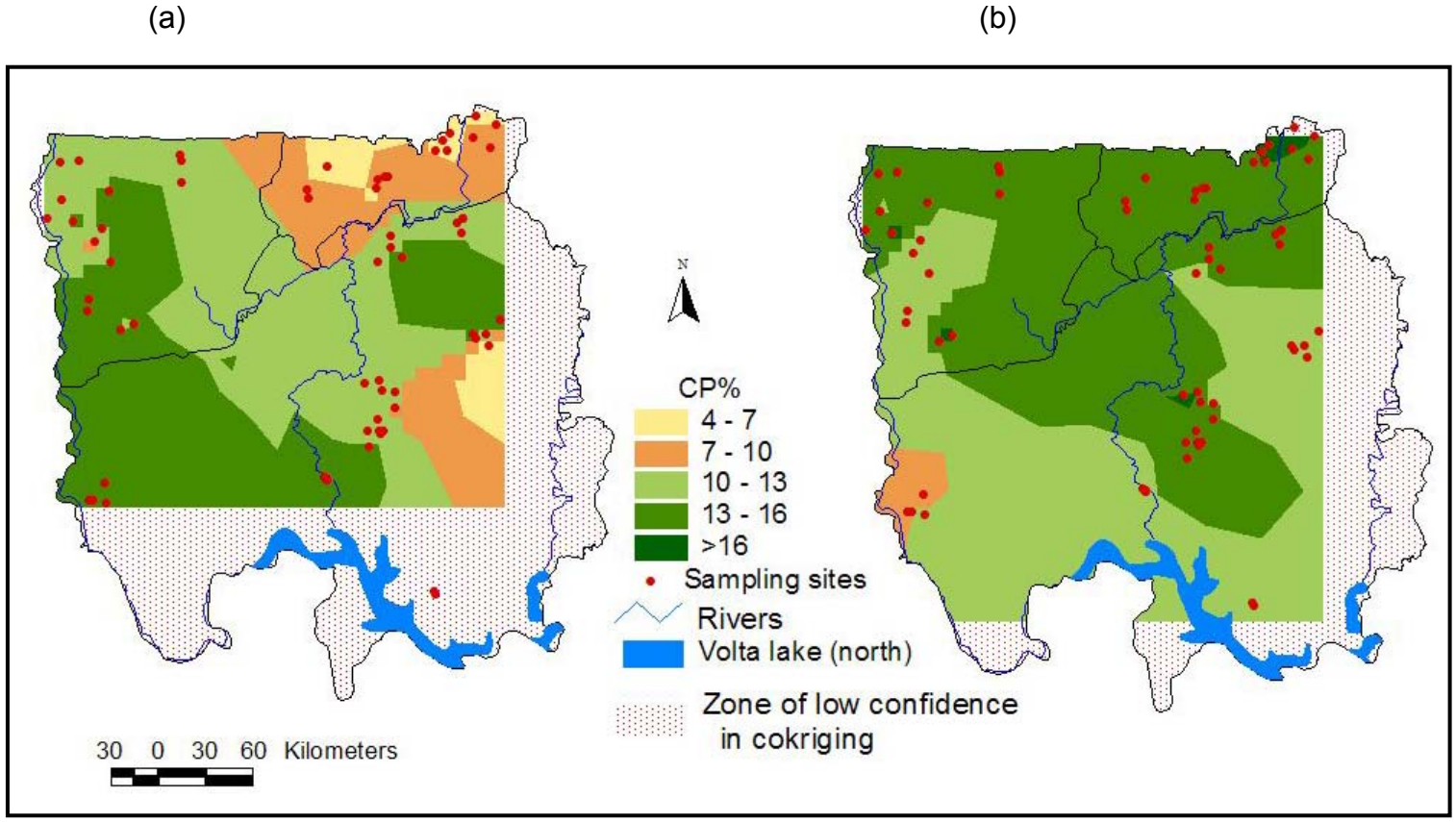


Fig. 5. Cokriged maps of northern savanna of Ghana depicting changes in CP% across the zone for the months of (a) March (dry season), and (b) July (wet season) for the year 2000.

region is relatively drier than the rest with poor lateritic soils and scattered low growing vegetation (Rose Innes 1977). Especially the northeastern most corner of the zone, referred to as the Sudan savanna, is heavily populated in terms of humans and livestock. Furthermore, almost all land in the area has been grazed and cultivated over a long period of time resulting in exhausted sheet-eroded soils over wide areas (Ramsay and Rose Innes 1963) which now supports mainly annual grass species of low quality. The lower CP% (7-10%) pattern occurring in the central eastern portion of the zone could be due to deviation of rainfall from the monthly normal for those localities in March. The results showed that available forage in about two-thirds of the zone in a westwards direction, exhibited CP% pattern between10-16%, with the highest range of 13-16% occurring in the southwestern corner of the zone. Higher rainfall regime (1148 mm isohyets, MOA 1991), and better soil conditions resulting in better growing conditions could account for slightly better forage species with higher nutrient quality occurring in southwestern corner resulting in the higher CP% range mapped for this area of the zone.

July cokriged estimated CP% surface map showed the highest CP (13-16%) pattern displayed in the northern portions of the savanna zone with a tongue-like shape extending into the central towards the southeastern parts of the zone. Apart from a small section of the southwest indicating 7-10% CP surface no other areas in the zone exhibited estimated forage CP% lower than 7%. At least this is an improvement on surface created for March. The changing patterns

observed in the forage quality maps for March and July follow the trend whereby forage quality is high at the onset of the rains (in this case, March), and quantity is low, while at the peak of the rains (July) quality becomes low while quantity increases. This pattern could be seen in the placement of highest CP (13 –16%) patterns for March and July. In order to ascertain how well the cokriged model estimated the NIRS predicted CP%, cross-validation regression analysis was performed. Results showed moderate degree of similarity between cokriged estimates and NIRS predicted CP% ($r^2$ = 0.687, SEp = 1.736 for March; $r^2$ = 0.513, SEp = 1.558 for July; Fig. 6) for the interpolated surfaces within the sampling zone.

The cokriged estimated DOM% surface maps for March and July 2000 are presented in Fig.7. Cokriged estimation resulted in the production of surface maps with DOM ranging from 37-67%. In March, forage quality in terms of DOM% was predominantly less than 50% (43-49%) for greater part of the zone, with pockets of 37-43% DOM range surfaces occurring within the northeastern corner, north central, and the north western fringes of the zone. The low DOM% estimated for March could result from poor forage quality due to little or no new forage growth within March. The mean rainfall recorded for the sampling sites in March was less than 24 mm, a rainfall level insufficient for substantial forage production considering the fact that the previous month, February had only trace rainfall. The months of February and March were characterized by rank

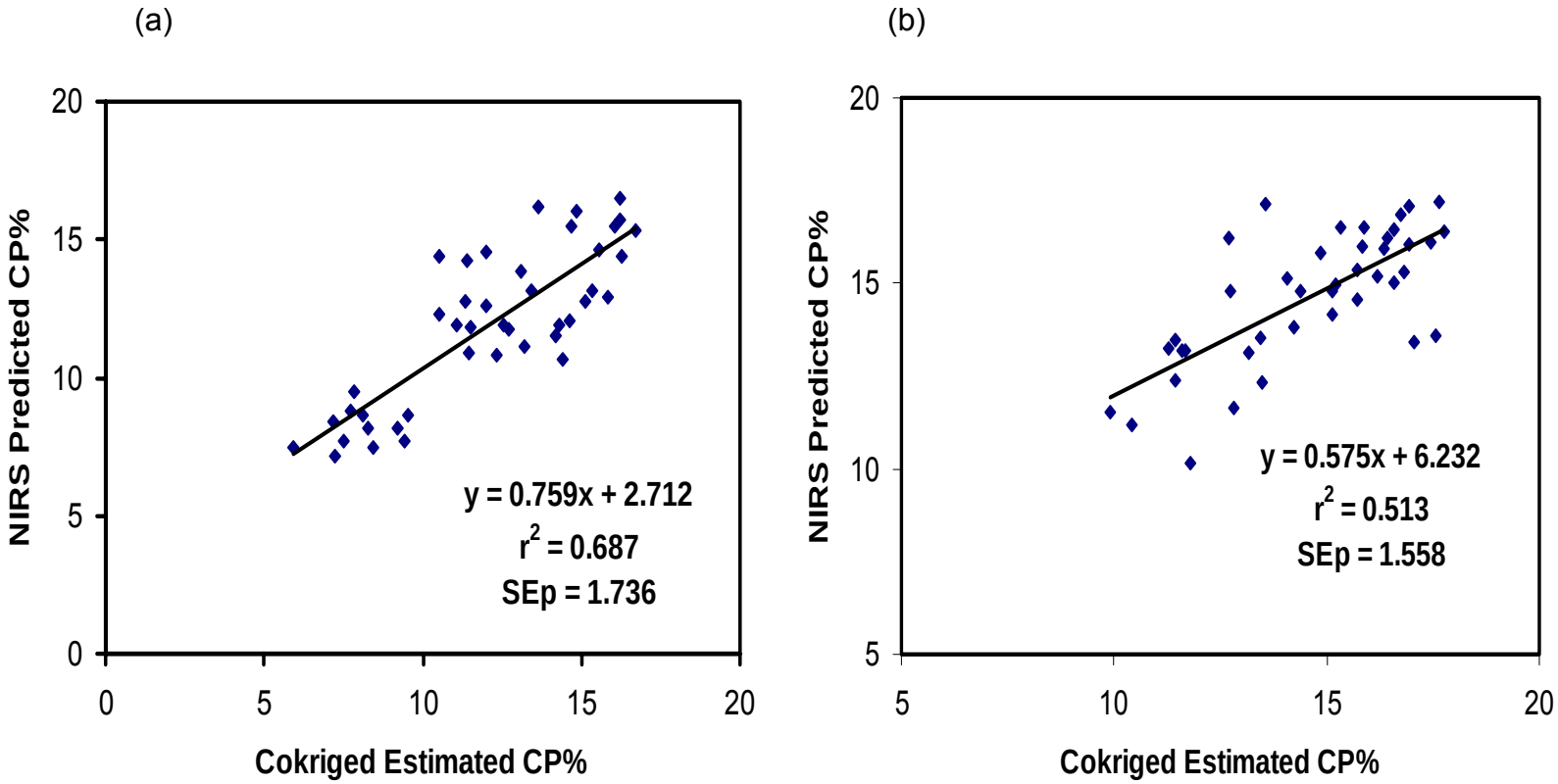


Fig.6. Cross validation results for the comparison of fecal NIRS predicted versus cokriged estimated CP% for (a) March (dry season), and (b) July (wet season) in year 2000.

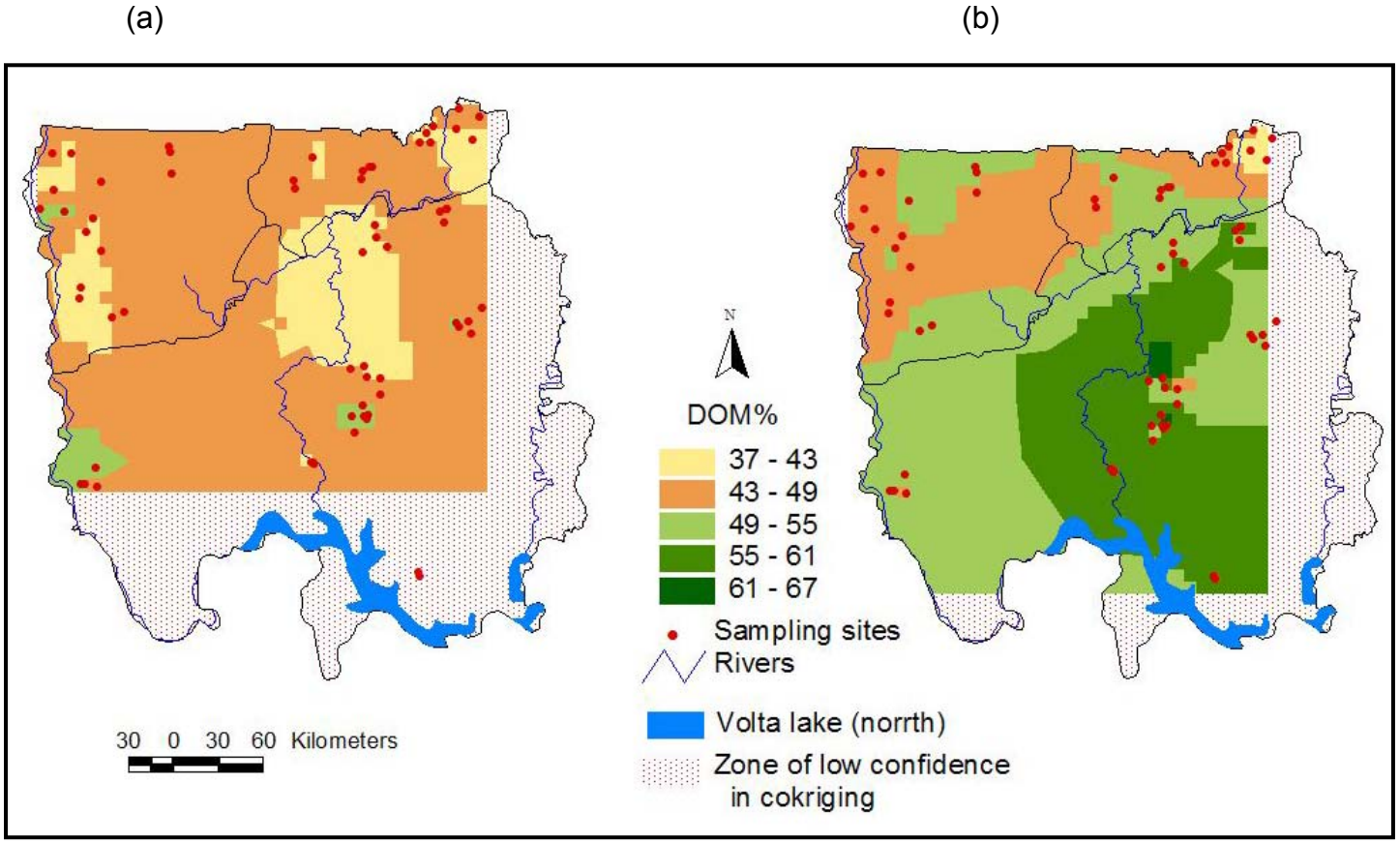


Fig. 7. Cokriged maps of northern savanna of Ghana depicting changes in DOM% across the zone for the months of (a) March (dry season), and (b) July (wet season) for the year 2000.

vegetation development, low in feeding value due to optimal lignification and effects of bush fires. The cross-validation regression analysis showed very low degree of similarity ($r^2$ = 0.132, SEp = 3.891, Fig. 8) between the cokriged estimates and the NIRS predicted DOM% for the sampling zone for March. Cokriged estimated surface map for July showed that forage quality in terms of DOM% was greater than 49% (49-61%) except for the northeastern corner where forage DOM ranged from 37-49% and pockets in northwestern area also exhibiting forage DOM range of 43-49%. The cokriged estimated map for July was definitely an improvement on the March map, since July falls within the rainy season with better forage growth potential, hence higher forage quality in terms of DOM%, though mean rainfall amounts for July in year 2000 was below the long term normal (LTN) (Fig.3). The cross-validation regression showed a moderate degree of similarity ($r^2$ = 0.584, SEp = 3.611, Fig. 8) between the cokriged estimates and the NIRS predicted DOM% for sampling zone. The poor to moderate cokriged estimation of fecal NIRS predicted DOM could be attributed to be low to fair correlation between average values of DOM and NDVI for March and July, respectively (Table 10). Though correlation between DOM and NDVI for July was greater than 0.30, the observation by Stuth et al. (2003a), as explained earlier on, equally apply in the case of DOM.

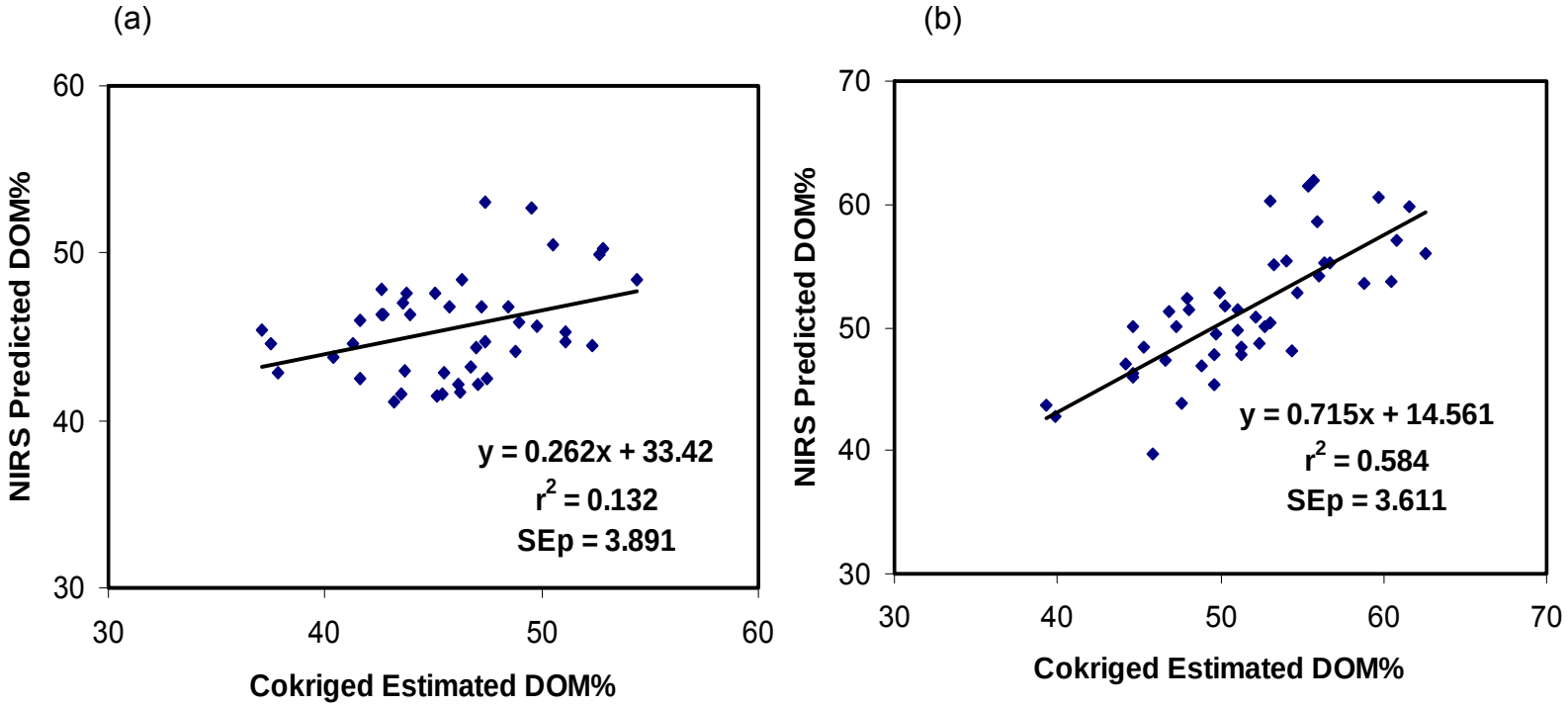


Fig. 8. Cross validation results for the comparison of fecal NIRS predicted versus cokriged estimated DOM% for (a) March (dry season), and (b) July (wet season) in year 2000.

## Summary and Conclusion

The possibility of using NDVI greenness data, a more spatially rich data set, and geostatistical tool of cokriging, an interpolation algorithm, which depends on the relationship between a reduced set of points of predicted CP and DOM values (%) and NDVI to create surface maps has been explored. Monthly average variations in NIRS predicted CP and DOM patterns were observed to follow the mean monthly rainfall pattern for the sampling zone (northern savanna). No exceptionally clear relationships could be established between NIRS predicted CP and DOM values (%), and NDVI values. Generally, where CP values (%) were positively related to NDVI data, the corresponding DOM values (%) produced zero to negative relationship with NDVI in the dry season months. The converse was true for the wet season months. The cokriging algorithm has been used successfully with NDVI to estimate and interpolate predicted CP and DOM data for the entire northern savanna from reduced point-based data enabling predicted diet quality surfaces to be mapped for the zone. The surface maps produced showed a clear trend in variation of predicted diet quality parameters (CP and DOM) in March and July chosen to represent the dry season and wet season of the year 2000. Within the experimental constraints, the cokriged estimated diet quality surface maps for the months of March and July, for cattle, were successfully developed.

Currently the technique of exploiting the relationship between diet quality parameter and NDVI along with cokriging algorithm to model the variability in diet quality and NDVI to create diet quality maps across landscapes appears to be just moderate. For the future, research into relating NDVI data more directly to grazeable forage devoid of tree canopy structure, which does not reflect grazing, should be explored. Such a technique may improve the relationship between NIRS predicted diet quality and NDVI thereby improving the cokriging results. Furthermore, the use of richer, denser, and more consistent sampling methodology with a more robust NIRS equation should be focus of further research.

# CHAPTER V

# GENERAL CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

In the fecal NIRS calibration studies, current US warm-season calibration equations developed for predicting diet quality parameters for cattle, sheep, and goats were not effective on West African diet quality samples. Enhanced calibration equation development incorporating diet-fecal pair data from West and East Africa in addition to historical data from ILRI research centers was successful. Calibration statistics obtained were similar in precision to dietary wet chemistry analysis, and equally comparable and in some cases better than published results. Cross validation statistics has also shown that the equations have high predictive capability of diet quality of free-ranging African livestock.

The African cattle calibration equation previously developed was used to successfully predict cattle fecal samples collected from February to August 2000 from selected household cattle located within the northern savanna of Ghana. Clearly defined relationships between predicted diet quality parameters (CP% and DOM%) and NDVI could not be established compared to high positive relationship reported between PHYGROW simulated available forage and NDVI data. However, coefficients of simple determination ($r^2$) of the semivariograms and cross-semivariograms for diet quality parameters and NDVI values were reasonable for cokriging to be performed. The cokriged cross validation results have shown that the capability of cokriging to estimate predicted CP% for March

and July, and DOM% for July was about average (> 50%). March cokriged DOM% estimation was rather poor. The technique of cokriging and creating diet quality maps can be described to be moderate in success in this study, though it is likely to be improved through further research.

## Recommendations

- More feeding trial experiments should be carried out in SSA countries not covered in this study to generate diet-fecal pair data for further upgrading the African calibration equations.
- African Governments should work towards the expansion of NIRS technology to cover all strategic livestock producing countries form the west, central, east, and south Africa.
- An international agreement should be reached between laboratories in Africa to ensure that all benefit from their respective work in each country.
- Further research into relating NDVI data more directly to grazeable forage devoid of tree canopy structure, which could possibly help relate NIRS predicted diet quality parameters to NDVI greenness data should be explored.
- The use of denser and a more consistent sampling strategy for household fecal sampling in relation to cokriging estimation should also be addressed to determine if satellite-based monitoring of animal nutrition is possible.

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# APPENDIX

Appendix Table 1a: Percentage composition of 5 low to medium crude protein rations fed to cattle to establish NIRS calibration reference set for Ghana during the dry season feeding trial. (Period 1)

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Grasses** | | | | | |
| *Andropogon gayanus* | 10% | 8% | 10% | 13% | 6% |
| *Hyparrhenia rufa* | 0% | 0% | 0% | 0% | 0% |
| *Panicun repens* | 0% | 5% | 0% | 0% | 10% |
| *Brachiaria deflexa* | 0% | 0% | 0% | 0% | 0% |
| *Rottboelia cochichinensis* | 0% | 5% | 5% | 8% | 10% |
| *Paspalum scrobiculatum* | 0% | 0% | 0% | 0% | 0% |
| **Browse** | | | | | |
| *Albezia lebbeck* | 0% | 0% | 10% | 4% | 9% |
| *Anogeissus leiocarpus* | 0% | 10% | 5% | 0% | 0% |
| *Cajanus cajan* | 0% | 0% | 0% | 10% | 0% |
| *Vitellaria paradoxum* | 10% | 0% | 8% | 5% | 0% |
| *Securinega virosa* | 0% | 5% | 0% | 10% | 10% |
| **Leguminous crop residues** | | | | | |
| Pigeon pea husk (*Cajanus cajan*) | 0% | 5% | 5% | 10% | 10% |
| Peanut vine hay (hualm) | 10% | 10% | 10% | 10% | 10% |
| Cotton seed (whole) | 0% | 2% | 7% | 5% | 5% |
| **Cereal crop residues** | | | | | |
| Rice straw (untreated) | 20% | 20% | 20% | 15% | 15% |
| Rice straw (urea treated) | 0% | 0% | 0% | 0% | 10% |
| Maize stover | 50% | 30% | 20% | 10% | 5% |

Appendix Table 1a: Continued

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Monocot-based diet** | **80%** | **68%** | **55%** | **46%** | **56%** |
| Grasses | 10% | 18% | 15% | 21% | 26% |
| Cereal crop residues | 70% | 50% | 40% | 25% | 30% |
| **Dicot-based diet** | **20%** | **32%** | **45%** | **54%** | **44%** |
| Browse species | 10% | 15% | 23% | 29% | 19% |
| Leguminous crop residues | 10% | 15% | 15% | 20% | 20% |
| Cotton seed (whole) | 0% | 2% | 7% | 5% | 5% |

Appendix Table 1b: Percentage composition of 5 medium to high crude protein rations fed to cattle to establish NIRS calibration reference set for Ghana during the dry season feeding trial. (Period 1)

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Grasses** | | | | | |
| *Andropogon gayanus* | 5% | 10% | 10% | 5% | 0% |
| *Hyparrhenia rufa* | 0% | 10% | 0% | 0% | 0% |
| *Panicun repens* | 0% | 0% | 0% | 0% | 5% |
| *Brachiaria deflexa* | 5% | 0% | 0% | 5% | 5% |
| *Rottboelia cochichinensis* | 0% | 0% | 0% | 5% | 0% |
| *Paspalum scrobiculatum* | 10% | 0% | 10% | 0% | 0% |
| **Browse** | | | | | |
| *Albezia lebbeck* | 0% | 10% | 10% | 10% | 10% |
| *Anogeissus leiocarpus* | 0% | 10% | 0% | 0% | 5% |
| *Cajanus cajan* | 10% | 5% | 10% | 5% | 0% |
| *Vitellaria paradoxum* | 0% | 5% | 0% | 5% | 0% |
| *Securinega virosa* | 10% | 0% | 10% | 10% | 5% |
| **Leguminous crop residues** | | | | | |
| Pigeon pea husk (*Cajanus cajan*) | 15% | 5% | 5% | 5% | 10% |
| Peanut vine hay (haulms) | 10% | 5% | 5% | 0% | 0% |
| Cotton seed (whole) | 5% | 10% | 10% | 20% | 30% |
| **Cereal crop residues** | | | | | |
| Rice straw (untreated) | 15% | 10% | 15% | 5% | 5% |
| Rice straw (urea treated) | 15% | 15% | 15% | 20% | 25% |
| Maize stover | 0% | 5% | 0% | 5% | 0% |

Table 1b: Continued

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Monocot-based diet** | **50%** | **50%** | **50%** | **45%** | **40%** |
| Grasses | 20% | 20% | 20% | 15% | 10% |
| Cereal crop residues | 30% | 30% | 30% | 30% | 30% |
| **Dicot-based diet** | **50%** | **50%** | **50%** | **55%** | **60%** |
| Browse species | 20% | 30% | 30% | 30% | 20% |
| Leguminous crop residues | 25% | 10% | 10% | 5% | 10% |
| Cotton seed (whole) | 5% | 10% | 10% | 20% | 30% |

Appendix Table 1c: Percentage composition of 6 low to medium crude protein rations fed to cattle to establish NIRS calibration reference set in Ghana during the wet season feeding trial. (Period 2)

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Grasses** | | | | | | |
| *Andropogon gayanus* | 0% | 0% | 0% | 10% | 15% | 25% |
| *Andropogon tectorum* | 30% | 30% | 20% | 25% | 9% | 0% |
| *Brachiaria lata* | 0% | 0% | 10% | 15% | 10% | 10% |
| *Pennisetum ciliare* | 0% | 0% | 0% | 0% | 0% | 10% |
| *Cynodon dactylon* | 0% | 0% | 0% | 0% | 15% | 15% |
| *Eluesine indica* | 0% | 0% | 10% | 0% | 0% | 0% |
| *Heteropogon contortus* | 0% | 10% | 10% | 0% | 0% | 0% |
| *Hyparrhenia rufa* | 30% | 30% | 25% | 30% | 30% | 20% |
| *Paspalum orboculare* | 30% | 15% | 10% | 0% | 0% | 0% |
| *Pennisetum violaceum* | 0% | 0% | 0% | 10% | 0% | 10% |
| *Rottboelia cochichinensis* | 0% | 0% | 0% | 5% | 5% | 10% |
| *Setaria barbata* | 0% | 0% | 0% | 0% | 10% | 0% |
| **Browse** | | | | | | |
| *Afzelia african* | 0% | 5% | 5% | 5% | 0% | 0% |
| *Albezia lebbeck* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Anogeissus leiocarpus* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Ceiba pentandra* | 10% | 10% | 10% | 0% | 0% | 0% |
| *Ficus gnaphalocarpa* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Khaya senegalensis* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Pterocarpus irrenaceus* | 0% | 0% | 0% | 0% | 6% | 0% |
| *Securinega virosa* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Tephrosia bracteolata* | 0% | 0% | 0% | 0% | 0% | 0% |
| **Pasture Legume** | | | | | | |
| *Stylosanthes scabra* cv verano | 0% | 0% | 0% | 0% | 0% | 0% |

Appendix Table 1c: Continued

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Monocot-based diet** | **90%** | **85%** | **85%** | **95%** | **94%** | **100%** |
| Grasses | 90% | 85% | 85% | 95% | 94% | 100% |
| **Dicot-based diet** | **10%** | **15%** | **15%** | **5%** | **6%** | **0%** |
| Browse species (non-legume) | 10% | 10% | 10% | 0% | 6% | 0% |
| Legume-based browse | 0% | 5% | 5% | 5% | 0% | 0% |

Appendix Table 1d: Percentage composition of 6 medium to high crude protein rations fed to cattle to establish NIRS calibration reference set in Ghana during the wet season feeding trial. (Period 2)

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Grasses** | | | | | | |
| *Andropogon gayanus* | 30% | 25% | 25% | 15% | 15% | 10% |
| *Andrropogon tectorum* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Brachiaria lata* | 0% | 15% | 15% | 13% | 5% | 0% |
| *Pennisetum ciliare* | 15% | 10% | 10% | 15% | 0% | 0% |
| *Cynodon dactylon* | 15% | 15% | 12% | 12% | 15% | 10% |
| *Eluesine indica* | 0% | 0% | 0% | 0% | 15% | 15% |
| *Heteropogon contortus* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Hyparrhenia rufa* | 10% | 0% | 0% | 0% | 0% | 0% |
| *Paspalum orboculare* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Pennisetum violaceum* | 10% | 0% | 0% | 0% | 0% | 0% |
| *Rottboelia cochichinensis* | 10% | 5% | 5% | 0% | 5% | 0% |
| *Setaria barbata* | 0% | 10% | 0% | 0% | 0% | 5% |
| **Browse** | | | | | | |
| *Afzelia african* | 0% | 0% | 0% | 0% | 0% | 5% |
| *Albezia lebbeck* | 0% | 10% | 8% | 15% | 15% | 15% |
| *Anogeissus leiocarpus* | 0% | 0% | 0% | 0% | 5% | 10% |
| *Ceiba pentandra* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Ficus gnaphalocarpa* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Khaya senegalensis* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Pterocarpus irrenaceus* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Securinega virosa* | 5% | 0% | 10% | 10% | 10% | 10% |
| *Tephrosia bracteolata* | 0% | 0% | 0% | 0% | 0% | 0% |
| **Pasture Legume** | | | | | | |
| *Stylosanthes scabra* cv verano | 5% | 10% | 15% | 20% | 15% | 20% |

Appendix Table 1d: Continued

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Monocot-based diet** | **90%** | **80%** | **67%** | **55%** | **55%** | **40%** |
| Grasses | 90% | 80% | 67% | 55% | 55% | 40% |
| **Dicot-based diet** | **10%** | **20%** | **33%** | **45%** | **45%** | **60%** |
| Browse species (non-legume) | 5% | 10% | 10% | 10% | 15% | 20% |
| Legume-based browse | 5% | 10% | 23% | 35% | 30% | 40% |

Appendix Table 2a: Percentage composition of 5 low to medium crude protein rations fed to sheep to establish NIRS calibration reference set in Ghana during the dry season feeding trial. (Period 1)

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Grasses** | | | | | |
| *Andropogon gayanus* | 20% | 20% | 15% | 10% | 0% |
| *Hyparrhenia rufa* | 20% | 15% | 10% | 0% | 10% |
| *Panicun repens* | 0% | 0% | 0% | 0% | 0% |
| *Brachiaria deflexa* | 0% | 0% | 0% | 0% | 0% |
| *Rottboelia cochichinensis* | 0% | 0% | 0% | 10% | 0% |
| *Paspalum scrobiculatum* | 0% | 0% | 0% | 0% | 10% |
| **Browse** | | | | | |
| *Albezia lebbeck* | 0% | 5% | 10% | 0% | 10% |
| *Anogeissus leiocarpus* | 10% | 10% | 0% | 5% | 0% |
| *Cajanus cajan* | 0% | 0% | 3% | 5% | 10% |
| *Faedherbia albida* (pod meal) | 0% | 5% | 2% | 0% | 0% |
| *Ficus gnaphalocarpa* | 5% | 5% | 5% | 5% | 5% |
| *Vitellaria paradoxum* | 5% | 0% | 0% | 5% | 5% |
| *Securinega virosa* | 0% | 0% | 5% | 10% | 0% |
| **Leguminous crop residues** | | | | | |
| Pigeon pea husk (*Cajanus cajan*) | 0% | 0% | 10% | 10% | 10% |
| Peanut vine hay (haulms) | 0% | 0% | 0% | 5% | 5% |
| Cotton seed (whole) | 0% | 0% | 5% | 5% | 10% |
| **Cereal crop residues** | | | | | |
| Rice straw (untreated) | 20% | 10% | 15% | 10% | 10% |
| Rice straw (urea treated) | 0% | 0% | 0% | 0% | 0% |
| Maize stover | 20% | 20% | 10% | 10% | 10% |
| Root crop residues | | | | | |
| Dried cassava peels (*Manihot sp*) | 0% | 10% | 10% | 10% | 5% |

Appendix Table 2a: Continued

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Monocot-based diet** | **80%** | **65%** | **45%** | **40%** | **40%** |
| Grasses | 40% | 35% | 25% | 20% | 20% |
| Cereal crop residues | 40% | 30% | 25% | 20% | 20% |
| **Dicot-based diet** | **20%** | **25%** | **35%** | **45%** | **45%** |
| Browse species | 10% | 25% | 25% | 30% | 30% |
| Leguminous crop residues | 10% | 0% | 10% | 15% | 15% |
| **Others** | **0%** | **10%** | **15%** | **15%** | **15%** |
| Cotton seed (whole) | 0% | 0% | 5% | 5% | 10% |
| Dried cassava peal meal | 0% | 10% | 10% | 10% | 5% |

Appendix Table 2b: Percentage composition of 5 medium to high crude protein rations fed to sheep to establish NIRS calibration reference set in Ghana during the dry season feeding trial. (Period 1)

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Grasses** | | | | | |
| *Andropogon gayanus* | 10% | 5% | 0% | 5% | 0% |
| *Hyparrhenia rufa* | 0% | 0% | 5% | 0% | 0% |
| *Panicun repens* | 0% | 5% | 0% | 0% | 5% |
| *Brachiaria deflexa* | 10% | 5% | 0% | 0% | 0% |
| *Rottboelia cochichinensis* | 0% | 0% | 0% | 5% | 0% |
| *Paspalum scrobiculatum* | 0% | 0% | 8% | 0% | 0% |
| **Browse** | | | | | |
| *Albezia lebbeck* | 5% | 10% | 10% | 10% | 0% |
| *Anogeissus leiocarpus* | 0% | 0% | 0% | 0% | 10% |
| *Cajanus cajan* | 10% | 10% | 10% | 5% | 10% |
| *Faedherbia albida* (pod meal) | 0% | 0% | 0% | 0% | 0% |
| *Ficus gnaphalocarpa* | 0% | 0% | 5% | 10% | 0% |
| *Vitellaria paradoxum* | 0% | 0% | 0% | 0% | 0% |
| *Securinega virosa* | 10% | 10% | 5% | 0% | 5% |
| **Leguminous crop residues** | | | | | |
| Cowpea vine hay (haulms) | 0% | 0% | 5% | 0% | 0% |
| Pigeon pea husk (*Cajanus cajan*) | 10% | 10% | 10% | 10% | 10% |
| Peanut vine hay | 5% | 5% | 0% | 4% | 0% |
| Cotton seed (whole) | 10% | 10% | 14% | 20% | 25% |
| **Cereal crop residues** | | | | | |
| Rice straw (untreated) | 10% | 10% | 8% | 5% | 0% |
| Rice straw (urea treated) | 5% | 6% | 10% | 15% | 25% |
| Maize stover | 10% | 9% | 5% | 5% | 0% |

Appendix Table 2b: Continued

| Functional Group/plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Root crop residues** | | | | | |
| Dried cassava peels (Manihot sp) | 5% | 5% | 5% | 6% | 10% |
| **Monocot-based diet** | 45% | 40% | 36% | 35% | 30% |
| Grasses | 20% | 15% | 13% | 10% | 5% |
| Cereal crop residues | 25% | 25% | 23% | 25% | 25% |
| **Dicot-based diet** | 40% | 45% | 45% | 39% | 35% |
| Browse species | 25% | 30% | 30% | 25% | 25% |
| Leguminous crop residues | 15% | 15% | 15% | 14% | 10% |
| **Others** | 15% | 15% | 19% | 26% | 35% |
| Cotton seed (whole) | 10% | 10% | 5% | 20% | 25% |
| Dried cassava peal meal | 5% | 5% | 14% | 6% | 10% |

Appendix Table 2c: Percentage composition of 6 low to medium crude protein rations fed to sheep to establish NIRS calibration reference set in Ghana during the wet season feeding trial. (Period 2)

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Grasses** | | | | | | |
| *Andropogon gayanus* | 0% | 0% | 0% | 25% | 0% | 0% |
| *Andrropogon tectorum* | 40% | 30% | 25% | 10% | 25% | 25% |
| *Brachiaria lata* | 0% | 10% | 0% | 0% | 10% | 10% |
| *Pennisetum ciliare* | 0% | 0% | 0% | 20% | 0% | 0% |
| *Cynodon dactylon* | 0% | 0% | 0% | 10% | 0% | 0% |
| *Eluesine indica* | 0% | 0% | 10% | 0% | 0% | 10% |
| *Heteropogon contortus* | 0% | 0% | 10% | 0% | 5% | 0% |
| *Hyparrhenia rufa* | 40% | 30% | 25% | 0% | 10% | 10% |
| *Paspalum orboculare* | 10% | 10% | 10% | 0% | 0% | 0% |
| *Pennisetum violaceum* | 0% | 0% | 0% | 0% | 0% | 10% |
| *Rottboelia cochichinensis* | 0% | 0% | 0% | 0% | 10% | 0% |
| *Setaria barbata* | 0% | 0% | 0% | 0% | 5% | 0% |
| **Browse** | | | | | | |
| *Afzelia african* | 0% | 0% | 0% | 0% | 10% | 0% |
| *Albezia lebbeck* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Anogeissus leiocarpus* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Ceiba pentandra* | 10% | 10% | 10% | 0% | 0% | 10% |
| *Ficus gnaphalocarpa* | 0% | 10% | 0% | 10% | 10% | 10% |
| *Khaya senegalensis* | 0% | 0% | 5% | 15% | 0% | 10% |
| *Pterocarpus irrenaceus* | 0% | 0% | 5% | 0% | 5% | 0% |
| *Securinega virosa* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Tephrosia bracteolata* | 0% | 0% | 0% | 10% | 10% | 5% |
| **Pasture Legume** | | | | | | |
| *Stylosanthes scabra* cv verano | 0% | 0% | 0% | 0% | 0% | 0% |

Appendix Table 2c: Continued

| Functional Group/Plant species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Monocot-based diet** | **90%** | **80%** | **80%** | **65%** | **65%** | **65%** |
| Grasses | 90% | 80% | 80% | 65% | 65% | 65% |
| **Dicot-based diet** | **10%** | **20%** | **20%** | **35%** | **35%** | **35%** |
| Browse species (non-legume) | 10% | 20% | 20% | 35% | 25% | 35% |
| Legume-based browse | 0% | 0% | 0% | 0% | 10% | 0% |

Appendix Table 2d: Percentage composition of 7 medium to high crude protein rations fed to sheep to establish NIRS calibration reference set in Ghana during the wet season feeding trial. (Period 2)

| Functional Group/Plant Species | Rations | | | | | | |
|---|---|---|---|---|---|---|---|
| **Grasses** | | | | | | | |
| *Andropogon gayanus* | 10% | 10% | 15% | 5% | 0% | 0% | 5% |
| *Andropogon tectorum* | 20% | 0% | 0% | 0% | 0% | 0% | 0% |
| *Brachiaria lata* | 10% | 15% | 0% | 10% | 15% | 15% | 10% |
| **Pennisetum ciliare** | 0% | 15% | 5% | 10% | 0% | 15% | 10% |
| *Cynodon dactylon* | 10% | 15% | 15% | 0% | 15% | 10% | 0% |
| *Eluesine indica* | 0% | 0% | 15% | 0% | 0% | 0% | 0% |
| *Heteropogon contortus* | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *Hyparrhenia rufa* | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *Paspalum orboculare* | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *Pennisetum violaceum* | 10% | 0% | 0% | 0% | 10% | 0% | 0% |
| *Rottboelia cochichinensis* | 0% | 10% | 5% | 0% | 0% | 0% | 0% |
| *Setaria barbata* | 0% | 0% | 0% | 0% | 10% | 0% | 0% |
| **Browse** | | | | | | | |
| *Afzelia african* | 10% | 10% | 10% | 10% | 0% | 0% | 0% |
| *Albezia lebbeck* | 0% | 0% | 0% | 0% | 10% | 10% | 10% |
| *Anogeissus leiocarpus* | 10% | 0% | 5% | 5% | 10% | 0% | 5% |
| *Ceiba pentandra* | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *Ficus gnaphalocarpa* | 10% | 0% | 5% | 0% | 0% | 10% | 0% |
| *Khaya senegalensis* | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *Pterocarpus irrenaceus* | 0% | 10% | 15% | 10% | 0% | 0% | 10% |
| *Securinega virosa* | 10% | 0% | 0% | 15% | 10% | 15% | 15% |
| *Tephrosia bracteolata* | 0% | 10% | 5% | 15% | 10% | 10% | 15% |
| **Pasture Legume** | | | | | | | |
| *Stylosanthes scabra* | 0% | 5% | 5% | 20% | 15% | 15% | 20% |

Appendix Table 2d: Continued

| Functional Group/Plant Species | Rations | | | | | | |
|---|---|---|---|---|---|---|---|
| **Monocot-based diet** | **60%** | **80%** | **80%** | **65%** | **65%** | **65%** | **25%** |
| Grasses | 60% | 80% | 80% | 65% | 65% | 65% | 25% |
| **Dicot-based diet** | **40%** | **20%** | **20%** | **35%** | **35%** | **35%** | **75%** |
| Browse species (non-legume) | 40% | 20% | 20% | 35% | 25% | 35% | 55% |
| Legume-based browse | 0% | 0% | 0% | 0% | 10% | 0% | 20% |

Appendix Table 3a: Percentage composition of 5 low to medium crude protein rations fed to goats to establish NIRS calibration reference set in Ghana during the dry season feeding trial. (Period 1)

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Grasses** | | | | | |
| *Andropogon gayanus* | 20% | 10% | 10% | 10% | 5% |
| *Hyparrhenia rufa* | 20% | 10% | 10% | 10% | 0% |
| *Panicun repens* | 0% | 0% | 0% | 0% | 0% |
| *Brachiaria deflexa* | 0% | 0% | 0% | 0% | 0% |
| *Rottboelia cochichinensis* | 0% | 0% | 0% | 0% | 5% |
| *Paspalum scrobiculatum* | 0% | 0% | 0% | 0% | 0% |
| **Browse** | | | | | |
| *Albezia lebbeck* | 0% | 5% | 10% | 10% | 10% |
| *Anogeissus leiocarpus* | 0% | 0% | 0% | 0% | 5% |
| *Cajanus cajan* | 0% | 0% | 0% | 0% | 0% |
| *Faedherbia albida* | 5% | 10% | 10% | 10% | 14% |
| *Faedherbia albida* (pod meal | 0% | 0% | 0% | 5% | 10% |
| *Ficus gnaphalocarpa* | 10% | 10% | 10% | 10% | 10% |
| *Vitellaria paradoxum* | 5% | 10% | 10% | 0% | 0% |
| *Securinega virosa* | 0% | 0% | 0% | 6% | 6% |
| **Leguminous crop residues** | | | | | |
| Pigeon pea husk (*Cajanus cajan*) | 0% | 0% | 0% | 5% | 10% |
| Peanut vine hay (haulms) | 0% | 0% | 0% | 5% | 5% |
| Cotton seed (whole) | 0% | 0% | 0% | 0% | 0% |
| **Cereal crop residues** | | | | | |
| Rice straw (untreated) | 20% | 20% | 15% | 12% | 10% |
| Rice straw (urea treated) | 0% | 0% | 0% | 0% | 0% |
| Maize stover | 20% | 20% | 15% | 12% | 5% |
| Root crop residues | | | | | |
| Dried cassava peels (*Manihot sp)* | 0% | 5% | 10% | 5% | 5% |

Appendix Table 3a: Continued

| Functional Group/Plant Species | Rations | | | | |
|---|---|---|---|---|---|
| **Monocot-based diet** | **80%** | **60%** | **50%** | **44%** | **25%** |
| Grasses | 40% | 20% | 20% | 20% | 10% |
| Cereal crop residues | 40% | 40% | 30% | 24% | 15% |
| **Dicot-based diet** | **20%** | **30%** | **40%** | **51%** | **70%** |
| Browse species | 20% | 35% | 40% | 41% | 55% |
| Leguminous crop residues | 0% | 0% | 0% | 10% | 15% |
| **Others** | **0%** | **5%** | **10%** | **5%** | **5%** |
| Cotton seed (whole) | 0% | 0% | 0% | 0% | 0% |
| Dried cassava peal meal | 0% | 5% | 10% | 5% | 5% |

Appendix Table 3b: Percentage composition of 6 medium to high crude protein rations fed to goats to establish NIRS calibration reference set in Ghana during the dry season feeding trial. (Period 1)

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Grasses** | | | | | | |
| *Andropogon gayanus* | 0% | 5% | 5% | 0% | 3% | 0% |
| *Hyparrhenia rufa* | 5% | 5% | 5% | 0% | 0% | 0% |
| *Panicun repens* | 0% | 0% | 0% | 5% | 0% | 0% |
| *Brachiaria deflexa* | 0% | 0% | 0% | 0% | 5% | 0% |
| *Rottboelia cochichinensis* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Paspalum scrobiculatum* | 5% | 0% | 5% | 0% | 0% | 6% |
| **Browse** | | | | | | |
| *Albezia lebbeck* | 8% | 8% | 13% | 14% | 15% | 17% |
| *Anogeissus leiocarpus* | 5% | 10% | 5% | 3% | 5% | 5% |
| *Cajanus cajan* | 10% | 7% | 0% | 0% | 0% | 0% |
| *Faedherbia albida* | 15% | 15% | 20% | 22% | 22% | 22% |
| *Faedherbia albida* (pod meal | 5% | 5% | 10% | 3% | 2% | 0% |
| *Ficus gnaphalocarpa* | 5% | 5% | 7% | 6% | 5% | 5% |
| *Vitellaria paradoxum* | 0% | 0% | 0% | 5% | 0% | 0% |
| *Securinega virosa* | 7% | 0% | 0% | 0% | 0% | 0% |
| **Leguminous crop residues** | | | | | | |
| Cowpea vine hay | 5% | 0% | 5% | 0% | 0% | 0% |
| Pigeon pea husk (*Cajanus cajan*) | 10% | 5% | 5% | 5% | 5% | 5% |
| Peanut vine hay (haulms) | 0% | 5% | 0% | 5% | 0% | 0% |
| Cotton seed (whole) | 0% | 10% | 10% | 12% | 15% | 17% |
| **Cereal crop residues** | | | | | | |
| Rice straw (untreated) | 5% | 5% | 0% | 5% | 3% | 0% |
| Rice straw (urea treated) | 0% | 0% | 5% | 10% | 15% | 15% |
| Maize stover | 5% | 5% | 5% | 0% | 0% | 3% |

Appendix Table 3b: Continued

| Functional Group/Plant species | Rations | | | | | |
|---|---|---|---|---|---|---|
| Root crop residues | | | | | | |
| Dried cassava peels (Manihot sp) | 10% | 10% | 5% | 5% | 5% | 5% |
| **Monocot-based diet** | **20%** | **20%** | **20%** | **20%** | **26%** | **24%** |
| Grasses | 10% | 10% | 10% | 5% | 8% | 5% |
| Cereal crop residues | 10% | 10% | 10% | 15% | 18% | 18% |
| **Dicot-based diet** | **70%** | **60%** | **65%** | **63%** | **54%** | **54%** |
| Browse species | 55% | 50% | 55% | 53% | 49% | 49% |
| Leguminous crop residues | 15% | 10% | 10% | 10% | 5% | 5% |
| **Others** | **10%** | **20%** | **15%** | **17%** | **20%** | **22%** |
| Cotton seed (whole) | 0% | 10% | 10% | 12% | 15% | 17% |
| Dried cassava peal meal | 10% | 10% | 5% | 5% | 5% | 5% |

Appendix Table 3c: Percentage composition of 6 low to medium crude protein rations fed to goats to establish NIRS calibration reference set in Ghana during the wet season feeding trial. (Period 2)

| Functional Group/plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Grasses** | | | | | | |
| *Andropogon gayanus* | 0% | 10% | 0% | 25% | 0% | 0% |
| *Andrropogon tectorum* | 30% | 20% | 30% | 0% | 20% | 20% |
| *Brachiaria lata* | 0% | 0% | 0% | 0% | 5% | 5% |
| *Pennisetum ciliare* | 0% | 20% | 0% | 0% | 0% | 0% |
| *Cynodon dactylon* | 0% | 10% | 0% | 0% | 0% | 5% |
| *Eluesine indica* | 0% | 0% | 0% | 10% | 5% | 0% |
| *Heteropogon contortus* | 0% | 0% | 0% | 5% | 7% | 5% |
| *Hyparrhenia rufa* | 30% | 5% | 30% | 25% | 23% | 15% |
| *Paspalum orboculare* | 20% | 0% | 15% | 0% | 0% | 0% |
| *Pennisetum violaceum* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Rottboelia cochichinensis* | 0% | 5% | 0% | 0% | 0% | 10% |
| Setaria barbata | 0% | 0% | 0% | 5% | 5% | 0% |
| **Browse** | | | | | | |
| *Afzelia african* | 0% | 0% | 0% | 0% | 5% | 5% |
| *Albezia lebbeck* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Anogeissus leiocarpus* | 0% | 5% | 0% | 0% | 0% | 5% |
| *Ceiba pentandra* | 15% | 0% | 8% | 10% | 0% | 5% |
| *Ficus gnaphalocarpa* | 5% | 5% | 10% | 10% | 15% | 10% |
| *Khaya senegalensis* | 0% | 10% | 7% | 10% | 10% | 0% |
| *Pterocarpus irrenaceus* | 0% | 0% | 0% | 0% | 0% | 10% |
| *Securinega virosa* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Tephrosia bracteolata* | 0% | 10% | 0% | 0% | 5% | 5% |
| **Pasture Legume** | | | | | | |
| *Stylosanthes scabra* cv verano | 0% | 0% | 0% | 0% | 0% | 0% |

Appendix Table 3c: Continued

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Monocot-based diet** | **80%** | **70%** | **75%** | **70%** | **65%** | **60%** |
| Grasses | 80% | 70% | 75% | 70% | 65% | 60% |
| **Dicot-based diet** | **20%** | **30%** | **25%** | **30%** | **35%** | **40%** |
| Browse species (non-legume) | 20% | 30% | 25% | 30% | 30% | 35% |
| Legume-based browse | 0% | 0% | 0% | 0% | 5% | 5% |

Appendix Table 3d: Percentage composition of 6 medium to high crude protein rations fed to goats to establish NIRS calibration reference set in Ghana during the wet season feeding trial. (Period 2)

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Grasses** | | | | | | |
| *Andropogon gayanus* | 0% | 5% | 5% | 10% | 5% | 5% |
| *Andrropogon tectorum* | 20% | 0% | 15% | 0% | 0% | 0% |
| *Brachiaria lata* | 0% | 0% | 5% | 10% | 5% | 0% |
| *Pennisetum ciliare* | 5% | 10% | 0% | 10% | 5% | 0% |
| *Cynodon dactylon* | 10% | 10% | 10% | 0% | 5% | 10% |
| *Eluesine indica* | 0% | 0% | 0% | 0% | 0% | 10% |
| *Heteropogon contortus* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Hyparrhenia rufa* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Paspalum orboculare* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Pennisetum violaceum* | 10% | 10% | 0% | 0% | 0% | 5% |
| *Rottboelia cochichinensis* | 0% | 5% | 10% | 0% | 0% | 0% |
| *Setaria barbata* | 10% | 0% | 5% | 0% | 0% | 0% |
| **Browse** | | | | | | |
| *Afzelia african* | 0% | 0% | 5% | 10% | 10% | 10% |
| *Albezia lebbeck* | 5% | 5% | 0% | 5% | 10% | 8% |
| *Anogeissus leiocarpus* | 10% | 10% | 10% | 10% | 10% | 15% |
| *Ceiba pentandra* | 0% | 0% | 0% | 0% | 0% | 0% |
| *Ficus gnaphalocarpa* | 0% | 0% | 5% | 10% | 5% | 13% |
| *Khaya senegalensis* | 10% | 10% | 0% | 0% | 0% | 0% |
| *Pterocarpus irrenaceus* | 0% | 10% | 0% | 5% | 0% | 0% |
| *Securinega virosa* | 5% | 10% | 15% | 15% | 15% | 7% |
| *Tephrosia bracteolata* | 10% | 10% | 10% | 5% | 10% | 7% |
| **Pasture Legume** | | | | | | |
| *Stylosanthes scabra* cv verano | 5% | 5% | 5% | 10% | 10% | 10% |

Table 3d: Continued

| Functional Group/Plant Species | Rations | | | | | |
|---|---|---|---|---|---|---|
| **Monocot-based diet** | **55%** | **40%** | **50%** | **30%** | **20%** | **30%** |
| Grasses | 55% | 40% | 50% | 30% | 20% | 30% |
| **Dicot-based diet** | **45%** | **50%** | **40%** | **70%** | **80%** | **70%** |
| Browse species (non-legume) | 35% | 50% | 40% | 45% | 50% | 42% |
| Legume-based browse | 10% | 10% | 10% | 25% | 30% | 28% |

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