Effects of Dietary Inclusion Levels of a Low Lignin Hull, High-Oil Groat Oat on the Performance, Carcass Characteristics and Rumen Fermentation Characteristics of Feedlot Cattle

A Thesis Submitted to the College of

Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of Master in Science in the

Department of Animal and Poultry Science

University of Saskatchewan

Saskatoon, Saskatchewan

Canada

By

Sushama Arya

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Animal and Poultry Science

University of Saskatchewan

6D 34 Agriculture Building

51 Campus Drive

Saskatoon SK, Canada, S7N 5A8

ABSTRACT

Two experiments were conducted to evaluate the effects of dietary inclusion level of a low lignin hull, high-oil groat (CDC SO-I) oat on the performance, carcass characteristics and rumen degradation characteristics of feedlot cattle. In the first trial, 200 crossbred steers (average weight of 427.3 ± 22.4 kg) were allocated to 20 pens. Five treatments, formulated by replacing barley with increasing levels of CDC SO-I oat (Barley grain:CDC SO-I oat ratios of 100:0; 75:25; 50:50; 25:75 and 0:100 ; DM basis) were used. Four pens were randomly allocated to each treatment diet. Over the entire study there was a linear decrease ($P< 0.01$) in DMI and ADG with increasing inclusion level of CDC SO-I oat, whereas feed efficiency (gain:feed) decreased ($P= 0.03$) quadratically. Days on feed also increased ($P= 0.03$) quadratically for the steers fed the higher levels of CDC SO-I oat. Increasing the inclusion level of CDC SO-I oat in the diet also decreased ($P< 0.01$) carcass weight, dressing percentage and grade fat linearly. However, there was no effect of treatment on rib eye area and lean yield percentage. There was no significant effect of treatment on marbling score. While the results of this trial point to a negative effect of CDC SO-I oat on finishing performance, there were minimal differences between cattle fed 100% barley as the concentrate versus those fed 75% barley: 25% oat blend.

Trial 2 involved a metabolism trial to determine the effect of CDC SO-I oat inclusion level on rumen fermentation parameters of 5 fistulated heifers fed the same diets used in Trial 1. A 5 × 5 Latin square experiment design was used. Rumen degradation parameters (rumen pH, VFA, osmolality and ammonia nitrogen levels) and feeding behavior (time spent eating, ruminating, chewing and drinking) were measured. Mean rumen pH for the barley-based diet was 5.88 which was not different ($P> 0.05$) than the mean pH of 5.5 for the oat-fed cattle. Treatment did not affect ($P> 0.05$) time spent below pH cutoff values of 5.8, 5.5 and 5.2. No effect of oat inclusion level ($P> 0.05$) was observed on total VFA levels, molar proportion of individual fatty acids and osmolality while isobutyrate ($P= 0.05$) and ruminal ammonia nitrogen concentrations

decreased linearly (P= 0.02) with the higher inclusion of CDC SO-I oat. Time spent eating was linearly (P< 0.01) increased with higher inclusion level of CDC SO-I oat.

Over all, the results of this study indicate that the replacement of barley by CDC SO-I oat in finishing diets decreases dry matter intake and as a result leads to reduced ADG, increased days on feed and lower slaughter and carcass weights. The reduced performance might be the result of higher fat content, high hull and/or faster degradation rate of oat starch leading to subacute ruminal acidosis in cattle fed higher levels of oat. However, replacing barley with CDC SO-I oat does not significantly change the rumen environment. The results of this study indicate that CDC SO-I oat can be successfully included up to a maximum level of 25% without any adverse effect on performance and carcass characteristics in the diets of finishing cattle.

Key words: CDC SO-I oat, feedlot cattle, rumen degradation characteristics, volatile fatty acids

ACKNOWLEDGEMENTS

First of all I am deeply indebted to my supervisor Dr. John J. McKinnon for accepting me as his student and for his inspiration, moral support, encouragement and motivation during the entire period of research. I would also like to express my gratitude to my committee members; Dr. D. Christensen, Dr. P. Yu, Dr. B. Lardner and committee chair, Dr. B. Laarveld for their timely help, guidance and valuable suggestions.

My special thanks go to Agricultural Development Fund for providing funding support for this project. I am grateful to the University of Saskatchewan for providing me scholarships during my M.Sc. program.

It is a pleasure to thank those who made this research possible. First, I would like to thank Teresa Binetruy and staff of Beef Research Station for helping me in my research and guiding me time to time. My hearty thanks go to Amanda Walker, Kate Baker, Lee-Anne Walter, Kiran Doranalli and Zhiyuan Niu, for the great help in collections during metabolic trials. My special thanks go to Pam Kish for helping me every time during my lab work and solving any problems I faced. I am also thankful to the staff of LRB for taking care of my animals when in need.

Last, but not least, I thank my family. I owe my deepest gratitude to my parents, D.P. Arya and Omvati Arya for educating me, for unconditional moral support and encouragement to chase my goal and having confidence in me all the times. I am grateful to my elder brother and sister for their love, affection and their confidence in me, I feel lucky to have them.

In the end, I can not forget support, encouragement, understanding, and affection of my husband Sukhbir whose patient love enabled me to complete this work. He at all times did lot of help during my experiments, corrections and proof reading for my research and thesis. This thesis is dedicated to my wonderful husband and our adorable son, Hrsh. It would have been next to impossible to write this thesis without their love, sacrifice, patience and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADF	Acid Detergent Fiber
ADL	Acid Detergent Lignin
ADG	Average Daily Gain
BW	Body Weight
CDC	Crop Development Centre
CDC SO-I	Crop Development Centre Super Oat-I
CP	Crude Protein
DE	Digestible Energy
DM	Dry Matter
DMI	Dry Matter Intake
EAA	Essential Amino Acid
EE	Ether Extract
$EBW^{0.75}$	Metabolic Body Weight Based On Empty Body Weight, kg
EBG	Empty Body Gain, kg
LLH-HOG	Low Lignin Hull-High Oil Groat
LDA	Longissimus Dorsi Area
NDF	Neutral Detergent Fiber
NE	Net Energy
NPN	Non-Protein Nitrogen
NE_m	Net Energy for Maintenance
NE_g	Net Energy for growth
peNDF	Physically Effective Neutral Detergent Fiber
RE	Retained Energy
SC	Subcutaneous
TDN	Total Digestible Nutrient
TMR	Total Mixed Ration
tdCP	Truly Digestible Crude Protein
tdFA	Truly Digestible Fatty Acid
tdNDF	Truly Digestible Neutral Detergent Fiber

tdNFC	Truly Digestible Non-Fiber Carbohydrate
USFAT	Ultrasound Subcutaneous Fat
USLDA	Ultrasound Longissimus Dorsi Area
VI	Voluntary Intake

1. INTRODUCTION

In western Canada and north–west United States, a key focus of feedlot management is on rapid and efficient lean and fat deposition in animals in a short time frame (Block et al. 2001). Routinely, oat is not included as a major energy source in feedlots. This may be due to variability in nutrient content and lower energy density. The whole oat contains a high proportion of hull, usually in the range of 20-30% (Crosbie et al. 1985). The hull is composed of high levels of fiber and indigestible lignin resulting in lower digestible energy and nutritive value of oat relative to other cereal grains. The interesting feature of oat grain is that its groat is a concentrated form of nutrients. The oat groat is rich in protein and oil (Welch et al. 1983). As available energy in lipid is more than twice that of carbohydrates or proteins per unit, high fat oat has the potential of being a high energy concentrate feed.

Regular oat with a high fiber and lignin content to its hull is not widely used in cattle finishing rations, but new improved varieties of oat have the potential to be used as an energy source for ruminants. The nutritional and caloric value of oat can be improved by increasing the oil and reducing the lignin content (indigestible part) of grain (Holland et al. 2001). This is the intent of the oat breeding project at the Crop Development Centre (CDC). The CDC developed and released a new variety of oat which has been licensed as CDC SO-I with two unique characteristics. These include a low acid-detergent lignin hull and high oil groat. CDC SO-I oat was developed for the ruminant feed market.

In most oat varieties, the hull is high in lignin, typically (11.5 to 16.7%) (Matz 1992; Knudsen 1997). The hull content as a proportion of the seed of CDC SO-I oat is

similar to other oat varieties (i.e 20-25%), but as a result of its low acid-detergent lignin content (1.5%), it is more digestible and thus more useable as an energy source. This oat has lower acid-detergent lignin (ADL) and other indigestible compounds like silica (Niu et al. 2007a). Due to high oil content of CDC SO-I oat, it can be used as potential energy source in feedlot rations.

Research (Zalinko et al. 2009) on an early prototype called low lignin hull-high oil oat (LLH-HOG) with feedlot cattle has shown variable results. This oat prototype contained 1% ADL and 9.3% of fat. In backgrounding rations, animals fed this variety had similar intake and equal performance in terms of feed conversion efficiency and average daily gain as compared to the barley-fed cattle, however during finishing, animals fed diets containing higher levels of this oat line had lower dry matter intakes and daily gains which resulted in reduced carcass weights, lower dressing %, reduced grade fat and reduced longissimus dorsi (*l.dorsi)* area. These authors postulated that the negative results from this study were the effects of the added fat from this line of oat on rumen fermentation characteristics and thus intake of the cattle. Excess added fat can reduce intake and thus lead to reduced performance (Ramirez and Zinn 2000). The present study was conducted to determine the nutritive value of CDC SO-I oat in beef cattle in comparison to conventional barley-based feedlot rations and to determine:

- What is the optimal level of CDC SO-I oat for finishing cattle?
- What are the rumen fermentation characteristics of this oat variety?

Considering the improved nutritional characteristics of CDC SO-I oat and favorable agronomic properties of oat such as higher yield and lower input costs relative to barley for many areas of Saskatchewan, it was hypothesized that strategic

supplementation of a high fat-low acid-detergent lignin oat in the growing and finishing rations can result in performance superior to or equal to that of barley fed cattle. The following study was initiated to test this hypothesis with the following objectives:

1. to investigate the effect of inclusion level of CDC SO-I in finishing diets on DMI, performance and carcass characteristics of feedlot cattle
2. to investigate the effect of inclusion level of CDC SO-I on the rumen environment (Rumen pH, volatile fatty acid, ammonia and osmolality)

The objective of the literature review that follows is to provide overall background, energy values and rumen degradation parameters of oat and to compare it with barley.

2. LITERATURE REVIEW

2.1. Canadian Agriculture

Agriculture is one of the most important industries in Canada. In 2006 in Canada, 12.8% of the employment and 8% of the total Canadian gross domestic product (GDP) was provided by agriculture and related agri-food industries. In Saskatchewan, agriculture and food processing contributes to 7% of total provincial GDP (Agriculture and Agri-Food Canada 2007). Grain and grain products are the most important commodities exported by Canada. In Canada, oat represents 6% of the total production and exports of grains and oilseeds. Canada ranked first in the oat export trade, accounting for 70-80% of world oat exports (Agriculture and Agri-food Canada 2006).

2.1.1. Limiting Factors for Canadian Agriculture

Climate and soil factors are the predominant constraints for all the crops grown in Canada. The length of season, distribution of temperature, precipitation, soil fertility and physical characteristics of land are other important factors which determine the type of crop grown in a particular area (Small 1999). There is much variability in the crop growing capacity of different soil regions of western Canada. Grain and oilseed farms are of particular importance in the prairie provinces, particularly those that grow wheat, oat, barley, canola, rye, and flax.

2.2. Oat

Oat (*Avena sativa L.*) plays an important role in Canadian agriculture. It is a self pollinating hexaploid crop. It was evolved through natural interspecific hybridization and polyploidization of three distinct diploid progenitors (Legget and Thomas 1995). It

is the fourth most important cereal crop in Canada after wheat, barley and corn, and ranks sixth in world crop production (Baker 1995; Welch 1995). Oat is commonly grown for silage, green feed or as crop forage and to a lesser extent as a cover crop to protect soil erosion (Suttie and Reynolds 2004). Demand for oat production is increasing slowly and continuously with the availability of a wide range of products that are utilized as animal feed as well as for human nutrition (Welch 1995). It is no longer considered a simple feed grain used only in the livestock sector. Oat is a rich source of complex carbohydrate including beta-glucan, bran and fibre, all traits that increases its value in the human food sector (Pearson 2009). However, due to its low metabolisable energy and high lignin content as compared to barley and corn, its use as a livestock feed is limited (Bird et al. 1998).

2.2.1. Origin of Oat Crop

The exact origin of oat is not known but it has been grown in Canada from the time of arrival of the first settlers (Stevens 2004). Oat is a crop of Mediterranean origin. During late prehistoric period, oat and rye were introduced to Europe from Asia as a weed in barley and wheat crops (Welch and McConnell 2001). Around 1000 BC, climatic conditions changed in the northern and western Europe, favoring the growth of oat. In North America, oats were introduced by early colonists (Welch and McConnell 2001). The common oat, *Avena sativa* is thought to have originated from European white or yellow-hulled oat. Oat then spread to the all other parts of the world where cool moist conditions were available (Stevens 2004). Initially it was accepted as a spring sown crop for food and feed grains in Europe but with time it was found that oat

could be grown as a winter crop in North America (Fraser and McCartney 2004).

In the past, oat was widely used in the food milling industry and as a feed for horses with the remainder used in feed market for ruminants (Small 1999). For horses, whole oat is the preferred grain, as the high hull content of whole oat helps in digestion (Särkijärvi and Saastamoinen 2006). Furthermore, the starch present in oat is more digestible than corn and barley starch (Herrera-Saldana et al. 1990). For inferior quality oat, cattle was the major feed market in Canada. In the early twentieth century, oat was grown in a larger area of Canada as compared to wheat and barley. But slowly with mechanization, horses were replaced by machine power and simultaneously production of oat started declining and this trend continued through the late 1970's (Small 1999). In addition to this, other factors also contributed to the decline in oat production over the last half century. The use of oat in ruminant rations declined due to its low energy density and less digestibility and was replaced by higher energy alternatives like barley in Canada. Secondly, because of its bulkiness, oat was not preferred for long distance transport (Brown et al. 2005).

Subsequent to changes in climatic conditions and availability of new varieties and changes in demand for high fibre diets in the human food sector, there has been renewed interest in oat cultivation. Oat breeders, agronomists and livestock nutritionists across the world are in the continuous process of developing new and improved varieties of oat better suited to demand and agro-climatic conditions (Suttie and Reynolds 2004). Oat breeders at the University of Saskatchewan have developed a new variety of oat specially for ruminant feed market having high fat and low lignin hull content. This variety which will be discussed latter in this review is known as CDC

SO-I oat.

2.2.2. Agro-climatic Characteristics of Oat Crop

In western Canada, oat is a preferred cereal for annual pasture or silage because of readily availability of seed and easy establishment of crop (Suttie and Reynolds 2004). Oat is a versatile crop in terms of production and well adapted to a variety of soil types (Forsberg and Reeves 1995). Oat is primarily a crop of temperate zones as it is well adapted to cool temperatures and moist climates. Oat can better tolerate acidic soil and excessive soil moisture than most of the other small-grain cereals but is less tolerant to salinity than barley and wheat (Suttie and Reynolds 2004). For higher yield of oat the preferred soil pH range is 5.0 to 6.5, but it can tolerate acidic soils with pH as low as 4.5 (Stoskopf 1985).

The important climatic factors which can affect the growth or yield of any crop are temperature and moisture. Cool moist years result in heavy yields of oat (Forsberg and Reeves 1995). Oat and barley have the poorest lodging resistance of all cereals (Stoskopf 1985). Oat is also susceptible to frost damage depending upon the intensity and duration of the freezing temperature. Temperatures around -8°C (17.6°F) usually will kill oat seedlings (Verhallen et al. 2001). Hot dry conditions are not suitable for oat growth. Between head emergence stage and maturity it is most sensitive to temperature. Due to availability of favorable climatic conditions, world oat production is intense between latitudes 35 to 65°N and 20 to 46°S. In North America, north central areas are best suited for oat production (Stevens 2004). The long warm days, characteristic of the Canadian prairies coupled with adequate moisture levels provides

producers with ideal oat-growing conditions. Oat is mainly grown in spring in most parts of the world. In North America where winters are long and harsh, short season maturing oat varieties are usually grown (Stevens 2004).

Type of fertilizer used on the soil also affects the composition and quality of oat grain (Black 1993). Givens et al. (2004) reported that content of protein, oils and metabolizable energy increases in oat cultivars grown with higher rates of nitrogen fertilizer. Hence looking at the overall production parameters, its tolerance to environment conditions, lower input of agro-chemical and fertilizer cost, growing oat cost and margins may be similar to that of wheat and barley (Givens et al. 2004).

2.2.3. Variation in Oat Grain Quality Traits

Variation in the nutritive value of oat grain is considerable. Variation in nutritive value can be the result of genotype and environmental factors (Biel et al. 2009). Normal varieties or husked oat have high proportion of hull accounting for 25% of the whole oat (Thompson et al. 2000). This high proportion of hull reduces the overall digestibility of the whole grain resulting in negative economic impact by increasing the cost of feeding and days on feed to reach a target end weight in finishing cattle. On the other hand, oat groat and hulless (naked) oat are superior in terms of energy density (Kirkkari 2008). In the last few years the hulless variety of oat is widely used in non ruminants. This oat has a loose hull and during harvest it falls away from the groat. As a result of less hull and indigestible proportion, these varieties have excellent feed and food value (Kirkkari 2008).

The important factors which affect the feeding value of oat includes proportion and digestibility of hull, and oil content of the groat. Hull is mainly composed of insoluble fibre such as arabinoxylans (arabinose, uranic acid and xylose residues), cellulose and lignin resulting in its lowered energy value (Knudsen 1997). Energy value of oat increases with more digestible hull (i.e. low lignin hull varieties are more digestible than high lignin hull varieties). Oat-based diets with low lignin hull cultivars (0.8% lignin) have better organic matter digestibility and ruminal degradability compared to high lignin hull (2.3% lignin) (Rowe and Crosbie 1988). Oil content of the groat increases the overall energy value of grain (Holland et al. 2001).

2.2.3.1. The Hull-Groat Relationship

Hull-groat ratio is always important when including oat in the ration. This ratio is one of the important factors determining the nutritive value of oat grain. Due to high fibrous nature of hull, it is always desired to have minimal hull content when utilizing oat as a food for humans or as a feed for animals. Oat hull, a byproduct of the oat industry containing hulls and fragments of endosperm, constitutes a major portion of the whole oat (Thompson et al. 2000). Oat hull has fiber with high NDF and ADF values (averaging 78% and 42% dry matter (DM) respectively), high lignin (8%) and low protein content (3.9%), resulting in lower energy value of the oat grain (1.90 Mcal kg^{-1} NE_m and 1.26 Mcal kg^{-1} NE_g) compared to barley (2.02 Mcal kg^{-1} NE_m and 1.36 Mcal kg^{-1} NE_g) and corn (2.16 Mcal kg^{-1} NE_m and 1.48 Mcal kg^{-1} NE_g) (NRC 1982; NRC 2001; Redaelli and Berardo 2007). A high proportion of hull decreases density as well the nutritive value of the oat hull is similar to low quality forage (Rowe et al. 2001).

The composition of oat groat is entirely different from the hull. The groat contains the bulk of nutritionally desirable constituents and is a concentrated form of nutrients enclosed in the cellulosic and fibrous hull (Crosbie et al. 1985). The oat groat is high in protein (11.2 to 16%) and oil content (4.8 to 9.2%) (Welch and McConnell 2001). It is interesting to mention that the hull of oat separates more easily from the groat relative to the barley hull when subjected to any kind of processing (Douglas and Dennis 2007). Some hulless oat cultivars are also available but due to agronomic issues, disease, and groat storage problems, are not widely grown (Young and Forsberg 1987). Presence of fiber in the hull makes oat an ideal feed for starting cattle. It is preferentially used to adapt weaned calves to grain and for shifting to higher energy rations (Boyles and Johnson 2006).

2.2.3.2. The Bran-Endosperm Relationship

The bran-endosperm relationship affects the chemical composition of the groat. Bran is a rich source of vitamins, proteins, lipids, minerals and fibers, whereas the endosperm is rich in carbohydrates. Bran and endosperm are the key fractions of oat groat and are influenced by genotype and environment (Youngs and Forsberg 1987).

2.3. Chemical Composition of Oat

Oat is grown throughout the world for a variety of products that can be obtained at different stages of maturity of the plant. These products include grain, forage and fodder, hay, haylage, silage and straw. Out of these, oat grain is primarily used in livestock feed, human food and for other industrial purposes (Welch 1995). Among all the cereals, the chemical composition of oat grain is highly variable and greatly

influenced by climatic factors (Pettersson et al. 1996; Biel et al. 2009). Other factors affecting chemical composition include variation due to genotype and interactions between environmental factors and genotype, harvest conditions, storage and post harvest treatments (Doehlert et al. 2001). The major nutrients present in the oat grain include starch, protein and lipid, and to a minor extent minerals (Table 2.1).

Table 2.1. Chemical Composition of oat grain (groat and bran) (reported as g /100 g of DM) (Adapted from Welch and McConnell, 2001)

Oat Grain	Moisture	Protein	Oil	Carbohydrate	Dietary Fiber	Ash
Groat	9	13.1	7.4	62.1	7	1.4
	(8.2-11.5)	(11.2-16.0)	(4.8-9.2)	(59.4-65.5)	(5.6-12.1)	(1.3-1.9)
Bran	8.8	18	8.8	46.2	15	2.6
	(8.8-10.0)	(8.6-21.4)	(7.1-10.8)	(40.0-61.0)	(9.6-17.5)	(1.8-3.7)

2.3.1. Protein Characteristics

Oat grain provides high quality protein which is preferred over other cereals for livestock feed and human nutrition. The biological value of oat protein together with amino acid composition is better than other cereals such as wheat, barley or maize (McMullen 2000). Typically in cereals as crude protein content increases, the essential amino acid content (as a % of total amino acid) declines. With oat grain, the amino acid profile remains constant with high nutritive value and the typical decline is less evident (Givens et al. 2004). Protein in the oat grain is mainly concentrated in the groat averaging 11 to 16%, with very little protein in the hull (McMullen 2000).

Oat has a low prolamine (alcohol-soluble fraction) and high globulin (salt-soluble fraction) content with high lysine in the globulin fraction. The whole oat on average contains 7 to 13% prolamine, 10 to 19% water soluble albumins, 52 to 56% salt soluble globulins and 21 to 27% glutelins as a % of total proteins (McMullen 2000). Different oat varieties also differ in the total protein content. Naked oat grain (hulless) has higher total protein content when compared to many other cereals. Biel et al. (2009) reported 14.3% of protein in naked oat compared to 11.5% in husked grain.

Subsequent to the use of nitrogen fertilizer, protein content in the oat increases (Lásztity 1998; Givens et al. 2004). With the increase in the crude protein content, most of essential amino acids (methionine, threonine, leucine, isoleucine and tryptophan) increases in both husked and naked varieties with slight variation in amino acid profile. However, relative increase of lysine in naked variety and cystine in husked variety is not significant (Givens et al. 2004).

Oat amino acid profile has a high lysine but low glutamine and proline content compared to other cereal proteins (Lásztity 1998). Different varieties of oat are quite variable in essential amino acids (lysine, threonine and methionine) but in general, oat has higher proportions of these amino acids compared to other cereals (Welch 1995; Kosieradzka and Fabijańska 2001; Givens et al. 2004). McMullen (2000) reported average concentration of lysine and threonine as 4.2 and 3.3 g/100g of amino acids, respectively. These are higher than that found in other cereal grains but still below reference standards of 5.5 and 4.0 g/100g as suggested by Food and Agriculture Organization (McMullen 2000). Oat has high content of essential amino acids except lysine, limiting its nutritive value (Biel et al. 2009) (Table 2.2). Oat protein is a good

source of sulphur amino acids and thus can be used successfully in combination with legumes which are low in methionine and cystine (Sujak et al. 2006). Separating different components of the groat revealed that bran of some oat cultivars have 25% higher lysine content along with high threonine, serine and alanine content than that found in the endosperm (McMullen 2000).

Table 2.2. Amino acid composition of whole oat grain and groat (g amino acid/100g amino acid recovered) (Adapted from Lásztity, 1996)

Amino Acid	Whole Oat	Groat
Lysine	4.2	4.5
Histidine	2.4	2.4
Arginine	6.4	6.8
Threonine	3.3	3.4
Valine	5.8	5.5
Methionine	2.3	2.2
Isoleucine	4.2	3.9
Leucine	7.5	7.6
Tyrosine	2.6	3
Phenylalanine	5.4	5.2

2.3.2. Carbohydrate Characteristics

The major storage polysaccharide in most of the plants is starch, stored in the form of water insoluble granules. Amylose and amylopectin combine to form a complex semi-crystalline polymer called starch (Shamekh et al. 1999). In both oat groat and bran, carbohydrate is the major component (Table 2.1). Carbohydrate present

in the oat bran is low in content but rich in dietary fiber (Welch and McConnell 2001). Starch content of various cereal grains is variable with wheat containing 54.2 to 77%, corn 63.7 to 78.4%, barley 52.2 to 71.7% and oat 34.4 to 70.0% (DM basis) (Waldo 1973; Huntington 1997). In the oat groat, the starch is present in the range of 59-65% (Welch and McConnell 2001). Welch (1995) reported amylose content of oat starch ranges between 18 to 34%. This range is somewhat narrow as compared to barley or maize in which high-amylose, amylopectin and waxy grain genotypes are reported (Welch and McConnell 2001). Oat starch granules are relatively smaller than that of wheat, around 3-12μm in diameter (Welch and McConnell 2001). In whole oat, starch concentration varies with the stage of maturity of the plant, low in young vegetative tissues and subsequently increasing with plant maturity. In oat hay, concentration of starch ranges from 3-4% (dry weight basis) during early development to 10-15% (dry weight basis) in mature plants (Chatterton et al. 2006).

According to the literature, the term dietary fiber (DF) is defined as the cell wall components including non-starch polysaccharides, oligosaccharides and lignin (Knudsen 2001). Some other nonsoluble parts like resistant starch, unhydrolysed protein, tannins and cutins are also included in dietary fiber (Virkki et al. 2005). In different analytical methods, dietary fiber has been separated into different components. The enzymatic-gravimetric method classifies dietary fiber as soluble, insoluble and total dietary fiber while the enzymatic-chemical method classifies it as soluble, insoluble and total non starch polysaccharides (Knudsen 2001).

Oat contains a valuable soluble fiber fraction, considered as a cholesterol lowering component in human nutrition. Oat fiber is a rich source of soluble fiber and

β-glucans (Givens et al. 2004). The main non-starch polysaccharides (NSPs) in dietary fibre of oat are β-glucan, arabinoxylans and cellulose. The β-Glucan and arabinoxylans are found as soluble and insoluble forms, the cellulose is the main insoluble component. β-glucan and arabinoxylans have the mixed-linkage β (1→3; 1→4)-D-glucan, while cellulose consists only of β (1→4)-D linkages. The β (1→4)-D linkages in cellulose make it stiff, crystalline and nonsoluble whereas the β (1→3)-D linkages of the β-glucan molecule break up easily making it soluble and flexible (Fincher and Stone 1986; Johansson et al. 2000). In oat groat the percentage of soluble fiber is 3.0- 5.4% whereas insoluble fiber accounts for 3.2- 8.0% (Welch 1995).

Due to natural variation and different analytical methods used, wide variation is seen in total fiber content of the groat (Welch and McConnell 2001) (Table 2.1)**.** β-glucan, a polymer of glucose is the main constituent of soluble fiber. It is interesting that among cereals, β-glucan is present in significant amounts in oat and barley. Oat groat contains 1.8 to 7.5% β-glucan (Welch 1995). The husked and naked varieties of oat differ in the crude fiber content and lack of husk in the naked variety makes it comparable to wheat, barley and maize. Tamime et al. (1997) and Medel et al. (1999) reported the crude fiber content of wheat, barley and maize as 1.3 to 2.2%, 2.4 to 5.6% and 2.1 to 2.4%, respectively. Biel et al. (2009) in their study reported crude fiber content in naked oat grain and husked oat as 2.1 to 3.8% and 12.1 to 16.4%, respectively.

Lignin and glycoproteins are the important ingredients of the cell wall of the endosperm of cereals, in addition to other polysaccharides (Virkki et al. 2005). Lignin, a diverse class of phenolic compounds, is a non-carbohydrate with high molecular

weight (Li et al. 2008). Lignin is quite resistant to both biological and chemical degradation (Hatfield and Fukushima 2005). It is closely associated with cellulose microfibrils, and thus is the major constituent that shields cellulose and hemicelluloses from enzymatic digestion. Lignin is widely known to reduce digestibility by reducing the degradation of plant material by rumen microbes (Jung and Allen 1995). Indigestible cell wall material reduces intake by the effect of ruminal fill. Traxler et al. (1998) reported that indigestibility of neutral detergent fiber (NDF) increases with the increased lignin concentration of the NDF. Digestibility of dietary fiber can be increased by reducing lignin content (Chang and Holtzapple 2000). Kasuya et al. (2008) reported that degradability of acid detergent lignin is lower than that of neutral detergent fiber and acid detergent fiber.

In whole oat grain, the content of lignin is about 4.9% on dry matter basis which is higher than that of barley grain (1.9%) (NRC 2001). A new variety of oat (CDC SO-I oat) has low acid detergent lignin content (1.7%) as compared to normal oat (4.9%).

Virkki et al. (2005) compared the water insoluble fiber (WIS) of oat and barley grain and reported higher β-glucan (11.5%) and less non starch polysaccharides (41.7%) in oat as compared to barley (6.7% and 48.6% respectively) (Table 2.3). The fat in the water insoluble fiber fraction of oat was twice that of barley. The same study reported higher water insoluble fiber in barley than that of oat (Table 2.4).

Table 2.2. Chemical composition (% dry weight) of Water insoluble fiber (Adapted from Virkki et al. 2005)

Components	Fat	Protein	NSP[z]	β-Glucan
Oat WIS[y]	9.2	17.3	41.7	11.5
Barley WIS	4.2	21.8	48.6	6.7

[z]NSP: Non Starch Polysaccharides; [y]WIS: Water insoluble fiber

Table 2.3. Chemical composition (% dry weight) of ground grains (Adapted from Virkki et al. 2005)

Cereals	Moisture	Ash	Protein	Fat	WIS[z]	TS[y] residue	NC[x] sugars	β-Glucan
Oat grain	8.6	2.2	13.4	8.5	6.1	57.9	48	4
Barley grain	8.7	2.1	11.8	4.4	13.7	60.1	55.1	3.7

[z]WIS: Water insoluble fiber; [y]TS: Total sugar residue; [x]NC sugars: Non-cellulosic sugars

2.3.3. Lipids and Lipid Composition

Compared to other cereals, oat is unique for its high fat content which averages 3 to 11% of grain weight (Frey and Holland 1999). Oat oil is nutritionally important as its energy content is valued as a feed for livestock and for industrial purposes (Zhou et al. 1999; Heneen et al. 2008). The oil in the oat is mainly concentrated in the

endosperm in the range of 2.0 to 11.8% and is mainly in the form of triglycerides (Peterson and Wood 1997; Welch and McConnell 2001; Banas et al. 2007) (Table 2.5). Some new varieties of oat have been developed with a very high-fat content (i.e up to 18% fat) (Peterson and Wood 1997; Leonova et al. 2008).

Table 2.4. Major lipid classes in Oat (g/100g of total lipids) (Adapted from Welch and McConnell, 2001)

Triglycerols	Phospholipids	Glycolipids	Free Fatty Acids	Sterols
62	16	10	6	6
(32.4-85.0)	(5.0-26.0)	(5.8-11.9)	(2.0-11.0)	(1.4-9.3)

In oat, the fatty acid composition of oil varies with location in the kernel. In other cereal grains, oil is mostly concentrated in the embryo and scutellum while the main storage site of lipid in the oat is in the endosperm (Peterson and Wood 1997). However, White et al. (2006), using transmission electron microscopy reported that germ cells and aleurone and sub-aleurone layers also contain oil bodies. Banas et al. (2007) reported that high levels of linoleic and linolenic acids are present in the oat embryo compared to whole grain.

Different cultivars of oat have different proportions of fatty acids. Husked and naked (hulless) oat differ in oil content. Naked oat has a high percentage of oil as compared to other cereals and is rich in unsaturated fatty acids (Zhou et al. 1998). Biel et al. (2009) compared normal and naked grain oat and reported the crude fat content of naked oat as 8.4%, nearly twice to that of normal grain oat.

Oat fat is a good source of essential unsaturated fatty acids with relatively low linolenic acid (18:3) and high oleic (18:1) and linoleic (18:2) fatty acid contents (Frey and Holland 1999; Givens et al. 2004; Biel et al. 2009). Linoleic (18:2), Oleic (18:1) and Palmitic acids (16:0) are the major fatty acids accounting for more than 95% of total fatty acids in oat (McMullen 2000). The fatty acid composition of conventional oat varieties and low lignin hull, high-oil groat oat are comparable (Table 2.6). Myristic (14:0), stearic (18:0) and linolenic (18:3) fatty acids are present in small amounts accounting to < 1 to 4% of total fatty acids (Welch 1995).

Table 2.5. The fatty acid composition of normal and low lignin hull high-oil groat oat (LLH-HOG) (Adapted from McMullen 2000; Zalinko et al. 2009)

Oat Variety	Fatty Acids (% of total fatty acids)				
	Myristic (14:0)	Palmitic (16:0)	Stearic (18:0)	Oleic (18:1)	Linoleic (18:2)
Normal oat	0.60	18.90	1.60	36.40	40.50
LLH-HOG	0.10	14.40	1.40	43.70	37.00

The proportion of ω-6 to ω-3 fatty acids in the diet is nutritionally important. Cultivated oat varieties have high levels of ω-6 (18:2) fatty acids (36-47%), and low levels of ω-3 (18:3) fatty acids (1-2%) (Welch et al. 1997; Zhou et al. 1998). Increasing the level of 18:3 fatty acids in oat can improve its nutritive value (Leonova et al. 2008). Some earlier studies (Zhou et al. 1998; Holland et al. 2001) reported that with increased oil content in oat varieties, there was an increased amount of 18:0 and 18:1 and decreased amounts of 16:0, 18:2, and 18:3 fatty acids.

The variation in groat oil and the composition of the fatty acids among oat varieties and lines, make it feasible for oat breeders to select a line with desired oil content and fatty acid composition by recurrent selection for traits of importance. Schipper et al. (1991) and Welch (1995) reported increased oleic acid and decreased linoleic and palmitic acids in oat varieties selected for high groat oil.

2.4. Oat as Animal Feed

Oat grain has three main markets: performance feed oat for horses, milling oat in food industry and feed oat for ruminants. Performance oat and milling oat industry utilize a high quality oat. Oat grain has long been an important cereal grain for livestock (Stevens 2004). Protein content of oat is highest among all grains. It is a good source of protein, fibre and minerals but as a result of high fiber it is less digestible. Due to its high fiber content, oat are better for breeding cattle and young livestock to adapt them for high grain ration. In recent years, some hulless varieties of oat have emerged with excellent feed and food value and have successfully been used in the swine and poultry industries (Brown et al. 2005).

2.4.1. Oat as Forage, Silage or Grain

Worldwide oat is grown for grain as well as for use as forage, silage, hay, and chaff. Some oat products have gained a place in the human food industry in the form of oatmeal, oat flour, oat bran and flakes but still the livestock industry is the primary outlet for the oat crop (Stevens 2004). Oat is primarily used as a feed grain in the livestock industry. Webster (1996) reported that about 75% of the oat that are grown

are used for animal feed on a world wide basis.

Oat as a forage has a high nutritive value with dry matter digestibility of 75% in dairy cattle (Stevens 2004). Organic matter in oat straw is more digestible than other cereal straws (Cuddeford 1995). Cuddeford (1995) also reported that spring sown oat straw had higher metabolizable energy than that from winter oat, but in general oat straw is softer and more acceptable to livestock and higher in net energy than other cereal straws (Stevens 2004).

In western Canada, spring or autumn grown cereals such as oat, barley, wheat, rye or triticale can be used as excellent summer or autumn pasture or silage (McCartney et al. 2004). In western Canada, oat is one of the major cereals used as a silage for livestock. In most parts of Alberta, yield of oat as a silage or green feed per unit area was reported higher than any other cereal crop (Suttie and Reynolds 2004).

2.4.2. Oat Grain as a Feed for Monogastric Animals

Oat being high in protein content can be an excellent feed for monogastrics but due to its high fibrous nature, it is less digestible than other cereal grains. In recent years, the market for hulless oat has emerged for pig and poultry rations. Hulless oat have loose hulls that fall away from the oat groat during harvest, making these varieties easily digestible and results in increased energy value for both monogastric and ruminant animals (Brown et al. 2005).

Various studies have been conducted with monogastric animals using oat as feed. Wiliczkiewicz et al. (2005) compared digestibility of various grain types (maize, barley, oat and rye) in chickens and geese. Relatively good digestion of the structural

carbohydrates (crude fiber, NDF, ADF and hemicellulose) was reported in the alimentary tract of chickens and geese. Crude fiber, NDF and ADF degradation rate was higher in the birds fed barley and oat compared to other groups. Hetland and Svihus (2001) reported that supplementing oat hulls in broiler diets result in higher feed intake. Increased levels of unsaturated neutral lipids in the white meat of broilers was reported when an oat-based diet was fed (Lopez-Bote et al. 1998).

Studies using low lignin hull, high-oil groat (LLH-HOG) oat variety revealed that it can be successfully utilized in pig diets (Thacker et al. 2004). The performance studies in broilers using LLH-HOG were discouraging as compared to wheat based diets, however this new variety was superior to other oat varieties (Thacker et al. 2009).

2.4.3. Oat Grain as a Feed for Ruminants

Feed grade cereal grains are mostly consumed by ruminants and it has been estimated that cattle consume about 60% of total grain fed to livestock (Cuddeford 1995). In Canada, barley is fed in greatest amounts followed by wheat, corn and oat. Oat is generally not included as major grain in feedlot diets due to low energy density and variability in the nutrient content of oat. Oat has high hull and fiber content (Stroh et al. 2000). These characteristics make it an ideal grain for starting cattle or for adapting weaned calves to a grain based ration (Boyles and Johnson 2006).

Moran (1986) compared wheat, barley and oat-based diets in dairy cows and reported higher milk and milk fat in cows fed with the oat-based diet even though the metabolizable energy (ME) was lowest in the oat-based diet. Martin and Thomas (1987) reported that feeding an oat-based diet reduces saturated fatty acid content in milk compared to a barley-based diet. Ekern et al. (2003) compared regular oat with

high fat oat-based diet in dairy cattle and reported increased milk production with increased proportion of stearic, oleic and linoleic fatty acids and decreased proportion of lauric, myristic and palmitic fatty acids in milk fat. In a recent study, Yu et al. (2009) compared the effects of replacing barley with CDC SO-I oat in lactating dairy cows and reported that cows fed diets containing combination of raw CDC SO-I oat and barley had higher fat corrected milk than cows fed barley-based diet, suggesting CDC SO-I oat can partially replace barley in dairy rations.

2.5. Energy Requirements of Growing and Finishing Beef

Energy is required for maintenance of body functions, growth and production. In animal nutrition, these requirements should be met by animal feed. Animals fed an energy deficient diet will meet its energy requirements at the expense of body reserves (fat and protein), resulting in reduced growth and production. Compared to other meat producing species (swine and poultry), beef cattle require higher dietary energy intake to produce a unit of edible protein (Evans et al. 2002).

The maintenance energy requirement is defined as the amount of energy required to maintain normal body functions under normal environmental conditions resulting in no net loss or gain of body condition (NRC 1996). Most of the energy consumed by beef cattle is lost, mainly passed undigested in the feces (20-40%), in the form of gases and urine (15-20%) and during digestion in producing heat (30%), hence leaving little energy (20%) for maintenance and gain (Cecava 1995).

The requirements of beef cattle for maintenance and growth are met through dietary energy available from consumption of feed. Dietary energy derived from different feeds can be expressed as total digestible nutrients. In past, the energy

requirements of the beef cow were measured using Total Digestible Nutrients (TDN) system. National Research Council (2001) estimates TDN as follows:

TDN (%) = tdNFC + tdCP + (tdFA x 2.25) + tdNDF – 7

Where *tdNFC* is truly digestible non-fibre carbohydrate, *tdCP* is truly digestible crude protein, *tdFA* is truly digestible fatty acid, and *tdNDF* is truly digestible neutral detergent fibre. TDN system is quite accurate in determining energy requirements of cattle when commonly used feeds are utilized. This system is based on composition and digestibility of crude protein, crude fat, nitrogen free extract and crude fiber (Cecava 1995).

The modern system for determining the energy requirements of beef cows is the net energy system. This system is more accurate in determining nutrient requirements and expected or desired performance (weight gain/loss) under a particular feeding system. The system is mainly based on two calculations: net energy for maintenance (NE_m) and net energy for gain (NE_g) (Lofgreen and Garrett 1968). The net energy system can be efficiently used to calculate the amount of a given ration needed to meet the energy need or in formulating a diet to supply the required energy per unit of dry matter. In addition, rate of gain can also be calculated using this system if the intake and energy concentration of the diet are known (Lofgreen and Garrett 1968).

Earlier, the mature size of an animal was used as a trait and the animal body weight was used to determine the maintenance energy requirements (Evans et al. 2002). Research now has shown that using mature weight alone is not correct for calculating maintenance energy requirements. It can be more precisely calculated by adjusting the mature weight for differences in body size (surface area) and using the metabolic body

weight (Evans et al. 2002). Metabolic body weight is calculated as a fractional power ($BW^{0.75}$) of shrunk body weight (NRC 1996). The NE_m requirements of beef cattle can be calculated as

$$NE_m = 0.077 \text{ Mcal/EBW}^{0.75}$$

EBW: empty body weight in kilograms.

Net energy for gain (NE_g) is defined as the energy content of the tissues accrued, a function of the proportion of fat and protein in the empty body tissue gain (NRC 1996). As energy in the growing animal is retained either as protein or fat, the composition of gain can be calculated using retained energy (RE):

Proportion of fat= 0.122×RE-0.146;

Proportion of protein= 0.248-0.0264×RE.

Retained energy is calculated using an equation that relates retained energy (RE) to empty body weight gain (EBG) for a given empty body weight (EBW):

$$RE = 0.0635 \times EBW^{0.75} \times EBG^{1.097}$$

Maintenance energy requirement of beef cattle depends on several factors such as body weight, sex, breed or genotype, environmental temperature, physiological state and previous nutrition of animal (Hotovy et al. 1991; NRC 2000). Various studies have reported differences in the maintenance energy requirements among different breeds. Holstein steers were found to have 23 percent more feed requirement than Hereford steers to maintain body energy demand (Garrett 1971). Jenkins and Ferrell (1984) and Ferrell and Jenkins (1985) compared Simmental bulls and heifers with Hereford cattle and reported higher feed requirement for the Simmental breed (Table 2.7). These

differences in energy requirements might be due to genetic diversity of breeds, differences in the methodologies or different environmental conditions (NRC 2000).

Table 2.6. Metabolizable energy requirement for maintenance (ME_m) of various breeds (Adapted from Ferrell and Jenkins 1985)

Breed or breed cross	Physiological state	ME_m (kcal/$BW^{0.75}$/day)
Angus-Hereford	Non-pregnant, non-lactating, 9-10yr	130
Charolais X	" " "	129
Jersey X	" " "	145
Simmental X	" " "	160
Angus	Non-pregnant, non-lactating, 5-6yr	118
Hereford	" " "	120
Simmental	" " "	134

Environmental temperature also affects the maintenance energy requirements of beef cattle. Ambient temperature higher than the upper critical temperature reduces feed intake and consequently productivity decreases. As a result of increased body temperature, tissue metabolic rate and energy required to dissipate heat increases, resulting in higher energy requirements for maintenance (Ames et al. 1994). Similarly, environmental temperature below lower critical temperature results in increased energy requirements for maintenance subsequent to increased metabolism of the tissues to maintain adequate body temperature (Nisa et al. 1999). NRC (2000) adapted an equation to calculate the NE_m with the change in the temperature.

$$NE_m = (0.0007 \times (20 - T_p)) + 0.077 \text{ Mcal/BW}^{0.75}$$

Where T_p (^{0}C) is the ambient air temperature. This equation suggests that NE_m requirement of cattle changes by 0.077 Mcal/$BW^{0.75}$ for each degree drop in temperature from 20 ^{0}C.

2.6. Rumen Fermentation Characteristics

In beef cattle, little information is available on ruminal degradation characteristics of oat and on variety differences. Hulled oat was shown to have lower ruminal degradability than hulless oat which in turn had higher ruminal degradability than barley (Mustafa et al. 1998). Ruminal degradation of starch varies with the type of grain. In addition, several other factors affect the rate and extent of starch digestion such as source of dietary starch, processing method involved, frequency of feeding and ruminal microbial response to the diet (Huntington 1997). As compared to corn, barley is more fermentable in the rumen and thus little starch is available to be digested in the small intestine. As a result of high degradation of barley starch in rumen, finishing cattle consuming corn-based high concentrate diet showed improved performance as compared with barley-based diet (Boss and Bowman 1996b). Processing of grains improves digestibility, however, it increases the degradation rate in the rumen.

In one study it was reported that degradation rate per hour of oat starch and protein is lower than that of barley (7.6% vs. 13.3% and 7.8% vs. 11.7%, respectively) (Herrera-Saldana et al. 1988). However, the same group further reported that oat starch has higher ruminal availability than wheat, barley and corn (Herrera-Saldana et al. 1990). Huntington (1997) reported lowest ruminal starch degradation rate for corn (55-70%), medium for barley and wheat starch (80-90%), and highest for oat (92-94%). Gozho and Mutsvangwa (2008) compared oat-based diet with corn and wheat-based

diet and reported higher total tract apparent starch digestibility in cows fed the oat-based diet.

Umucalilar et al. (2002) reported higher DM degradability of barley and wheat (80%) compared to corn (66.7%) and oat (66.5%). Other workers reported numerically higher DM degradation rates in barley (11.6, 40.1 and 26.5% per hour) than that of oat (10.0, 21.9 and 11.3% per hour) (Sauvant et al. 1985; Prestløkken 1999; Fuhr 2006). Bulk density also affects the ruminal starch digestibility. Zinn (1990) reported decrease in ruminal pH and increase in postruminal and total tract digestibility of starch with decreased flake density of corn, however effect of bulk density of oat have not been reported.

A recent study (Yu and Niu 2009) compared the DM degradation rates of CDC SO-I oat and other varieties of oat (CDC Dancer and Derby) and reported no difference in the degradation rate of starch and protein among these varieties. High degradable starch in cereal grains when fermented in the rumen can lead to subacute acidosis (Krehbiel et al. 1995).

2.6.1. Rumen pH

Rumen pH is used as an indicator of rumen environment and animal health. Ruminal pH is determined by the balance between acid produced, acid absorbed from the rumen and buffering capacity of saliva produced (Rustomo et al. 2006). Rumen pH will drop if more acid is produced than absorbed (Krehbiel et al. 1995; Brown et al. 2000). Acidosis is primarily associated with the increased amount of acid produced from the fermentation of feed and secondly by the buffering capacity of the saliva

produced in response to type and quality of feed (Rustomo et al. 2006). Subacute ruminal acidosis is a serious problem in cattle fed high grain finishing rations and is characterized by a ruminal environment with a pH between 5.2 and 5.6 (Owens et al. 1998). Duration (i.e. total time) of ruminal pH below 5.6 or 5.8 in a 24 hour period is a more accurate measure of acidosis than mean daily ruminal pH (Keunen et al. 2002; Krause et al. 2002; Krause and Combs 2003).

Low ruminal pH can adversely affect animal performance by interfering with microbial function, resulting in decreased microbial protein synthesis (Krajcarski-Hunt et al. 2002). In addition, fiber digestion and feed intake is also affected by reduced ruminal pH (Plaizier et al. 2008). Processed grain results in reduced ruminal pH as compared to whole grain due to more exposure to rumen bacteria (Yang et al. 2000; Beauchemin et al. 2001).

Fiber in the diet stimulates chewing and saliva production thus affecting rumen buffering capacity (Allen 1997). Yang and Beauchemin (2009) reported that increasing forage to concentrate ratio or forage particle length in the diet increases ruminal pH and reduces volatile fatty acid concentration.

Physically effective NDF (peNDF) is defined as the proportion of feed responsible for chewing and saliva production and calculated by multiplying the proportion of particles retained on a 1.18-mm sieve with NDF concentration of the feed (Mertens 1997). This peNDF reflects the physical characteristic such as particle size of the fiber and is essential to stabilize ruminal pH, as it helps in increasing the rate of passage and absorption of VFA thus increasing the buffering capacity of the rumen (Zebeli et al. 2008).

2.6.1.1. Measurement of Rumen pH

Rumen pH is a reliable indicator of ruminal acidosis. Several techniques are used to measure ruminal pH. Major techniques include spot sampling and in-dwelling rumen pH probes. Measurement of ruminal pH by spot sampling method (i.e., by stomach tube) is not very accurate due to saliva contamination and diurnal variation (Duffield et al. 2004; Alzahal et al. 2007). Spot sampling method involves collecting ruminal fluid by one of several methods: rumenocentesis, stomach tube or via ventral rumen cannula (Duffield et al. 2004). Each method requires immediate measurement of ruminal fluid pH after collection.

Correct measurement of pH values also depends on the technique used. Duffield et al. (2004) demonstrated that ruminal fluid collected through stomach tube and from ventral sac had pH measurements 0.35 and 0.33 units higher than pH from fluid samples collected by rumenocentesis. Ruminal pH declines shortly after feeding subsequent to microbial fermentation and then gradually recovers, hence the time of rumen fluid collection affects pH especially with spot sampling methods (Keunen et al. 2002), as these methods indicate pH at only one particular time.

Development of indwelling pH probes has allowed for the automated monitoring of ruminal pH over a continuous period of time (Dado and Allen 1993). Subsequent to high diurnal variation of rumen pH, continuous monitoring using in-dwelling pH probe system over a period of time is more advantageous than other techniques (Duffield et al. 2004). Indwelling pH probe system improved the post feeding ruminal pH measurements, as more frequent measurements are feasible as compared to spot sampling techniques. This improved monitoring system made it feasible to understand

the interaction between diet, time, feed intake, rumen fermentation, eating behavior and ruminal pH (Maekawa et al. 2002b; Krause et al. 2009). In addition, with this technique it is possible to measure the time during which pH stays below a critical value (5.8, 5.5 and 5.2). This can be used as an indicator of severity of ruminal acidosis (mild, moderate, severe) with a particular diet (Bevans et al. 2005; Khafipour et al. 2009).

2.6.2. Volatile Fatty Acids

Microbial fermentation of dietary carbohydrates in the rumen results in the production of volatile fatty acids (VFAs). VFAs are the main source of energy for maintenance and growth in the ruminants (Allen 1997). Feeding rapidly degradable grains and diets with decrease forage:concentrate ratio results in increased production of VFA in the rumen (Hersom 2008). This increase in volatile fatty acids and lactic acid production in the rumen results in a rapid drop in rumen pH, if rumen buffering capacity cannot counterbalance the increased VFA production (Plaizier et al. 2008). The major VFA's produced in the rumen of grain fed cattle include acetate (48-56% of total VFA), propionate (25-42%) and butyrate (8-16%) (Beauchemin et al. 2003; Bevans et al. 2005; Szasz et al. 2005). However, diet is the predominant factor in deciding type and ratios of VFA produced. Feeding a high roughage diet leads to more production of acetate while feeding a high grain diet leads to a greater proportion of propionate (Penner et al. 2009).

These volatile fatty acids are utilized for various purposes. Acetate is the main energy source by directly entering the TCA cycle. In addition it also acts as a precursor for fatty acid synthesis and is used mainly in peripheral tissues, especially fat and

muscle (Van der Walt and Linington 1989; Bergman 1990). Propionate is mainly utilized for blood glucose synthesis, in addition to its value as an energy source (Danfaer et al. 1995). Butyrate is mainly metabolized by rumen epithelium as an energy source and a part is metabolized to ketone bodies (acetoacetate and β-hydroxybutyrate) which can be utilized as an energy source in extra-hepatic tissues (Van Houtert 1993).

2.6.3. Osmolality

Rumen osmolality, a measure of ruminal solute concentration, defined as the number of osmoles of dissolved solutes per liter of solution (osmol/L). The main solutes include VFA, minerals, lactate, and glucose. On a roughage-based diet, ruminal osmolality normally ranges from 240 to 265 mOsm/L while with concentrate diet, it ranges from 280 to 300 mOsm/L (Owens et al. 1998).

In severe acidosis, the osmolality can be as high as 515 mOsm/L (Owens et al. 1998). In severe acidosis, rumen osmolality is higher than plasma osmolality; this negatively affects absorption and increased production of endotoxins and histamines leading to rumen stasis and systemic acidosis. In acute cases, fluid from blood is withdrawn into the rumen as a consequence of higher osmotic pressure leading to dehydration and cardiovascular collapse (Vasconcelos and Galyean 2008). The rapid influx of water subsequent to higher ruminal osmotic pressure results in swelling and rupture of ruminal papillae and subsequently ruminal microbes may enter into the liver via the portal system, leading to liver abscesses (Owens et al. 1998; Tadepalli et al. 2009). The occurrence of liver abscesses and parakeratosis (thickening of the rumen

wall) are usually observed after a period of time following the initial incidence of ruminal acidosis.

2.6.4. Ammonia

Ammonia is produced in the rumen by microbial degradation of proteins and non protein nitrogenous (NPN) compounds. Ammonia concentration in the rumen depends on several factors such as type and composition of animal feed, time of feeding, feeding frequency and ruminal microbial population (Moya et al. 2009). Ammonia is utilized for microbial protein synthesis and the extent of ammonia utilization in the rumen depends on the several factors such as rate of ammonia release, the type and availability of carbohydrates, ruminal microbial flora and N availability (Cole and Todd 2008; Moya et al. 2009). Carbohydrate availability in rumen determines the efficacy of ammonia utilization and rate of microbial synthesis (Koenig et al. 2003; Cole and Todd 2008). Limited supply of carbohydrates can result in suppressed microbial ammonia utilization (Cole and Todd 2008). Carbohydrate availability in the rumen is a key factor for efficiency of ruminal ammonia and dietary N utilization (Hristov et al. 2005a).

The rumen microbes provide essential amino acids to ruminants, hence maximizing microbial protein synthesis is considered beneficial (Lapierre et al. 2006). Ruminal microbes synthesize their required amino acids by degrading low quality plant proteins and NPN compounds. Ruminal ammonia N concentration in the range of 2-13 mg/dL is considered optimum for microbial protein synthesis (Boucher et al. 2007).

2.7. Comparison of Oat and Other Major Cereal Grains

One of the major operating costs for feedlot operations is feed cost. Cereal grains are included in the rations of feedlot cattle as a source of energy for improving animal performance and carcass characteristics. Utilization of cereal grains as a livestock feed dramatically increased during the 1950's (Abercrombie 1982). North American feedlot operations use high concentrate diets to maximize gain, and have energy efficient growth and fat deposition (Coleman et al. 1993; Vaage et al. 1998). This practice reduces the days on feed and eliminates some of the problems associated with feeding roughages such as variation in quality and problems of availability, storage and processing (McEwen et al. 2007).

Inclusion of cereal grains in cattle rations is specifically related to geographical region. Availability and local growing conditions reduces the cost of grain. In the United States and in eastern Canada, corn is predominantly used as a grain source for finishing rations (Kincheloe et al. 2003) whereas barley is mostly used as a source of energy in north western United States (Bradshaw et al. 1996) and in western Canada. Barley is excellent source of energy for livestock, particularly in areas where climate and soil fertility are not suitable for corn production (Boss and Bowman 1996a).

For efficient utilization and increased digestibility of barley, processing is required. It has been reported that processing of barley results in enhanced ruminal nitrogen efficiency, decreased ruminal methane loss, and increased total tract starch digestibility (Zinn 1993). This processing, however, tends to increase the cost of feeding barley as compared to oat in which processing does not significantly affect digestibility (Campling 1991). Due to the relatively high cost associated with barley

feeding, there is a need for an alternative source of energy. In comparison to barley, oat is usually cheaper in western Canada in terms of input costs and yield.

Whole or rolled oat have similar DM digestibility when used in rations in lactating cows at levels up to 25% DM with no effect of processing on milk production (Moran 1986). Whole barley is poorly digested because of the seed hull. Processing results in ruptured pericarp, exposing starch granules thus aiding in microbial fermentation by improving the starch availability in the rumen (McAllister et al. 1991; Beauchemin et al. 1994). Rolled barley is efficiently utilized by cattle as compared to whole barley (Mathison et al. 1991).

A backgrounding study comparing the effect of processing of CDC SO-I oat revealed that this product is an excellent feed grain for growing cattle and processing (i.e. dry rolling) is not required when CDC SO-I oat is fed at approximately 35% (DM basis) in diets during backgrounding (McKinnon et al. Unpublished). As such, in addition to the agronomic benefits of growing oat for feed, producers can save the processing costs required for barley feeding.

2.7.1. Comparison of Energy Values of Different Cereal Grains

As compared to other cereal grains, oat grain is more variable in nutrient density (Bird et al. 1998), but in terms of metabolisable energy it is closer to barley than corn (Owens et al. 1997). The net energy value of corn for maintenance (NE_m) and gain (NE_g) have been reported as 2.16 Mcal kg^{-1} and 1.48 Mcal kg^{-1}, respectively (NRC 2001). The energy value of barley grain has been reported as 2.02 Mcal kg^{-1} NE_m and 1.36 Mcal kg^{-1} NE_g (NRC 2001). The energy value of dry rolled oat has been reported as 1.90 Mcal kg^{-1} NE_m and 1.26 Mcal kg^{-1} NE_g (NRC 2001). From energy prospective,

the feeding value of barley is 88-90% of corn for feedlot cattle. Barley contains higher crude protein content (10 to 20% with average of 13%) (Hockett 2000) than corn (9 to 11.5% with average of 9.7%) (Herrera-Saldana et al. 1990; Sniffen et al 1992). Generally there is less need for protein supplement in barley as compared to corn-based diet when fed to cattle, thus increasing the economic value of barley and reducing its feeding cost (Lardy and Bauer 1999). In comparison to barley, oat has a higher content of fiber and fat but lower starch content (Ekern et al. 2003). The TDN value of oat grain is 78.5% compared to 82.7% for barley (NRC 2001).

2.8. The New Improved Variety of Oat

The nutritional characteristics of traditional oat cultivars can be improved by utilizing breeding techniques to increase its oil content or reducing its indigestible lignin content. One of the efficient tools to improve oat grain quality and to produce high-yielding cultivars is interspecific hybridization. New improved varieties of oat can be selected for traits like high protein, low lignin, high oil content and disease resistance (Leonova et al. 2008).

In the last few years, hulless oat varieties emerged in the market and are used in both monogastric and ruminant rations. These varieties had excellent nutritional feed values such as higher protein and fat content with a good balance of amino acids compared to traditional oat. Biel et al. (2009) reported that naked oat (hulless) has less fiber and larger amount of total protein and crude fat compared to other cereals.

In recent years, a new variety of oat known as low lignin hull- high oil groat oat (LLH-HOG) has been developed. This variety has a low-lignin hull (1.1%) and high oil groat (6.5) and has promising results in dairy cattle rations as a replacement of barley

(Fuhr 2006). Fuhr (2006) reported higher milk yield, similar milk fat percentage and yield and similar DMI in dairy cows fed LLH-HOG compared to barley-fed cows. Following further breeding trials, a refined variety was licensed as CDC SO-I oat. Recent studies have been conducted to compare the degradation characteristics of CDC SO-I with normal oat varieties (CDC Dancer and Derby). Niu et al. (2007 b) compared these oat varieties and reported that CDC SO-I oat has higher truly digestible NDF and fatty acid content, and lower truly digestible non-fiber carbohydrate compared to the other two varieties. The results of this study indicated more slowly digestible carbohydrate and less indigestible carbohydrate in CDC SO-I oat. The same study reported energy values of CDC SO-I oat similar to that of barley. Yu et al. (2008) analyzed the protein value and protein degradation characteristics of CDC SO-I oat and compared it with CDC Dancer and Derby. The authors concluded that total absorbed metabolizable protein supply increases by 9-13% by using CDC SO-I oat in dairy cattle compared to other two oat varieties.

2.9. Summary

As a result of rising and cyclic prices of major cereal grains, it is important to look for alternative feeds for feedlot cattle to lower the cost of gain. Some earlier studies have been conducted in ruminants using oat as an alternative cereal grain (Devlin et al 1977; Moran 1986). These studies provide some promising results in terms of selecting oat grain as an energy source in beef and dairy rations. In order to continue the search for an alternative grain, recent studies (Ekern et al 2003; Fuhr 2006; Zalinko et al. 2009) have been conducted using oat grain as energy source for dairy and beef cattle.

Recently, the Crop Development Center at the University of Saskatchewan developed a new variety of oat (CDC SO-I), with low lignin hull and high oil groat. This new variety of oat is specially developed for the ruminant feed market. Previous feeding trials with initial lines of this variety have shown promise in both dairy and beef feeding trials, particularly in backgrounding programs where inclusion levels have been relatively low. However, in finishing trials (Zalinko et al. 2009) it was noted that this variety resulted in a depression in feed intake when fed at high inclusion levels, potentially due to an effect of processing (hull separation) and/or high oil content of the diet. The objectives of the research described here is to determine feeding recommendations for CDC SO-I oat that can be used by the oat and cattle industries to maximize the use of this cereal grain to optimize performance and carcass quality relative to barley fed cattle.

3. LOW LIGNIN HULL-HIGH OIL OAT (CDC SO-I): AN ALTERNATIVE TO BARLEY IN FEEDLOT RATIONS

3.1. Introduction

Feed is one of the major components of total operating cost for feedlot operations. Cereal grains are selected based upon the cost of grain, degree of processing required, availability and price. Barley is the most common source of energy used in feedlot diets in the north-west United States and in western Canada (Bradshaw et al. 1996). Due to the competitive nature of the industry and the cyclic nature of the supply and price of cereal grains such as barley, there arises a need to look for alternative feeds for feedlot cattle. In western Canada, oat (*Avena sativa*) is readily available and economical to grow (Willenborg et al. 2005).

Oat grain is typically not included as a major energy source in the diets of growing and finishing cattle. This may be due to variability in nutrient content and low energy density of the oat grain (Welch et al. 1983; Bird et al. 1998). Oat has a high hull content which typically averages 25% of the kernel weight. The hull tends to be poorly digestible due to its high acid detergent lignin content (5.5 to 6.0 % DM basis) (Thompson et al. 2002). As a result, the net energy content for oat is lower (1.85 and 1.22 Mcal kg^{-1} DM NE_m and NE_g, respectively) compared to barley (2.06 and 1.40 Mcal kg^{-1} DM NE_m and NE_g, respectively) and corn (2.18 and 1.50 Mcal kg^{-1} DM NE_m and NE_g, respectively) (NRC 1996).

The nutritional value of oat can be increased through plant breeding by increasing its digestible energy content. This can be accomplished by increasing the oil content of the groat and/or reducing the lignin content (indigestible part) of the hull

(Holland et al. 2001). It has been reported that an oat-based diet with a low-lignin hull cultivar resulted in improved organic matter digestibility, increased apparent digestibilities of NDF, ADF and improved ruminal degradability of fiber components in comparison to an oat cultivar with a high-lignin hull (Rowe and Crosbie 1988).

The Crop Development Centre (CDC) of the University of Saskatchewan recently developed a new variety of oat licensed as CDC SO-I with two unique characteristics: a low acid detergent lignin hull and high oil groat. CDC SO-I oat is specially developed for the ruminant feed market. A recent study by Niu et al. (2007a) compared the *in situ* degradation characteristics of CDC SO-I oat and conventional oat cultivars and reported that CDC SO-I oat is more digestible due to its lower lignin and non-fiber carbohydrate content.

Zalinko et al. (2009) used a prototype of this variety (LLH-HOG) with a low acid detergent lignin content (1.0 % DM basis) but a slightly higher fat content (9.3% DM basis) in steers during backgrounding and finishing rations. In backgrounding rations, animals fed this variety had equal performance in terms of feed conversion efficiency and average daily gain as compared to the barley-fed cattle. However, during finishing, steers fed this variety had reduced DMI, daily gain and poor gain to feed ratio which resulted in longer days on feed, reduced carcass weight and lower dressing percentage. It was hypothesized that the reduced feed intake during this initial study was due to an excessive level and type of dietary fat in the oat diet relative to the barley or corn diets. Further research is required to determine the optimal level of this new oat variety in finishing diets and to determine if it can replace barley grain as the energy source in finishing diets.

Hence, the present study was designed and the diets were formulated with graded levels of CDC SO-I oat replacing barley. The hypothesis of this study was that strategic supplementation of the low lignin hull-high oil groat oat in the finishing ration would result in performance equal to or superior to that of barley-fed cattle. The objective was to investigate the effect of increasing inclusion level of CDC SO-I oat in finishing diets on DMI, performance and carcass characteristics of feedlot cattle.

3.2. Materials and Methods

3.2.1. Animal and Diet

Two hundred crossbred steers (427.3 ± 22.4 kg) were purchased from a local auction market and housed at the Beef Cattle Research Unit, University of Saskatchewan, Saskatoon, SK. Upon arrival all steers were identified and processed including vaccination against infectious bovine rhinotracheitis, bovine respiratory syncytial virus, bovine viral diarrhea, parainfluenza 3 (Star Vac®, Novartis Animal Health Canada Inc., Missisauga, ON); Haemophilus somnus and Pasteurella haemolytica (Somnu-Star Ph®, Novartis Animal Health Canada Inc., Missisauga, ON); clostridial diseases (Covexin® 8, Schering-Plough Animal Health, Schering Canada, Point-Claire, PQ) and treated for parasites with ivermectin (IvomecTM, MSD AgVet, Kirkland, PQ, Canada). All steers were implanted on arrival with Synovex S® (Wyeth Animal Health, Guelph, ON) and after 90 days with Synovex Choice (Wyeth Animal Health, Guelph, ON). The animals used for this experiment were cared for under the guidelines of the Canadian Council on Animal Care (1993).

All steers were housed in pens with dimensions of 12 m × 24 m with 3.3 m high, 20% porosity windbreak fencing. All pens had automatic waterers. Prior to the start of

the trial, the steers were adapted from a silage-based backgrounding diet (50% silage, 30% barley, 5% supplement and 15% brome grass hay; DM basis) to the assigned treatment diets over a 2 week period by gradually decreasing the forage by 10% and increasing the grain until the final desired forage to grain level was reached (Table 3.1).

Five experimental diets were designed based upon increasing inclusion levels of CDC SO-I oat. Each diet was randomly assigned to 4 pens (4 pens per treatment). The control diet was a typical finishing diet composed of barley grain (88.4%), barley silage (6.2%) and pelleted supplement 5.5% (DM basis). In diets 2 through 5, oat replaced 25, 50, 75 and 100% of the barley grain portion of the diet (DM basis), respectively. The ingredient composition of pelleted supplement is given in Table 3.1. Diets were formulated to meet protein requirements for finishing cattle (NRC 1996) and for 1.92 Mcal kg^{-1} of NE_m and 1.28 Mcal kg^{-1} of NE_g based on the assumption that the net energy content of the CDC SO-I oat is equivalent to that of barley (NRC 1996) (Table 3.1). Steers were fed *ad libitum* twice daily at 0900 and 1600 h.

Table 3.1. Ingredient and chemical composition of barley and CDC SO-I oat grain treatments used in feedlot finishing trial

	Barley grain : CDC SO-I oat grain				
	100-0	75-25	50-50	25-75	0-100
Ingredient Composition (% DM basis)					
Barley Silage	6.2	6.2	6.2	6.2	6.2
Pellets	5.5	5.5	5.5	5.5	5.5
Barley	88.3	66.2	44.2	22.1	0.0
CDC SO-I Oat	0.0	22.1	44.1	66.2	88.3
Total	100.0	100.0	100.0	100.0	100.0
Pelleted Supplement (% DM basis)					
Barley	50.7	50.7	50.7	50.7	50.7
Canola Oil	3.5	3.5	3.5	3.5	3.5
Limestone	22.9	22.9	22.9	22.9	22.9
Rum Premix[z]	7.2	7.2	7.2	7.2	7.2
TM salt[y]	7.1	7.1	7.1	7.1	7.1
LS106[x]	8.6	8.6	8.6	8.6	8.6
Total	100.0	100.0	100.0	100.0	100.0
Chemical composition (% DM basis) ± SD					
CP	15.2 ± 1.19	14.6 ± 0.78	14.7 ± 1.10	13.9 ± 0.91	13.4 ± 0.76
NDF	20.2 ± 1.36	21.9 ± 1.28	23.3 ± 1.45	24.5 ± 2.35	27.4 ± 1.81
ADF	8.4 ± 0.43	10.0 ± 0.59	11.3 ± 1.45	11.3 ± 0.85	13.4 ± 0.78
Ether Extract	2.6 ± 0.11	3.6 ± 0.11	4.0 ± 0.15	4.6 ± 0.12	6.0 ± 0.13
ADL	3.1 ± 0.01	2.8 ± 0.23	2.6 ± 0.21	2.3 ± 0.08	1.9 ± 0.12
Calcium	0.48 ± 0.04	0.45 ± 0.32	0.46 ± 0.29	0.46 ± 0.15	0.51 ± 0.48
Phosphorus	0.38 ± 0.13	0.36 ± 0.12	0.33 ± 0.26	0.36 ± 0.01	0.35 ± 0.24
Formulated Energy profile					
NEm (Mcal/kg)	1.92	1.92	1.92	1.92	1.92
NEg (Mcal/kg)	1.28	1.28	1.28	1.28	1.28

[z] Contained Barley 97%, Rumensin premix 3% (Monensin Sodium 27 mg/kg)
[y] Contained Zinc 10,000 mg/kg, Iodine 200mg/kg, Manganese 10,000 mg/kg, Copper 4000 mg/kg, Cobalt 60 mg/kg, Selenium 120 mg/kg, Salt 95%
[x] Vitamin A 440500 IU/kg, Vitamin D 88,000 IU/kg

3.2.2. Experimental Design and Performance Measurements

The trial was conducted as a completely randomized design. Steers were stratified by weight and assigned to one of twenty pens (10 head per pen). Each pen was randomly assigned to one of the five treatments. The trial period was of 162 days in duration. All cattle were weighed on two consecutive days prior to the morning feeding at the start and end of test to determine initial and final weights, as well as every 14 days throughout the trial. Ultrasound measurements of subcutaneous fat (USFAT) depth and *l.dorsi* area (USLDA) were taken at the start and end of test and once every month according to Bergen et al. (1997) using an Aloka 500 V realtime ultrasound machine and a 17 cm linear array transducer (Aloka 500, Corometrics Medical System, Wallingford, CT). The target weight at the end of the finishing phase was 630 kg (shrunk weight basis). All cattle were slaughtered at a commercial packing plant (XL Beef Inc., Moose Jaw, SK). Carcass traits including hot carcass weight, grade fat, marbling score and lean yield were collected by Canadian Beef Grading Agency (CBGA) graders.

Net energy for maintenance (NE_m) for different treatment diets was calculated using performance data (DMI, animal weights and ADG) according to Zinn et al. (2002).

$$NE_m = [-b \pm (b^2 - 4ac)^{1/2}]/2a$$

a = -0.877DMI, b = 0.877EM + 0.41DMI + RE, and c = −0.41EM

EM (expected maintenance energy; Mcal/day) = $0.077BW^{0.75}$

BW is the mean shrunk body weight = full weight × 0.96

The formula for retained energy for large-framed yearlings (RE = $[0.0437BW^{0.75}]$ $ADG^{1.097}$; NRC, 1984) was used. NE_g was calculated using NE_m as per Zinn and Shen

(1998; $NE_g = NE_m \times 0.877 - 0.41$). Shrunk body weight (full weight × 0.96) was used for calculating performance.

3.2.3. Grain Samples and Sample Collection

Both the CDC-SO-I oat and barley were grown on the University of Saskatchewan farm, Saskatoon, SK., in 2006. Prior to the start of the trial the oat grain was cleaned (5.5 slotted sieve) to remove any thin unfilled kernels. Processing of both the barley and oat was done at the university feed mill with dry rolling using a Roskamp Series 9 Model J double roll roller mill with fine and coarse groove roll sets. The bulk densities of the processed barley and oat grains were 48.9 ± 4.62 kg $hL^{-1}$and 37.3 ± 3.01 kg hL^{-1}, respectively.

Daily pen feed intake values were recorded. Samples of forages and concentrates were taken weekly to determine DM content while the bunk samples and orts were taken bimonthly and stored at – 20 °C for particle size separation.

3.2.4. Chemical Analysis

Forages were oven dried at 55°C for 48 h and together with all other feed samples were ground to pass through a 1-mm screen (Christy & Norris Laboratory Mill, Christy & Norris Ltd, Chelmsford, England). Dry matter (DM) content of feed samples were analyzed by drying at 135°C for 2 h (AOAC, 2005; method 930.15). Acid detergent fibre (ADF) using Ankom 200 fibre analyzer (method 973.18), crude protein using a 2400 Kjeltec analyzer unit (method 984.13), ether extract (EE) (method 920.39) and acid detergent lignin (ADL) (ADF method 973.18 followed by 72% H_2SO_4 treatment) (AOAC, 2005) were also analyzed. Neutral detergent fibre (NDF) content

was determined with heat stable α-amylase and sodium sulfite (Van Soest et al. 1991). Calcium (AOAC, 2005; method 927.02) and Phosphorus (using molybdovanadate reagent; AOAC, 2005; method 965.17) were analyzed after ashing for 5 h at 500°C using Atomic Absorption Spectrophotometer (Model 2380, Perkin-Elmer, Rexdale, Ontario, Canada) and UV visible spectrophotometer (Pharmacia LKB-Ultrospec III spectrophotometer, Cambridge, England) respectively. All measurements were performed in duplicate.

3.2.5. Particle Separation

Samples of grain, orts and total mixed ration were subjected to particle size separation using a three step procedure. Initially, a Carter-Day dockage tester (Carter-Day Co., Minneapolis, MN, USA) with round-hole sieves (screen size-0.30 and 0.25 cm) and riddle with 26 holes across (#25 riddle) was used to separate hulls, large particles and fines. Large particles were further air classified using a seed blower (Ames Powercount Co., Brookings, SD, USA) to separate hull particles. In the last step, particles left below the column were further sorted as per their density using a Spherical- Nonspherical sorter (Agriculex SNS-1, Canada) with lateral slope adjustment of 14 cm and horizontal slope adjustment of 5.5 cm at the Crop Science Laboratory, University of Saskatchewan, Saskatoon, SK. The same steps were repeated until the entire sample was separated and then collected in separate pre-weighed paper bags. Separated samples were weighed, dried thoroughly at 55°C and weighed to determine DM content. The proportion of hulls, large particles and fines were reported as a percent of the entire feed sample (DM basis).

3.2.6. Statistical Analysis

The trial was conducted as a completely randomized design with pen as the experimental unit. The Proc Mixed Procedure of the Statistical Analysis System (SAS Institute, Inc. Cary, NC, 2003) with treatment as the fixed effect was used to carry out the analysis of variance for all performance and carcass results. Statistical significance was declared at $P \leq 0.05$. Polynomial orthogonal contrasts were used to test the significance of linear, quadratic, cubic and quartic effects of CDC SO-I oat inclusion level. The Kenward Roger adjustment on denominator degrees of freedom was used. For the marbling data, the glimmix macro provided by SAS Institute, Inc. (SAS Institute, Inc. Cary, NC) was utilized with a binomial error structure and logit transformation of data.

3.3. RESULTS AND DISCUSSION

The composition and chemical analysis of the total mixed rations are given in Table 3.1. All treatment diets met or exceeded NRC (1996) CP requirements for the type of cattle and rate of gain expected in this trial. As such there was no need for any supplemental protein. Replacement of barley with CDC SO-I oat resulted in increased levels of ADF, NDF and EE, while ADL levels decreased with higher inclusion rates of CDC SO-I oat (Table 3.1). These differences reflect nutrient profiles of the barley and oat grain used in the trial (Table 3.2). The CDC SO-I oat had a ADL content of 1.7% while EE level was 6.3%. This contrasted to respective values in barley of 1.9% and 2.4%.

Table 3.2. Chemical composition (% DM basis) of CDC SO-I oat and barley grain used in feedlot finishing trial

Chemical composition	CDC SO-I Oat Grain	Barley Grain
	Mean ± SD	Mean ± SD
DM%	91.61 ± 0.67	89.91 ± 0.62
CP%	13.56 ± 0.25	15.72 ± 0.76
ADF%	12.62 ± 1.16	6.24 ± 0.86
NDF%	29.51 ± 2.02	18.34 ± 2.17
EE %	6.30 ± 0.42	2.40 ± 0.32
ADL%	1.70 ± 0.24	1.90 ± 0.13

3.3.1. Performance Data

The effects of different inclusion levels of barley and CDC SO-I oat on the performance of feedlot steers is given in Table 3.3. From day 1 to 86 of the trial, steers fed increasing levels of CDC SO-I oat exhibited a linear decrease in ADG ($P< 0.01$), DMI ($P< 0.01$) and feed efficiency (gain: feed ratio) ($P= 0.03$). Respective values for the barley-fed cattle were 112, 108 and 104% of that of the 100% oat-fed cattle. From day 86 to slaughter, both DMI ($P< 0.01$) and ADG ($P= 0.02$) continued to exhibit a linear decrease as CDC SO-I oat inclusion levels increased. However, gain: feed during this period exhibited a cubic effect ($P= 0.01$) with poorest efficiencies at 25 and 100% CDC SO-I oat (Table 3.3). As a result, over the course of the entire trial, DMI ($P< 0.01$) and ADG ($P< 0.01$) decreased linearly as CDC SO-I inclusion level increased, while feed efficiency showed a quadratic ($P= 0.03$) response with the poorest efficiency at 100% CDC SO-I oat inclusion level. Days on feed increased ($P= 0.03$) in a quadratic

fashion as CDC SO-I oat inclusion level increased. It should be noted that while performance was found to decrease linearly, the effects of the new variety were greatest at the 50% inclusion level or greater. For example, over the course of the trial, DMI, ADG, gain:feed and days on feed were very similar between the control and the 25% CDC SO-I oat inclusion level (Table 3.3). No effect ($P > 0.05$) of treatment diets were observed on the calculated net energy of gain (NE_g) values (Table 3.3). The results indicated that the efficiency of utilization of energy available for gain was same among steers fed barley-based diet and oat-based diets.

Table 3.3. Effect of inclusion level of barley and oat (CDC SO-I) on the performance of feedlot steers

	Barley grain : CDC SO-I Oat grain							Contrasts[z]			
Parameter	100 : 0	75 : 25	50 : 50	25 : 75	0 : 100	SEM[y]	P_{trt}	Linear	Quadratic	Cubic	Quartic
Live weight (kg)											
Start of test	410.0	410.5	410.0	410.3	410.5	0.42	0.84	0.58	0.88	0.47	0.49
Day 86	575.3	576	567.8	561.8	559.3	3.28	<0.01	<0.01	0.73	0.25	0.72
End of test	630.8	624.3	623.3	624.5	614	3.76	0.08	0.01	0.69	0.17	0.74
Day 1 to 86											
Gain (kg)	165.3	165.7	157.7	151.5	148.6	3.35	<0.01	<0.01	0.69	0.29	0.77
DMI (kg/d)	10	9.9	9.7	9.5	9.3	0.13	0.02	<0.01	0.79	0.88	0.81
ADG (kg/d)	1.95	1.95	1.86	1.78	1.75	0.04	<0.01	<0.01	0.69	0.27	0.81
Gain : feed	0.194	0.198	0.191	0.188	0.187	0.0031	0.15	0.03	0.71	0.20	0.63
Day 86 to Slaughter											
Gain (kg)	55.0	48.1	55.5	63.0	54.8	3.26	0.08	0.18	0.85	0.01	0.96
DMI (kg/d)	12.3	12.7	11.4	10.8	10.1	0.36	<0.01	<0.01	0.26	0.18	0.28
ADG (kg/d)	1.70	1.49	1.57	1.56	1.13	0.13	0.07	0.02	0.30	0.11	0.93
Gain : feed	0.138	0.117	0.138	0.143	0.112	0.008	0.06	0.33	0.26	0.01	0.62
Start of test to Slaughter											
Gain (kg)	220.3	213.8	213.2	214.5	203.5	3.94	0.10	0.02	0.63	0.17	0.77
DMI (kg/d)	11.0	10.9	10.5	10.1	9.7	0.16	<0.01	<0.01	0.35	0.53	0.84
ADG (kg/d)	1.85	1.83	1.78	1.70	1.52	0.04	<0.01	<0.01	0.06	0.66	0.77
Gain : feed	0.169	0.169	0.169	0.169	0.157	0.0028	0.03	0.02	0.03	0.20	0.77
NE_g (Mcal kg^{-1})	1.38	1.36	1.39	1.40	1.35	0.024	0.16	0.73	0.38	0.13	0.94
Days on feed	121	118	123	129	137	2.7	<0.01	<0.01	0.03	0.46	0.68

[z] Orthogonal polynomial contrasts: Linear, quadratic, cubic and quartic effects of CDC SO-I oat inclusion levels

[y] Pooled standard error of mean.

Performance and feed intake of cattle fed the 100% barley-based control diet was similar to or superior to that reported by other workers who fed barley-based finishing rations to steers in a similar environment (Block et al. 2001; Williams et al. 2008). Superior performance of barley vs. oat-fed cattle in terms of gain and feed conversion efficiency has been reported by other workers (Staigmiller and Adams 1989; Huuskonen 2009). However, due to the nature of CDC SO-I oat (i.e. low lignin hull, high-oil groat), the results of the present study were not expected. Typically one would expect that productive efficiency of cattle would be improved by adding a more digestible, higher energy feedstuff to the ration.

Fat addition to finishing diets is a common method to improve the productive efficiency of cattle by increasing the energy density of the diet (Allen 2000; Hess et al. 2008). Zinn (1988) reported that supplementation of 4% yellow grease in the diet resulted in increased rate of weight gain by 12.5% and increased the NE_m value of the diet by 8.5% and NE_g by 9.4%. Several earlier studies have shown that addition of 4 to 8% tallow or blended tallow-vegetable oil mixtures to finishing diets improved daily gain, and/or feed efficiency (Zinn 1989a; Huffman et al. 1992; Ramirez and Zinn 2000). Increase oil content of the groat has been reported to increase the energy content of oat grain (Frey and Holland 1999). However, it is clear that the increased fat content of the CDC SO-I oat did not compensate for reduced DMI in this study.

Research with fat addition to cattle diets has in some cases shown a negative effect of fat supplementation on DMI, particularly when dietary fat levels approach 8% or greater (Zinn 1989b; Choi and Palmquist 1996). Several mechanisms have been proposed for this fat induced depression in DMI in ruminants. These include negative

effects on rumen fermentation, gut motility, palatability of the diet and systemic effects on endocrine and hepatic metabolism (Allen 2000). Zinn (1989b) found that supplementation of either 4 or 8% fat in the diet of feedlot cattle fed a barley-based finishing diet resulted in depressed ruminal and total tract digestion of organic matter, starch and ADF. Ramirez and Zinn (2000) reported both a depression in DMI and in ruminal and total tract digestion of organic matter and neutral detergent fibre when 4% tallow, yellow grease or griddle grease was supplemented to a diet with a magnesium level of 0.18%. Zalinko et al. (2009) using a prototype of CDC SO-I oat with 9.3% fat reported reduced DM intake, lower ADG and gain:feed ratio in steers during the finishing period, resulting in reduced carcass weights, lower dressing %, reduced grade fat and smaller *l.dorsi* area. Depression in nutrient utilization however is not always a response to added fat (Huffman et al. 1992; Atkinson et al. 2006).

High fat levels in ruminant diets reduce the digestibility of non-lipid energy sources by disrupting ruminal fermentation. The detrimental effect of added fat on ruminal fiber digestion is the result of antimicrobial effects of fatty acids (Jenkins 1994; Doreau and Chilliard 1997). Fungi play an important role in hydrolyzing ester linkages between lignin, hemicellulose and cellulose, and help in breaking down of digesta particles. Faichney et al. (2002) reported that increasing the free lipid (5.9%) content in the diet resulted in total disappearance of anaerobic fungi and reduced the protozoal population as compared to animals fed levels of 2.1- 4% fat. In the same study, it was reported that degradation of fat was reduced by 45-60%, hemicellulose by 7% and cellulose by 9% at the higher free lipid levels in the diet.

In the present study, reduced fiber digestion with high fat levels cannot entirely

explain the reduced DMI with higher levels of CDC SO-I oat, as the silage level in the formulated diets was maintained at 6.9% (DM basis), the main source of dietary fiber. An alternative explanation for the possible effect of high fat on DMI is through satiety signals in the hypothalamus, regulating appetite and feed intake (Choi and Palmquist 1996; Relling and Reynolds 2007).

In the present study, the total fat level of the 100% oat-based diet was 6.0% (DM basis). This level of fat addition is not typically associated with a depression in feed intake, particularly of the magnitude seen in the current study (i.e. 10.9 vs. 9.7 kg d^{-1}) for the 100% barley-fed vs. the 100% oat-fed cattle (Table 3.3). Earlier studies reported that the hypophagic effects of added fat are not only associated with the level of fat addition but also with the type of fat and degree of saturation (proportion of saturated to unsaturated fatty acids) (Allen 2000; Benson et al. 2001; Litherland et al. 2005; Relling and Reynolds 2007).

Harvatine and Allen (2005) compared unsaturated vs. saturated fat at the level of 2.5% added fat and noted a reduction in DMI (0.8 kg d^{-1}) of Holstein cows with unsaturated fatty acids. The unsaturated fatty acids were derived from calcium salts of palm fatty acid and contained about 2.5 times more unsaturated fatty acids, particularly C18:1 (Oleic acid) and C18:2 (Linoleic acid), than the saturated fatty acids which were derived from prilled hydrogenated free fatty acid. Unsaturated fatty acid concentration of the diet negatively affects the intake of feed in cattle (Bremmer et al. 1998). Gibb et al. (2004) noted a 14% reduction in DMI of steers fed high linoleic acid sunflower seeds relative to those fed a control barley grain-based diet. Litherland et al. (2005) studied the effects of unsaturated free fatty acids (UFA) (soy FFA) and unsaturated triglycerides

(TG) (soy oil) on DMI in dairy cows. Both UFA and TG decreased DMI, however the effect of UFA was 2 times more pronounced than TG.

Zalinko et al. (2009) noted the following differences between a prototype of the CDC SO-I oat and barley in terms of fatty acid profile (Table 3.4). This low lignin high oil groat oat grain had a fatty acid profile (% of total extracted fatty acids) relative to barley grain of 14.4 vs. 19.8% for palmitic acid; 1.4 vs. 1.1% for stearic acid; 43.7 vs. 14.8% for oleic acid; 37.0 vs. 55.9% for linoleic acid and 1.1 vs. 6.6 % for arachidonic acid. These values for this low lignin high oil groat oat were similar to the fatty acid profile of oat grain that had been selected through 9 cycles for increased oil content (Holland et al. 2001). In the present study, the 100% oat-based diet had a total fat content of 6% vs. 2.6% for the 100% barley based diet, it is possible that the higher consumption of unsaturated fatty acids as the oat level in the diet increased in the present study may have contributed to the reduction in DMI. This would be particularly true for diets with 50% and greater CDC SO-I oat content. Long chain fatty acids released in the rumen are known to have toxic effects on gram negative bacteria which can lead to negative effects on digestibility and intake (Angelidaki and Ahring 1992).

Table 3.4. The relative fatty acid profile of low lignin high oil groat oat and barley grain (adapted from Zalinko et al. 2009)

	Fatty acid (% of total FA)								
Cereal grain	C 16:0	C 18:0	C 18:1	C 18:2n6	C 20:4	SFA	MUFA	PUFA	Total FA (mg/g)
CDC SO-I oat	14.4	1.4	43.7	37	1.1	16.1	44.8	38.1	63.8
Barley	19.8	1.1	14.8	55.9	6.6	21.2	15.7	62.5	15.8

The negative effects of high dietary fat levels on the intake and subsequent performance of the 100% oat-fed steers is not the only possible explanation for the linear decrease in feed intake as the oat level in the diet increased from 0 to 100% and dietary fat levels increased from 2.6 to 6.0% (Table 3.1). An alternative explanation for the decline in DMI associated with increasing levels of the new oat variety may be associated with the nature of the oat kernel and the effects of processing. The oat kernel is comprised of the hull (~25% of kernel weight) and the groat. The groat is high in protein, starch and oil (Crosbie et al. 1985). Table 3.5 indicates that processing, either dry rolling and/or mixing in the feed wagon results in a higher proportion ($P< 0.01$) of hulls in the oat and oat-based diets than in the barley or barley-based diets. Examination of the bunk samples and orts indicates that 100% barley diet had 11.6% and 12.3% less hulls than that of the 100% oat-based diet respectively (Table 3.5). Oat hulls mainly composed of insoluble fibre (up to 80% of their total dry weight). The chemical constituents of the oat hulls (on a dry weight basis) includes protein (1.59–

10.19%), NDF (57.60–85.29%), ADF (24.87–50.15%), Ash (2.89-6.00%) and ADL (0.47 – 7.75%) (Redaelli and Berardo 2007). NDF content of the feed has been negatively associated with the feed intake through its rumen fill effect (Van Soest 1994). Increased NDF resulted in increased ruminating and total chewing time (Beauchemin and Buchanan-Smith 1989). Rumination has an upper limit depending upon the body size of animal and thus act as a time constraint i.e time spent ruminating high NDF feed competes with the time spent in eating (Van Soest 1994).

The passage rate of digesta through the gastrointestinal tract determines the rate at which nutrient will be digested and absorbed in ruminants in addition to other factors such as rate of fermentation of feed and DMI (Colucci et al. 1982). Feed energy value of high fiber diet is affected by the passage rate or rumen outflow rate because of their lower intestinal digestibility. With the high fiber diet, passage rate of ruminal digesta increases and consequentaly digestibility decreases with the increased passage rate (Van Soest 1994). The combination of these factors could explain the linear drop in DMI as dietary inclusion level of the oat increased.

Table. 3.5. Particle size separation of grains, bunk samples and orts of treatment diets

	% Fraction (DM Basis)					
	Bunk Samples			Ort Samples		
	Hulls	Large particles	Fines	Hulls	Large particles	Fines
Trt 1	9.3 ± 0.79	70.7 ± 6.01	19.9 ± 5.86	10.3 ± 1.15	72.0 ± 2.32	17.6 ± 1.34
Trt 2	12.1 ± 1.51	65.9 ± 5.18	22.0 ± 4.03	12.3 ± 1.04	72.1 ± 3.35	15.6 ± 3.07
Trt 3	16.2 ± 1.48	61.2 ± 6.96	22.6 ± 7.12	17.2 ± 2.37	66.9 ± 2.67	15.9 ± 3.49
Trt 4	19.0 ± 2.06	65.2 ± 7.03	15.8 ± 6.03	19.8 ± 2.57	69.2 ± 2.51	11.1 ± 0.95
Trt 5	21.1 ± 2.68	65.1 ± 5.82	13.8 ± 4.79	22.6 ± 4.20	66.2 ± 3.95	11.2 ± 1.84
P_{trt}	<0.01	0.01	<0.01	<0.01	<0.01	<0.01

Values: Mean (% basis) ± standard deviation of the mean
LP- Particles above the round-hole sieves with screen size-0.30 cm
Fines- Particles below the round-hole sieves with screen size-0.25 cm
Bunk samples Trt 1 to 5: Bunk samples with increasing inclusion levels (0, 25, 50, 75 and 100%) of CDC SO-I
Orts samples Trt 1 to 5: Feed leftovers with increasing inclusion levels (0, 25, 50, 75 and 100%) of CDC SO-I

In addition to the above discussed factors, reduced performance of steers fed higher levels of CDC SO-I oat might be due to subacute ruminal acidosis (SARA). Subacute ruminal acidosis is a serious problem in cattle fed high grain finishing rations and is characterized by ruminal environment with pH between 5.2 and 5.6 (Owens et al. 1998). As a result of high degradation rate of oat starch, the steers fed high levels of oat might experience subacute ruminal acidosis. Huntington (1997) reported higher ruminal starch degradation rate for oat (92-94%) compared to barley starch (80-90%). Gozho and Mutsvangwa (2008) compared oat-based diet with corn and wheat-based diet and reported higher total tract apparent starch digestibility in cows fed the oat-based diet. Studies comparing the degradation rates of CDC SO-I oat and barley starch are not reported in the literature. Yu and Niu (2009) compared the DM degradation rates of CDC SO-I oat and other varieties of oat (CDC Dancer and Derby) and reported no difference in the degradation rate of starch and protein among these varieties. Hence, there is a need to conduct a study to investigate the effect of different inclusion levels of CDC SO-I oat on rumen fermentation characteristics.

3.3.2. Carcass Traits

Steers fed higher inclusion levels of CDC SO-I oat had lower ($P< 0.01$) carcass weight, lower ($P< 0.01$) dressing % and reduced ($P= 0.01$) grade fat. These results reflect the lower DMI of the steers fed the oat-based diet. Similar results were reported by Schimek et al. (1997) when hulless oat was compared with corn. No treatment differences were noted for grader rib eye area and lean yield % (Table 3.6).

Table. 3.6. Effects of inclusion level of barley and CDC SO-I oat on the carcass characteristics of feedlot steers

	Barley grain : CDC SO-I oat grain						Contrasts[z]				
Parameters	100-0	75-25	50-50	25-75	0-100	SEM[y]	P_{trt}	Linear	Quadratic	Cubic	Quartic
Carcass wt (kg)	376.0	372.0	368.0	365.5	362.3	1.93	<0.01	<0.01	0.68	0.9	0.82
Dressing %	58.9	58.9	58.4	57.8	58.0	0.22	<0.01	<0.01	0.62	0.06	0.87
Average fat (mm)	8.8	8.5	9.0	7.8	7.3	0.50	0.13	0.03	0.25	1.00	0.25
Grader Fat (mm)	7.8	7.0	7.8	6.5	6.0	0.46	0.06	0.01	0.39	0.61	0.12
Grader REA(cm^2)	100.3	97.5	96.0	98.8	96.8	1.61	0.39	0.28	0.35	0.26	0.39
Lean Yield %	61.8	61.8	61.5	62.0	62.3	0.30	0.47	0.20	0.28	1.00	0.43

[z] Orthogonal polynomial contrasts: Linear, quadratic, cubic and quartic effects of CDC SO-I oat inclusion levels
[y] Pooled standard error of mean

Ultrasonographic measurements of back fat thickness (USFAT) and *l.dorsi* area (UDLDA) indicated that USFAT tended to be lower ($P = 0.07$) and USLDA decreased ($P < 0.01$) linearly for steers fed higher levels of CDC SO-I oat (Table 3.7). These results indicated slower rate of development of adipose tissue and muscle in CDC SO-I oat-fed steers.

Table. 3.7. Ultrasonographic measurements on SC and LDA of steers fed diets consisting of different levels of barley and CDC SO-I oat

	Barley grain : CDC SO-I oat grain						Contrasts[z]				
Parameter	100-0	75-25	50-50	25-75	0-100	SEM[y]	P_{trt}	Linear	Quadratic	Cubic	Quartic
SC fat depth (mm)											
Initial	4.0	4.0	4.3	4.3	4.3	0.27	0.90	0.39	0.81	0.77	0.74
Final	8.0	8.0	8.3	7.5	7.5	0.40	0.24	0.07	0.21	1.00	0.47
Longissimus dorsi area (cm^2)											
Initial	78.3	77.5	76.8	76.3	75.0	1.36	0.52	0.11	0.96	0.69	0.59
Final	102.5	101.3	99.0	99.0	96.3	1.48	0.07	0.01	0.89	0.71	0.51

[z] Orthogonal polynomial contrasts: Linear, quadratic, cubic and quartic effects of CDC SO-I oat inclusion levels
[y] Pooled standard error of mean.

Effect of CDC SO-I oat inclusion level on marbling score is given in Table 3.8. There was no effect of treatment on percentage of steers with AA and AAA marbling scores, while percentage of steers with marbling score A tended to be higher (P= 0.07) with higher inclusion levels of CDC SO-I oat (Table 3.8). Decline in DMI particularly at the higher oat inclusion levels translated into reduced net energy intake and as a result reduced growth and carcass traits as well as longer days on feed to a fixed target end-point.

Table. 3.8. Percentage of steers fed diets consisting of different levels of barley and CDC SO-I oat with different marbling scores

	Barley grain : CDC SO-I oat grain						
Marbling Score	100 : 0	75 : 25	50 : 50	25 : 75	0 : 100	SEM[z]	P Value
A	2.5	28.3	17.5	11.1	34.3	6.53	0.07
AA	77.6	66.6	65.0	72.3	62.9	8.12	0.71
AAA	19.9	5.1	17.5	16.7	2.8	5.74	0.27

[z] Pooled standard error of mean.

3.4. CONCLUSIONS

Replacement of barley grain with CDC SO-I oat resulted in reduced performance and carcass characteristics of finishing steers. This was particularly true for cattle fed diets with 50% or more oat as the cereal grain. The reduced DMI may be attributed to a combination of factors such as the level and nature of fatty acids comprising the CDC SO-I oat, high NDF content of the oat and oat hulls, low bulk density and consequently rumen fill effect and faster degradation rate of oat starch. The reduced performance and carcass characteristics were a direct result of reduced DM intake and as a consequence reduced energy intake. This resulted in longer days on feed to a targeted finishing weight.

4. COMPARISON OF RUMEN FERMENTATION CHARACTERISTICS AND FEEDING BEHAVIOR OF ANIMALS FED CDC SO-I OAT AND BARLEY

4.1. INTRODUCTION

In the North American cattle feedlot industry, feeding is aimed to maximize energy intake in order to achieve rapid and efficient gain. Cereal grains typically constitute 80-90% of the finishing diet. The level and type of cereal grain has a significant influence on microbiology, physiology and biochemistry of ruminant digestion. Ruminal fermentation parameters (i.e. pH, VFA levels, NH_3-N and osmolality) change when one grain type or level is replaced by another. This allows for the potential of manipulation of rumen fermentation and ultimately control of growth and performance of the animal.

The manipulation of rumen fermentation is of interest in the case of dairy cows where the ratio between the glucogenic and non-glucogenic volatile fatty acids affects milk composition and body energy gain (Sawal and Kurar 1998). In ruminants, manipulation of rumen fermentation results in a change in the proportions of propionic, butyric and acetic acids. Methane production decreases with increased propionic acid production, however it increases with increased production of acetic and butyric acid (Orskov et al. 1974).

It is of interest to mention that the rate of cereal grain fermentation in the rumen can affect cattle performance and the incidence of acidosis. A high rate of fermentation is desired with typical feedlot rations in order to maximize efficient production. However, for the prevention of acidosis, a slow rate of fermentation is preferred (Owens et al. 1998). Highly fermentable starch results in rapid production of fermentation acids

which can disrupt the normal rumen environment, resulting in a greater incidence of bloat (Cheng et al. 1998). Bloat and laminitis have adverse effects on the performance of the animal.

Oat does not require extensive processing as diets containing 25% whole or rolled oat when fed to lactating cows were found to have the same DM digestibility as well milk production was not affected by processing (Moran 1986). In contrast, whole barley is poorly digested because of the seed husk. Rolled barley is efficiently utilized by cattle compared to whole barley (Mathison et al. 1991). Besides the benefits of processing grain, there are some drawbacks. As a result of excessive processing, barley starch becomes highly fermentable in the rumen with little starch escaping for digestion in the small intestine (Orskov 1986). This rapid fermentation results in a drop in rumen pH leading to health problems like acidosis, rumenitis, laminitis and liver abscesses (Nocek 1997; Narayanan et al. 1997; Yang et al. 2000; Beauchemin et al. 2001). The incidence of liver abscesses increases with highly fermentable grains such as barley and with decreased levels of roughage in the finishing rations. Severe cases of liver abscesses can result in reduced performance and carcass yield (Nagaraja and Chengappa 1998).

Recently, the Crop Development Centre (CDC) of the University of Saskatchewan developed a new variety of oat called CDC SO-I with low lignin hull and high oil groat. This variety has been specially developed for animal feed market. A recent study on the protein and carbohydrate fractions of various varieties of oat (CDC Dancer, Derby and CDC SO-I) reported that CDC SO-I oat has more slowly digestible carbohydrate, less indigestible carbohydrate and less slowly digestible protein compared

to other oat varieties (Niu et al. 2007b). Furthermore, the same group reported that CDC SO-I oat had similar degradation rates of starch and protein to the CDC Dancer and Derby (Yu and Niu 2009). Little information is available on the rumen fermentation characteristics of CDC SO-I oat in comparison to commonly used cereal grains such as barley. The previous study using the same treatment diets with feedlot steers resulted in reduced performance with higher levels of CDC SO-I oat and it was postulated that subacute ruminal acidosis might be the reason for reduced performance subsequent to higher ruminal degradation of oat starch. Hence, the present study was conducted to investigate the effect of inclusion levels of CDC SO-I oat on the rumen environment (rumen pH, volatile fatty acids, ammonia and osmolality) including feeding behavior.

4.2. MATERIALS AND METHODS

4.2.1. Animals

Five spayed Hereford heifers (487 ± 70 Kg), surgically fitted with soft plastic ruminal cannula with 10 cm diameter opening (Bar Diamond, Parma ID) were used to investigate the effects of CDC SO-I oat on rumen fermentation parameters. The animals were housed and fed in individual pens in the Livestock Research Building at the Department of Animal and Poultry Science, University of Saskatchewan. Pens were 13 m^2 in size, with steel panel structure outfitted with rubber floor mats and individual automated water bowls. The animals used for this experiment were cared as per the guidelines laid down by Canadian Council on Animal Care (1993).

4.2.2. Experimental Design and Dietary Treatments

The experimental design was a 5 × 5 Latin square. The five treatment diets were used for five periods. The control diet was composed of barley grain (86.4%), barley silage (8.2%) and pelleted supplement (5.4%) (DM basis). For the 4 treatment diets, barley grain was replaced by CDC SO-I oat at 25, 50, 75 and 100% (DM basis). Each treatment diet had the same proportion of forage and concentrate, and was formulated as per NRC (1996) recommendations for energy and protein. Each treatment contained 27 mg kg^{-1} (DM basis) monensin sodium (Elanco Animal Health, Guelph, ON, Canada). The ingredient composition of each supplement is given in Table 4.1. Each morning, fresh feed was weighed and mixed before feeding. Animals were fed twice daily at 0800 and 1600 h. Feed bunks were cleaned each morning prior to feeding and orts were weighed to determine daily feed intake.

Table. 4.1. Ingredient and chemical composition of treatment diets used for metabolic trial

	Barley grain : CDC SO-I oat grain				
	100-0	75-25	50-50	25-75	0-100
Ingredient Composition (% DM basis)					
Barley Silage	8.2	8.2	8.2	8.2	8.2
Pellets	5.4	5.4	5.4	5.4	5.4
Barley	86.4	64.8	43.2	21.6	0.0
CDC SO-I Oat	0.0	21.6	43.2	64.8	86.4
Total	100.0	100.0	100.0	100.0	100.0
Pelleted Supplement (% DM basis)					
Barley	48.9	50.9	51.94	52.96	53.99
Limestone	22.9	22.9	22.93	22.96	22.99
Rum Premix[z]	7.2	7.2	7.2	7.2	7.2
Urea	5.4	3.2	2.2	1.1	0.0
TM salt[y]	7.1	7.1	7.1	7.1	7.1
LS106[x]	8.7	8.7	8.7	8.7	8.7
Total	100.0	100.0	100.0	100.0	100.0
Chemical composition (% DM basis) ± SD					
CP	11.6 ± 0.91	12.8 ± 0.85	12.9 ± 0.87	12.9 ± 0.71	13.5 ± 0.96
NDF	23.9 ± 1.42	25.3 ± 1.25	26.2 ± 1.49	27.9 ± 1.27	29.2 ± 1.81
ADF	9.1 ± 0.64	10.0 ± 0.42	10.3 ± 0.52	11.6 ± 0.81	12.4 ± 0.69
ADL	3.1 ± 0.21	2.8 ± 0.23	2.7 ± 0.09	2.3 ± 0.32	1.9 ± 0.45
Ether Extract	2.6 ± 0.19	3.5 ± 0.21	4.4 ± 0.45	5.6 ± 0.42	6.7 ± 0.62
Calcium	0.61 ± 0.12	0.64 ± 0.34	0.66 ± 0.22	0.66 ± 0.16	0.68 ± 0.25
Phosphorus	0.41 ± 0.16	0.43 ± 0.26	0.40 ± 0.14	0.40 ± 0.18	0.39 ± 0.19

[z] Contained Barley 97%, Rumensin premix 3% (Monensin Sodium 27 mg/kg)
[y] Contained Zinc 10,000 mg/kg, Iodine 200mg/kg, Manganese 10,000 mg/kg, Copper 4000 mg/kg, Cobalt 60 mg/kg, Selenium 120 mg/kg, Salt 95%
[x] Vitamin A 440500 IU/kg, Vitamin D 88,000 IU/kg

The CDC-SO-I oat and barley were grown on the University of Saskatchewan farm, Saskatoon, SK., in 2006. Prior to the start of the trial, the oat grain was cleaned (5.5 slotted sieve) to remove thin unfilled kernels.

Each trial period was 28 days in duration including a 14 day adaptation period, a 7 day voluntary intake period and a 7 day collection period. Animals were gradually adapted to the assigned experimental diets from day 1 through day 14. From day 14-21, the voluntary intake (VI) of each animal was measured by offering the high concentrate experimental diets at amounts approximately 10% higher until they reached the maximum intake. Day 21 to 28 of each period was used for data collection. The heifers were monitored visually for eating and ruminating behavior for a 24 hour period on day 21. From day 22 to 24 the heifers were placed on restricted feed intake (90% of VI). Feed restriction was done to ensure complete consumption of diets. Rumen fluid was collected on day 24.

4.2.3. Feeding Behavior

On day 21 of each period, feeding behavior including time spent eating, ruminating, drinking, lying and standing (Yang et al. 2000) was recorded for each animal starting at 0800 h. This behavior was recorded at 5 min intervals over a 24 h period. The observation methods were adapted from earlier studies (Yang et al. 2001; Maekawa et al. 2002a, 2002b) assuming that each behavioral activity lasts for the entire five minute period. Total time spent eating and ruminating were taken together to calculate the total time spent chewing and results were reported as time in minutes.

4.2.4. Rumen Fluid Collection

Samples of rumen contents were collected every 2 h for 24 h on day 24 of each period starting at 0800h before feeding for determination of ruminal osmolality, volatile fatty acid (VFA) and ammonia-nitrogen (NH_3-N) concentration, and for recording rumen pH. Ruminal contents were collected via the rumen cannula from 4 different regions (rumen mat, reticulum, dorsal sac, and ventral sac). The collected ruminal contents were combined and then strained through 4 layers of cheesecloth. Rumen pH (spot sample) was measured in duplicate immediately after straining using a portable pH meter Model 265A (Orion Research Inc., Beverly, MA). A 5-ml sub-sample of strained ruminal fluid was mixed with 1 ml of 25% (wt/vol) meta-phosphoric acid (HPO_3) for determination of VFA concentration. Another 5-ml sub-sample was mixed with 1 ml of 1% (vol/vol) H_2SO_4 for determination of NH_3-N. A 5-ml sub-sample not acidified was collected for determination of osmolality. All samples were stored at -20°C until analyzed.

4.2.5. In-dwelling continuous pH measurements

From day 26 to 28 of each period, in-dwelling pH measurements were taken using the in-dwelling continuous pH System (Dascor, Escondido, CA) as described by Penner et al. (2006). Briefly, the data logger and pH electrode was attached to weights and placed within the ventral sac of rumen. This system continuously measures pH at 30 second intervals over a 23 h period. Probes were taken out daily from the rumen between 0700 and 0800 h, cleaned, standardized (pH 4 and 7) and the recorded data downloaded daily for further analysis. Rumen pH data was obtained from indwelling pH probes over the 23 h period for all three days and was averaged for each minute to

obtain the minimum pH, mean pH and maximum pH. The pH data collected was divided into three categories of acidosis: mild (pH 5.8-5.5); moderate (pH 5.5-5.2) and acute (pH <5.2) (Penner et al. 2007). These pH profiles provided basis to determine the state of ruminal acidosis of each animal. Additionally, total time (min/d) and total area (pH × min) for each pH range was calculated.

4.2.6. Chemical Analysis

Individual feed ingredient and bunk samples of total mixed ration were collected for each period throughout the trial. Forage samples were oven dried at 55 °C for 48 h to determine DM content. All samples were ground using a hammer mill to pass through a 1-mm screen (Christy & Norris Laboratory Mill, Christie- Norris Ltd, Chelmsford, UK). Dry matter content of feed samples was analyzed by drying at 135°C for 2 h (AOAC, 2005; method 930.15). Neutral detergent fiber (NDF) with heat stable α-amylase and sodium sulfite (Van Soest et al. 1991) and Acid detergent fiber (ADF) content of the feed samples were analyzed with an Ankom 200 fibre analyzer ™ (Ankom Technology, NY) (AOAC, 2005; method 973.18). Acid detergent lignin (ADF method 973.18 followed by 72% H_2SO_4 treatment) and ether extract were determined (AOAC, 2005; method 920.39). Crude protein was analyzed using 2400 Kjeltec auto-analyzer unit (FOSS Analytical, Hillerød, Denmark) (AOAC, 2005; method 984.13). Calcium (AOAC, 2005; method 927.02) and Phosphorus (using molybdovanadate reagent; AOAC, 2005; method 965.17) were analyzed after ashing for 5 h at 500°C using Atomic Absorption Spectrophotometer (Model 2380, Perkin-Elmer, Rexdale, Ontario, Canada) and UV visible spectrophotometer (Pharmacia LKB-Ultrospec III

spectrophotometer, Cambridge, England) respectively. All measurements were performed in duplicate.

4.2.7. Volatile Fatty Acid Analysis

For VFA analysis, acidified rumen fluid samples were first thawed and then centrifuged at 5000×g for 15 min at 4°C using a Beckman Centrifuge (Model J6-MC; Palo Alto, CA). One ml of supernatant was then pipetted into microcentrifuge tubes. To this 450 µL of acetonitrile (99.9% v/v) and 50 µL of internal standard (97.91 mM Trimethylacetic in methanol) were added and further centrifuged at 13.3×g for 10 min at 4°C using a microcentrifuge (Model 17 R-MC ; Palo Alto, CA). The supernatant was subsequently transferred into GC vials for analysis. In each sample, acetate, propionate, isobutyrate, butyrate, isovalerate, valerate were analyzed by injecting into an Agilent 6890 Series GC system (Wilmington, DE). Ten µL of sample was injected in an Agilent Technologies high performance GC Capillary Column (30.0 m × 320 µm × 0.25 µm, Wilmington, DE) using an Agilent 7683 Series injector (Wilmington, DE). Injector and flame ionization detector temperature was held constant at 250°C. A calibration curve was prepared from internal and external standards to calculate the molar proportion of each VFA. Standards used to prepare a standard curve were purchased from Nu-Chek Prep, Inc. (Elysian, MN). Total VFA concentration was calculated by adding the concentrations of all individual acids (Ghorbani et al. 2002; Beauchemin et al. 2003).

4.2.8. Rumen Ammonia Concentration

The ammonia concentration of rumen fluid was analyzed using phenol-hypochlorite method (Broderick and Kang 1980). Briefly, frozen acidified rumen fluid samples were thawed and centrifuged at 18000×g for 10 min at 4°C using a microcentrifuge (Model 17 R-MC; Palo Alto, CA). Fifty µL of supernatant was then diluted with 2.5 mL of phenol reagent and 2.0 mL of hypochlorite reagent and mixed together. The samples were then placed in 95°C water bath for 5 min. After cooling, each sample was analyzed in duplicate along with standards and blanks. The coefficient of determination for calibration curves for these analytes approached 0.98. Ammonia concentration was analyzed at 630 nm using a SpectraMax Plus Spectrophotometer (Molecular Devices, CA, USA).

4.2.9. Rumen Fluid Osmolality

Rumen fluid osmolality was analyzed by using a Vapro™ Vapor Pressure Osmometer (Model 5520; Wescor Inc., Logan, Utah). For analyzing osmolality, first the osmometer was calibrated using the standards 290, 1000 and 100 mOsm/L. Frozen non-acidified rumen fluid samples were thawed and then centrifuged at 1000×g for 15 min using a Beckman Centrifuge (Model TJ-6; Palo Alto, CA). Analysis of each sample was done in duplicate and if the second reading was not ± 3 mOsm/L of the first reading, further readings were taken until two consecutive readings with ± 3 mOsm/L were obtained.

4.2.10. Statistical Analysis

The Proc Mixed Procedure of the Statistical Analysis System 9.1 (SAS Institute, Inc. 2003) was used to carry out the analysis of variance for all rumen fermentation parameters (pH, VFA, Ammonia and osmolality concentration) and feeding behavior. The model includes repeated measures with heifer as a random effect and treatment as fixed effect. Statistical significance was assumed with $P< 0.05$ and trends were discussed with $0.05 < P < 0.10$. The Kenward Roger adjustment was used on denominator degrees of freedom. Polynomial orthogonal contrasts were used to test the linear, quadratic, cubic and quartic effects of CDC SO-I oat inclusion level on rumen fermentation parameters and feeding behavior.

4.3. RESULTS AND DISCUSSION

4.3.1. Diets

All the diets used for this trial were formulated to meet a minimum protein level of 11.5% which meets NRC (1996) requirements for the cattle used in this study. Due to differences in chemical composition of the oat and barley grain, different pelleted supplements were formulated for each treatment diet (Table 4.1). The crude protein level of CDC SO-I oat used was higher (13.8) than barley grain (12.9) (Table 4.2). Therefore in order to maintain a minimum CP level of 11.5% in the barley-based diets, urea was included in the supplement. DMI tended ($P= 0.10$) to be lower with higher inclusion levels of CDC SO-I oat, a finding that mirrored the results of the feedlot trial. Reduced DMI might be the consequence of combined effects of high fat level, high hull content and higher degradation rate of oat starch as revealed by numerically lower pH

and longer time spent below cut-off pH points in diets with higher levels of CDC SO-I oat.

Table. 4.2. Chemical composition of CDC SO-I Oat and barley grain (% DM basis) used in metabolic trial

Chemical Composition	CDC SO-I Oat Grain	Barley Grain
	Mean ± SD[z]	Mean ± SD[z]
DM%	91.9 ± 0.65	90.3 ± 0.59
CP%	13.8 ± 0.32	12.9 ± 0.28
ADF%	11.7 ± 1.90	6.0 ± 1.2
NDF%	28.9 ± 2.06	20.0 ± 2.16
EE%	6.7 ± 0.45	2.7 ± 0.39
ADL%	1.7 ± 0.17	1.9 ± 0.22

[z]SD= Standard Deviation

4.3.2. Rumen Fermentation parameters

4.3.2.1. Rumen pH

Rumen pH measurements using two different sampling methods (in-dwelling pH probe and spot sampling) are given in Table 4.3. There was minimal effect of CDC SO-I oat inclusion level on mean rumen pH with either method of analysis. Figure 4.1 provides the diurnal fluctuation in rumen pH for all the treatment diets. As expected rumen pH declined shortly after feeding and then gradually recovered, typical for grain fed cattle (Keunen et al. 2002; Rustomo et al. 2006). Although not statistically different, rumen pH decline was steeper and to a greater extent on the 100% oat diet (Figure 4.1). Mean rumen pH over a 24 h period for the barley-based diet using in-dwelling pH probe was 5.9. Cattle fed the barley-based diet spent a total of 73, 40 and

14 min below pH cutoff values of 5.8, 5.5 and 5.2, respectively. These cut-off values represent pH values associated with mild, moderate and severe acidosis, respectively (Krause et al. 2002; Penner et al. 2007). Cattle fed 100 % CDC SO-I oat had a mean pH of 5.5 and spent numerically a longer time i.e. 190, 113, 70 min, below pH cutoff values of 5.8, 5.5 and 5.2, respectively, although there was no statistical effect (P> 0.05) of oat inclusion level on these parameters (Table 4.3).

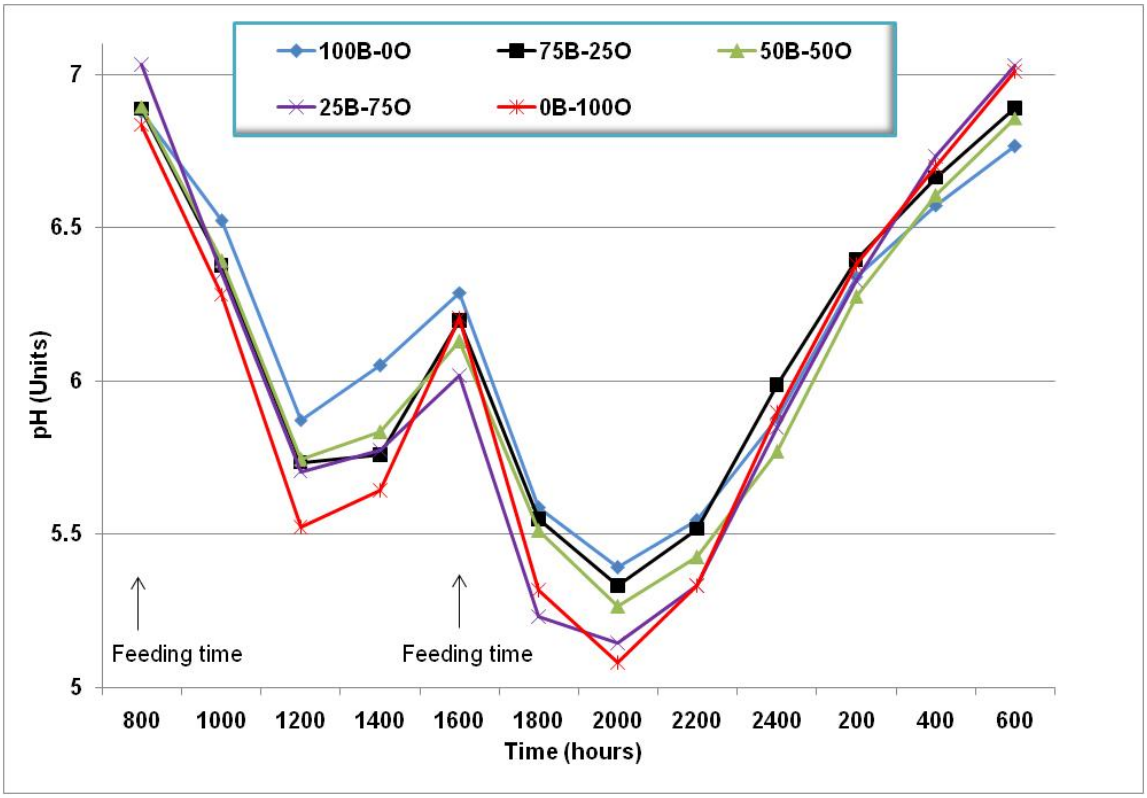

Figure 4.1. Effects of increasing inclusion levels of CDC SO-I oat on rumen pH as measured with continuous in-dwelling pH monitors.

Table 4.3. Rumen pH measurements of heifers fed increasing inclusion levels of CDC SO-I oat.

	Barley grain : CDC SO-I oat							P-Value Contrasts[z]		
	100-0	75-25	50-50	25-75	0-100	SEM[y]	P_{trt}	Linear	Quadratic	Cubic
Mean Daily Rumen pH										
In-Dwelling pH	5.9	6.1	5.9	6.0	5.5	0.16	0.30	0.97	0.55	0.21
Spot Sample pH	6.1	6.1	6.1	6.1	6.0	0.12	0.83	0.26	0.87	0.99
Rumen pH Parameter 5.8 or lower										
Mean pH	5.5	5.5	5.5	5.5	5.3	0.08	0.40	0.79	0.75	0.70
Total time (min)	127.5	134.9	117.9	165.0	373.4	98.29	0.24	0.81	0.82	0.82
Time between 5.8 & 5.5 (min)	73.0	95.1	65.0	110.0	189.8	64.77	0.56	0.76	0.84	0.62
Total pH area (pH×min)	38.5	71.3	46.8	97.4	270.0	113.90	0.78	0.83	0.95	0.84
pH area between 5.8 & 5.5 (pH×min)	19.3	59.9	35. 5	86.3	183.7	55.60	0.27	0.50	0.92	0.56
Rumen pH Parameter 5.5 or lower										
Mean pH	5.2	5.4	5.3	5.3	5.2	0.08	0.37	0.30	0.28	0.48
Time between 5.5 & 5.2(min)	40.4	30.3	29.9	37.5	113.2	24.55	0.11	0.93	0.71	0.99
pH area between 5.5 & 5.2 (pH×min)	23.2	4.5	19.3	2.9	67.1	16.30	0.17	0.35	0.92	0.37
Rumen pH Parameter 5.2 or lower										
Mean Ph	4.9	5.1	5.0	5.1	4.9	0.13	0.47	0.36	0.66	0.57
Time below 5.2(min)	14.1	9.5	24.1	17.5	70.4	16.04	0.20	0.69	0.94	0.53
pH area below 5.2 (pH×min)	1.7	0.9	5.0	1.9	19.0	4.60	0.26	0.81	0.79	0.55

[z] Orthogonal polynomial contrasts: Linear, quadratic and cubic effects of CDC SO-I oat inclusion levels
[y] Pooled standard error of mean.

Recent studies (Cerrato et al. 2007; Rustomo et al. 2006; Wales et al. 2004) reported that rumen microbial fermentation is not only affected by the low pH value at a single point of time, but also depends on the amount of time for which the pH is suboptimal and the degree of fluctuation in the pH values. Minimal duration of a low rumen pH does not affect fermentation to a large extent (Calsamiglia et al. 2002). Wales et al. (2004) reported that rapid fluctuation in rumen pH (5.1-6.0) is more detrimental to rumen microbes than slightly lower but constant pH (5.6) over a longer period of time. In the latter case, rumen microbes adapt to a suboptimal but constant pH; whereas, they are unable to tolerate rapid fluctuations in pH (Wales et al. 2004). Several workers have proposed that the area below a threshold pH (as a function of time) is more appropriate to measure the extent of ruminal acidosis than just pH alone (Beauchemin et al. 2003; Cerrato-Sánchez et al. 2008). In the present study, there was no difference ($P > 0.05$) in the mean pH area (pH×min) below cut-off pH values of 5.8, 5.5 and 5.2 for the cattle fed 100% barley-based diet versus those fed the 100% oat diet.

The lack of effect of fat addition from the CDC SO-I oat on rumen pH is not surprising. Several earlier studies reported that fat supplementation (4 to 6% tallow or yellow grease) with high grain finishing rations has minimal or a slight depressing effect on rumen pH (Krehbiel et al. 1995; Plascencia et al. 1999; Montgomery et al. 2008). Atkinson et al. (2006) and Kucuk et al. (2004) reported that supplementation with safflower oil or soybean oil (0 to 9% of DM) had no influence on rumen pH. Similarly, Zinn (1989b) and Elliott et al. (1996) found no effect of a variety of supplemental fat sources at inclusion rates up to 8% of DM on rumen pH. In the present study the fat level in the diets varied from 2.6% in the 100% barley-based diet

to 6.7% in the 100% oat-based diets. The results of the present study show that inclusion of high fat oat does not affect ruminal pH and is in agreement with these earlier studies.

4.3.2.2. Ruminal VFA, Ammonia and Osmolality

Diurnal fluctuation in the total ruminal VFA concentration is shown in Figure 4.2. For all the treatment diets, total VFA increases shortly after feeding and then declines with time to pre-feeding levels. This diurnal pattern is common in high grain diets and is reflected in diurnal changes in rumen pH (Ikuta et al. 2003). No significant effect of CDC SO-I oat inclusion rate was noted on total VFA level or on the molar proportion of individual fatty acids other than minor effects on isobutyrate (Table 4.4). Khan et al. (2008) reported no significant differences in total VFA concentration and levels of individual fatty acids (acetate, propionate, butyrate and β-hydroxy butyrate) in calves fed oat vs. barley-based diets.

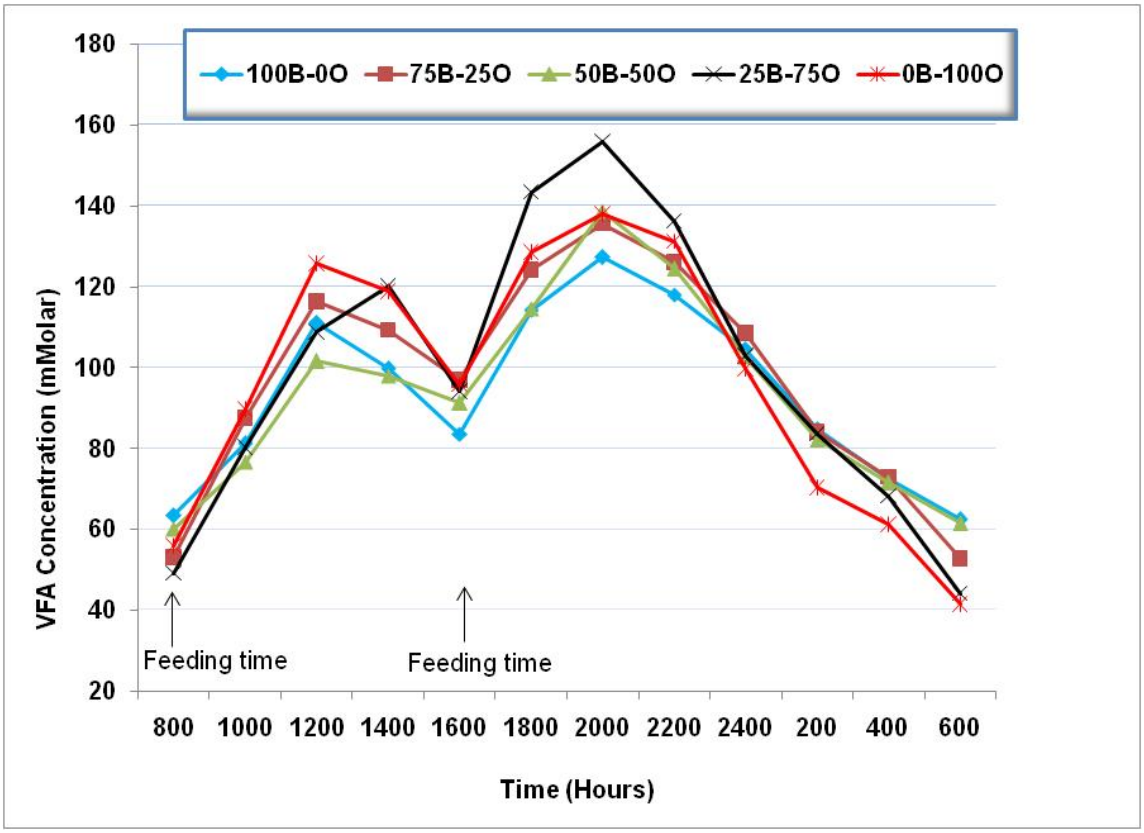

Figure. 4.2. Effects of increasing inclusion levels of CDC SO-I oat on rumen total VFA concentrations.

Table. 4.4. Effects of increasing inclusion levels of CDC SO-I oat on rumen fluid parameters of heifers.

	Barley grain : CDC SO-I oat							P-Value Contrasts[z]			
	100-0	75-25	50-50	25-75	0-100	SEM[y]	P_{Trt}	Linear	Quadratic	Cubic	Quartic
Total VFA(mM/L)	93.6	97.3	93.3	98.9	101.5	5.94	0.75	0.29	0.70	0.78	0.49
Acetate %	51. 6	53.0	54.3	49.7	50.9	3.06	0.83	0.63	0.57	0.53	0.49
Propionate%	31.9	34.9	31.5	37.6	35.9	4.17	0.62	0.31	1.00	0.88	0.24
A:P ratio	1.8	1.8	2.2	1.4	1.5	0.42	0.66	0.44	0.60	0.68	0.26
Isobutyrate %	0.9	0.8	0.8	0.6	0.6	0.14	0.35	0.05	0.78	0.78	0.71
Butyrate %	11.0	7.9	8.7	8.3	8.8	1.68	0.71	0.46	0.34	0.58	0.61
Isovalerate %	2.6	1.5	2.4	1.6	1.9	0.74	0.59	0.50	0.63	0.58	0.20
Valerate %	1.7	1.6	1.8	1.9	1.6	0.43	0.99	0.90	0.82	0.65	0.93
Ammonia (mg/dl)	11.4	7.9	7.0	6.2	5.5	1.71	0.17	0.02	0.39	0.66	0.87
Osmolality (mOsm/L)	283.3	277.1	270.5	288.6	288.5	12.37	0.75	0.55	0.40	0.62	0.48

[z] Orthogonal polynomial contrasts: Linear, quadratic, cubic and quartic effects of CDC SO-I oat inclusion levels

[y] Pooled standard error of mean

Significant effect of time ($P < 0.01$) for all parameters measured

Findings from the present study mirror those of Elliott et al. (1996) who fed a variety of fat sources to supply 5% fatty acids to the diet of dairy cows. Variable effects of fat supplementation on the ruminal VFA molar proportions were observed in several previous studies. Atkinson et al. (2006) reported no effect of increased supplementation of safflower oil (0 to 9% of DM) on total ruminal VFA concentration while Boggs et al. (1987) reported decreased total VFA concentration at 7.5% tallow. It is interesting to mention that oat addition did not decrease total VFA production. Such a result would be expected if a toxic effect of long chain fatty acid release on rumen bacteria was occurring due to the level of oil in the oat and its fatty acid composition. Hristov et al. (2005b) compared the linoleic acid or oleic acid-rich safflower oil (5% of dietary DM) and reported no effect of type of oil on ruminal pH, total and individual VFA concentrations, A:P ratio and ammonia concentration.

The results of this study however contrast with earlier studies who reported decreased ruminal molar concentrations of acetate, increased concentration of propionate and decreased acetate to propionate ratio with increased dietary supplementation of safflower oil (0 to 9% of DM) (Atkinson et al. 2006) or tallow/blended animal-vegetable fat (7.5%) (Boggs et al. 1987; Zinn 1989b). On the other hand Kucuk et al. (2004) reported no effect of increased dietary soybean oil (0-9.4%) on the molar concentrations of acetate, propionate or acetate to propionate ratio. Supplementation of fat in the diet increases the molar proportion of propionate subsequent to increased availability of glycerol from ruminal lipolysis (Chalupa et al. 1986). In the rumen, glycerol rapidly converts to propionate. The lack of an effect of treatment on the molar proportion of propionate might be the result of incomplete

hydrolysis of long chain fatty acids present in CDC SO-I oat.

The molar proportions of total VFA in the present study with 100% barley and 100% oat-based diet were lower (93.6 and 101.5 mM L^{-1}, respectively) than reported earlier (132.23 and 120.21 mM L^{-1}, respectively) by Franks et al. (1972) at similar level of grain inclusion. However, the later group reported no difference in the levels of total VFA between barley and oat-based diets, a finding similar to our observation. Walsh et al. (2009) with a diet containing 90% barley grain reported total VFA as 180 mM L^{-1}. Franks et al. (1972) reported lower molar proportions of propionic acid (33.2%) and higher butyric acid (17.2%) in a barley-based diet compared to an oat-based diet (40.1% and 10.9% respectively), a finding contradictory to our observations (Table 4.4). However, the molar proportions of other individual volatile fatty acids were comparable to the present study.

The only significant effect observed during this study with higher inclusion of CDC SO-I oat was a linear decrease (P= 0.05) in molar proportions of isobutyrate which is consistent with the findings of Atkinson et al. (2006). There was no effect observed on the proportions of butyrate, isovalerate or valerate.

CDC SO-I oat inclusion level had no effect on rumen osmolality. This is consistent with the findings that total VFA concentrations were not affected by treatment. The concentration of ruminal ammonia decreased (P= 0.02) with the increasing inclusion level of CDC SO-I oat. This despite the fact that dietary CP levels tended to increase with CDC SO-I oat inclusion levels (Table 4.1). Increased ruminal NH_3 concentrations with the barley-based diets are likely the result of differences in urea supplementation in the composition of supplement used (Table 4.2). In order to

target CP levels typical of finishing diets, urea was added to the barley-based diets. Inclusion levels of urea in the supplement ranged from 5.39% in the supplement of the 100% barley-based control ration to 0% in the 100% CDC SO-I oat ration supplement. Boucher et al. (2007) also noted that increasing amounts of urea (0-0.9% in total mixed ration) increased rumen ammonia concentrations quadratically.

It may also be possible that ruminal NH_3 concentration in this study reflect the high dietary fat level associated with CDC SO-I oat. Ikwuegbu and Sutton (1982) reported that supplemental fat (0-40 ml linseed oil/d) decreases ruminal NH_3 concentration. Atkinson et al. (2006) and Montgomery et al. (2008) reported no effect of increased fat supplementation (0-9%) on ruminal NH_3 concentration. Aldrich et al. (1993) noted that with highly degradable starch sources, ruminal NH_3 concentration tends to decrease.

The fact that rumen pH, total VFA concentration and A:P ratio were not influenced by CDC SO-I oat supplementation would indicate that the rate and extent of rumen fermentation of starch and other nutrients did not differ between the barley and oat diets. The literature is somewhat conflicting in this area. Herrera-Saldana et al. (1988) in one study found that oat starch was degraded at a slower rate than that of barley while in another study (Herrera-Saldana et al. 1990) reported oat starch was degraded faster than wheat, barley and corn. Other workers have also reported numerically higher DM degradation rates in barley (11.6, 40.1 and 26.5% per hour) than that of oat (10.0, 21.9 and 11.3% per hour) (Sauvant et al. 1985; Prestløkken 1999; Fuhr 2006). In a recent study by Yu and Niu (2009) the starch and protein degradation rate of CDC SO-I oat was reported similar to other varieties of oat (CDC Dancer and Derby)

suggesting highly degradable starch in oat.

The relative low mean daily rumen pH of the oat-fed cattle (5.5) indicates an acidic rumen and that as with feeding barley-based diet, proper feeding management and bunk management procedures are necessary to minimize problems with acidosis and other digestive disorders.

4.3.3. Feeding Behavior and feed intake

Heifers spent more time eating ($P< 0.01$) total mixed ration (TMR) containing higher inclusion levels of CDC SO-I oat compared to diets with higher levels of barley. Quartic effect ($P< 0.05$) were observed on chewing and drinking behavior with higher inclusion levels of CDC SO-I oat. No effect of treatment was noted on time spent ruminating, lying, and other activities such as standing, licking, rubbing (Table 4.5). More time spent eating with higher inclusion levels of CDC SO-I oat in the present study was likely the result of sorting of feed against hulls in favor of groat.

Beauchemin and Buchanan-Smith (1989) reported increased time spent in eating, ruminating and chewing with increased proportion of NDF (26% to 34%) in the diet. Some earlier research indicated that chewing time (eating and ruminating) increased with increased NDF content of the diet (Oba and Allen 2000) and stimulated saliva production and rumen buffering capacity (Yang et al. 2001; Yang and Beauchemin 2006). However in this study, the effect of increased NDF content of the diet with increasing levels of CDC SO-I oat failed to enhance rumen buffering capacity supported by relative low mean daily rumen pH of the oat-fed cattle (5.5) and the amount of time spent below each of the critical pH cut-off points (5.8, 5.5, 5.2).

Table. 4.5. Effects of increasing inclusion levels of CDC SO-I oat on dry matter intake and feeding behavior of heifers fed high concentrate diets.

	Barley grain : CDC SO-I oat							P-Value Contrasts[z]			
	100-0	75-25	50-50	25-75	0-100	SEM[y]	P Trt	Linear	Quadratic	Cubic	Quartic
DMI (Kg)	11.4	11.5	11.4	10.9	10.5	0.63	0.42	0.10	0.34	0.78	0.92
Time (min/day)											
Eating	68	84	132	89	108	8.3	<0.01	<0.01	<0.01	0.15	<0.01
Ruminating	314	288	327	269	292	23.6	0.47	0.41	0.99	0.83	0.10
Chewing[x]	382	372	459	358	400	26.7	0.12	0.80	0.41	0.59	0.014
Drinking	21	31	16	37	21	3.6	<0.01	0.61	0.25	0.31	<0.01
Lying	243	237	227	231	216	23.4	0.94	0.45	0.98	0.82	0.80
Other[w]	859	822	804	842	803	36.4	0.76	0.44	0.72	0.40	0.59

[z] Orthogonal polynomial contrasts: Linear, quadratic, cubic and quartic effects of CDC SO-I oat inclusion levels
[y] Pooled standard error of mean.
[x] Chewing = Eating + Ruminating
[w] Other = Standing + Licking + Rubbing

4.4. CONCLUSIONS

The results of this study indicate that CDC SO-I oat is similar to barley in terms of rumen fermentation characteristics, particularly pH, VFA production and composition and osmolality. Both cereal grains produced rumen environment with pH that averaged less than 6.0 over the course of the day, with considerable time spent below critical pH cut-off points that are indicative of SARA. This indicates that as with barley, it is necessary with CDC SO-I oat to ensure proper feeding and bunk management protocols to minimize acidosis related concerns and reduced performance associated with digestive disturbances.

5. GENERAL DISCUSSION AND CONCLUSIONS

Biofuel production poses a challenge to the use of major cereal grains in animal rations, affecting the relative demand of cereals and especially corn and wheat. With the increasing price of wheat, barley and corn, oat grain (*Avena sativa*) has potential as an attractive option to other cereals in feedlot rations. However, oats are considered inferior to barley and corn in terms of energy value due to the higher hull and lignin content of oat grain (Crosbie et al. 1985). The feed oat market is typically small compared to barley and corn in western Canada. Although the protein content of oat is highest of all grains, its high fiber content reduces its nutritive value and thus its price. Traditional oat used in feedlots increases the days on feed for the animals to reach the target weight and thus cost of feeding increases. The new variety of oat, CDC SO-I oat has low levels of lignin in its hull and high oil in the groat, increasing its energy content. Its energy content is reported to be equal to that of barley for backgrounding cattle (Zalinko et al. 2009). Superior performance of barley-fed cattle versus oat-fed cattle has been reported by other workers (Huuskonen 2009).

The productive efficiency of cattle can be increased by increasing the energy density of diet or by fat addition, a common method to increase the energy density (Hess et al. 2008). Daily gain, and/or feed efficiency of animals have been shown to improve by addition of tallow or blended tallow-vegetable oil mixtures to finishing diets (Zinn 1989a; Ramirez and Zinn 2000; Huffman et al. 1992). Due to the improved nature of CDC SO-I oat (i.e. low lignin hull; high oil groat), animals fed CDC SO-I oat were expected to have the same performance as barley-fed cattle.

In the feedlot trial, significantly lower feed intake was observed with the increasing inclusion levels of CDC SO-I oat. As a result of reduced feed intake, the performance of animals in terms of average daily gain and days on feed was also negatively affected. While the high oil content of CDC SO-I oat was believed to increase the energy density of oat, the increased fat content of the CDC SO-I oat was clearly unable to compensate for reduced DMI in this study.

The reduced performance with oat supplementation might have been due to poor digestion of the added fat or reduced digestibility of basal diet due to added fat (Jenkins 1990; 1994). The high fat content negatively affects the rumen fermentation by interfering with fiber digestion resulting in lower DM and fiber digestibility (Boggs et al. 1987; Zinn 1989b; Allen 2000). High fat ruminant diets reduce the digestibility of non-lipid energy sources by interrupting ruminal fermentation and protein metabolism in the rumen. The detrimental effects of added fat on ruminal fiber digestion may be due to antimicrobial effects of fatty acids (Jenkins 1994). Faichney et al. (2002) compared the effect of polyunsaturated free lipid in a total lipid content of 7% of the dry matter. They concluded that the anaerobic fungi in rumen disappeared if polyunsaturated free lipid was >6% of total lipid and resulted in reduced fibre digestion. The anaerobic fungi play an important role in hydrolyzing ester linkages between lignin, hemicellulose and cellulose, and help in breaking down of digesta particles in the rumen and for effective fiber digestion.

CDC SO-I oat had high oleic acid and lower linoleic acid compared to barley (43.7 vs. 14.8% and 37.0 vs. 55.9% respectively). The percentage of total unsaturated fatty acids (mono and polyunsaturated) in oat and barley grain was 82.9 and 78.2%

respectively. Diets containing 100% oat had a total fat content of 6% vs. 2.6% for the 100% barley-based diet, thus higher consumption of unsaturated fatty acid is associated with higher inclusion levels of CDC SO-I oat. The reduction in DMI observed in the present study might be the effect of higher consumption of unsaturated fatty acids. There should thus be a metabolic effect or a shift in population. Unsaturated fatty acids negatively affect the digestibility and intake by decreasing the concentration of protozoa and having toxic effects on Gram negative bacteria (Angelidaki and Ahring 1992; Oldick and Firkins 2000). This would be particularly true for diets with 50% and greater oat content.

The negative effects of high dietary fat levels on the intake and subsequent performance of the 100% oat-fed steers is not the only possible explanation for the linear decrease in feed intake. An alternative explanation for the decline in DMI associated with increasing levels of CDC SO-I oat may be related to the higher proportion of hull. Oat hulls contain hydroxycinnamic acids, mainly ferulic acid inhibitory to the biodegradability of plant cell wall polysaccharides (Borneman et al. 1986; 1990). Hull, a major portion of oat grain, contains higher indigestible NDF. NDF content of the feed has been negatively associated with the feed intake through its rumen fill effect (Van Soest 1994). It is suggested that with higher proportions of oat, increased fat content decreases NDF digestibility (Huuskonen 2009).

The passage rate of digesta through the gastrointestinal tract determines the rate at which nutrient will be digested and absorbed in ruminants in addition to other factors such as rate of fermentation of feed and DMI. Feed energy of diet is affected by the passage rate or rumen outflow rate because of their lower intestinal digestibility. With

the high fiber in the diet, passage rate of ruminal digesta increases and consequentaly digestibility decreases with the increased passage rate (Van Soest 1994). The combination of these factors could explain the linear drop in DMI as dietary inclusion level of the oat increased.

Another possible reason for the reduced performance of steers fed higher levels of CDC SO-I oat was thought to be subacute ruminal acidosis (SARA) associated with higher degradation rate of oat starch as earlier studies reported higher ruminal starch degradation rate for oat compared to barley starch (Huntington 1997). With the replacement of barley with CDC SO-I oat, rumen fermentation characteristics in terms of rumen pH, VFA levels and rumen osmolality remains unchanged. The similar ruminal environment with barley and CDC SO-I oat indicates similar rate and extent of degradation of oat and barley starch. Both cereal grains produced rumen environment with average pH less than 6.0 and considerable time spent below pH cut-off points over the course of the day, indicative of sub acute ruminal acidosis.

In conclusion, replacement of barley with CDC SO-I oat resulted in reduced performance and carcass characteristics of finishing steers as a consequence of reduced DM and energy intake. This was particularly true for cattle fed diets with higher inclusion levels of oat. This reduced DMI was likely the result of relative high unsaturated fatty acids and/or high hull content of the CDC SO-I oat. The results of this study would point out that CDC SO-I oat can be successfully included in the finishing rations to a maximum level of 25% without adversely affecting the performance of finishing cattle. No negative effects of higher oat inclusion levels relative to barley were observed on rumen fermentation parameters. However, as with barley-based diets

there is a need for proper feeding and bunk management protocols to minimize digestive disturbances such as sub-acute acidosis. Further research is required to understand the reason for the negative effect of CDC-SO-I oat supplementation on DM intake when fed at high inclusion levels. The effects of type of fatty acids and hull content need to be separately investigated in future studies.

Animal nutritionists and plant breeders should work together for developing new and improved varieties required for livestock industry. Emphasis should be given for the development of new cultivars with desirable qualities of oat for livestock such as low and/or easily digestible hull content and with desirable proportions of saturated and unsaturated fatty acid proportions.

6. REFERENCES

Abercrombie, K. 1982. "Intensive livestock feeding: Reckless folly or an emergency food reserve?" Ceres. **15:** 38-41

Agriculture and Agri-food Canada 2006. Oats: Situation And Outlook, Bi-weekly Bulletin October 23, 2006 Volume 19 Number 14. [Online] Available: http://dsp-psd.pwgsc.gc.ca/Collection/A27-18-19-14E.pdf [2009 July 25]

Agriculture and Agri-Food Canada 2007. An overview of the Canadian agriculture and agri-food system. Page 56-57. [Online] Available: http://www4.agr.gc.ca/resources/prod/doc/pol/pub/sys/pdf/sys_2007_e.pdf [2009 July 25]

Aldrich, J. M., Muller, L. D., Varga, G. A. and Griel Jr, L. C. 1993. Nonstructural carbohydrate and protein effects on rumen fermentation, nutrient flow, and performance of dairy cows. J. Dairy Sci.**76:** 1091–1105

Allen, M. S. 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. J. Dairy Sci. **83:** 1598-1624

Allen, M.S. 1997. Relationship between fermentation acid production in the rumen and the requirement for physically effective fiber. J. Dairy Sci. **80:** 1447-1462

Alzahal, O., Rustomo, B., Odongo, N. E., Duffield, T. F. and McBride, B.W. 2007. Technical note: a system for continuous recording of ruminal pH in cattle. J. Anim. Sci. **85:** 213–217

Ames, D. R., Brink, D. R. and Williams, C. L. 1994. Adjusting protein in feedlot diets during thermal stress. J. Anim. Sci. **44:** 136-140

Angelidaki, I. and Ahring, B. K. 1992. Effects of free long-chain fatty acids on thermophilic anaerobic digestion. Appl. Microbiol. Biotech. **37:** 808-812

AOAC. 2005. Official Methods of Analysis. 18th ed. Assoc. off. anal. chem., Arlington, VA.

Atkinson, R. L., Scholljegerdes, E. J., Lake, S. L., Nayigihugu, V., Hess, B. W. and Rule, D. C. 2006. Site and extent of digestion, duodenal flow, and intestinal

disappearance of total and esterified fatty acids in sheep fed a high-concentrate diet supplemented with high-linoleate safflower oil. J. Anim. Sci. **84:** 387-396

Baker, N. R. 1995. International trade in oats. Pages 62-87 in R. W. Welch, ed. The oat crop: production and utilization. Chapman and Hall, New York, NY, USA.

Banas, A., Debski, H., Banas, W., Heneen, W. K., Dahlqvist, A., Bafor, M., Gummeson, P., Marttila, S., Ekman, A., Carlsson, A. S. and Stymne, S. 2007. Lipids in grain tissues of oat (*Avena sativa*): differences in content, time of deposition, and fatty acid composition. J. Exp. Bot. **58:** 2463-2470

Beauchemin, K. A. and Buchanan-Smith, J. G. 1989. Effects of dietary neutral detergent fiber concentration and supplementary long hay on chewing activities and milk production of dairy cows. J. Dairy Sci. **72:** 2288-2300

Beauchemin, K. A., McAllister, T. A., Dong, Y. B., Fair, I. and Cheng, K. J. 1994. Effects of mastication on digestion of whole cereal grains by cattle. J. Anim. Sci. **72:** 236-246

Beauchemin, K. A., Yang, W. Z. and Rode, L. M. 2001. Effects of barley grain processing on the site and extent of digestion of beef feedlot finishing diets. J. Anim. Sci. **79:** 1925-1936

Beauchemin, K. A., Yang, W. Z., Morgavi, D. P., Ghorbani, G. R., Kautz, W. and Leedle, J. A. Z. 2003. Effects of bacterial direct fed microbials and yeast on site and extent of digestion, blood chemistry, and subclinical ruminal acidosis in feedlot cattle. J. Anim. Sci. **81:** 1628–1640

Benson, J. A., Reynolds, C. K., Humphries, D. J., Rutter, S. M. and Beever, D. E. 2001. Effects of abomasal infusion of long-chain fatty acids on intake, feeding behavior and milk production in dairy cows. J. Dairy Sci. **84:** 1182-1191

Bergman, E. N. 1990. Energy contributions of volatile fatty acids from the gastrointestinal tract in various species. Physiol Rev. **70:** 567-90

Bevans, D. W., Beauchemin, K. A., Shwartzkopf-Genswein, K. S., McKinnon, J. J. and McAllister, T. A. 2005. Effect of rapid or gradual grain adaptation on subacute acidosis and feed intake by feedlot cattle. J. Anim. Sci. **83:** 1116–1132

Biel, W., Bobko, K. and Maciorowski, R. 2009. Chemical composition and nutritive value of husked and naked oats grain J. Cereal Sci. **49:** 413-418

Bird, S., McDonagh, M. B., Dicker, R. W., Robinson, D. L. and Oddy, V. H. 1998. The effect of finishing rations based on dry rolled oat or barley grain and previous nutritional history on growth, live animal and carcass characteristics and meat quality attributes of lot-fed cattle. [Online] Available: http://www.beef.crc.org.au/nutrition [2009 Apr 20th]

Black, C. A. 1993. Soil fertility evaluation and control, page 537. CRC Press, LLC, USA

Block, H. C., McKinnon, J. J., Mustafa, A. F. and Christensen, D. A. 2001. Manipulation of cattle growth to target carcass quality. J. Anim. Sci. **79**: 133-140

Boggs, D. L., Bergen, W. G. and Hawkins, D. R. 1987. Effects of tallow supplementation and protein withdrawal on ruminal fermentation, microbial synthesis and site of digestion. J. Anim Sci. **64:** 907-914

Borneman, W. S., Akin, D. E. and Van Eseltine. W. P. 1986. Effect of phenolic monomers on ruminant bacteria. Appl. Environ. Microbiol. **52:** 1331-1339

Borneman, W. S., Hartley, R. D., Morrison, W. H., Akin, D. E. and Ljungdahl, L. G. 1990. Feruloyl and *p*-coumaroyl esterases from anaerobic fungi in relation to plant cell wall degradation. Appl. Microbiol. Biotechnol. **33:** 345-351

Boss, D. L. and Bowman, J. G. P. 1996a. Barley varieties for finishing steers: I. Feedlot performance, in vivo diet digestion, and carcass characteristics. J. Anim. Sci. **74:** 1967-1972

Boss, D. L. and Bowman, J. G. P. 1996b. Barley varieties for finishing steers: ii. ruminal characteristics and rate, site, and extent of digestion. J. Anim. Sci. **74**: 1973-1981

Boucher, S. E., Ordway, R. S., Whitehouse, N. L., Lundy, F. P., Kononoff, P. J. and Schwab, C. G. 2007. Effect of incremental urea supplementation of a conventional corn silage-based diet on ruminal ammonia concentration and synthesis of microbial protein. J. Dairy Sci. **90:** 5619-5633

Boyles, S. and Johnson, L. 2006. Beef information, Oats as a feed for beef cattle. Ohio University Extension. [Online] Available: http://beef.osu.edu/library/oats1.html [2009 Apr 20th]

Bradshaw, W. L., Hinman, D. D., Bull, R. C., Everson, D. O. and Sorensen, S. J. 1996. Effects of barley variety and processing methods on feedlot steer performance and carcass characteristics. J. Anim. Sci. **74**: 18-24

Broderick, G. A. and Kang, J. H. 1980. Automated simultaneous determination of ammonia and total amino acids in ruminal fluid and *in vitro* media. J. Dairy Sci. **63:** 64-75

Brown, D., Bouphasiri, C. and Verchomin, S. 2005. A case study of the canadian oat market: The evolution from the central desk system to the open market.Alberta Agriculture, Food and Rural Development. [Online] Available: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agc6751/$FILE/OatsStudyNov2005.pdf [2009 July 29]

Brown, M. S., Krehbiel, C. R., Galyean, M. L., Remmenga, M. D., Peters, J. P., Hibbard, B., Robinson, J. and Moseley, W. M. 2000. Evaluation of models of acute and subacute acidosis on dry matter intake, ruminal fermentation, blood chemistry, and endocrine profiles of beef steers. J. Anim. Sci. **78:** 3155-3168

Calsamiglia, S., Ferret, A. and Devant, M. 2002. Effects of pH and pH fluctuations on microbial fermentation and nutrient flow from a dual-flow continuous culture system. J. Dairy Sci. **85:** 574-579

Campling, R. C. 1991. Processing cereal grains for cattle—A review. Livestock Prod. Sci. **28:** 223-234

Canadian Council on Animal Care. 1993. Guide to the care and use of experimental animals. Vol. 1., 2nd ed. E. D. Olfert, B.M. Cross and A. A. McWilliam, eds. CCAC, Ottawa, ON

Cecava, M. J. 1995. Rumen physiology and energy requirements. Pages 3-24. *in* T. W. Perry and M. J. Cecava, eds. Beef cattle feeding and nutrition, Second Edition. Academic press, Inc.

Cerrato, M., Calsamiglia, S. and Ferret, A. 2007. Effects of time at suboptimal pH on nutrient digestion and rumen microbial fermentation on a dual flow continuous culture system. J. Dairy Sci. **90:** 1486-1492

Cerrato-Sanchez, M., Calsamiglia, S. and Ferret, A. 2008. Effect of the magnitude of the decrease of rumen pH on rumen fermentation in a dual-flow continuous culture system. J. Anim. Sci. **86:** 378-383

Chalupa, W., Vecchiatelli, B., Esler, A., Kronfeld, D. S., Sklan, D. and Palmquist, D. L. 1986. Ruminal fermentaion *in vivo* as influenced by long-chain fatty acids. J. Dairy Sci. **69:** 1293–1301

Chang, V. S. and Holtzapple, M. T. 2000. Fundamental factors affecting biomass enzymatic reactivity, Appl. Biochem. Biotechnol. **84–86:** 5–37

Chatterton, N. J. Watts, K. A. Jensen, K. B., Harrison, P. A. and Horton, W. H. 2006. Nonstructural carbohydrates in oat forage. J. Nutr. International Nutritional Sciences Symposia, **136:** 2111S-2113S

Cheng, K. J., McAllister, T. A., Popp, J. D., Hristov, A. N., Mir, Z. and Shin, H. T. A. 1998. Review of bloat in feedlot cattle. J. Anim. Sci. **76**: 299-308

Choi, B. and Palmquist, D. L. 1996. High fat diets increase plasma cholecystokinin and pancreatic polypeptide, and decrease plasma insulin and feed intake in lactating cows. J. Nutr. **126:** 2913-2919

Cole, N. A. and Todd, R. W. 2008. Opportunities to enhance performance and efficiency through nutrient synchrony in concentrate-fed ruminants. J. Anim Sci. **86:** E318-33

Coleman, S. W., Evans, B. C. and Guenther, J. J. 1993. Body and carcass composition of Angus and Charolais steers as affected by age and nutrition. J. Anim. Sci. **71:** 86-95

Colucci, P. E., Chase, L. E. and Van Soest, P. J. 1982. Feed intake, apparent diet digestibility, and rate of particulate passage in dairy cattle. J. Dairy Sci. **65:** 1445-1456

Crosbie, G. B., Tarr, A.W., Portmann, P, A. and Rowe, J. B. 1985. Variation in hull composition and digestibility among oat genotypes. Crop Sci. **25:** 678- 680

Cuddeford, D. 1995. Oats for animal feed. Pages 321-368 *in* R. W. Welch, ed. The oat crop: Production and utilization. Chapman & Hall, New York, NY, USA.

Dado, R. G. and Allen. M. S. 1993. Continuous computer acquisition of feed and water intakes, chewing, reticular motility, and ruminal pH of cattle. J. Dairy Sci. **76:** 1589-1600

Danfaer, A., Tetens, V. and Agergaard, N. 1995. Review and an experimental study on the physiological and quantitative aspects of gluconeogenesis in lactating ruminants. Comp. Biochem. Physiol. Part B: Biochem. Mol. Biol. **111:** 201-10.

Devlin, T. J., Ingalls, J. R. and Sharma, H. R. 1977. Evaluation of high fat oats in rations of growing and finishing ruminants. Can. J. Anim. Sci. **57:** 735-743

Doehlert, D. C., McMullen, M. S. and Hammond, J. J. 2001. Genotypic and environmental effects on grain yield and quality of oat grown in north dakota. Crop Sci. **41:** 1066-1072

Doreau, M and Chilliard, Y. 1997. Digestion and metabolism of dietary fat in farm animals. Br. J. Nutr. **78:** Suppl. 1, S15-S35

Douglas C. D. and Dennis P. W. 2007. Influence of physical grain characteristics on optimal rotor speed during impact dehulling of oats. Cereal Chemistry. **84:** 294-300

Duffield, T., Plaizier, J. C., Bagg, R., Vessie, G., Dick, P., Wilson, J., Aramini, J. and McBride, B. W. 2004. Comparison of techniques for measurement of rumen pH in lactating dairy cows. J. Dairy Sci. **87:** 59–66

Ekern, A., Havrevoll, Ø., Haug, A., Berg, J., Lindstad, P. and Skeie, S. 2003. Oat and barley based concentrate supplements for dairy cows. Acta Agric. Scand., Sect. A, Animal Sci. **53:** 65-73.

Elliott, J. P., Drackley, J. K. and Weigel, D. J. 1996. Digestibility and effects of hydrogenated palm fatty acid distillate in lactating dairy cows. J. Dairy Sci. **79:** 1031–1039

Evans, J. L., Golden, B. L. and Hough, B. L. 2002. A new genetic prediction for cow maintenance energy requirements. [Online] Available: http://www.beefimprovement.org/proceedings/02proceedings/Evans_02BIF.pdf [2009 Oct 05]

Faichney, G. J., Grodon, G. L. R., Welch, R. J. and Rintoul, A. J. 2002. Effect of dietary free lipid on anaerobic fungi and digestion in the rumen of sheep. Aust J Agric Res. **53:** 519-527

Ferrell, C. L. and Jenkins, T. G. 1985. Energy utilization by Hereford and Simmental males and females. Anim. Prod. **41:** 53-61

Fincher, G. B. and Stone, B. A. 1986. Cell walls and their components in cereal grain technology. pp. 207–295. *In* Pomeranz, Y., ed., Advances in cereal science and technology. Vol. 8. American Association of Cereal Chemists, St Paul, MN, USA

Forsberg, R. A. and Reeves, D. L. 1995. Agronomy of oats. Pages 223-251 *in* R.W. Welch, ed. The oat crop: Production and utilization. Chapman & Hall, New York, NY, USA

Franks, L.G., Newsom, J.R., Renbarger, R.E. and Totusek, R. 1972. Relationship of rumen volatile fatty acids to type of grain, sorghum grain processing method and feedlot performance. J. Anim. Sci. **35:** 404-409

Fraser J. and McCartney D. 2004. Fodder Oats in North America. Pages 19-36 *in* J.M. Suttie and S.G. Reynolds, eds. Fodder oats: a world overview, Food and Agriculture Organization of the United Nations. Plant production and Protection Series No. 33. Rome, Italy

Frey, K. J. and Holland, J. B. 1999. Nine cycles of recurrent selection for increased groat-oil content in oat. Crop Sci. **39:** 1636-1641

Fuhr, L. G., 2006. Low lignin hull, high oil groat oat grain in lactating dairy cow ration. Masters thesis, University of Saskatchewan, Saskatoon, SK.

Garrett, W. N. 1971. Energetic efficiency of beef and dairy steers. J. Anim. Sci. **32:** 451-456

Ghorbani, G. R., Morgavi, D. P., Beauchemin, K. A. and Leedle, J. A. Z. 2002. Effects of bacterial direct-fed microbials on ruminal fermentation, blood variables, and the microbial populations of feedlot cattle. J. Anim. Sci. **80**: 1977-1986

Gibb, D. J., Owens, F. N., Mir, P. S., Mir, Z., Ivan, M. and McAllister, T. A. 2004. Value of sunflower seed in finishing diets of feedlot cattle. J. Anim. Sci. **82:** 2679-2692

Givens, D. I., Davies, T. W. and Laverick, R. M. 2004. Effect of variety, nitrogen fertiliser and various agronomic factors on the nutritive value of husked and naked oats grain. Anim Feed Sci. Technol. **113:** 169-181

Gozho, G. N. and Mutsvangwa, T. 2008. Influence of carbohydrate source on ruminal fermentation characteristics, performance, and microbial protein synthesis in dairy cows. J. Dairy Sci. **91:** 2726-2735

Harvatine, K. J. and Allen, M. S. 2005. The effects of production level on feed intake, milk yield, and endocrine responses to two fatty acid supplements in lactating cows. J. Dairy Sci. **88:** 4018-4027

Hatfield, R. and Fukushima, R. S. 2005. Can lignin be accurately measured ? Crop Sci. **45:** 832-839

Heneen, W. K., Karlsson, G., Brismar, K., Gummeson, P. O., Marttila, S., Leonova, S., Carlsson, A.S., Bafor, M., Banas, A., Mattsson, B., Debski, H. and Stymne, S. 2008. Fusion of oil bodies in endosperm of oat grains. Planta. **228:** 589-599

Herrera-Saldana, R. E., Huber, J. T. and Poore, M. H. 1990. Dry matter, crude protein, and starch degradability of five cereal grains. J. Dairy Sci. **73:** 2386-2393

Herrera-Saldana, R., Huber, J. T., Poore, M. H. 1988. *In vitro* and *in situ* dry matter, crude protein and starch degradability of five cereal grains. J. Dairy Sci. **71:** 177

Hersom. M. J. 2008. Opportunities to enhance performance and efficiency through nutrient synchrony in forage-fed ruminants. J. Anim. Sci. **86:** E306–E317

Hess, B. W., Moss, G. E. and Rule, D. C. 2008. A decade of developments in the area of fat supplementation research with beef cattle and sheep. J. Anim Sci. **86:** E188-204

Hetland, H. and Svihus, B. 2001. Effect of oat hulls on performance, gut capacity and feed passage time in broiler chickens. Br. Poult. Sci. **42:** 354-361

Hockett, E.A. 2000. Barley. Pages 81-126 *in* K. Kulp and J. G. Ponte, eds Handbook of cereal science and technology, Second Edition. Marcel Dekker Inc., New York, NY, USA

Holland, J.B., Frey, K.J. and Hammond, E.G. 2001. Correlated responses of fatty acid composition, grain quality, and agronomic traits to nine cycles of recurrent selection for increased oil content in oat. Euphytica.**122:** 69-79

Hotovy, S. K., Johnson, K. A., Johnson, D. E., Carstens, G. E., Bourdon, R. M. and Seidel, G.E. 1991. Variation among twin beef cattle in maintenance energy requirements. J. Anim. Sci. **69:** 940-946

Hristov, A. N., Kennington, L. R., McGuire, M. A. and Hunt, C. W. 2005b. Effect of diets containing linoleic acid- or oleic acid-rich oils on ruminal fermentation and nutrient digestibility, and performance and fatty acid composition of adipose and muscle tissues of finishing cattle. J. Anim. Sci. **83:** 1312-1321

Hristov, A. N., Ropp, J. K., Grandeen, K. L., Abedi, S., Etter, R. P., Melgar, A. and Foley, A. E. 2005a. Effect of carbohydrate source on ammonia utilization in lactating dairy cows**.** J Anim Sci. **83:** 408-421

Huffman, R. P., Stock, R. A., Sindt, M. H. and Shain, D. H. 1992. Effect of fat type and forage level on performance of finishing cattle. J. Anim. Sci. **70:** 3889-3898

Huntington, G. B. 1997. Starch utilization by ruminants: From basics to the bunk. J. Anim. Sci. **75:** 852–867

Huuskonen. A. 2009. The effect of cereal type (barley versus oats) and rapeseed meal supplementation on the performance of growing and finishing dairy bulls offered grass silage-based diets. Livest. Sci. **122:** 53-62

Ikuta, K., Nishimori, K., Okada, K. and Yasuda, J. 2003. Comparison of diurnal variation of the rumen fluid character between the different sampling sites or feeding systems in dairy cows. Japanese Journal of Veterinary Clinics. **26:** 47-52

Ikwuegbu, O. A. and Sutton. J. D. 1982. The effect of varying the amount of linseed oil supplementation on rumen metabolism in sheep. Br. J. Nutr. **48:** 365–371

Jenkins, T. C. 1990. Nutrient digestion, ruminal fermentation, and plasma lipids in steers fed combinations of hydrogenated fat and lecithin. J. Dairy Sci. **73:** 2934-2939

Jenkins, T. C. 1994. Regulation of lipid metabolism in the rumen. J. Nutr. **124:** 1372-1376

Jenkins, T. G. and Ferrell, C. L. 1984. Characterization of postweaning traits of Simmental and Hereford bulls and heifers. Anim. Prod. **39:** 355-364

Johansson, L., Virkki, L., Maunu, S., Lehto, M., Ekholm, P. and Varo, P. 2000. Structural characterization of water soluble beta-glucan of oat bran. Carbohydr. Polym. **42:** 143-148

Jung, H. G and Allen, M. S. 1995. Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. J. Anim. Sci. **73:** 2774-2790

Kasuya, N., Xu, Q., Kobayashi, Y., Fukuda, K., Enishi, O., Iiyama, K. and Itabashi, H. 2008. Cell wall degradation of tropical and temperate forage grasses measured by nylon bag and in vitro digestion techniques. Anim. Sci. J. **79:** 200-209

Keunen, J. E., Plaizier, J. C., Kyriazakis, I., Duffield, T. F., Widowski, T. M., Lindinger M. I. and McBride, B.W. 2002. Effects of a subacute ruminal acidosis model on the diet selection of dairy cows. J. Dairy Sci. **85:** 3304–3313

Khafipour, E., Krause, D. O. and Plaizier, J. C. 2009. A grain-based subacute ruminal acidosis challenge causes translocation of lipopolysaccharide and triggers inflammation. J. Dairy Sci. **92:** 1060-1070

Khan, M. A., Lee, H. J., Lee, W. S., Kim, H. S., Kim, S. B., Park, S. B., Baek, K. S., Ha, J. K. and Choi, Y. J. 2008. Starch source evaluation in calf starter: II. Ruminal parameters, rumen development, nutrient digestibilities, and nitrogen utilization in Holstein calves. J. Dairy Sci. **91:** 1140-1149

Kincheloe, J. J., Bowman, J. G. P., Surber, L. M. M., Boss, D. L., Anderson, K. A. and T. K. Blake. 2003. Effects of barley or corn on performance and digestibility in finishing diets. Proc. West. Sec. Am. Soc. Anim. Sci. **54:** 362-365

Kirkkari A. M. 2008. Comparative economic analysis for production of naked vs. conventional oat. Acta Agriculturae Scandinavica, Section B - Plant Soil Science. **58:** 305-313

Knudsen, K. E. B. 1997. Carbohydrate and lignin contents of plant materials used in animal feeding. Anim. Feed Sci. Technol. **67:** 319-338

Knudsen, K. E. B. 2001. The nutritional significance of dietary fibre analysis. Anim Feed Sci. Technol. Congrès Session of the Pig Commission of the European Association of Animal Production. **90:** 3-20

Koenig, K. M., Beauchemin, K. A. and Rode. L. M. 2003. Effect of grain processing and silage on microbial protein synthesis and nutrient digestibility in beef cattle fed barley-based diets. J. Anim. Sci. **81:** 1057-1067

Kosieradzka, I. and Fabijańska, M. 2001. Comparison of the nutritive value of naked and husked oat protein with wheat and maize. J. Anim. Feed Sci. **10:** 309-314

Krajcarski-Hunt, H., Plaizier, J. C., Walton, J. P., Spratt, R. and McBride, B. W. 2002. Short communication: Effect of subacute ruminal acidosis on *in situ* fiber digestion in lactating dairy cows. J. Dairy Sci. **85:** 570-573

Krause, K. M. and Combs, D. K. 2003. Effects of forage particle size, forage source, and grain fermentability on the performance and ruminal pH in midlactation cows. J. Dairy Sci. **86:** 1382-1397

Krause, K. M., Combs, D.K., and Beauchemin, K.A. 2002. Effects of forage, particle size, and grain fermentability in midlactation cows. II. Ruminal pH and chewing activity. J. Dairy Sci. **85:** 1947-1957

Krause, K. M., Dhuyvetter, D. V. and Oetzel, G. R. 2009. Effect of a low-moisture buffer block on ruminal pH in lactating dairy cattle induced with subacute ruminal acidosis. J. Dairy Sci. **92:** 352-364

Krehbiel, C. R., Stock, R. A., Shain, D. H., Richards, C. J., Ham, G. A., McCoy, R. A., Klopfenstein, T. J., Britton, R. A. and Huffman, R. P. 1995. Effect of level and type of fat on subacute acidosis in cattle fed dry-rolled corn finishing diets. J. Anim. Sci. **73:** 2438-2446

Kucuk, O., Hess, B. W. and Rule, D. C. 2004. Soybean oil supplementation of a high-concentrate diet does not affect site and extent of organic matter, starch, neutral

detergent fiber, or nitrogen digestion, but influences both ruminal metabolism and intestinal flow of fatty acids in limit-fed lambs. J. Anim. Sci. **82:** 2985-2994

Lapierre, H., Pacheco, D., Berthiaume, R., Ouellet, D. R., Schwab, C. G., Dubreuil, P., Holtrop, G. and Lobley, G. E. 2006. What is the true supply of amino acids for a dairy cow? J. Dairy Sci. **89:** E1-14

Lardy, G. and Bauer, M. 1999. Feeding barley to beef cattle. EB-70. [Online] Available: http://www.ag.ndsu.edu/pubs/ansci/beef/eb70w.htm [2009 July 23]

Lásztity, R. 1996. Oat proteins. Pages 275-294 *in* Lásztity R, ed. The chemistry of cereal proteins. CRC Press Inc. Boca Raton, Florida, USA

Lásztity, R. 1998. Oat grain - a wonderful reservoir of natural nutrients and biologically active substances. Food Reviews International. **14:** 99-119

Leggett J. M. and Thomas, H. 1995. Oat evolution and cytogenetics. Pages 121-149 *in* R.W. Welch ed. The oat crop: Production and utilization. Chapman & Hall, New York, NY, USA

Leonova, S., Shelenga, T., Hamberg, M., Konarev, A. V., Loskutov, I., Carlsson, A. S. 2008. Analysis of oil composition in cultivars and wild species of oat (Avena sp.). J. Agric. Food Chem. **56:** 7983-7991

Li. X., Weng, J. K. and Chapple, C. 2008. Improvement of biomass through lignin modification. Plant J. **54:** 569-581

Litherland, N. B., Thire, S., Beaulieu, A. D., Reynolds, C. K., Benson, J. A. and Drackley, J. K. 2005. Dry matter intake is decreased more by abomasal infusion of unsaturated free fatty acids than by unsaturated triglycerides. J. Dairy Sci. **88:** 632-643

Lofgreen, G. P., and Garrett. W. N. 1968. A system of expressing net energy requirements and feed values for growing and finishing beef cattle. J. Anim. Sci. **27:** 793–806.

Lopez-Bote, C. J., Gray, J. I., Gomaa, E. A. and Flegal, C. J. 1998. Effect of dietary oat administration on lipid stability in broiler meat. Br. Poult. Sci. **39:** 57-61

Maekawa, M., Beauchemin, K. A. and Christensen, D. A. 2002a. Effect of concentrate level and feeding management on chewing activities, saliva production, and ruminal ph of lactating dairy cows. J. Dairy Sci. **85:** 1165-1175

Maekawa, M., Beauchemin, K. A. and Christensen, D. A. 2002b. Chewing activity, saliva production, and ruminal pH of primiparous and multiparous lactating dairy cows. J. Dairy Sci. **85:** 1176-1182

Martin, P.A. and Thomas, P. C. 1987. Reduction in the saturated fatty acid content of cows' milk fat through diet formulation. Proceedings of the Nutritional Society. **46:** 114A

Mathison, G. W., Engstrom, D. F. and Macleod, D. D. 1991. Effect of feeding whole and rolled barley to steers in the morning or afternoon in diets containing differing proportions of hay and grain. Anim. Prod. **53:** 321-330

Matz S. A. 1992. Ingredients from other grains. Pages 23-52. *in* ed. 3rd Bakery technology and engineering. Pan-Tech International, Inc. Mc Allen TX

McAllister, T. A., Rode, L. M., Cheng, K. J. and Forsberg, C. W. 1991. Selection of a sterilization method for the study of cereal grain digestion. J. Anim. Sci. **69:** 3039-3043

McCartney, D., Townley-Smith, L., Vaage, A. and Pearen, J. R. 2004. Cropping systems for annual forage production in North East Saskatchewan. Can. J. Plant Sci. **84:** 187-194

McEwen, P. L., Mandell, I. B., Brien, G. and Campbell, C. P. 2007. Effects of grain source, silage level, and slaughter weight endpoint on growth performance, carcass characteristics, and meat quality in Angus and Charolais steers. Can. J. Anim. Sci. **87:** 167-180

McMullen, M. S. 2000. Oats. Pages 127-148 *in* K. Kulp and J. G. Ponte, ed. Handbook of cereal science and technology. New York, Marcel Dekker

Medel, P. Salado, S. de Blas, J. C. and Mateos, G. G. 1999. Processed cereals in diets for early-weaned piglets. Anim. Feed Sci. Technol. **82:** 145-156

Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. **80:** 1463–1481

Montgomery, S. P., Drouillard, J. S., Nagaraja, T. G., Titgemeyer, E. C. and Sindt, J. J. 2008. Effects of supplemental fat source on nutrient digestion and ruminal fermentation in steers. J. Anim. Sci. **86:** 640-650

Moran, J. B. 1986. Cereal grains in complete diets for dairy cows: A comparison of rolled barley, wheat and oats and of three methods of processing oats. Anim. Prod. **43:** 27-36

Moya, D., Calsamiglia, S., Ferret, A., Blanch, M., Fandiño, J. I., Castillejos, L. and Yoon, I. 2009. Effects of dietary changes and yeast culture (Saccharomyces cerevisiae) on rumen microbial fermentation of Holstein heifers. J. Anim Sci. **87:** 2874-2881

Mustafa, A. F., Christensen, D. A. and McKinnon, J. J. 1998. Chemical characterization and ruminal nutrient degradability of hulled and hull-less oats. J. Sci. Food Agric. **77:** 449-455

Nagaraja, T. G. and Chengappa, M. M. 1998. Liver abscesses in feedlot cattle: a review. J. Anim. Sci. **76**: 287-298

Narayanan, S., Nagaraja, T. G., Okwumabua, O., Staats, J., Chengappa, M. M., and Oberst, R. D. 1997. Ribotyping to compare *Fusobacterium necrophorum* isolates from bovine liver abscesses, ruminal walls, and ruminal contents. Appl. Environ. Microbiol. **63**: 4671-4678

National Research Council. 1982. United States-Canadian tables of feed composition: nutritional data for United States and Canadian feeds. 3rd ed. National Academy Press, Washington, DC, USA

National Research Council. 1984. Nutrient requirements of beef cattle. 6th ed. National Academy Press, Washington, DC, USA

National Research Council. 1996. Nutrient requirements of beef cattle. 7th ed. National Academy Press, Washington, DC, USA

National Research Council. 2000. Nutrient requirements of beef cattle. 7th ed. revised) National Academy Press, Washington, DC, USA

National Research Council. 2001. Nutrient requirements of dairy cattle. 7th revised ed. National Academy Press, Washington, DC, USA

Nisa, M. U., Sarwar, M., Bilal, Q. and Feroz, M. A. 1999. Effect of temperature stress on nutrient utilization and different physiological functions of ruminant animals. Int. J. Agri. Biol. **1:**174-178

Niu, Z., Rossnagel, B. G. and Yu, P. 2007a. Chemical characteristics and nutritive values of super-genotype of oat vs. normal varieties of oats for ruminants. J. Anim. Feed Sci. **16:** 266-271

Niu, Z., Rossnagel, B. G. and Yu, P. 2007b. Using Cornell system and NRC dairy model to predict nutrient supply from new super-genotype of oat grain in comparison with two normal varieties of oat. J. Anim. Feed Sci. **16:** 517-522

Nocek, J. E. 1997. Bovine acidosis: Implications on laminitis. J. Dairy Sci. **80:** 1005-1028

Oba, M. and Allen, M. S. 2000. Effects of brown midrib 3 mutation in corn silage on productivity of dairy cows fed two concentrations of dietary neutral detergent: 2. Chewing activities. J. Dairy Sci. **83:**1342–1349

Oldick, B. S. and Firkins, J. L. 2000. Effects of degree of fat saturation on fiber digestion and microbial protein synthesis when diets are fed twelve times daily. J. Anim. Sci. **78:** 2412-2420

Ørskov, E. R. 1986. Starch digestion and utilization in ruminants. J. Anim. Sci. **63**: 1624-1633

Orskov, E. R., Fraser, C. and Gordo, J. G. 1974. Effect of processing of cereals on rumen fermentation, digestibility, rumination time, and firmness of subcutaneous fat in lambs. Br. J. Nutr. **32:** 59-69

Owens, F. N., Secrist, D. S., Hill, W. J. and Gill. D. R. 1997. The effect of grain source and grain processing on performance of feedlot cattle: a review. J. Anim. Sci. **75:** 868-879

Owens, F. N., Secrist, D. S., Hill, W. J., and Gill, D. R. 1998. Acidosis in cattle: a review. J. Anim. Sci. **76**: 275-286

Pearson.C. 2009. Government of Alberta, Agriculture and Rural Development 2008. Marketing oats in Canada. [Online] Available: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sis10952) [2009 July 27]

Penner, G. B., Beauchemin, K. A., and Mutsvangwa, T. 2006. An evaluation of the accuracy and precision of a stand-alone submersible continuous ruminal pH measurement system. J. Dairy Sci. **89:** 2132-2140

Penner, G. B., Beauchemin, K. A., and Mutsvangwa, T. 2007. Severity of ruminal acidosis in primiparous Holstein cows during the periparturient period. J. Dairy Sci. **90:** 365-375.

Penner, G. B., Taniguchi, M., Guan, L. L. Beauchemin, K. A. and Oba, M. 2009. Effect of dietary forage to concentrate ratio on volatile fatty acid absorption and the expression of genes related to volatile fatty acid absorption and metabolism in ruminal tissue. J. Dairy Sci. **92:** 2767-2781

Peterson, D. M. and Wood, D. F. 1997. Composition and structure of high-oil oat. J Cereal Sci. **26:** 121-128

Pettersson, A., Lindberg, J. E. Thomke, S. and Eggum, B.O. 1996. Nutrient digestibility and protein quality of oats differing in chemical composition evaluated in rats and by an in vitro technique. Anim Feed Sci. Technol. **62**: 203–213

Plaizier, J. C., Krause, D. O., Gozho, G. N. and McBride, B. W. 2008. Subacute ruminal acidosis in dairy cows: The physiological causes, incidence and consequences. Vet J. **176:** 21-31

Plascencia, A., Estrada, M. and Zinn, R. A. 1999. Influence of free fatty acid content on the feeding value of yellow grease in finishing diets for feedlot cattle. J. Anim. Sci. **77:** 2603-2609

Prestløkken, E. 1999. In situ ruminal degradation and intestinal digestibility of dry matter and protein in expanded feedstuffs. Anim Feed Sci. Technol. **77:** 1-23

Ramirez, J. E. and Zinn, R. A. 2000. Interaction of dietary magnesium level on the feeding value of supplemental fat in finishing diets for feedlot steers. J. Anim. Sci. **78:** 2072

Redaelli, R. and Berardo, N. 2007. Prediction of fibre components in oat hulls by near infrared reflectance spectroscopy. J Sci Food Agric. **87:** 580–585

Relling, A. E. and Reynolds, C. K. 2007. Feeding rumen-inert fats differing in their degree of saturation decreases intake and increases plasma concentrations of gut peptides in lactating dairy cows. J. Dairy Sci. **90:** 1506-1515

Rowe, J. B. and Crosbie, G. B. 1988. The digestibility of grain of two cultivars of oats differing in lignin content. Aust. J. Agric. Res. **39:** 639-644

Rowe, J. B., May, P. J., Crosbie, G. and Corbett, J. 2001. Knowing your oats. Recent Advances in Animal Nutrition in Australia. **13:** 211-221

Rustomo, B., AlZahal, O., Odongo, N. E., Duffield, T. F. and McBride, B. W. 2006. Effects of rumen acid load from feed and forage particle size on ruminal pH and dry matter intake in the lactating dairy cow. J. Dairy Sci. **89:** 4758-4768

Särkijärvi, S. and Saastamoinen, M. 2006. Feeding value of various processed oat grains in equine diets. Livestock Science. **100:** 3-9

SAS, 2003. User's Guide: Statistics, version 9.1.3. SAS Inst. Inc. Cary, NC

Sauvant, D., Bertrand, D. and Giger, S. 1985. Variations and previsions of the in sacco dry matter digestion of concentrates and by-products. Anim. Feed Sci. Technol. **13:** 7-23

Sawal, R. K. and Kurar, C. K. 1998. Milk yield and its fat content as affected by dietary factors: A review. Asian-australas. J. Anim. Sci. **11:** 217-233

Schimek, D., Bauer, M., Caton, J., Anderson, V., Dhuyvetter, D. and Berg, P. 1997. Influence of hull-less oats on feedlot performance and carcass characteristics in beef steers. [Online] Available: http://www.ag.ndsu.nodak.edu/carringt/97beef/art6.htm [2008 Nov. 20]

Schipper, H., Frey, K. J. and Hammond, E. G. 1991. Changes in fatty acid composition associated with recurrent selection for groat-oil content in oat. Euphytica. **56:**81-88

Shamekh, S., Forssell, P., Suortti, T., Autio, K. and Poutanen, K. 1999. Fragmentation of oat and barley starch granules during heating. J. Cereal Sci. **30:** 173 -182

Small, E. 1999. New crops for Canadian agriculture. p. 15–52. In: J. Janick (ed.), Perspectives on new crops and new uses. ASHS Press, Alexandria, VA. [Online]

Available: http://www.hort.purdue.edu/newcrop/proceedings1999/pdf/v4-15.pdf [2009 July 27]

Sniffen, C. J., O'Connor, J. D., Van Soest, P. J., Fox, D. G. and Russell, J. B. 1992. A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. J Anim Sci. **70:** 3562-3577

Staigmiller, R. B. and Adams, D. C. 1989. Free-choice grain and forage diets for early-weaned beef calves. Nutrition Reports International. **39:** 1053-1059

Stevens, E. J., Armstrong, K. W., Bezar, H. J., Griffin, W. B. and Hampton. J. G. 2004. Fodder oats: an overview. Pages 11-17 *in* J.M. Suttie and S.G. Reynolds. Fodder oats: a world overview, Food and Agriculture Organization of the United Nations. Plant production and Protection Series No. 33. Rome, Italy [Online] Available: http://www.fao.org/docrep/008/y5765e/y5765e06.htm#bm06.1 [2009 July 27]

Stoskopf, N. C. 1985. Cereal grain crops. Chapter 22. Barley and oat. Pages 444-458. Reston publishing company, Inc, Virginia.

Stroh, T. L., Ringwall, K. A., Gross, J., Lamb, C., Poland , W. W., Ottmar, G., Helmuth, K. J. and Nelson, J. L. 2000. Utilizing North Dakota grown hull-less oat to successfully grow and develop yearling horses. Annual Report. [Online] Available: http://www.ag.ndsu.nodak.edu [2007 Oct. 20]

Sujak, A., Kotlarz, A. and Strobel, W. 2006. Compositional and nutritional evaluation of several lupin seeds. Food Chem. **98**: 711-719

Suttie J. M. and **Reynolds S. G. 2004.** Background to fodder oats worldwide. Pages 1-10 *in* J.M. Suttie and S.G. Reynolds, eds.Fodder oats: a world overview food and agriculture organization of the united nations**.** Plant Production and Protection Series No. 33[Online] Available: http://www.fao.org/docrep/008/y5765e/y5765e00.htm. [2009 July 29]

Szasz, J. I., Hunt, C. W., Turgeon, O. A. Jr., Szasz P. A. and Johnson K. A. 2005. Effects of pasteurization of potato slurry by-product fed in corn-or barley-based beef finishing diets. J Anim Sci. **83:** 2806-2814

Tadepalli, S., Narayanan, S. K., Stewart, G. C., Chengappa, M. M. and Nagaraja, T. G. 2009. Fusobacterium necrophorum: A ruminal bacterium that invades liver to cause abscesses in cattle. Anaerobe. **15:** 36-43

Tamime, A. Y., Muir, D. D., Barclay, M. N. I., Khaskheli, M., and McNulty, D. 1997. Laboratory-made Kishk from wheat, oat and barley: 1. Production and comparison of chemical and nutritional composition of Burghol. Food Res. Int. **30:** 311–317

Thacker, P. A., Soita, H. W. and Rossnagel, B. G. 2004. Performance of growing-finishing pigs fed barley-based diets supplemented with normal or high-fat oat. Can. J. Anim. Sci. **84:** 229-236

Thacker, P. A., Widyaratne, G, and Rossnagel, B. G. 2009. Comparison of normal and low-lignin hull/high-oil groat oat as energy sources for broiler chicks. J. Sci. Food Agri. **89:** 2236-2242

Thompson, R. K., McKinnon, J. J., Mustafa, A. F., Maenz, D. D., Racz, V. J. and Christensen, D. A. 2002. Chemical composition, ruminal kinetic parameters, and nutrient digestibility of ammonia treated oat hulls. Can. J. Anim. Sci. **82:** 103-109

Thompson, R. K., Mustafa, A. F., McKinnon, J. J., Maenz, D. and Rossnagel, B. 2000. Genotypic differences in chemical composition and ruminal degradability of oat hulls. Can. J. Anim. Sci. **80**: 377–379

Traxler, M. J., Fox, D. G., Van Soest, P. J., Pell, A. N., Lascano, C. E., Lanna, D. P., Moore, J. E., Lana, R. P., Velez, M. and Flores, A. 1998. Predicting forage indigestible NDF from lignin concentration. J. Anim. Sci. **76:** 1469-80

Umucalilar, H. D., Coşkun, B. and Gülşen, N. 2002. In situ rumen degradation and in vitro gas production of some selected grains from Turkey. J Anim Physiol Anim Nutr. **86:** 288-297

Vaage, A. S., McCartney, D. H., McKinnon, J. J. and Bergen, R. D. 1998. Effect of prolonged backgrounding on growth performance and carcass composition of crossbred beef steers. Can. J. Anim. Sci. **78:** 359-367

Van der Walt, J.G. and Linington, M.J. 1989. A review of energy metabolism in producing ruminants. Part 1: Metabolism of energy substrates. J. S. Afr. Vet. Assoc. **60:** 223-227

Van Houtert, M. F. J. 1993. The production and metabolism of volatile fatty acids by ruminants fed roughages: a review. Anim Feed Sci. Technol. **43:** 189-225

Van Soest, P. J., Robertson, J. B. and Lewis, B. A. 1991. Methods for dietary fiber, neutral detergent fiber, and non starch polysaccharides in relation to animal nutrition. J. Dairy Sci. **74:** 3583-3597

Van Soest, P.J., 1994. Intake. Page 337-353. In Nutritional Ecology of the Ruminant. Cornell University Press, Ithaca, USA.

Vasconcelos, J. T. and Galyean, M. L. 2008. ASAS centennial paper: Contributions in the Journal of Animal Science to understanding cattle metabolic and digestive disorders. J. Anim. Sci. **86:** 1711-1721

Verhallen, A., Hayes, A. and Taylor, T. 2001. Cover Crops: Oats. Ministry of Agriculture, Food and Rural Affairs. [Online] Available: http://www.omafra.gov.on.ca/english/crops/facts/cover_crops01/oats.htm [2009 June 25]

Virkki, L., Johansson, L., Ylinen, M., Maunu, S. and Ekholm, P. 2005. Structural characterization of water-insoluble nonstarchy polysaccharides of oats and barley. Carbohydr. Polym. **59:** 357-366

Waldo, D. R. 1973. Extent and Partition of Cereal Grain Starch Digestion in Ruminants. J. Anim Sci. **37:** 1062-1074.

Wales, W. J., Kolver, E. S., Thorne, P. L. and Egan. A. R. 2004. Diurnal variation in ruminal pH on the digestibility of highly digestible perennial ryegrass during continuous culture fermentation. J. Dairy Sci. **87:** 1864-1871

Walsh, K., O'Kiely, P., Taweel, H.Z., McGee, M., Moloney, A. P. and Boland, T. M. 2009. Intake, digestibility and rumen characteristics in cattle offered whole-crop wheat or barley silages of contrasting grain to straw ratios. Anim. Feed Sci. Technol. **148:** 192-213

Webster F. H. 1996. Chapter 6. Pages 179-203 *in* Cereal Grain Quality by R.J. Henry and P.S. Kettlewell. Chapman & Hall, London

Welch, R. W. 1995. The chemical composition of oats. Pages 279-320 *in* R. W. Welch ed. The oat crop: Production and utilization. Chapman & Hall, New York, NY, USA

Welch, R. W. and Leggett, J. M. 1997. Nitrogen content, oil content and oil composition of oat cultivars (*A. sativa*) and wild *Avena* species in relation to nitrogen fertility, yield and partitioning of assimilates. J. Cereal Sci. **26:** 105-120

Welch, R. W. and McConnell, J. M. 2001. Oats. Pages 367- 390 *in* D.A.V. Dendy and B. J. Dobraszczyk, eds. Cereal and cereal products: chemistry and technology. Gaithersburg, Md. Aspen Publishers

Welch, R. W., Hayward, M. V. and Jones, D. I. H. 1983. The composition of oat husk and its variation due to genetic and other factors. J. Sci. Food Agri. **34:** 417-426

White, D. A., Fisk, I. D. and Gray, D. A. 2006. Characterisation of oat (*Avena sativa* L.) oil bodies and intrinsically associated E-vitamers. J. Cereal Sci. **43:** 244-249

Wiliczkiewicz, A., Orda, J., Jamroz, D. and Skorupińska, J. 2005. Effect of non starch polysaccharides of cereal grains on digestibility and intestinal microflora of chickens and geese. EJPAU **8:** 40. [Online] Available: http://www.ejpau.media.pl/volume8/issue4/art-40.html [2009 July 29]

Willenborg, C. J., Wildeman, J. C., Miller, A. K., Rossnagel, B. G. and Shirtliffe, S. J. 2005. Oat germination characteristics differ among genotypes, seed sizes, and osmotic potentials. Crop Sci. **45:** 2023-2029

Williams, L. M., Block, H. C., Christensen, D. A., Racz, V., Ataku, K., Wildeman, B. and McKinnon, J. J. 2008. Effect of feeding a processed barley/canola meal pellet on performance and carcass quality of feedlot steers. Can. J. Anim. Sci. **88:** 667-676

Yang, W. Z. and Beauchemin, K. A. 2006. Effects of physically effective fiber on chewing activity and ruminal pH of dairy cows fed diets based on barley silage. J. Dairy Sci. **89:** 217-228

Yang, W. Z. and Beauchemin. K. A. 2009. Increasing physically effective fiber content of dairy cow diets through forage proportion versus forage chop length: Chewing and ruminal pH. J. Dairy Sci. **92:** 1603-1615

Yang, W. Z., Beauchemin, K. A. and Rode, L. M. 2000. Effects of barley grain processing on extent of digestion and milk production of lactating cows. J. Dairy Sci. **83:** 554-568

Yang, W. Z., Beauchemin, K. A. and Rode, L. M. 2001. Barley processing, forage:concentrate, and forage length effects on chewing and digesta passage in lactating cows. J. Dairy Sci. **84:** 2709-2720

Youngs, V. L. and Forsberg, R. A. 1987. Pages 457-499 *in* R.A. Olson and K.J. Frey, eds. Nutritional quality of cereal grains: Genetic and agronomic improvement. American society of Agronomy Inc., Madison, Wisconsin, USA

Yu, P. and Niu, Z. 2009. Using a complex non-TDN based model (the DVE/OEB system) to predict microbial protein synthesis, endogenous protein, degradation balance, and total truly absorbed protein supply of different varieties of cereal oats for ruminants. Anim. Sci. J. **80:** 273-279.

Yu, P., Rossnagel, B. G. and Niu. Z. 2008. Protein value of a new genotype oat (CDC SO-I) for the NRC dairy model: Protein degradation balance and kinetics, protein fractions and total metabolizable protein supply. Can. J. Anim. Sci. **88:** 507 -513

Yu. P., Rossnagel, B. G., Niu, Z. and Christensen, D. A. 2009. A newly developed genotype of oat (cv. CDC SO-I) for lactating dairy cows: effect of micronized oat and different cereal combinations on productive performance of lactating dairy cows. J. Dairy Sci. Submitted

Zalinko, G., Racz, V. J., Rossnagel, B. G., Christensen, D. A., McKinnon, J. J. 2009. Performance and carcass characteristics of steers fed a low acid-detergent lignin hull, high-oil groat oat in growing and finishing diets**.** Can. J. Anim. Sci. **89:** 521-530

Zebeli, Q., Dijkstra, J., Tafaj, M., Steingass, H., Ametaj, B. N. and Drochner, W. 2008. Modeling the adequacy of dietary fiber in dairy cows based on the responses of ruminal ph and milk fat production to composition of the diet. J. Dairy Sci. **91:** 2046-2066

Zhou, M. X., Holmes, M. G., Robards, K. and Helliwell, S. 1998. Fatty acid composition of lipids of Australian oats. J. Cereal Sci. **28:** 311–319.

Zhou, M., Robards, K., Glennie-Holmes, M. and Helliwell, S. 1999. Oat lipids. J. Am. Oil Chem. Soc. **76:** 159-169

Zinn R. A. 1993. Influence of processing on the comparative feeding value of barley for feedlot cattle. J Anim Sci. **71:** 3-10

Zinn R. A. 1990. Influence of flake density on the comparative feeding value of steam-flaked corn for feedlot cattle. J Anim Sci. **68:** 767-775

Zinn, R. A. 1988. Comparative feeding value of supplemental fat in finishing diets for feedlot steers supplemented with and without monensin. J. Anim.Sci. **66:** 213-227

Zinn, R. A. 1989a. Influence of level and source of dietary fat on its comparative feeding value in finishing diets for steers: Feedlot cattle growth and performance. J. Anim. Sci. **67:** 1029-1037

Zinn, R. A. 1989b. Influence of level and source of dietary fat on its comparative feeding value in finishing diets for feedlot steers: Metabolism. J. Anim. Sci. **67:** 1038-1049

Zinn, R. A. and Shen, Y. 1998. An evaluation of ruminally degradable intake protein and metabolizable amino acid requirements of feedlot calves. J. Anim. Sci. **76**: 1280-1289

Zinn, R. A., Owens, F. N. and Ware. R. A. 2002. Flaking corn: processing mechanics, quality standards, and impacts on energy availability and performance of feedlot cattle. J. Anim. Sci. **80**: 1145-1156