NorFor –
The Nordic feed evaluation system

EAAP publication No. 130

edited by:
Harald Volden

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EAAP – European Federation of Animal Science

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The European Association for Animal Production wishes to express its appreciation to the *Ministero per le Politiche Agricole e Forestali* and the *Associazione Italiana Allevatori* for their valuable support of its activities

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Wageningen Academic
Publishers

ISBN: 978-90-8686-162-0
e-ISBN: 978-90-8686-718-9
DOI: 10.3920/978-90-8686-718-9

ISSN 0071-2477

Photographer: Jens Tønnesen
from Dansk Landbrugs Medier

First published, 2011

Wageningen Academic Publishers
P.O. Box 220
6700 AE Wageningen
The Netherlands
www.WageningenAcademic.com
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Preface

The present volume is the first comprehensive, published description of the Nordic Feed Evaluation System, NorFor. It includes the results of extensive work initiated as a project in 2001 by the farmers' dairy cooperatives in Denmark, Norway, Iceland and Sweden. The overall aim was to create an identical, common feed evaluation system for all four countries to facilitate communication between farmers, consultants and feed industry representatives. Additional goals were to make dissemination of relevant research findings faster and more efficient, both within the four countries and internationally.

Towards that end, a group of experts in ruminant nutrition was commissioned to develop such a system. Since we regarded this as a request to overhaul the current national systems comprehensively, we concluded that it provided an opportunity to develop a completely new feed evaluation system based robustly on current, published knowledge.

NorFor was a development project that ran from 2002 to 2006 and included comparisons of various feed evaluation systems applied in western countries. The development also included validation of the models based on available research data from the Nordic countries. Significant parts of the development work involved close cooperation with scientists at the agricultural universities and research institutes in the Nordic countries. In addition, we have shared information and have had constructive discussions with experts in the feed industry and feed laboratories. We greatly appreciate the past and ongoing cooperation. From 2007 onwards, NorFor has been jointly funded and managed by the four organizations mentioned above through a cooperative organization (NorFor F.M.B.A.).

The present description of NorFor includes all parts of the model. References to the most important sources of information are also given. We thereby provide a description of the biological basis for NorFor. The NorFor project group hopes this volume will be useful for dairy farmers, advisors, scientists and all other actors in the dairy industry in the four NorFor countries. We also recommend the reader to use the IT tools, since many of the nutritional interactions in the model are easier to use and understand if they are applied than if the texts, tables and graphs are read.

NorFor
Anders H. Gustafsson
Leader of NorFor 2002-2009

Acknowledgements

This publication summarizes the entire work of NorFor, including development and documentation. Numerous people have contributed to the compilation of this written document. NorFor has been developed over several years, thus the nature of their contributions has differed greatly. However, despite these differences, every contribution was equally appreciated. Thus, NorFor F.M.B.A. and the authors would like to sincerely thank everyone who has contributed to the project, and to this first version of the NorFor scientific publication.

The main author of the present publication was Harald Volden, of TINE and the Norwegian University of Life Sciences, who has been the leader of the NorFor scientific development group.

In addition, various people have played important roles in preparing the publication, including: Nicolaj I. Nielsen of AgroTech and the Danish Cattle Association; Maria Åkerlind of the Swedish Dairy Association; and Peder Nørgaard of the University of Copenhagen. Other persons, listed in the relevant chapters in this publication, have also contributed as authors.

In addition, the following persons (in alphabetical order of family names) have contributed in different working groups during the development and/or documentation of NorFor:

- Feed evaluation and feeding standards:
  Ole Aaes, Jan Bertilsson, Anders H. Gustafsson, Øystein Havrevoll, Mårten Hetta, Mogens Larsen, Maria Mehlqvist, Elisabeth Nadeau, Nicolaj I. Nielsen, Peder Nørgaard, Åshild Randby, Arnt Johan Rygh, Ingunn Schei, Harald Volden and Maria Åkerlind
- Feed analysis and tables:
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- IT-system:
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- Communication:
  Marie Liljeholm, Maria Mehlqvist and Arnt Johan Rygh
- National advisory tools:
  Åse Marit Flittie Anderssen, Henrik Martinussen, Patrik Nordgren, Berglind Ósk Óðinsdóttir and Maria Åkerlind.

We would also like to thank all scientists who have contributed to fruitful discussions and made valuable comments on the model and documents.

The present documentation was reviewed by Torben Hvelplund, University of Aarhus, Denmark, and Peter Udén, Swedish University of Agricultural Sciences, Sweden and they are greatly acknowledged for their work.

Responsibility for the final content of the model and this present EAAP publication of the NorFor systems rests entirely with the authoring group and NorFor F.M.B.A.

Glossary

Abbreviation	Unit	Parameter name
AA		Amino acids
AA-N	g N/100 g N	Amino acid nitrogen in feedstuff
AA_j		Individual amino acid
AA_j_AAT_N		Individual amino acid absorbed in small intestine
AAT_N	g/d	Amino acids absorbed in the small intestine
AAT_N_bal	%	AAT balance
AAT_N_dep	g/d	AAT for deposition in cows
AAT_N_Eff	%	AAT efficiency of utilisation
AAT_N_gain	g/d	AAT requirement for weight gain in primiparous cows and growing cattle
AAT_N_gest	g/d	AAT requirement for gestation in cows and heifers
AAT_N_maint	g/d	AAT requirement for maintenance
AAT_N_milk	g/d	AAT requirement for milk production
AAT_N_mob	g/d	AAT for mobilisation in cows
AAT_N_NEG	g/MJ	Available AAT to energy ratio in growing cattle
AAT_N_NEG_Min	g/MJ	AAT/NEG minimum recommendation
AAT_N_NEL	g/MJ	Available AAT to energy ratio in cows
AAT_{N20}	g/kg DM	Standard feed value for AAT at 20 kg DMI
AAT_{N8}	g/kg DM	Standard feed value for AAT at 8 kg DMI
ACF	g/kg DM	Acetic acid in feedstuff
ADG	g/d	Average daily body weight gain
ADG_calc	g/d	Estimated daily weight gain
Age	days	Current age
Age_end	days	Age at calving or sale
Age_start	days	Age at the start of a feeding period
ALF	g/kg DM	Alcohol in feedstuff
APL		Animal production level
Avail_AAT	g/d	Available AAT for milk production
b_car	mg/kg DM	Beta-carotene in feedstuff
BCS		Body condition score, from 1 to 5
BCS_change	BCS/d	Daily change in body condition score
BCS_kg	kg/BCS	Weight per unit body condition score
BUF	g/kg DM	Butyric acid in feedstuff
BW	kg	Current body weight
BW_birth	kg	Body weight at birth
BW_calc	kg	Calculated body weight at a given age
BW_end	kg	Body weight at calving or sale
BW_mat	kg	Body weight for a mature animal
BW_start	kg	Body weight at the start of a feeding period
C12:0	g/100 g FA	Lauric acid in feedstuff
C14:0	g/100 g FA	Myristic acid in feedstuff
C16:0	g/100 g FA	Palmitic acid in feedstuff
C18:0	g/100 g FA	Stearic acid in feedstuff
C18:1	g/100 g FA	Oleic acid in feedstuff
C18:2	g/100 g FA	Linoleic acid in feedstuff
C18:3	g/100 g FA	Linolenic acid in feedstuff
C20:5	g/100 g FA	EPA, Eicosapentaenoic acid in feedstuff

Abbreviation	Unit	Parameter name
C22:6	g/100 g FA	DHA, Docosahexaenoic acid in feedstuff
Ca	g/kg DM	Calcium in feedstuff
Ca_gain	g/d	Calcium requirement for weight gain in growing cattle and primiparous cows
Ca_gest	g/d	Calcium requirement for gestation
Ca_intake_Min	g/d	Calcium minimum recommendation
Ca_main	g/d	Calcium requirement for maintenance
Ca_milk	g/d	Calcium requirement for milk production
CAD	mEq/kg DM	Cation anion difference in feedstuff
CFat	g/kg DM	Crude fat in feedstuff
CFatD	%	Apparent total digestibility of crude fat
CHO		Carbohydrates
CHOD	%	Apparent total digestibility of carbohydrates
CI	min/kg DM	Chewing index of feedstuff
Cl	g/kg DM	Chloride in feedstuff
Cl_gain	g/d	Chloride requirement for weight gain in growing cattle and primiparous cows
Cl_gest	g/d	Chloride requirement for gestation
Cl_intake_Min	g/d	Chloride minimum recommendation
Cl_main	g/d	Chloride requirement for maintenance
Cl_milk	g/d	Chloride requirement for milk production
Co	mg/kg DM	Cobalt in feedstuff
conc_share	% of DM	Concentrate share in ration
corrNDF_fac		Correction factor for kdNDF
CP	g/kg DM	Crude protein in feedstuff
CP_intake	g/d	Daily intake of crude protein
CPcorr	g/kg DM	Crude protein corrected in feedstuff
CPD	%	Apparent total digestibility of crude protein
CT_o	min/kg NDF	Observed chewing time
Cu	mg/kg DM	Copper in feedstuff
DIM	days	Days in milk
DH		Danish Holstein
DM	g/kg	Dry matter in feedstuff
DM1	g/kg	Dry matter, first step
DM2	g/kg DM1	Dry matter, second step
DM_{corr}	g/kg	Dry matter, corrected for volatile losses
DM_{uncorr}	g/kg	Dry matter, not corrected for volatile losses
DMI	kg DM/d	Dry matter intake
DMIc	kg DM/d	Dry matter intake of concentrate
DMI_{std}	8 or 20 kg DMI	Dry matter intake when calculating standard feed values
EB	%	Energy balance
EBW	kg	Empty body weight
EBWG	g/d	Empty body weight gain
ECM	kg/d	Energy corrected milk
ECM_response	kg/d	Predicted ECM response
ECMherd	kg/d	Average daily ECM yield per cow in the herd
e_Comp	g/100g	Amino acid composition in endogenous amino acids
eCP	g/d	Endogenous crude protein
ED		Efficient degradability

Abbreviation	Unit	Parameter name
EFOS	% of OM	Organic matter digestibility of feedstuff (EFOS method)
EI	min/kg DM	Eating index
Ep	MJ/MJ	Energy retained as protein
erd		Effective rumen degradability
erd_CP	%	Effective rumen degradation of crude protein
erd_NDF	%	Effective rumen degradation of NDF
erd_RestCHO	%	Effective rumen degradation of residual fraction
erd_ST	%	Effective rumen degradation of starch
ET_o	min/kg NDF	Observed eating time
f_milk	g/kg milk	Observed or expected fat content in milk
FA	g/kg CFat	Fatty acids in feedstuff
FA<C12	g/kg CFat	Sum of fatty acids with less than 12 carbons
FAS		Feed analysis system
Fat_mass	kg	Fat mass
Fe	mg/kg DM	Iron in feedstuff
FFM	kg	Fat free mass
FOF	g/kg DM	Formic acid in feedstuff
FPF	g/kg DM	Fermentation products in feedstuff
FRC	none	Feed ration calculator
FV	FV/kg DM	Fill value of feedstuff
FV_intake	FV/d	Intake of fill value
FV_MR	none	Fill value metabolic regulation factor
FV_r	FV/kg DM	Fill value roughage
FV_SubR	none	Fill value substitution rate factor
FVcorr		Fill value corrected for ammonia and acids
gain_fat	g/d	Daily fat gain
gain_prot	g/d	Daily protein gain
$\text{gain\_response}_{AAT}$	g/d	Predicted weight gain from avaliable AAT_N
$\text{gain\_response}_{NEG}$	g/d	Predicted weight gain from avaliable energy
GE	MJ/d	Gross energy
gest_day	days	Days of gestation
I	mg/kg DM	Iodine in feedstuff
IB		Icelandic breed
iCP	g/kg CP	Indigestible crude protein in feedstuff
IC	FV/d	Intake capacity
IC_bull	FV/d	Growing bulls intake capacity
IC_cow	FV/d	Intake capacity of lactating cows
IC_dry	FV/d	Intake capacity of dry cows
IC_exercise		Effect of exercise on instake capacity
IC_gest		Effect of gestation on intake capacity
IC_heifer	FV/d	Growing heifers intake capacity
IC_Jersey	FV/d	Intake capacity of growing cattle of Jersey breed
iNDF	g/kg NDF	Indigestible NDF in feedstuff
iST	g/kg ST	Indigestible starch in feedstuff
IVOS	% of OM	Organic matter digestibility of feedstuff (IVOS method)
JER		Jersey
K	g/kg DM	Potassium in feedstuff
K_excreted	g/d	Potassium excreted in faeces and urine

Abbreviation	Unit	Parameter name
K_gain	g/d	Potassium requirement for weight gain in growing cattle and primiparous cows
K_gest	g/d	Potassium requirement for gestation
K_intake_Min	g/d	Potassium minimum recommendation
K_main	g/d	Potassium requirement for maintenance
K_milk	g/d	Potassium requirement for milk production
K_u	g/d	Potassium utilization total
K_u_pct	%	Potassium utilization
kd	%/h	Fractional degradation rate
kdCP	%/h	Degradation rate of potentially degradable crude protein in feedstuff
kdNDF	%/h	Degradation rate of potentially degradable NDF in feedstuff
kdRestCHO	%/h	Degradation rate of rest fraction in feedstuff
kdST	%/h	Degradation rate of potentially degradable starch in feedstuff
k_g	MJ/MJ	Utilisation of ME to NE for growth
k_{g_corr}	MJ/MJ	Utilisation of ME to NE for growth
k_m	MJ/MJ	Utilisation of ME to NE for maintenance
k_{mg}	MJ/MJ	Utilisation of ME to NE for growth and maintenance
kp	%/h	Fractional passage rate
l_milk	g/kg milk	Observed or expected lactose content in milk
LAF	g/kg DM	Lactic acid in feedstuff
li_mCFat	g/d	Microbial crude fat synthesis in the large intestine
li_mCP	g/d	Microbial protein synthesis in the large intestine
lid_NDF	g/d	NDF digested in the large intestine
lid_ST	g/d	Starch from feed digested in the large intestine
m_Comp	g/100 g	Individual amino acid composition of microbial amino acids
MBT	none	Mobile bag technique
mCFat	g/d	Microbial crude fat
mCP	g/d	Microbial crude protein
ME	MJ/d	Metabolizable energy
Mg	g/kg DM	Magnesium in feedstuff
Mg_gain	g/d	Magnesium requirement for weight gain in growing cattle and primiparous cows
Mg_gest	g/d	Magnesium requirement for gestation
Mg_intake_Min	g/d	Magnesium minimum recommendation
Mg_main	g/d	Magnesium requirement for maintenance
Mg_milk	g/d	Magnesium requirement for milk production
Mn	mg/kg DM	Manganese in feedstuff
Mo	mg/kg DM	Molybdenum in feedstuff
MP	g/d	Metabolizable protein
MPY	g/d	Milk protein yield
MRT	H	Mean retention time in the rumen
MR		Effect of metabolic regulation on intake capacity
mST	g/d	Microbial starch in the rumen
MY	kg/d	Milk yield
N		Nitrogen

Abbreviation	Unit	Parameter name
N_excreted	g/d	Nitrogen excreted in faeces and urine
N_faeces	g/d	Nitrogen excreted in faeces
N_gain	g/d	Nitrogen utilization for weight gain in primiparous cows and growing cattle
N_gest	g/d	Nitrogen utilization for gestation
N_milk	g/d	Nitrogen utilization for milk
N_u	g/d	Nitrogen utilization total
N_u_pct	%	Nitrogen utilization
N_urine	g/d	Nitrogen excreted in urine
N_urine_pct	%	Nitrogen excreted in urine (percentage)
Na	g/kg DM	Sodium in feedstuff
Na_gain	g/d	Sodium requirement for weight gain in growing cattle and primiparous cows
Na_gest	g/d	Sodium requirement for gestation
Na_intake_Min	g/d	Sodium minimum recommendation
Na_main	g/d	Sodium requirement for maintenance
Na_milk	g/d	Sodium requirement for milk production
NDF	g/kg DM	Neutral detergent fibre in feedstuff
NDFD	%	Apparent total digestibility of NDF
NDFIr	kg/d	Intake of roughage NDF
NDFr	g/kg DM	NDF in roughage
NDS	g/kg DM	Neutral detergent solubles
NDSD	g/g	Digested neutral detergent solubles
NE	none	Net energy
NE_gest	MJ/d	Net energy requirement for gestation
NE_maint	MJ/d	Net energy requirement for maintenance
NEG	MJ/d	Net energy growth
NEG_bal	%	Energy balance for growing cattle
NEG_DM	MJ/kg DM	Net energy growth
NEG_gain	MJ/d	Energy requirement for growth of growing cattle
NEL	MJ/d	Net energy lactation
NEL_{20}	MJ/kg DM	Standard feed value for NEL at 20 kg DMI
NEL_8	MJ/kg DM	Standard feed value for NEL at 8 kg DMI
NEL_bal	%	Energy balance for cows
NEL_dep	MJ/d	Energy requirement for deposition in cows
NEL_DM	MJ/kg DM	Net energy for lactation in ration
NEL_gain	MJ/d	Energy requirement for weight gain in primiparous cows
NEL_milk	MJ/d	Energy requirement for milk production
NEL_mob	MJ/d	Energy supply from mobilisation in cows
NEL_variable	%	Energy balance variable, depending on mobilisation and deposition
NH_3N	g N/ kg N	Ammonia nitrogen in feedstuff
NIRS	none	Near infrared spectroscopy
NR		Norwegian Red
OM	g/kg DM	Organic matter in feedstuff
OMD	%	Apparent total digestibility of organic matter
P	g/kg DM	Phosphorus in feedstuff
P_excreted	g/d	Phosphorus excreted in faeces and urine

Abbreviation	Unit	Parameter name
P_gain	g/d	Phosphorus requirement for weight gain in growing cattle and primiparous cows
P_gest	g/d	Phosphorus requirement for gestation
P_intake_Min	g/d	Phosphorus minimum recommendation
P_main	g/d	Phosphorus requirement for maintenance
p_milk	g/kg milk	Observed or expected protein content in milk
P_milk	g/d	Phosphorus requirement for milk production
P_u	g/d	Phosphorus utilization, total
P_u_pct	%	Phosphorus utilization
PBV_N_DM_Min	g/kg DM	Minimum recommendation of PBV_N
PBV_N	g/d	Protein balance in rumen, total
PBV_{N20}	g/kg DM	Standard feed value for PBV at 20 kg DMI
PBV_{N8}	g/kg DM	Standard feed value for PBV at 8 kg DMI
pdCP	g/kg CP	Potentially degradable crude protein in feedstuff
pdNDF	g/kg NDF	Potentially degradable NDF in feedstuff
pdST	g/kg ST	Potentially degradable starch in feedstuff
PL	mm	Most frequent particle length of feedstuff
PRF	g/kg DM	Propionic acid in feedstuff
Protein_mass	kg	Protein mass
Protein_respons	g/d	Predicted milk protein yield
q		Ratio between ME and GE
r_emCP	g/kg rd OM	Efficiency of microbial protein synthesis in the rumen
r_kp1	%/h	Rumen passage rate of NDF particles>6mm from pool 1 to 2
r_kp2	%/h	Rumen passage rate of NDF particles>6mm from pool 2
r_kpc	%/h	Rumen passage rate of protein and starch particles<=6mm
r_kpl	%/h	Rumen passage rate of liquid
r_kpNDFc	%/h	Rumen passage rate of NDF particles<=6mm
r_kpNDFr	%/h	Rumen passage rate NDF particles>6mm
r_kpr	%/h	Rumen passage rate of protein and starch particles>6mm
r_mAA	g/d	Microbial synthesis of amino acids in the rumen
r_mCFat	g/d	Microbial crude fat synthesis in the rumen
r_mCP	g/d	Microbial protein synthesis in the rumen
r_mOM	g/d	Microbial synthesis of organic matter in the rumen
r_mST	g/d	Microbial starch synthesis in the rumen
r_outOM	g/d	Passage of organic matter to small intestine
RD		Red Danish
rd_CFat	g/d	Crude fat degraded in the rumen
rd_CP	g/d	Crude protein degraded in the rumen
rd_CPcorr	g/d	Corrected crude protein degraded in the rumen
rd_FPF	g/d	Fermentation products from feed degraded in the rumen
rd_NDF	g/d	NDF degraded in the rumen
rd_NH_3N_CP	g/d	NH_3-crude protein degraded in the rumen
rd_OM	g/d	Rumen degraded organic matter

Abbreviation	Unit	Parameter name
rd_pdCP	g/d	Potentially degradable crude protein degraded in the rumen
rd_pdNDFc	g/d	Potentially degradable NDF in concentrate degraded in the rumen
rd_pdNDFr	g/d	Potentially degradable NDF in roughage degraded in the rumen
rd_pdST	g/d	Potentially degradable starch degraded in the rumen
rd_RestCHO	g/d	Rest CHO fraction degraded in the rumen
rd_sCP	g/d	Soluble crude protein degraded in the rumen
rd_sST	g/d	Soluble starch degraded in the rumen
rd_ST	g/d	Total starch degraded in the rumen
RestCHO	g/kg DM	Rest fraction in feedstuff
RestCHOcorr	g/kg DM	Rest fraction corrected in feedstuff
RFA	g/kg CFat	Residual fatty acids
RI	min/kg DM	Rumination index
RLI	g/g NDF	Rumen load index, rumen degraded starch and rest fraction per unit of NDF
Rough_share	% of DM	Roughage percentage in the diet
roughage_appetite	%	Roughage appetite proportion
RT_o	min/kg NDF	Observed ruminating time
RUP		Rumen undegradable protein
S	g/kg DM	Sulphur in feedstuff
s+pdCP	g/kg CP	Sum of sCP and pdCP in feedstuff
sCP	g/kg CP	Soluble crude protein in feedstuff
Se	mg/kg DM	Selenium in feedstuff
si_outOM	g/d	Passage of organic matter to the large intestine
sid_AA	g/d	Amino acids from feed digested in the small intestine
sid_AA_j		Individual amino acids from feed digested in the small intestine
sid_CFat	g/d	Crude fat from feed digested in the small intestine
sid_CP	g/d	Crude protein from feed digested in the small intestine
sid_eAA	g/d	Endogenous amino acids digested in the small intestine
sid_mAA	g/d	Microbial amino acids digested in the small intestine
sid_mCP	g/d	Microbial crude protein digested in the small intestine
sid_mFA	g/d	Microbial fatty acids digested in the small intestine
sid_mST	g/d	Microbial starch digested in the small intestine
sid_ST	g/d	Starch from feed digested in the small intestine
SH		Swedish Holstein
SR		Swedish Red
sST	g/kg ST	Soluble starch in feedstuff
ST	g/kg DM	Starch in feedstuff
ST_SU_DM	g/kg DM	Content of starch and sugar in the diet
ST_SU_intake	g/d	Total intake of starch and sugar
STD	%	Apparent total digestibility of starch
SU	g/kg DM	Sugar in feedstuff

Abbreviation	Unit	Parameter name
SubR	none	Substitution rate
TAF	g/kg DM	Total acids in feedstuff
TCL	mm	Theoretical cutting length
td_CFat	g/d	Total apparently digested crude fat
td_CHO	g/d	Total apparently digested carbohydrates
td_CP	g/d	Total apparently digested crude protein
td_CPcorr	g/d	Total apparently digested crude protein corrected
td_OM	g/d	Total apparently digested organic matter
TMR	g/kg DM	Total mixed ration
uNDF	g/kg DM	Undegraded NDF
uNDS	g/kg DM	Undegraded neutral detergent solids
uOM	g/g	Undegraded organic matter
Urea N		Urea nitrogen
VFA		Volatile fatty acids
VitA	1000 IU/kg DM	Vitamin A in feedstuff
VitD	1000 IU/kg DM	Vitamin D in feedstuff
VitE	IU/kg DM	Vitamin E in feedstuff
VOS	% of OM	Organic matter digestibility of feedstuff *in vitro* (VOS method)
YHerd	kg ECM/year	Yield level in the herd
Zn	mg/kg DM	Zinc in feedstuff
WPC	weeks	Weeks post calving

1. Introduction

H. Volden and A.H. Gustafsson

Feed is one of the major expenses in modern cattle production. In addition to feed prices, its overall costs are affected by the efficiency of feed utilization and the output of animal products to be marketed. Hence, there is a clear need to evaluate feed quality in order to maximise profitability. This requires information on both animal requirements and nutrient supply, since formulation of an appropriate ration involves balancing available feeds in proportions that match the amounts of nutrients supplied to the animals' nutrient requirements as closely as possible. There are two principal methods used to describe animal nutrition: those based on mechanistic approaches, which describe responses to nutrients from chemical and physiological processes in the gastrointestinal tract and intermediary, and empirical approaches describing simple relationships between nutrient intakes and production responses. The challenge in the development of new feed evaluation systems is to accurately predict responses to nutrients so that any difference in product income and feed costs can be maximized, while improving overall feed efficiency. Feed efficiency is also of great importance due to its impact on enteric methane emission to the atmosphere and nitrogen and phosphorus passing into the environment.

Feed evaluation for cattle has long traditions. Important milestones are introductions of the Weende analysis by Henneberg and Stohmann (1864), and the starch equivalent system by Kellner (1912). In the Nordic countries the introduction of the milk production value by Hansson (1913) and the Scandinavian feed unit by Møllgaard (1929) were of great magnitude for modern cattle production. Extensive research in the 1950's and 60's further improved our knowledge in feed evaluation, and in the period from 1970 to 1990 most countries introduced new systems for energy based either on metabolizable energy (ME) or net energy for lactation (NEL) or growth (NEG) (Van der Honing and Alderman, 1988). Also the knowledge of protein evaluation for cattle have increased considerably during the last 40 years, from use of total or digestible crude protein to the protein evaluation systems that predict the host animal amino acid (AA) supply from dietary protein escaped ruminal degradation and from microbial protein synthesized in the rumen (Madsen, 1985; NRC, 1985; Vérité *et al*., 1987; AFRC, 1992; Tamminga *et al*., 1994).

Traditional feed evaluation systems are additive and generally do not take into account interactions in digestion and nutrient metabolism. When interactions and non-linear relationships are considered, in attempts to describe feed metabolism, individual feeds will no longer have fixed values. Hence, the value of a given feedstuff will depend on how the feed is used. This means that the feed value cannot be determined until we know which feed ration will be used and the production situation in which it will be applied. Therefore, the development of a new feed evaluation system must consist of a ration evaluation system which can be used to optimize nutrient supply and production responses, rather than a system that can predict individual feed values. Development of new feed evaluation systems (Russell *et al*., 1992; Sniffen *et al*., 1992; Fox *et al*., 1992; NRC, 2001) and mechanistic models (Baldwin, 1995; Danfær *et al*., 2006), which describe nutrient supply and the nutritional requirements of cattle, are important for understanding ruminant nutrition and constitute an important step towards implementing more sophisticated nutritional strategies to optimize production responses in cattle. The use of non-linear semi-mechanistic feed evaluation systems for ration optimization requires powerful computing tools. Recent improvements in non-linear optimization tools and algorithms enable the development of more complex feed evaluation systems that can also be used in practice.

The aim of this book is to provide a detailed description of the semi-mechanistic feed evaluation system NorFor, which has already been implemented by advisory services in four Nordic countries, i.e. Denmark, Iceland, Norway and Sweden.

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9_1, © Wageningen Academic Publishers 2011

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2. Overall model description

H. Volden

The NorFor system is a semi-mechanistic, static and science-based model, which predicts nutrient supply and requirements for maintenance, milk production, growth and pregnancy in cattle. The model can be divided into five parts: (1) an input section describing characteristics of the animal and feeds available; (2) a module simulating processes in the digestive tract and the intermediary metabolism, termed the feed ration calculator (FRC); (3) a module predicting feed intake; (4) a module predicting the physical structure of the diet; and (5) an output section describing nutrient supply, nutrient balances and production responses (Figure 2.1).

The input variables for the model are animal and feed characteristics. For dairy cows, the main input variables are body weight (BW), stage of lactation, pregnancy day and planned or potential daily milk production. For growing animals (bulls, steers and heifers) input variables are BW and average daily weight gain (ADG). The feed dry matter (DM) is separated into ash, crude protein (CP), crude fat (CFat), neutral detergent fibre (NDF), starch (ST), sugar (SU), fermentations products (FPF) such as organic acids and alcohols, and a residual fraction (RestCHO). The CP is divided into soluble (sCP), potentially degradable (pdCP), indigestible (iCP) and ammonia (NH_3N). The NDF is divided into a total indigestible (iNDF) and a potentially degradable (pdNDF) fraction. The ST is divided into soluble (sST), potentially degradable (pdST) and indigestible (iST) fractions. The FPF are separated into lactic acid (LAF), volatile fatty acids (VFA) and alcohols. Fractional degradation rates (kd) of the soluble and potentially degradable feed fractions are also required for the model.

The FRC consists of four sections: (1) the rumen, (2) the small intestine, (3) the large intestine and (4) metabolism (Figure 2.2). Feed organic matter (OM) entering the rumen is either fermented and used for microbial production, or it escapes from the rumen for further digestion in the lower digestive tract. Ruminal degradation of CP, ST and NDF in concentrate feeds are assumed to follow first-order single-compartment kinetics, while degradation of NDF in roughage is modelled as a

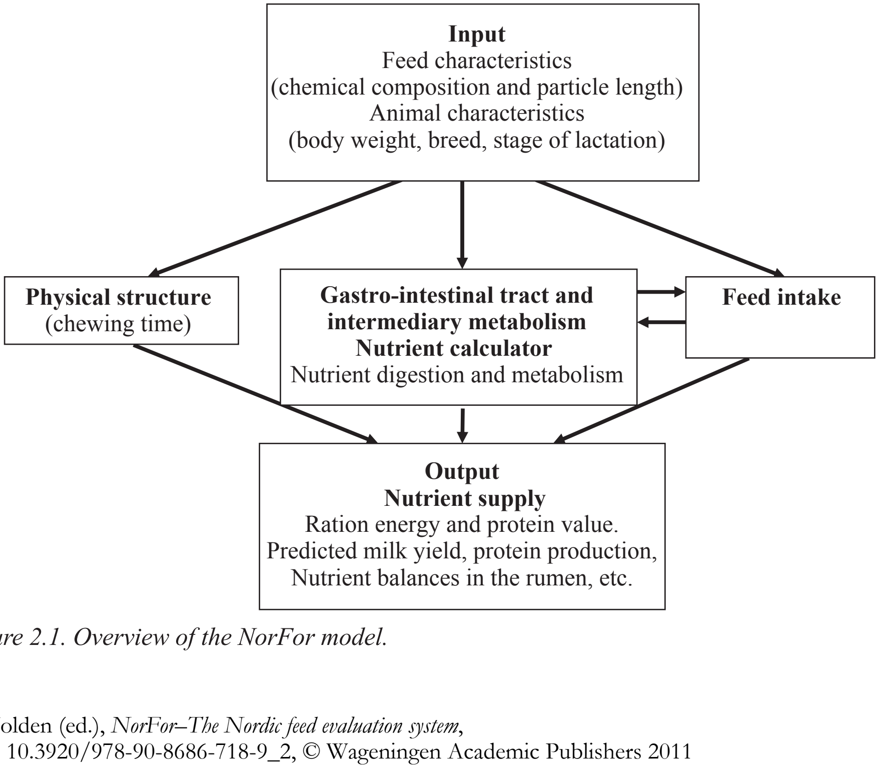

Figure 2.1. Overview of the NorFor model.

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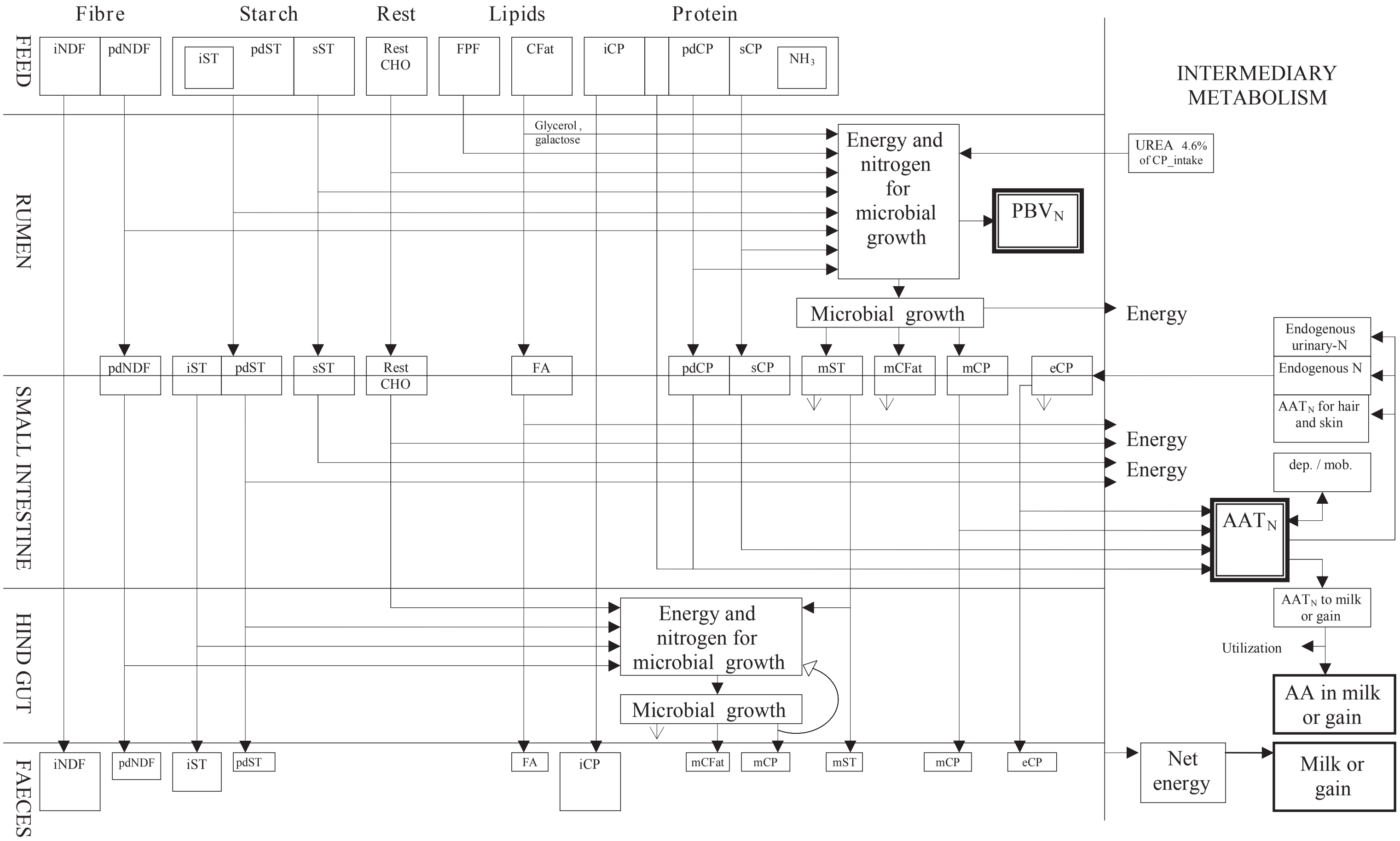

Figure 2.2. Flow diagram of the gastrointestinal tract and intermediary compartments of the NorFor feed evaluation system. For all abbreviations check the abbreviation list.

two-compartment system, with a non-escapable and an escapable pool. The nutrients available for microbial growth come from ruminally degraded NDF, ST, RestCHO, glycerol, CP and LAF. The efficiency of microbial synthesis depends on the level of feed intake and diet composition. The input to the small intestine consists of OM from microbes, unfermented feed fractions escaping from the rumen and endogenous secretions. These components are partly digested in the small intestine and are either metabolised or enter the large intestine. The OM passing into the large intestine is subjected to microbial fermentation, and the digested OM not used for microbial synthesis is absorbed and metabolised. Faecal excretion consists of OM from microbes synthesised in the large intestine, feed that has escaped previous digestion and undigested rumen microbial material. The intermediary metabolism section yields ME calculated from total tract digestible OM. Net energies for maintenance, lactation, growth and pregnancy are predicted from the ME. Different coefficients are used to calculate NE for maintenance, lactation, and growth. Net energy for lactation is used for dairy cows, while NEG is used as the energy measurement for growing cattle.

The nitrogen (N) fractions entering the intermediary metabolism consist of NH_3N absorbed from the rumen, dietary, microbial and endogenous amino acids (AA) absorbed from the small intestine, and NH_3N from the large intestine. The absorbed AAs are utilized for maintenance, growth, pregnancy and milk production. The efficiency of AA utilization is specific for each production/process. The metabolizable protein available for animal production is assigned as amino acids absorbed from the small intestine (AAT_N). The N which is not used for maintenance or production is excreted in the urine.

Predicting nutritive value is only one part of ration formulation as formulation involves both the selection of feed ingredients and the prediction of feed intake. Therefore, the NorFor system contains a module to predict the intake of feeds. For prediction of feed intake dietary fill values (FV) and animal intake capacity (IC) are applied. In roughages, FV is calculated from OM digestibility (OMD) and NDF content, and in ensiled forages the basic FV is also corrected for content of VFA, LAF and NH_3N. Animal IC is dependent on BW, milk yield, stage of lactation, lactation number, ADG and physical activity. The model uses a combination of dietary physical effects and metabolic factors to impact feed intake, and the effect of easily fermentable carbohydrates on roughage intake is accounted for by using a substitution rate factor (SubR).

A minimum amount of large particles is essential for optimal rumen function. Hence, a module to evaluate the physical structure of the diet is included in NorFor. The dietary physical effect is described by a total chewing index (CI), which is calculated as the sum of an eating (EI) and ruminating (RI) index for each individual feed. The EI value reflects the associated chewing activity as feed is consumed and is calculated from the particle length and NDF content of the feed. The RI value is calculated from particle length, NDF content and a hardness factor, which is dependent on the iNDF content of the feed. The hardness factor reflects the lignification of the structural fibre of the feed and the associated physical force required for the comminution of large particles.

The output from a model calculation in NorFor describes the intake of the individual feeds in the total ration. It consists of variables describing efficiencies of digestion and nutrient utilization, production (milk, ADG), N excretion, nutrient balances, energy (NEL or NEG) and protein (AAT_N) values of the ration.

3. Animal input characteristics.

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Animal characteristics are needed for calculation of nutrient requirements and IC for both cows and growing cattle. Information on animal parameters, such as BW, is also needed when calculating ruminal variables, such as passage rates of feed fractions out of the rumen and efficiency of microbial protein synthesis. Moreover, the physical activity of the animal (simply classified according to whether it is loose or tied up) will affect the IC and energy requirements.

3.1 Input data for cows

All required input data for cows are listed in Table 3.1 and default values for different breeds are compiled in Table 3.2. The information needed for cows in the system is breed, lactation number, BW, stage of lactation (days in milk) and milk production. Pregnancy and whether the cow is dry or lactating are also factors required for determining IC and requirements for gestation. When calculating energy and protein requirements for gestation, information on mature body weight (BW_mat) is needed since this variable is breed-specific (see Table 3.2 and Sections 9.1.3 and 9.2.5). BW_mat is also needed to determine protein requirements for growth in primiparous cows (Section 9.2.3).

Animal weight changes can be estimated as changes in body condition score (BCS), where the BW per condition scores depends on the breed. The BCS in NorFor uses a scale from 1 to 5, where 1 is thin and 5 is fat (Gillund *et al*., 1999). One unit of BCS corresponds to 60 kg BW except for Jersey which is set to 45 kg BW; these values are based on data from several previous studies (e.g. Enevoldsen and Kristensen,1997; Gillund *et al*., 1999; Nielsen *et al*., 2003; Bossen, 2008).

Table 3.1 Input data for cows in NorFor.

Input data	Unit
Dry cow	none[1]
Lactation number	No.
Days in milk	days
Daily milk yield	kg/day
Protein content in milk	g/kg
Fat content in milk	g/kg
Lactose content in milk	g/kg
Yield level of the herd	kg ECM
Body weight, current	kg
Body weight, mature[2]	kg
Weight gain in primiparous cows	kg/day
Days of gestation	days
Daily change in body condition score	BCS/day
Weight per unit body condition score[2]	kg/BCS
Activity	none[1]
Breed[3]	none[1]

[1] No unit.

[2] Default values can be taken from Table 3.2.

[3] Abbreviations for breeds are explained in Table 3.2.

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DOI 10.3920/978-90-8686-718-9_3, © Wageningen Academic Publishers 2011

Table 3.2. Default values for mature body weight (BW_mat) and the weights corresponding to a body condition score unit (BCS_kg) for dairy cows of different breeds.

Abbr.	Dairy breed	BW_mat kg	BCS_kg kg/BCS
DH	Danish Holstein	640	60
IB	Icelandic breed	470	60
JER	Jersey	440	45
NR	Norwegian Red	600	60
RD	Danish Red	660	60
SH	Swedish Holstein	640	60
SR	Swedish Red	620	60

The energy requirement for milk production is based on the production of energy corrected milk (ECM), which can be calculated from either of two equations (Sjaunja *et al.*, 1990) depending on whether information on milk lactose content is available:

$$\mathrm{ECM} = \mathrm{MY} \cdot \left(0.01 + 0.122 \cdot \frac{\mathrm{f\_milk}}{10} + 0.077 \cdot \frac{\mathrm{p\_milk}}{10} + 0.053 \cdot \frac{\mathrm{l\_milk}}{10}\right) \quad 3.1$$

$$\mathrm{ECM} = \mathrm{MY} \cdot \left(0.25 + 0.122 \cdot \frac{\mathrm{f\_milk}}{10} + 0.077 \cdot \frac{\mathrm{p\_milk}}{10}\right) \quad 3.2$$

where ECM is the energy corrected milk, kg/day; MY is the daily milk yield, kg/day; and f_milk, p_milk and l_milk are the contents of fat, protein and anhydrous lactose in milk, respectively, g/kg.

When formulating feed rations for groups of cows, the daily ECM yield (ECMherd) can be estimated from breed-specific lactation curves:

$$\mathrm{ECMherd} = a + b \cdot \mathrm{YHerd} - c \cdot \mathrm{DIM} + \ln(\mathrm{DIM}) \cdot d \quad 3.3$$

where ECMherd is the daily estimated ECM yield, kg/d; YHerd is the herd's average ECM yield per cow, kg/305 d; DIM is days in milk; a, b, c and d are regression coefficients presented in Table 3.3 for primiparous and multiparous cows of different breeds.

Standard lactation curves are available for different dairy breeds and lactation numbers. The ECMHerd value refers to the herd's 305-d lactation yield, which is based on national herd recording data. Danish cow recording data (Danish Cattle Association) have been used to parameterize the standard lactation curves for the dairy breeds Jersey, Danish Holstein and Danish Red. Icelandic, Norwegian and Swedish national herd recording data are the basis for the standard lactation curves for the Icelandic breed, Norwegian Red, Swedish Holstein and Swedish Red cattle, respectively (Farmers Association of Iceland; Tine Dairies in Norway; Swedish Dairy Association).

Daily milk protein yield is calculated from milk yield and milk protein content according to Equation 3.4. Protein production is essential for calculating the AA requirement for milk production:

$$\mathrm{MPY} = \mathrm{MY} \cdot \mathrm{p\_milk} \quad 3.4$$

where MPY is the milk protein yield, g/day; MY is the milk yield, kg/day; and p_milk is the milk protein content, g/kg.

Table 3.3. The multiple regression coefficients a, b, c and d is used to predict daily ECM yield from standardised lactations curve in Equation 3.3.

Breed[1]	Lactation	a	b	c	d
DH	primiparous	-3.10	0.00325	0.01685	1.140
DH	multiparous	3.17	0.00338	0.06040	1.025
IB	primiparous	0.88	0.00288	0.04009	1.627
IB	multiparous	6.34	0.00269	0.06234	1.569
JER	primiparous	-8.15	0.00324	0.02810	2.654
JER	multiparous	-2.98	0.00335	0.05630	2.305
NR	primiparous	-7.09	0.00314	0.06440	3.741
NR	multiparous	-0.59	0.00310	0.09100	3.378
RD	primiparous	-6.20	0.00335	0.02138	1.750
RD	multiparous	1.45	0.00330	0.06973	1.844
SH	primiparous	-4.05	0.00299	0.03560	2.591
SH	multiparous	2.93	0.00299	0.06100	1.997
SR	primiparous	-4.46	0.00304	0.03970	2.677
SR	multiparous	-0.21	0.00317	0.06920	2.520

[1] The abbreviations of the different breeds are shown in Table 3.2.

3.2 Input data for growing cattle

When calculating nutrient requirements and the IC for growing cattle, information on BW, ADG, sex, breed and activity are needed, and for heifers the days of gestation are also required (Table 3.4).

Table 3.4. Input data for growing cattle.

Parameter	Unit
Sex	none[1]
Breed[2]	none[1]
Activity	none[1]
Body weight[3]	kg
Average daily gain[3]	g/day
Days of gestation (heifers)	days
Body weight, birth[4]	kg
Body weight, start[4]	kg
Body weight, end[4]	kg
Body weight, mature[4]	kg
Age, start[4]	days
Age, current[4]	days
Age, end[4]	days

[1] No unit.

[2] The classifications of different breeds are shown in Table 3.5.

[3] Body weight and daily gain are required parameters and can be estimated from the parameters that are marked by [4].

[4] These parameters are required if current body weight and average daily gain data are not available.

3.2.1 Estimation of body weight and daily weight gain from a growth function

When planning feed rations for animals of different ages, data of BW_mat, age and BW at the start of the rearing period and planned age and BW at the end of the rearing period are needed. Expected BW and ADG can be estimated from the following logistic growth equation based on:

$$BW\_calc = BW\_start \cdot e^{(A \cdot (1 - e(-B \cdot (Age - Age\_start))))} \tag{3.5}$$

where BW_calc is the estimated BW for the current age, kg; BW_start is the BW at the start, kg; A is described in Equation 3.7; B is described in Equation 3.8; Age is the current age, days; Age_start is the age at start, days. If Age_start is 0 the BW_start is the same as BW_birth.

$$ADG\_calc = \left(BW\_start \cdot e^{(A \cdot (1 - e(-B \cdot (Age - Age\_start + 1))))} - BW\_start \cdot e^{(A \cdot (1 - e(-B \cdot (Age - Age\_start))))}\right) \cdot 1000 \tag{3.6}$$

where ADG_calc is the estimated average daily gain for the current age, g/day; BW_start is the BW at the start, kg; A is described in Equation 3.7; B is described in Equation 3.8; Age is the current age, days; Age_start is the age at start, days. If Age_start is 0 the BW_start is the same as BW_birth.

Factor A and B in Equations 3.5 and 3.6 are calculated as:

$$A = \ln\left(\frac{BW\_mat \cdot 1.1}{BW\_start}\right) \tag{3.7}$$

$$B = \frac{\ln\left(\frac{\ln(BW\_mat \cdot 1.1 / BW\_start)}{\ln(BW\_mat \cdot 1.1 / BW\_end)}\right)}{Age\_end - Age\_start} \tag{3.8}$$

where A and B are factors used in Equations 3.5 and 3.6; BW_mat is the mature body weight, kg; BW_start is the body weight at start or at birth, kg; BW_end is the body weight at the end of the feeding period; Age_start is the age at start, days; and Age_end is the age at the end of the feeding period, days. If Age_start is 0 days, the BW_start is the same as BW_birth.

An example of the logistic growth function of ADG and BW during the rearing period is shown in Figure 3.1.

The end of the feeding period depends on whether the animal will be sold, slaughtered or used for replacement. Default values for birth weights (BW_birth) and BW_mat that can be used for estimating BW and ADG for different breeds and gender are shown in Table 3.5. BW_birth values for beef breeds were collected from Danish, Norwegian and Swedish national recording data compiled by the Danish Cattle Association, Norwegian Meat and Poultry Research Centre and Cattle statistics (2007), respectively. Values for BW_mat were taken from Danish, Norwegian and Swedish slaughter data for animals over 4 years of age over the last 10 years supplied by the Danish Cattle Association; Norwegian Meat and Poultry Research Centre and Swedish Dairy Association, respectively.

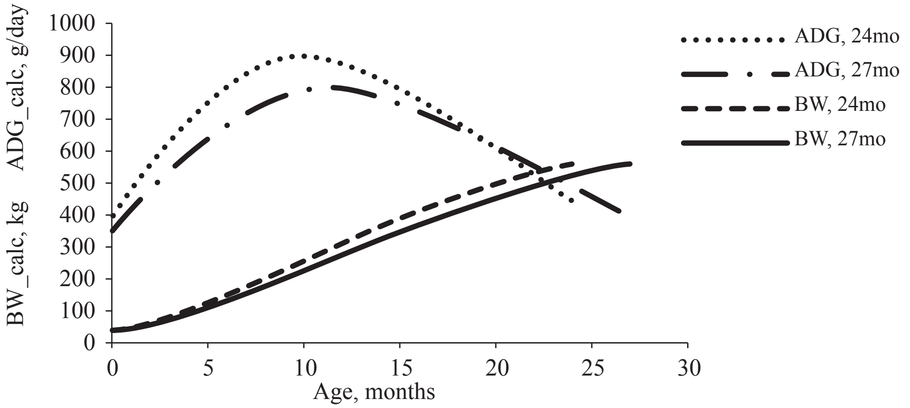

Figure 3.1. A logistic growth function predicting BW (BW_calc) and estimated weight gain (ADG_calc) during the rearing of a heifer which is scheduled to calve at a live weight of 560 kg at either 24 or 27 months of age. To achieve a final weight of 560 kg, the weight gain is faster for a heifer finished at 24 months of age (ADG, 24mo; BW, 24mo) than for a heifer finished at 27 months (ADG, 27mo; BW, 27mo).

Table 3.5. Default values for birth weight (BW_birth) and mature body weight (BW_mat) for heifers, bulls and steers of different breeds.

Breeds	BW_birth for heifer kg	BW_birth for bulls kg	BW_mat for heifer kg	BW_mat for bulls kg	BW_mat for steers kg
Early maturing dairy breeds					
Danish Holstein	40	41	640	950	750
Danish Red	40	41	660	950	750
Icelandic breed	33	33	470	800	700
Jersey	28	30	440	650	550
Norwegian Red	39	41	600	950	750
Swedish Holstein	39	41	640	950	750
Swedish Red	39	41	620	950	750
Early maturing beef breeds					
Aberdeen Angus	36	38	700	950	750
Dexter	21	24	340	450	400
Galloway	34	35	550	850	750
Hereford	40	42	700	950	750
Highland cattle	29	30	500	700	600
Tiroler Grauvieh	39	42	700	950	750
Late maturing beef breeds					
Belgian Blue	44	47	850	1,200	1,050
Blonde d'Aquitaine	44	47	850	1,200	1,050
Charolais	46	49	750	1,200	1,050
Chianina	50	55	850	1,200	1,050
Limosin	41	43	750	1,200	1,050
Piemontese	41	43	750	1,200	1,050
Saler	39	41	750	1,200	1,050
Simmenthal	44	46	750	1,200	1,050
Early·late maturing breed					
Crossbred[1]	42	44	750	1,050	950

[1] Crossbreeds of early and a late maturing breeds are assigned specific factors in some of the equations in Chapter 9.

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4. Feed fraction characteristics

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Absorbed nutrients are provided from fermentation and digestion in the gastrointestinal tract, and the predictions are sensitive to the nutrient profiles of the feed. NorFor has an extensive feed table (www.norfor.info) that lists chemical composition and digestion characteristics of typical Nordic feedstuffs. The feed table values are continuously updated as new information becomes available.

4.1 Definition of roughage and concentrates

Roughage and concentrates are feedstuff classes that are generally used and several criteria characterize both groups of feedstuffs, e.g. fibre content, energy density, moisture content and particle length. In NorFor it is necessary to identify a feedstuff either as 'roughage' or 'concentrate'. This is decided from information on particle length; feedstuffs with particle lengths greater or less than 6 mm are characterized as roughages and concentrates, respectively. The identification of feedstuff class is necessary when describing the feed FV and in the calculation of the CI. This information is also necessary to predict the fractional passage rate of a feed fraction out of the rumen. Feedstuffs are further classified as liquid, fine, coarse, rolled, chopped, and unchopped, since this is used for identification of most frequent particle length (PL) which affects the calculated CI values.

4.2 Division of organic matter

The DM is separated into OM and ash. The OM is further divided into the following components: CP, NDF, ST, CFat, LAF, VFA, alcohols and a calculated RestCHO fraction including SU. The main chemical components are further divided into sub-fractions (Figure 4.1) that have uniform rates of kd in the rumen.

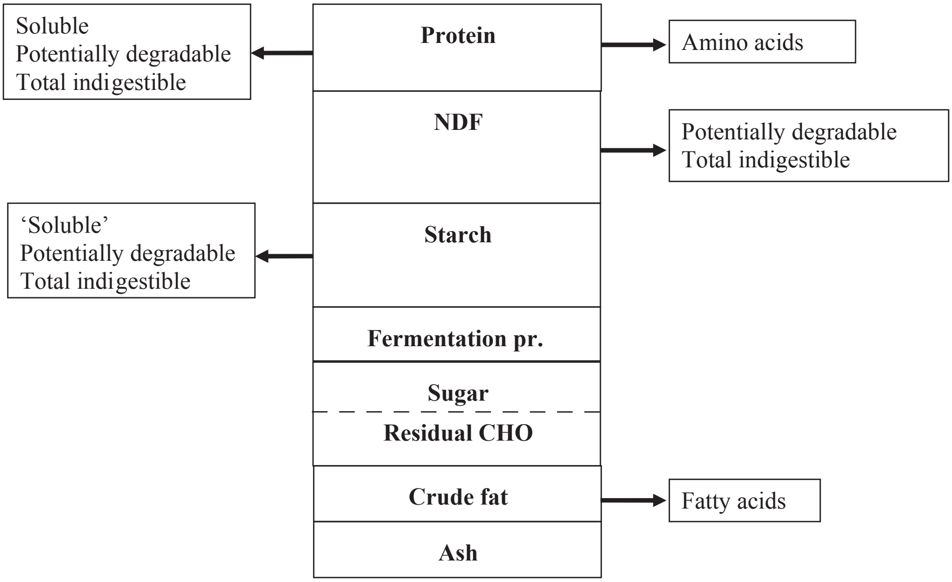

Figure 4.1. The feed fractionation scheme in NorFor.

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4.3 Crude protein fractions and amino acids

The composition and properties of dietary proteins strongly influence protein metabolism in the gastrointestinal tract of ruminants, hence information on these variables is essential for robust feed evaluation. Feed CP (N·6.25) consists primarily of AA and smaller amounts of non-amino nitrogen, which is composed of NH_3N, urea and nucleic acids. In NorFor CP is partitioned into three fractions: (1) soluble (sCP), (2) potentially degradable in the rumen (pdCP) and (3) total tract-indigestible (iCP). As example, Table 4.1 presents average CP fractions for a limited number of common feedstuffs.

The sCP fraction contains soluble proteins, peptides, free AA, and non-amino nitrogen. When calculating ruminal degradation of the sCP fraction instantaneous degradation of NH_3N and urea is assumed and a fractional degradation rate of 150%/h is used for the soluble AA fractions (Russel *et al*., 1992; Volden *et al*., 1998, 2002). The pdCP fraction is assumed to be insoluble, but degradable by microbes in the rumen. Individual rates of degradation (kdCP) for the pdCP fraction are estimated from ruminal degradation profiles using the *in sacco* technique (see Section 5.2.2 for a description of the method), assuming that the degradation profile follows first-order kinetics. Intestinal digestibility of the undegraded rumen feed protein (RUP) may vary considerably between feeds (Hvelplund, 1985; Van Straalen and Tamminga, 1990; Volden and Harstad, 1995). The *in sacco* mobile bag technique (MBT) provides an easy and fast method to determine intestinal digestibility of protein (Hvelplund *et al*., 1992, 1994) (see Section 5.2.4 for a description of the method). In NorFor, the MBT technique is used to determine feed iCP. The iCP represents a protein fraction that is completely resistant to both microbial degradation in the rumen and digestion in the small intestine. However, ruminal pre-incubation has been shown to have important effects on the intestinal digestion of protein in several feeds (Volden and Harstad, 1995;Vanhatalo *et al*., 1996). Consequently, iCP is determined in feed residues after 16 and 24 h of ruminal incubation for concentrates and roughages, respectively. Volden and Harstad, 1995 observed that pre-incubation in the rumen increased intestinal digestion and thus reduced the iCP. This implies that the feed protein contains a fraction that is not degradable

Table 4.1. Crude protein (CP) fractions in selected feeds and the corresponding fractional degradation rate of the potential degradable protein fraction.

Feedstuff	NorFor feed code	CP g/kg DM	Protein fractions, g/kg CP			kdCP[4] %/h
			sCP[1]	pdCP[2]	iCP[3]	
Barley	001-0016	113	290	670	36	11.3
Wheat	001-0020	131	220	750	29	14.3
Maize	001-0014	96	114	886	51	2.5
Peas	003-0006	239	711	289	28	9.1
Rape seed	002-0007	218	280	660	85	9.5
Rape seed meal	002-0042	388	216	734	58	9.5
Soybean meal	002-0053	516	160	840	11	7.9
Maize silage, high digestibility	006-0307	78	464	432	140	4.6
Maize silage, low digestibility	006-0309	75	437	459	140	4.6
Grass silage, high digestibility	006-0461	173	668	267	38	12.1
Grass silage, low digestibility	006-0463	144	628	228	49	8.0

[1] sCP=soluble crude protein fraction.

[2] pdCP=potentially degradable crude protein.

[3] iCP=total indigestible crude protein.

[4] kdCP=fractional degradation rate of pdCP.

in the rumen, but is digestible in the small intestine, explaining why the sum of sCP + pdCP + iCP in most feedstuffs is not 1000 g/kg CP. The remaining CP fraction is added to the protein fraction digested in the small intestine.

The amount of RUP is one of the primary factors determining the amount of dietary AAs entering the small intestine. NorFor predicts individual AAs absorbed from the small intestine. Thus, information regarding the AA profile of the RUP is required. A variable fraction of the feed protein is degraded in the rumen and the AA profile of the RUP may differ from the AA profile of the intact feed protein. Several authors have compared the AA profiles of intact feed protein and *in sacco* residues after ruminal incubation (Skórko-Sajko *et al*., 1994; Skiba *et al*., 1996; Weisbjerg *et al*., 1996; Zebrowska *et al*., 1997; Prestløkken, 1999; Harstad and Prestløkken, 2000; Harstad and Prestløkken, 2001). Although a limited number of feeds were evaluated, the acquired data suggest that there are only minor differences between the AA profiles of intact feed protein and RUP. Therefore, the AA profile and the sum of AA nitrogen (AA-N) in RUP are assumed to be the same as those of the original feedstuff. The NorFor feedstuff table (www.norfor.info) has information on the AA profiles of individual feeds.

4.4 Carbohydrate fractions

Carbohydrates (CHO) are heterogeneous feed constituents that collectively comprise the largest component of cattle diets, and make the major contribution to supporting ruminal microbial growth. CHO digestion in the gastrointestinal tract varies considerably and the end-products from ruminal fermentation and intestinal digestion are the major nutrient supply for animal production. Moreover, the rate of CHO degradation in the rumen is a major factor affecting ruminal pH and thus the rumen environment and feed utilization. A good balance between the different CHO fractions is essential to maintain normal rumen function and optimize rumen fermentation.

Carbohydrates can be divided into two main fractions, structural and non-structural The structural CHO originates from plant cell wall material (consisting of cellulose, hemicellulose and lignin), which in NorFor is defined as NDF (Van Soest, 1994). The NDF fraction is further divided into a potentially degradable fraction (pdNDF) and a total indigestible fraction (iNDF). The iNDF is determined from ruminal *in sacco* incubation for 288 h (see Section 5.2.3 for a description of the method), and the pdNDF fraction is estimated as total NDF minus iNDF. In concentrates, the rate of pdNDF degradation (kdNDF) is estimated by *in sacco* degradation, assuming first-order degradation kinetics (see Section 5.2.2 for a description of the method). In roughage, kdNDF is predicted from the combination of *in vivo* OMD and iNDF and using the Lucas principle applied to the excretion of non-fibre matter (Weisbjerg *et al*., 2004a, b). A complete description of the method and calculations is presented in Section 6.1. Examples of NDF content and degradation characteristics in commonly used feedstuffs are presented in Table 4.2.

The non-structural carbohydrates consist of carbohydrate-based cell contents, including ST, SU, β-glucans and some of the pectins. In NorFor ST and SU are determined analytically, while β-glucans and pectins are part of the RestCHO fraction.

Starch is an important feed constituent for high-yielding cattle due to its high digestibility and importance as a source of substrates for propionic acid fermentation in the rumen. Inadequate ST intake may depress microbial activity and thus reduce microbial protein synthesis. However, excessive levels of ST may depress fibre digestibility and roughage utilization, as well as causing ruminal acidosis and abnormalities in the rumen tissue (Owens *et al*., 1998). Starch digestibility in the rumen depends on grain type, grain processing and particle length (Mills *et al*., 1999; Offner and Sauvant, 2004; Larsen *et al*., 2009). In NorFor, ST is partitioned into three fractions (Table 4.3): 'soluble' (sST), potentially degradable (pdST) and indigestible (iST). The ST fractions are calculated from *in sacco* degradation profiles (see Section 5.2.2). The sST fraction represents small starch particles

Table 4.2. NDF fractions in selected feeds and the corresponding fractional degradation rate of the potential degradable NDF fraction.

Feedstuff	NorFor feed code	NDF g/kg DM	NDF fractions, g/kg NDF		kdNDF[3] %/h
			pdNDF[1]	iNDF[2]	
Barley	001-0016	198	836	164	3.2
Wheat	001-0020	127	831	169	3.5
Maize	001-0014	111	913	87	3.0
Peas	003-0006	126	984	16	10.4
Rape seed	002-0007	188	686	314	13.3
Rape seed meal	002-0042	290	500	500	6.7
Soybean meal	002-0053	133	939	61	5.0
Maize silage, high digestibility	006-0307	338	828	172	3.4
Maize silage, low digestibility	006-0309	397	803	197	3.1
Grass silage, high digestibility	006-0461	501	888	112	5.0
Grass silage, low digestibility	006-0463	597	793	207	3.7

[1] pdNDF=potentially degradable NDF.

[2] iNDF=total indigestible NDF.

[3] kdNDF=fractional degradation rate of pdNDF.

Table 4.3. Starch fractions in selected feeds and the corresponding fractional degradation rate of the potential degradable starch fraction.

Feedstuff	NorFor feed code	Starch g/kg DM	Starch fractions, g/kg ST			kdST[4] %/h
			sST[1]	pdST[2]	iST[3]	
Barley	001-0016	615	350	650	3	39.2
Wheat	001-0020	667	399	601	5	59.5
Maize	001-0014	712	230	770	30	9.0
Peas	003-0006	511	230	770	30	9.0
Maize silage, high digestibility	006-0307	347	500	500	10	40.0
Maize silage, low digestibility	006-0309	299	500	500	10	40.0

[1] sST=small starch granules ('water soluble starch fraction').

[2] pdST=potentially degradable starch.

[3] iST=total indigestible starch.

[4] kdST=fractional degradation rate of pdST.

that are lost from nylon bags washed in cold water. It is assumed that the sST fraction follows the ruminal liquid pool and the fractional degradation rate is set to 150%/h, irrespective of feed source. The pdST fraction is calculated as the difference between the asymptotic value obtained from *in sacco* incubation and the sST value. The iST fraction is assumed to be completely resistant to digestion in the small intestine and is determined by the MBT (Norberg *et al*., 2007). The fractional degradation rates (kdST) of pdST are feed-specific and highly variable, ranging from 9%/h (maize) to 79%/h (oats) (Table 4.3). The kdST is estimated from *in sacco* degradation profiles.

The RestCHO fraction includes β-glucans, pectic substances and SU. Although the SU fraction may be analytically determined, it is categorized as a part of the RestCHO fraction. This is because SU is not routinely analyzed in all samples and tabulated values are normally used. The RestCHO is estimated by:

$$\text{RestCHO} = 1000 - \text{Ash} - \text{CP} - \text{CFat} - \text{NDF} - \text{ST} - \text{FPF} \qquad 4.1$$

where RestCHO is the residual carbohydrate fraction in the feed, g/kg DM; Ash is the ash content in the feed, g/kg DM; CP is the crude protein content in the feed, g/kg DM; CFat is the crude fat content in the feed, g/kg DM; NDF is the NDF content in the feed, g/kg DM; ST is the starch content in the feed, g/kg DM; and FPF is the sum of the fermentation products in the feed, Equation 4.7.

If the feedstuff contains low molecular weight N fractions, such as urea and NH_3N, the RestCHO is corrected (RestCHOcorr) using the following formulas:

For urea correction:

$$\text{RestCHOcorr} = 1000 - \text{Ash} - \text{CPcorr} - \text{CP} \cdot \frac{\text{UreaN}}{2915} - \text{CFat} - \text{NDF} - \text{ST} - \text{FPF} \qquad 4.2$$

For ammonia correction:

$$\text{RestCHOcorr} = 1000 - \text{Ash} - \text{CPcorr} - \frac{\text{CP}}{6.25} \cdot \frac{\text{NH}_3\text{N}}{1000} - \text{CFat} - \text{NDF} - \text{ST} - \text{FPF} \qquad 4.3$$

where RestCHOcorr is the residual carbohydrate fraction corrected for low molecular nitrogen fractions in the feed, g/kg DM; Ash is the ash content in the feed, g/kg DM; CP is the crude protein content in the feed, g/kg DM; CFat is the crude fat content in the feed, g/kg DM; NDF is the neutral detergent fibre content in the feed, g/kg DM; ST is the starch content in the feed, g/kg DM; FPF is the sum of fermentation products in the feed, Equation 4.7, g/kg DM; CPcorr is crude protein content in the feed corrected for low molecular N fractions, g/kg DM; NH_3N is the ammonia N content in feed, g/kg N; UreaN is the urea N content in feed, g/kg N; 2915 corresponds to the CP content of one kg of urea.

The CPcorr is calculated as:

$$\text{CPcorr} = \left(1 - \frac{\text{NH}_3\text{N}}{1000}\right) \cdot \text{CP} \qquad 4.4$$

where CPcorr is the crude protein content in the feed corrected for low molecular weight N fractions, g/kg DM; CP is the crude protein content in the feed, g/kg DM; and NH_3N is the ammonia or urea N content in the feed, g/kg N.

The RestCHO fraction represents the rapidly fermented water-soluble CHO fractions; a heterogeneous group of carbohydrates, ranging from SU, which has a high ruminal degradation rate (Weisbjerg *et al.*, 1998) to soluble fibre fractions, which have moderate degradation rates (Sniffen *et al.*, 1992; Lanzas *et al.*, 2007). In NorFor the fractional degradation rate of RestCHO in roughage (kdRestCHO) is calculated as:

$$\text{kdRestCHO} = \left(1 - \frac{\text{SU}}{\text{RestCHO}}\right) \cdot 10 + \left(\frac{\text{SU}}{\text{RestCHO}}\right) \cdot 150 \qquad 4.5$$

where kdRestCHO is the degradation rate of the rest carbohydrate fraction, %/h; SU is the sugar content, g/kg DM; RestCHO is the rest carbohydrate fraction, Equation 4.1; the fractional degradation rate of SU is 150%/h; and the fractional degradation rate of the non-sugar part of the RestCHO fraction is 10%/h. In concentrate feeds the kdRestCHO is set to 150%/h.

4.5 Crude fat and fatty acids

Fat normally constitutes a low proportion of cattle diets. However, fat is often used as an energy source for high productivity cattle. On a weight basis, fat is approximately 2.2 times more energy-rich than CP or CHO, although the energy value is dependent on the proportion of fatty acids (FA) in the CFat. However, rumen microorganisms cannot tolerate high levels of fat (Jenkins, 1993). Therefore, both the level and type of FA are important factors to consider when optimizing cattle diets. The NorFor feedstuff table (www.norfor.info) includes information on FA profiles of individual feedstuffs. However, individual FA metabolism in the gastro intestinal tract is not expressed and is, therefore, not implemented in the metabolism module. Consequently, only information on dietary FA composition can be evaluated, which is important when focusing on the optimal FA level of the diet, on milk fat quality and milk off-flavours. The proportion of FA in the CFat varies between feeds. The main storage lipids in plant seeds and grains are triacylglycerols, which consist of three fatty acids attached to glycerol. In these feeds the proportion of FA in CFat is 80 to 85% (Danfær *et al*., 2006). In contrast, forage lipids are mainly in the form of galactolipids, which contain galactose in addition to glycerol and unsaturated fatty acid moieties. Thus, their FA proportions are substantially lower: approximately 45% (Danfær *et al*., 2006). When the rumen OM fermentation is predicted in NorFor, the glycerol and galactose are added to the fermentable feed fractions, and serve as energy sources for microbial growth.

4.6 Fermentation products

Ensiled forages dominate as winter roughages in the Nordic countries. The feedstuffs have highly variable FPF (i.e. VFA, LAF and alcohols) contents. The VFA (acetic, propionic and butyric acids) can collectively account for up to 70 g, and LAF (the major organic acid) for 40 to 150 g per kg DM of the silage. The VFA, which are end-products of ruminal fermentation, are not energy sources for rumen microorganisms. Lactic acid represents a minor source of energy for microbial growth, and the ATP yield from lactic acid metabolism is only 25% of the yield from CHO fermentation (Van Soest, 1994). A high content of fermentation products in silages has a negative effect on forage intake (Huhtanen *et al*., 2002, 2007). Therefore, NorFor incorporates the relative silage index (Huhtanen *et al*., 2002) when calculating feed intake (see Section 6.2). The silage index requires information on fermentation acids (TAF), calculated as:

$$\mathrm{TAF} = \mathrm{LAF} + \mathrm{ACF} + \mathrm{PRF} + \mathrm{BUF} \qquad 4.6$$

where TAF is the content of total fermentation acids in the feed, g/kg DM; LAF is the content of lactic acid in the feed, g/kg DM; ACF is the acetic acid content in the feed, g/kg DM; PRF is the propionic acid content in the feed, g/kg DM; BUF is the butyric acid content in the feed, g/kg DM.

Ensiled forage also contains variable amounts of alcohol (Randby *et al*., 1999). This is taken into account when FPF is calculated:

$$\mathrm{FPF} = \mathrm{TAF} + \mathrm{FOF} + \mathrm{ALF} \qquad 4.7$$

where FPF is the content of fermentation products in the feed, g/kg DM; TAF is the content of fermentation acids in the feed, Equation 4.6, g/kg DM; FOF is the content of formic acid in the feed, g/kg DM; ALF is the content of alcohol in the feed, g/kg DM.

4.7 Minerals

Mineral elements may adversely affect production, animal health and reproduction (NRC, 2001). Several elements are also important for maintaining normal rumen function. NorFor predicts mineral supply and incorporates requirements for the following elements: Calcium (Ca), Phosphorus (P), Magnesium (Mg), Potassium (K), Sodium (Na), Chlorine (Cl), Sulfur (S), Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu), Cobalt (Co), Selenium (Se), Molybdenum (Mo) and Iodine (I). Animal mineral requirements are described in Chapter 9. The NorFor feedstuff table (www.norfor.info) includes information on the mineral content of individual feedstuffs.

4.8 Vitamins

Rumen microbes synthesize adequate amounts of vitamin K to meet the requirements of most cattle, except in young calves. However, cattle require a dietary source of vitamins A and E. Vitamin D is also normally included in the diet. NorFor incorporates requirements for vitamins A, E and D (see Chapter 9) and the NorFor feedstuff table (www.norfor.info) provides information on the vitamin A, E and D contents of individual feedstuffs.

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5. Feed analyses and digestion methods

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Feed characteristics are determined via chemical analyses and digestion methods. Specific NorFor methods for determining parameters such as DM, sCP, iNDF and the *in sacco* methods are fully described in this chapter. Tables 5.1 and 5.2 present an overview of the feed analysis and digestion methods, respectively.

Table 5.1. Recommended NorFor feed analysis methods.

Parameter	Abbrev.	Unit	Reference method	NorFor method
Dry matter in concentrate	DM	g/kg	EC No. 152/2009	
Dry matter in roughage	DM	g/kg		See Section 5.1.1
Ash	Ash	g/kg DM	EC No. 152/2009	
Crude protein	CP	g/kg DM	EC No. 152/2009 or Dumas	See Section 5.1.2
Soluble CP	sCP	g/kg CP		See Section 5.1.3
Ammonia nitrogen	NH_3N	g N/kg N	Free choice of MgO-method or Autoanalyzer (Broderick and Kang, 1980)	
Individual AA[1]	AA_j	g/100g CP	EC No. 152/2009	
Crude fat	CFat	g/kg DM	EC No. 152/2009	
Individual FA[2]	FA_j	g/100 g FA	CEN ISO/TS 17764-1:2007 CEN ISO/TS 17764-2:2007	
Neutral detergent fibre	NDF	g/kg DM	ISO 16472:2006 IDT	
Starch	ST	g/kg DM	Spectrophotometric method or the plate count method described by Bach Knudsen (1997) and Bach Knudsen *et al.* (1987)	
Lactic, propionic, butyric, formic acids and alcohol (ethanol)	LAF, PRF, BUF, FOF, ALF	g/kg DM	HPLC or GC	
Sugar	SU	g/kg DM	EC No. 152/2009	
Calcium	Ca	g/kg DM	ICP or free choice of method	
Phosphorus	P	g/kg DM	EC No. 152/2009 or ICP	
Magnesium	Mg	g/kg DM	ICP or free choice of method	
Potassium	K	g/kg DM	ICP or free choice of method	
Sodium	Na	g/kg DM	ICP or free choice of method	
Chloride	Cl	g/kg DM	EC No. 152/2009 or ICP	
Sulphur	S	g/kg DM	ICP or free choice of method	

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DOI 10.3920/978-90-8686-718-9_5,

Table 5.1. Continued.

Parameter	Abbrev.	Unit	Reference method	NorFor method
Iron, Copper, Manganese and Zinc	Fe, Cu, Mn, Zn	g/kg DM	EC No. 152/2009 or ICP	
Other micro minerals		g/kg DM	Free choice of method	
Vitamin A	VitA	IU/kg DM	EC No. 152/2009 or Jensen *et al*. (1998)	
β-carotene	b-car	IU/kg DM	EC No. 152/2009 or Jensen *et al*. (1998)	
Vitamin D	VitD	IU/kg DM	Any appropriate method is acceptable	
Vitamin E	VitE	IU/kg DM	EC No. 152/2009 or Jensen *et al*. (1999)	

[1] The amino acids that can be reported in the NorFor feed tables are: alanine, arginine, asparagine, cysteine, glutamine, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, threonine, tryptophan, tyrosine and valine.

[2] The fatty acids that can be reported in the NorFor feed tables are FA<C12 (the sum of fatty acids with less than 12 carbons): C12:0, C14:0, C16:0, C18:0, C18:1, C18:3, C20:5, C22:6 and RFA (sum of residual fatty acids).

Table 5.2. Recommended NorFor digestion methods.

Parameter	Abbrev.	Unit	Type of method	Method description
Organic matter digestibility	OMD	%	*In vivo* and *in vitro* methods	See Section 5.2.1
Potential degradable CP	pdCP	g/kg CP	*In sacco* method	See Section 5.2.2
Indigestible CP	iCP	g/kg CP	Mobile bag technique	See Section 5.2.4
Degradation rate of CP	kdCP	%/h	*In sacco* method	See Section 5.2.2
Potential degradable NDF	pdNDF	g/kg NDF	*In sacco* method	See Section 5.2.3
Indigestible NDF	iNDF	g/kg NDF	*In sacco* method	See Section 5.2.3
Degradation rate of NDF in concentrates	kdNDF	%/h	*In sacco* method	See Section 5.2.2
Soluble ST	sST	g/kg ST	*In sacco* method	See Section 5.2.3
Potential degradable ST	pdST	g/kg ST	*In sacco* method	See Section 5.2.3
Indigestible ST	iST	g/kg ST	Mobile bag technique	See Section 5.2.4
Degradation rate of ST	kdST	%/h	*In sacco* method	See Section 5.2.3

5.1 Feed analyses

5.1.1 Dry matter in roughage

Dry matter is defined as the proportion of the sample remaining after drying to a constant weight at a defined temperature, and after compensation for the loss of volatile compounds in some feeds (e.g. silage). The DM value can be determined either by a single- or two-step method. The single-step method is used when only DM is required, while the two-step method is recommended when the sample is used for further chemical analyses. The drying temperature of 60 °C is chosen to be consistent with the NDF method, described by Mertens (ISO 16472:2006 IDT), and is also used for sample preparation before other chemical, *in vitro* or *in sacco* analyses. Note that in concentrates

DM is determined at a temperature of 103 °C, as described in European Commission Regulation EC No. 152/2009.

In the single-step procedure, roughage samples should be dried to constant weight at 60 °C and thereafter weighed hot or kept in a desiccator until weighing. The uncorrected DM is calculated as:

$$DM_{uncorrSinglestep} = \frac{Dry\_weight}{Fresh\_weight} \cdot 1000 \qquad 5.1$$

where $DM_{uncorrSinglestep}$ is the uncorrected dry matter before compensation for volatiles, g/kg; Dry_weight is the sample weight after drying, g; and Fresh_weight is the sample weight before drying, g.

Volatiles lost during drying are added to the uncorrected DM as described in Equation 5.5 to 5.7.

In the two-step procedure, the dried sample after the first drying step (DM1) should be equilibrated in room temperature for a minimum of four hours and weighed, so DM1 can be calculated as:

$$DM1_{Twostep} = \frac{Equilibrated\_weight}{Fresh\_weight} \cdot 1000 \qquad 5.2$$

where $DM1_{Twostep}$ is the DM1 obtained from the two-step procedure, g/kg; Equilibrated_weight is the dry sample weight after 4 h equilibration in air, g; and Fresh_weight is the sample weight before drying, g.

After DM1 determination the sample can be ground. The second DM (DM2) determination in the ground sample should also be performed at 60 °C for 16 h when it is used to prepare samples for chemical analyses. The sample should then be weighed while still warm or kept in a desiccator until weighing (DM2), then:

$$DM2_{Twostep} = \frac{Dry\_weight}{weight\_before\_drying} \cdot 1000 \qquad 5.3$$

where $DM2_{Twostep}$ is the DM2 obtained from the two-step procedure, g/kg; Dry_weight is the sample weight after the second drying, g; and weight_before_drying is the sample weight before the second drying, g.

Uncorrected DM in the two-step procedure is calculated as:

$$DM_{uncorrTwostep} = \frac{DM1 \cdot DM2}{1000} \qquad 5.4$$

where $DM_{uncorrTwostep}$ is the uncorrected DM before compensation for volatiles, g/kg; DM1 is the DM in first step, Equation 5.2; and DM2 is the DM in the second step, Equation 5.3.

Since DM is intended to be the water free proportion of the feed, volatile compounds lost during drying should be added to the uncorrected DM. These compounds include lactic acid, VFA, lower alcohols and ammonia. In drying at 60 °C, lower alcohols are assumed to be completely lost, large proportions of ammonia and VFA are lost, but only a small amount of lactic acid is lost (Porter and Murray, 2001). The losses of VFA and lactic acid increase with decreasing pH. Table 5.3 shows the correction factors for the losses, which result in the equations below.

Final DM for silage with a pH lower than 5 is calculated as (Porter and Murray, 2001):

$$DM_{corr} = DM_{uncorr} + \begin{pmatrix} LAF \cdot (0.45 - 0.09 \cdot pH) + ACF \cdot (1.5 - 0.223 \cdot pH) \\ + PRF \cdot (1.4 - 0.182 \cdot pH) + BUF \cdot (1.9 - 0.272 \cdot pH) \\ + ALF + NH_3N \cdot 0.6 \end{pmatrix} \qquad 5.5$$

Table 5.3. Correction of DM for loss of volatiles, g/kg.

Volatile compound	pH	Factor for equations
Lactic acid	Only if pH<5	$0.45-0.09 \cdot pH$
Acetic acid	For all pH	$1.5-0.223 \cdot pH$
Propionic acid	For all pH	$1.4-0.182 \cdot pH$
Butyric acid	For all pH	$1.9-0.272 \cdot pH$
Lower alcohols	For all pH	1
Ammonia nitrogen	For all pH	0.6

Final DM for silage with a pH higher than 5 is calculated as:

$$DM_{uncorr} + \begin{pmatrix} ACF \cdot (1.5 - 0.223 \cdot pH) + PRF \cdot (1.4 - 0.182 \cdot pH) \\ + BUF \cdot (1.9 - 0.272 \cdot pH) + ALF + NH_3N \cdot 0.6 \end{pmatrix} \quad 5.6$$

where DM_{corr} is the corrected and final dry matter, g/kg; DM_{uncorr}, Equations 5.1 and 5.4, g/kg; ACF is the amount of acetic acid in feed, g/kg uncorrected DM; PRF is the amount of propionic acid in feed, g/kg uncorrected DM; BUF is the amount of butyric acid in feed, g/kg uncorrected DM; ALF is the amount of lower alcohols in the feed, g/kg uncorrected DM and NH_3N is ammonia nitrogen, g/kg uncorrected DM.

We have also developed a simple equation, which corrects for losses of volatiles when analyzed for in silage samples. The equation was developed from Norwegian grass silage samples that were analyzed for fermentation products and estimated losses of volatiles. When DM<700 g/kg, uncorrected DM of silage should be corrected for loss of volatiles by the equation:

$$DM_{corr} = 0.99 \cdot DM_{uncorr} + 10 \quad 5.7$$

where DM_{corr} is the corrected and final DM compensated for losses of volatiles, g/kg; and DM_{uncorr} is the uncorrected DM, Equations 5.1 and 5.4.

The simple procedure to recalculate the chemical composition of a sample on a corrected DM basis for the two-step procedure is illustrated in Equation 5.8:

$$X_{corr} = X_{uncorr} \cdot 1000 \cdot \frac{DM_{uncorr}}{DM2 \cdot DM_{corr}} \quad 5.8$$

where X_{corr} is the chemically analyzed parameter, i.e. NDF, CP, ST, etc., g/kg corrected DM; X_{uncorr} is the analyzed parameter per kg prepared sample, g/kg DM1; DM_{uncorr} is the uncorrected DM, Equations 5.1 and 5.4; DM2 is the DM measured in the second step, Equation 5.3; and DM_{corr} is the DM corrected for volatile loss, Equation 5.5, 5.6 or 5.7.

5.1.2 Crude protein

For CP determination, in addition to nitrogen content analyzed by Kjeldahl or Dumas·6.25 as shown in Table 5.1, ammonia losses during drying should also be taken into account. If ammonia is not analysed in fresh samples, it is assumed that 60% of the ammonia is emitted during drying (see Section 5.1.1):

$$CP = \left(\frac{N}{DM2} + NH_3N \cdot 0.6 \right) \cdot \frac{DM_{uncorr}}{DM_{corr}} \cdot 6.25 \quad 5.9$$

where CP is the crude protein, g/kg corrected DM; N is the amount of nitrogen analysed, g/kg DM1; NH_3N is the ammonia analysed in the fresh sample, g/kg uncorrected DM; DM2 is the DM measured in the second step, Equation 5.3; DM_{uncorr} is the uncorrected DM, Equation 5.1 or 5.4; DM_{corr} is the DM corrected for volatiles, Equations 5.5, 5.6 or 5.7.

5.1.3 Soluble crude protein

The procedure to determine sCP in all types of animal feeds is described in Table 5.4. A dried and milled sample is extracted in a borate-phosphate buffer (pH 6.75) at 39 °C for 1 hour. After centrifugation, the sCP in the supernatant is determined using the Kjeldahl or some other suitable method for total nitrogen determination. For silage samples the content of NH_3N should be corrected for losses during drying, and in the calculation of sCP.

5.2 Digestion methods used to predict digestion of nutrients

5.2.1 Organic matter digestibility

The reference method for OMD is based on sheep fed at maintenance (EAAP, 1969). In roughage OMD can also be determined from different *in vitro* analysis, which has been calibrated against the *in vivo* method. In NorFor three *in vitro* methods are available, i.e. VOS (rumen digestible organic matter), IVOS (*in vitro* organic matter digestibility) and EFOS (enzyme digestible organic matter). These methods are briefly described below.

The VOS method was developed in Sweden and described by Lindgren 1979, 1983, 1988. A 0.5 g dried sample is incubated at 38 °C for 96 h in a solution formed by mixing 49 ml buffer and 1 ml rumen fluid. Incubation residues are then combusted to determine the VOS digestibility coefficient of OM. The OMD *in vivo* is calculated from the VOS value. For forage with more than 50% grass or a whole crop of maize or cereals, and hence less than 50% leguminous plants on a DM basis, the OMD is calculated as follows (Lindgren, 1983):

$$\mathrm{OMD} = -2.0 + 0.90 \cdot \mathrm{VOS} \qquad 5.12$$

For forage samples containing more than 50% leguminous plants (Lindgren, 1983):

$$\mathrm{OMD} = 23.0 + 0.62 \cdot \mathrm{VOS} \qquad 5.13$$

where OMD is the calculated *in vivo* digestibility of organic matter, % of OM; and VOS is the digestibility of organic matter *in vitro*, % of OM.

The IVOS method is based on the method presented by Tilley and Terry (1963). Samples are incubated for 48 h in rumen fluid, followed by 48 h digestion by pepsin and HCl, the only major modification being that residues are combusted to determine OM digestibility. *In vivo* OMD can be calculated from IVOS using the equations of Møller *et al*. (1989).

For grass, clover grass, legumes and silages of grass, clover grass, legumes and small grain whole crops OMD is calculated from:

$$\mathrm{OMD} = 4.10 + 0.959 \cdot \mathrm{IVOS} \qquad 5.14$$

Table 5.4. Description of the method to determine the soluble CP (sCP) (modified from Hedqvist and Udén, 2006).

Item	Procedure
Sample preparation	• The samples are dried as specified for the NorFor samples and ground by a hammer mill to pass a 1 mm sieve. Avoid heating during grinding. See note 1.
Reagents	• Only use recognized analytical grade reagents. • Water: distilled or deionised water. • Mono-sodium dihydrogen phosphate monohydrate ($NaH_2PO_4 \cdot H_2O$) (CAS-No 10049-21-5). • Di-sodium tetraborate decahydrate ($Na_2B_4O_7 \cdot 10\ H_2O$) (CAS-No. 17.48-96-4). • Borate-phosphate buffer (modified from Licitra *et al.*, 1996), pH 6.75±0.05. Dissolve 12.2 g of sodium dihydrogen phosphate and 8.91 g of sodium tetraborate in 900 ml of water. Check the pH with a pH-meter and if necessary adjust the pH. Dilute with water in a 1000 ml volumetric flask. Prepare fresh buffer solution daily. • Sulphuric acid, ρ_{20} 1.84 g/ml. • Catalyst: Kjeltabs CF 5 g ($CuSO_4 \cdot 5H_2O$: approximately 0.10 g Cu per tablet, Thompson and Capper Ltd.) or equivalent. • Titrate for the auto-burette in the Kjeltech apparatus, with for example 0.1 M HCl.
Equipment	• Analytical balance (capable of weighing to the nearest 1 mg). • Centrifuge test tubes, 50 ml, with lids. • Dispenser or pipette 50±0.5 ml. • Water bath, thermostatted at 39±0.5 °C (or incubating chamber, 39±0.5 °C). • Glass rods. • Centrifuge suitable for the centrifuge tubes and capable of spinning at 3,000 g (given values of g are for the bottom of the test tubes). • Pipette 20±0.2 ml. • Kjeldahl equipment or other equipment for total nitrogen determination in liquids. • Heating block suitable for digesting the samples. • pH-meter, calibrated and capable of measuring pH to the nearest 0.01 pH unit.
Procedure	• Weigh approximately 1.5 g of the test sample to the nearest 1 mg in a centrifuge tube (see note 2). • Add 50±0.5 ml borate-phosphate buffer, pre-heated to 39 °C, to the samples (see note 3). • A blank sample of 50 ml borate-phosphate buffer should be included in each series of samples. • To hydrate the sample, mix it gently (e.g. with a glass rod) then place the lid on the tube and shake the sample thoroughly. • Incubate in a water bath or an incubating chamber at 39±0.5 °C for 1 h±5 minutes, and shake the tubes manually every 15 minutes. • Centrifuge the tubes at 3,000·g for 10 min (see note 4). • Pipette 20±0.2 ml of the supernatant and transfer to Kjeldahl tubes. • Add salt/catalyst and the appropriate volume of sulphuric acid to the tubes according to the standard procedure in the lab. Some feed samples foam extensively when the acid is added. Foaming during digestion in the Kjeldahl analysis can be reduced if the acidified samples are allowed to stand at room temperature for 1-2 hours or overnight. • Increase the temperature of the digestor stepwise, to prevent foaming of the samples. Do not include the time it takes to reach working temperature in the total digestion time. • Analyse the nitrogen content by Kjeldahl distillation. • Calculate the content of soluble crude protein.

Table 5.4. Continued.

Item	Procedure
Calculations	The content of sCP per kg CP, for all samples in which the ammonium nitrogen content is zero, can be calculated as: $sCP = \frac{(V_1 - V_0)\cdot c\cdot 14.007\cdot 6.25\cdot V_2}{m\cdot CP\cdot V_3}\cdot 1000$ 5.10 For silage samples, which have to be corrected for a 60% loss of ammonium nitrogen during drying, the equation is: $sCP = \frac{\frac{(V_1 - V_0)\cdot c\cdot 14.007\cdot 6.25\cdot V_2}{m\cdot V_3} + \frac{0.60\cdot NH_3N\cdot 1000\cdot 6.25}{DM1}}{CP_{uncorr} + \frac{0.60\cdot NH_3N\cdot 1000\cdot 6.25}{DM1}}\cdot 1000$ 5.11 where sCP is the soluble crude protein g/kg CP; V_0=volume of HCl used for titration of a blank sample, ml; V_1=volume of HCl used for titration of sample, ml; V_2=volume of added buffer, ml; V_3 is the volume of pipetted extract, ml; c is the concentration of titrant (mol/l); m is the sample size, g; CP_{uncorr} is the CP in pre-dried sample, g/kg DM1; 14.007 is the molar weight of nitrogen, g/mol; 6.25=Factor for converting nitrogen content to crude protein; DM1is the DM in first step, Equation 5.2; and NH_3N is ammonia nitrogen g/kg fresh sample (see note 5).

[1] The particle length of the ground material should be verified regularly according to EU regulations for animal feed analysis (EC No. 152/2009). All the material should be able to pass through a sieve with a quadratic square mesh of 1·1 mm. Heating of samples during grinding should be avoided.

[2] 1.5 g sample and 50 ml buffer are recommended. If using the common 50 ml centrifuge tubes from Falcon, NUNC, Greiner etc. the tubes will be very full when using 50 ml of buffer and the shaking might cause problems. In these circumstances we recommend using 1.2 g sample and 40 ml of buffer. Depending on the facilities in the laboratory other multiples with this sample:buffer ratio could be used, e.g. 3 g of sample and 100 ml buffer.

[3] Analytical steps involving sulphuric acid addition should be performed in sequence without any interruption.

[4] Some insoluble particles (containing trapped air), particularly from forage may float on the surface after centrifugation, but if the supernatant is carefully pipetted the insoluble matter will not cause contamination. The particles may be removed with a spoon or a paper tissue. If they still cause problems the supernatant can be carefully poured into a beaker through a tea-strainer and then pipetted.

[5] For samples containing measurable amounts of ammonium it is necessary to correct the sCP for loss of sCP as ammonia during drying. This loss is currently set to 60%.

For maize whole crop silage the equation used to calculate OMD is (Søegaard *et al.*, 2001):

$$OMD = 6.73 + 0.950\cdot IVOS \qquad 5.15$$

where OMD is the calculated *in vivo* digestibility of organic matter, % of OM; and IVOS is the digestibility of organic matter *in vitro*, % of OM.

The digestibility of fresh whole crop cereals (barley, wheat, maize), straw and concentrates can be determined using the EFOS method (Weisbjerg and Hvelplund, 1993). The EFOS method begins with a 24 h pepsin-HCl treatment of the sample, after which the sampled is heated to 80 °C for 45 min, treated for 24 h with an enzyme mixture at 40 °C, and then incubated for a further 19 h at 60 °C.

For fresh whole crops of wheat, barley and maize the equation used to calculate OMD *in vivo* is (Søegaard *et al.*, 2001):

$$\mathrm{OMD} = 20.4 + 0.727 \cdot \mathrm{EFOS} \qquad 5.16$$

For straw the following equation should be used (Hvelplund *et al.*, 1999):

$$\mathrm{OMD} = 22.0 + 0.752 \cdot \mathrm{EFOS} \qquad 5.17$$

For concentrate mixtures, the equation presented by Weisbjerg and Hvelplund (1993) should be used:

$$\mathrm{OMD} = 5.38 + 0.867 \cdot \mathrm{EFOS} \qquad 5.18$$

where OMD is the calculated *in vivo* digestibility of organic matter, % of OM; and EFOS is the digestibility of organic matter *in vitro*, % of OM.

5.2.2 *In sacco* rumen degradation of crude protein, NDF and starch

The *in sacco* technique is used for determining kdCP in roughage and concentrate, kdNDF in concentrate and kdST in roughage and concentrate. It is also used to determine pdCP, sST, pdST and iNDF. The *in sacco* method has several weaknesses, e.g. particle losses, microbial contamination of feed residues, different ruminal environment outside vs. inside the bag and pre-treatment of feed samples (Nozière and Michalet-Doreau, 2000). Therefore, an important task for the NorFor feed table and analysis group was to standardize critical parts of the *in sacco* procedure to minimize between-laboratory variation. The NorFor *in sacco* standard protocol, based on the work of Madsen *et al*. (1995), are presented in Table 5.5.

Table 5.5. Standard in sacco *procedure in NorFor for determining feed degradation characteristics, modified from Madsen* et al. *(1995).*

Item	Procedure
Animals and diet	Non-lactating dairy cows of the Nordic dairy cow population. Cows are fed at maintenance level and the diet consists of hay, straw and concentrate. The hay and straw to concentrate ratio is 67:33. The CP content of the diet should be higher than 120 g/kg DM. The concentrate should contain a minimum of three sources of protein. Daily ration is divided into two or more meals of equal size with an adaptation period of 14 days. If animals have been on pasture or fed diets or feeding levels totally different from the standard, the minimum adaptation period is 21 days.
Replication	Three cows are required for the determination of each feed parameter, except for iNDF determinations, where two cows are needed. The number of bags per animal is not specified. There is no need to replicate the number of days.
Sample preparation	Preferably the samples should be freeze-dried, but oven drying at 45 °C is also acceptable. For NDF determination, a drying temperature of 60 °C is recommended. The samples should be ground in a mill with a screen size of 1.5 mm. Cutter mill is preferable but a hammer mill is also acceptable. Sample size should be 1.0-2.0 g of dried sample depending on the bag surface area.

Table 5.5. Continued.

Item	Procedure
Bags	Bag size refers to internal dimensions when the bag is sealed and mounted on the carrying device to be used. There should be 10 mg sample/cm^2 when samples of the required size are placed in the bag. The internal length:internal width ratio should preferably be 1:1.3 (and thus 8.1·6.2 cm for 1.0 g samples and 11.4·8.8 cm for a 2.0 g sample). Bags should have round corners. The pore size should be 38 µm. Recommended bag material is polyester of the model Saatifil PES 38/31 manufactured by Saatitech S.p.A (22070 Veniano, Como, Italy). Any method can be used to seal the filled bags, but the standardized internal bag length must not be altered. Currently, the bags are mounted on a rubber stopper in Denmark and Iceland. In Norway the bags are closed with a rubber band, while in Sweden the open end of the bag is inserted through a slit and strapped. The bags may be re-used for incubations for a maximum of 20 runs.
Incubation interval	When determining kdCP, the incubation times should be 0, 2, 4, 8, 16, 24 and 48 h, while for roughage and concentrates with low degradation rates the time should be extended up to 96 h. As a rule, concentrates in which less than 80% of total N has disappeared after 48 h should be incubated for 96 h. When determining kdNDF the incubation times should be 2, 4, 8, 16, 24, 48 and 96 h. The 0 h is omitted from the calculation. When determining the starch degradation rate the incubation times should be 0, 2, 4, 8, 16, 24, 48 and 72 h.
Incubation conditions	The bags should be pre-soaked prior to incubation (including 0 hr bags) for 20 minutes at 39 °C in tap water without agitation. The bags that will be incubated for 2, 4 and 8 h should be inserted simultaneously 15-30 minutes prior to morning feeding. For bags that will be incubated for longer times the insertion time is not specified. The inserted bags should be placed in the ventral rumen. The bag attachment device should allow the bags to be squeezed by rumen contractions.
Rinsing	Bags removed from the rumen, and 0 h bags, must first be rinsed in cold tap water with no squeezing or manipulation before machine washing. Bags may be machine-washed immediately or freeze-stored after the cold tap water rinsing and thawed before machine washing. Bags incubated for all times, 0 to 96 h, should be washed. It is preferable to use identical washing machines and identical washing programs. Use a washing program without spinning and a water temperature of 25 °C. At present, stomacher treatment is allowed after the machine-washing to reduce microbial contamination of roughage samples; this procedure is used in Denmark. After rinsing the residues are quantitatively removed from the bags and analyzed for chemical constituents. Alternatively, bags including the residues are dried in an oven at 45 °C for 48 h and then weighted after equilibrated in room temperature. Residues are analyzed for chemical constituents.
Residue analysis	Analyze the remaining samples for nitrogen, NDF or starch. There is no specified quantitative analysis of the residues from each cow or analysis of pooled residues from emptied bags.
Calculations	Calculations should be conducted by non-linear curve fitting, by applying the least squares method to untransformed values. Degradation profiles should currently be fitted without a lag phase.
Calculation of kdNDF	The curve fitting function for NDF degradation is: $\mathrm{NDFD}_t = \frac{\mathrm{NDF} - \mathrm{NDF}_t}{\mathrm{NDF}}$ 5.19 where NDFD$_t$ is NDF degraded at time t, g/g; NDF$_t$ is the remaining amount of NDF at time t; NDF is the amount of NDF in the bags prior to ruminal incubation. If the

Table 5.5. Continued.

Item	Procedure
Calculation of kdNDF (continued)	incubation residue at time t is too small for analysis, then the NDF content from the previous time should be used. Fit the equation according to Ørskov and McDonald (1979): $NDFD_t = NDFD_{curvefit} \cdot (1 - e^{-kdNDF_{96} \cdot t})$ 5.20 where $NDFD_t$ is the degraded NDF fraction at time t; $NDFD_{curvefit}$ is the asymptotic value of pdNDF obtained from the curve fitting and $kdNDF_{96}$ is the degradation rate of NDF. There is a restriction that $NDFD_{96}$ should be ≤1. When iNDF at 288 h (Section 5.2.3) is available, report NDFD at 288 h as pdNDF and correct kdNDF according to: $kdNDF = \frac{NDFD_{curvefit} \cdot kdNDF_{96}}{pdNDF}$ 5.21 where kdNDF is the corrected degradation rate for NDF, $NDFD_{curvefit}$ is the asymptotic value of degraded NDF obtained from the curve fitting and pdNDF is the potentially degradable NDF fraction determined from iNDF estimated from the 288 h ruminal incubation.
Calculation of kdCP and pdCP	The curve fitting for crude protein degradation is applied to data on degraded fractions at times 0, 2, 4, 8, 16, 24, and 48 h, and if available 96 h. If the incubation residue at time t is too small for the analysis, CP content from the previous time should be used: $CPD_t = \frac{CP - CP_t}{CP}$ 5.22 where CPD_t is the CP degraded at time t, g/g; CP_t is the remaining amount of CP at time t; and CP is the amount of crude protein in the bags prior to ruminal incubation. Ruminal CP degradation is fitted to the following equation: $CPD_t = CPD_0 + CPD_{curvefit} \cdot (1 - e^{-kdCP \cdot t})$ 5.23 where CPD_t is the CP degraded at time t, CPD_0 is the intercept or an estimate of solubility of the CP at time 0 h, $CPD_{curvefit}$ is the asymptotic value of the insoluble but degradable proportion of crude protein obtained from the curve fitting, and kdCP is the degradation rate of CP. Restriction conditions are $0 \leq CPD_0 \leq 1$, $0 \leq CPD_{96} \leq 1$ and $0 \leq (CPD_0 + CPD_{96}) \leq 1$. CP particle losses should be corrected for according to Weisbjerg *et al*. (1990): $pdCP = \left(CPD_{curvefit} + (CPD_0 - sCP) \cdot \frac{CPD_{curvefit}}{1 - CPD_0} \right) \cdot 1000$ 5.24 where pdCP is the potential degradable protein fraction, (g/kg CP); $CPD_{curvefit}$ is the asymptotic value of the potentially degradable fraction obtained from the curve fitting, CPD_0 is the *in sacco* soluble fraction at time 0 and sCP is the buffer soluble crude protein, analysed according to Section 5.1.3. There is no correction for microbial contamination, except for the possible stomacher treatment.

Table 5.5. Continued.

Item	Procedure
Calculation of kdST, sST and pdST	The curve fitting for starch degradation is applied to data on degraded fractions at times 0, 2, 4, 8, 16, 24, 48 and 72 h. If the incubation residue at time t is too small for analysis, the ST content from the previous time should be used: $STD_t = \frac{ST - ST_t}{ST}$ 5.25 where STD_t is the ST degraded at time t, g/g; ST_t is the remaining amount of ST at time t, ST is the amount of ST in the bags prior to ruminal incubation. ST degradation is fitted with the following equation: $STD_t = STD_0 + STD_{curvefit} \cdot \left(1 - e^{-kdST \cdot t}\right)$ 5.26 where STD_t is the ST degraded at time t, STD_0 is the intercept or an estimate of solubility of ST at time 0 h, $STD_{curvefit}$ is the asymptotic value of the insoluble, but degradable proportion of ST obtained from the curve fitting, and kdST is the degradation rate constant of ST. Restriction conditions are $0 \leq STD_0 \leq 1$, $0 \leq STD_{72} \leq 1$ and $0 \leq (STD_0 + STD_{72}) \leq 1$. STD_0 and $STD_{curvefit}$ in Equation 5.26 are the same as soluble starch and potentially degradable starch (g/kg ST).

5.2.3 Indigestible NDF

The method for determining iNDF involves incubating feed samples *in sacco* for 288 h in the rumen, and essentially follows the method described in Section 5.2.2 for determining *in sacco* NDF degradation. Feed samples of 2 g are incubated in bags with 10-15 µm pores and 100-200 cm^2 effective surface area, equivalent to 10-20 mg sample/cm^2. For the iNDF determination the polyester cloth Saatifil PES 12/6 (Saatitech S.p.A., 22070 Veniano, Como, Italy) with pore size 12 µm and open surface area of 6% is recommended. Each determination should be performed on at least two animals.

The iNDF content is calculated as:

$$iNDF = \left(\frac{NDF_{288}}{NDF}\right) \cdot 1000 \qquad 5.27$$

where iNDF is the total indigestible NDF fraction in the feed, g/kg NDF; NDF_{288} is the amount of NDF in the bag remaining after 288 h of ruminal incubation, mg; and NDF is the amount of NDF in the bag before ruminal incubation, mg.

For measuring iNDF in roughage in commercial feed laboratories near infrared spectroscopy (NIRS) calibrations have been developed (Nordheim *et al*., 2007).

5.2.4 Indigestible crude protein and indigestible starch

The reference method for determining iCP and iST is the MBT technique. The procedure, based on the work of Madsen *et al*. 1995), is described in Table 5.6.

Table 5.6. The standard mobile nylon bag procedure for determining intestinal digestibility of rumen undegraded protein and starch, modified from Madsen et al. *(1995).*

Item	Procedure
Animals and diet	Duodenal fistulated cows fed at maintenance level or at production level (Michalak *et al*., 2003). When cows are fed at maintenance level the diet is the same as for the ruminal *in sacco* procedure (Table 5.5).
Replications	Minimum two replicates per cow.
Nylon bags	The bag's pore size should be 11-15 µm. The bag surface area should be 6·6 cm.
Samples	Concentrate sample size is 10 to 15 mg per cm^2 of the bag's surface area, approximately 1 g. Roughage sample size is 5 to 7 mg per cm^2, approximately 0.5 g. The samples should be pre-incubated in the rumen. Concentrate samples should be incubated in the rumen for 16 hours and roughage for 24 hours.
Pre-incubation	Step 1. Place the sample bag in 0.004 M HCl solution at pH=2.4 for 1 h. Step 2. Place the sample bag in a pepsin/HCl solution (100 mg pepsin per litre of 0.004 M HCl solution) for 2 h at 40 °C in a shaking water bath.
Incubation in the duodenum and collection from faeces.	After pre-incubation the bags are introduced to the duodenum through a duodenal cannula. When determining the iCP fraction the bags are collected from the faeces, while when determining the AA profile of digestible protein the bags are collected from an ileal cannula.
Washing	Rinse the bags with tap water. Then wash the bags in a sieve basket in cold running water for two hours as described by Hvelplund *et al.* (1992). Alternatively the bags can be washed in a washing machine using the same procedure as for the rumen bags (Table 5.5).
Calculation	Indigestible crude protein is calculated as: $\mathrm{iCP} = \left(\frac{N_{MBT}}{N}\right)\cdot 1000$ 5.28 where iCP is the indigestible crude protein in the feed, g/kg CP; N_{MBT} is the nitrogen content in the bag residue that has passed through the small intestine, g; and N is the amount of nitrogen in the weighed sample, g. Indigestible starch is calculated as: $\mathrm{iST} = \left(\frac{ST_{MBT}}{ST}\right)\cdot 1000$ 5.29 where iST is the indigestible starch in the feed, g/kg ST; ST_{MBT} is the starch content in the residue bag that passed through the small intestine, g; and ST is the amount of starch in the weighed sample, g.

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6. Feed calculations in NorFor

H. Volden

NorFor has an extensive feed characterization program. In addition to the feed constituents described in Chapter 4, several feed characteristics are calculated from information based on chemical fractions, and their degradation and digestion characteristics. Nevertheless, efficient use of a feed evaluation system in practice requires commercial feed analyses that are reliable and can be performed at a low cost. Therefore, several feed characteristics are predicted using either *in vitro* methods or NIRS.

6.1 Calculation of kdNDF in roughage

The *in sacco* method was originally used to predict the kdNDF in roughage. However, the fractional kd is a non-linear parameter and Nordheim *et al*. 2007 showed that the NIRS method was not suitable for predicting kdNDF. Therefore, an alternative method was introduced that can be used to estimate kdNDF from the combination of OMD and NDF digestibility (Weisbjerg *et al*., 2004a,b, 2007), which can be predicted from either *in vitro* or NIRS data calibrated to *in vivo* OMD determined at maintenance level. Digestibility of NDF can be determined from OMD and feed NDF concentration combined with information on the digestibility of NDS (neutral detergent solubles) (Weisbjerg *et al*., 2004a). This method assumes that the sum of excreted NDF and NDS accounts for the total undigested OM. Using the Lucas principle (Lucas *et al*., 1964), Weisbjerg *et al*. (2004a) estimated a true NDS digestibility of 101.3% and an endogenous loss of 90.2 g NDS per kg ingested DM (see Equation 6.2). The *in vivo* digestibility of pdNDF (D; Equation 6.8) can be determined by combining NDF digestibility determined at maintenance and pdNDF. When D is known and assumed to be equal to rumen digestibility, then the kdNDF can be calculated. NorFor uses a two-compartment model to estimate effective rumen NDF degradation (Allen and Mertens, 1988), and from this model the fractional degradation rate can be solved (Huhtanen *et al*., 2006). In NorFor the kdNDF in roughage is estimated using the following formulas:

$$\mathrm{NDS} = 1000 - \mathrm{Ash} - \mathrm{NDF} \tag{6.1}$$

$$\mathrm{NDSD} = 1.013 - \frac{90.2}{\mathrm{NDS}} \tag{6.2}$$

$$\mathrm{uOM} = \mathrm{OM} \cdot (1 - \mathrm{OMD}) \tag{6.3}$$

$$\mathrm{uNDS} = \mathrm{NDS} \cdot (1 - \mathrm{NDSD}) \tag{6.4}$$

$$\mathrm{uNDF} = \mathrm{uOM} - \mathrm{uNDS} \tag{6.5}$$

$$\mathrm{NDFD} = \frac{(\mathrm{NDF} - \mathrm{uNDF})}{\mathrm{NDF}} \tag{6.6}$$

$$\mathrm{pdNDF}_{\mathrm{corr}} = 1000 - \frac{\left(\dfrac{(448.1 - 5.072 \cdot \mathrm{OMD} \cdot 100)}{\mathrm{NDF} \cdot 0.001} + \mathrm{iNDF}\right)}{2} \tag{6.7}$$

$$\mathrm{D} = \frac{\mathrm{NDFD}}{\left(\dfrac{\mathrm{pdNDF}_{\mathrm{corr}}}{1000}\right)} \tag{6.8}$$

$$\mathrm{kdNDF} = -3.475 + \frac{\sqrt{48.30 + \dfrac{46.37 \cdot \mathrm{D}}{1 - \mathrm{D}}}}{2} \tag{6.9}$$

where NDS is the content of neutral detergent solubles, g/kg DM; NDSD is the digestibility of NDS, g/g; OM is the organic matter content of the feed, g/kg DM; uOM is the undigested OM,

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9_6, © Wageningen Academic Publishers 2011

g/kg DM; OMD is organic matter digestibility, %; uNDS is the undigested NDS, g/kg DM; uNDF is undigested NDF, g/kg DM; NDFD is the digestibility of NDF, g/g; D is the digestibility of pdNDF, g/g; $pdNDF_{corr}$ is the corrected potentially degradable NDF, g/kg NDF; iNDF is the total indigestible NDF, g/kg NDF; and kdNDF is the fractional degradation rate of pdNDF, %/h.

In the calculation of kdNDF, a rumen retention time of pdNDF of 60 h is assumed, this represents the mean rumen retention time of sheep fed at maintenance and provides the basis for the determination of OMD. Evaluation of the method showed that calculated kdNDF values were very sensitive to pdNDF. Therefore, an adjusted pdNDF ($pdNDF_{corr}$) parameter was introduced, which yields a more robust relationship between NDF and OM digestibility, and makes the calculation less sensitive when values of pdNDF and OMD are extreme. The regression formula in Equation 6.7, which is used to predict iNDF from OMD, is based on data acquired from 20,190 forage samples obtained from the NorFor feed analysis database.

6.2 Calculation of the fill value in roughage

Feed intake is calculated from information regarding animal IC and feed FV. Concentrate feedstuffs have a fixed FV of 0.22 FV/kg DM (Kristensen, 1983) whereas a variable FV is used for roughages (Table 6.1) and is calculated from the OMD and the NDF content. The roughage FV is estimated as:

$$FV = \frac{0.86 - OMD \cdot 0.005}{0.94 + 0.56 \cdot e^{-0.000029 \cdot \left(\frac{NDF}{10}\right)^{2.9}}} \qquad 6.10$$

where FV is roughage fill value, kg DM; OMD is organic matter digestibility, %; and NDF is feed NDF content, g/kg DM.

The numerator in Equation 6.10 was originates from the Danish fill unit system (Kristensen, 1983) and the denominator provides a correction for roughage type, which can be explained by differences in NDF content (e.g. between grasses and maize).

The intake of grass silage is dependent on fermentation quality, i.e. the content of fermentation acids and NH_3N in the ensiled feed. Based on a meta-analysis, Huhtanen *et al*. (2002) developed a relative silage index, which corrects silage intake based on information on total acids (TAF; Equation 4.6) and NH_3N. The relative silage index is in NorFor used to correct the FV according to the following formula:

Table 6.1. Fill value (FV) in selected roughage feeds and their corresponding organic matter digestibility (OMD) and NDF content.

Feedstuff	NorFor feed code	FV, FV/kg DM	OMD, %	NDF, g/kg DM
Clover grass, 6-8 cm, 20% clover	006-0059	0.41	79.0	380
Maize silage, high digestibility	006-0307	0.39	78.7	338
Maize silage, low digestibility	006-0309	0.44	74.6	397
Grass silage, high digestibility	006-0461	0.50	76.5	501
Grass silage, low digestibility	006-0463	0.58	66.5	597
Wheat straw, untreated	006-0413	0.68	44.0	820

$$FV_{corr} = \frac{0.86 - OMD \cdot 0.005}{0.94 + 0.56 \cdot e^{-0{,}000029\left(\frac{NDF}{10}\right)^{2{,}9}}} \cdot \left(1 - \left(\frac{-0.000531 \cdot \left((TAF)^2 - 6400\right)}{100} + \frac{-4.765 \cdot \left(\ln(NH_3N) - \ln(50)\right)}{100}\right)\right) \qquad 6.11$$

where FVcorr is the silage fill value corrected for silage fermentation products, FV/kg DM; OMD is the organic matter digestibility, % as described in Section 5.2.1; NDF is the feed NDF content, g/kg DM; TAF is the content of total fermentation acids in the ensiled feed, g/kg DM, Equation 4.6; and NH_3N is the content of ammonia N in the ensiled feed, g/kg N.

Equation 6.11 shows that in ensiled forage there is a break point in calculated FV at a TAF value of 80 g/kg DM and a NH3N content of 50 g/kg N. Higher values results in a higher FV and vice versa. Using this approach, NorFor is able to take into account the effect of silage fermentation quality on forage intake.

6.3 Calculation of fractional degradation rate (kd) in feed mixtures

Feed mixtures (e.g. compound feeds from the feed industry) are commonly used as inputs to the NorFor system. Feed characteristics (based on composition) are often calculated from tabulated values. However, the kd of the potentially degradable feed fraction is a non-linear parameter, hence a simple weighted mean of kd in a feed mixture cannot be calculated (Danfær *et al.*, 2006). In a simple one-compartment model for rumen degradability, the rumen effective degradability (ED) can be estimated according to the general formula:

$$ED = \frac{kd_1}{kd_1 + kp} \cdot pdXX_1 + \frac{kd_2}{kd_2 + kp} \cdot pdXX_2 + \cdot\cdot \frac{kd_n}{kd_n + kp} \cdot pdXX_n = \frac{kd_a}{kd_a + kp} \cdot (pdXX_1 + pdXX_2 + \cdot\cdot\, pdXX_n) \qquad 6.12$$

where $kd_{1,\,2,\ldots,n}$ are the fractional degradation rates of feeds 1, 2, …, n, , %/h; $pdXX_{1,\,2,\,\ldots,\,n}$ are the potentially degradable feed fraction of feeds 1, 2, …, n, g/kg; kd_a is the aggregated kd of feeds 1, 2, …, n, %/h; and kp is the fractional passage rate of pdXX, %/h.

The ED equation can be solved with respect to kd_a:

$$kd_a = \frac{kp}{\left(\frac{\sum_i \left(Share_i \cdot XX_i \cdot \frac{pdXX_i}{1000}\right)}{\sum_i \left(\left(Share_i \cdot XX_i \cdot \frac{pdXX_i}{1000}\right) \Big/ \left(1 + \frac{kp}{kdXX_i}\right)\right)}\right) - 1} \qquad 6.13$$

where kd_a is the aggregated fractional degradation rate of the feed mixture, %/h; $pdXX_i$ is potentially degradable CP, ST or NDF for the i=1…n'th feed, g/kg; Share is the proportion of the feed in the mixture, %; and kp is the fractional passage rate of pdXX, %/h.

When kd_a is calculated for pdCP and pdST a kp of 3.337%/h is assumed and for pdNDF a kp of 2.8705%/h is used. These fractional kp values represent those for cows fed at maintenance level, corresponding to the feeding level at which the *in sacco* kd is determined.

6.4 Cation-anion difference

The dietary balance of acids and bases influences many physiological variables and metabolic functions, including growth rate, appetite, amino acid and energy metabolism, calcium utilization, vitamin metabolism, intestinal absorption and kidney function (Underwood and Suttle, 1999). Reducing the dietary cation-anion difference (CAD) in the dry period feed is often recommended to prevent milk fever (NRC, 2001). The CAD is expressed in milliequivalents (mEq) per kg DM or in the total ration as mEq per cow and day. In NorFor, the following equation is used to calculate CAD:

$$\mathrm{CAD} = \left(\left(\frac{K}{39.1} + \frac{Na}{23.0} \right) - \left(\frac{Cl}{35.5} + \frac{S \cdot 2}{32.0} \right) \right) \cdot 1000 \qquad 6.14$$

where CAD is the dietary cation-anion difference, mEq/kg DM; K is the potassium content in feed, g/kg DM; Na is the sodium content in feed, g/kg DM; Cl is the chloride content in feed, g/kg DM; S is the sulphur content in feed, g/kg DM; 39.1, 23.0, 35.5 and 32.0 is the molecular weight of K, Na, Cl and S, respectively.

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7. Digestion and metabolism in the gastrointestinal tract

H. Volden and M. Larsen

In NorFor the digestion and metabolism are simulated in three compartments: (1) the rumen, (2) the small intestine and (3) the large intestine. This chapter describes the modelling of the digestion processes in the three compartments and the microbial OM synthesis in the rumen and large intestine. Most of the equations in this chapter could have been presented in a simpler form, but we present them here in the format they are implemented in the computer program since we believe this makes it easier to follow their biological rationale.

7.1 Rumen

Fractional rates of degradation and passage are used to calculate the ruminal digestion and fermentation of nutrients. Reliable estimates of digestion are highly dependent on correct estimates of feed passage rates (Allen and Mertens, 1988) and both extrinsic and intrinsic feed factors have to be considered (Robinson *et al*., 1987b; Lechener-Doll *et al*., 1991; Huhtanen and Kukkonen, 1995). Fibre degradation rate is dependent not only by intrinsic attributes of the fibre fraction, but also by factors influencing rumen environment (Hoover, 1986; Van Soest, 1994) and NorFor takes this into account when estimating ruminal fibre digestion. Moreover, microbial activity depends on nutrient degradation and passage rates, and the amount of bacterial OM synthesized in the rumen is calculated from the sum of carbohydrates, proteins, glycerol and lactic acid fermented. The efficiency of rumen microbial OM synthesis is highly variable (Hespell and Bryant, 1979; Volden, 1999) and in NorFor, efficiency is dependent on both feed intake level and diet composition.

7.1.1 Rumen fractional passage rates

Undegraded ruminal feed fractions are assumed to have passage rates, corresponding to one of the following four ruminal phases: (1) liquid, (2) roughage CP and ST particles, (3) concentrate particles or (4) NDF in roughage particles. The equations proposed by Sauvant *et al*. (1995) are used to calculate the fractional passage rates of liquid (r_kpl), and the pdCP and pdST in roughage particles (r_kpr):

$$r\_kpl = 2.45 + 0.055 \cdot \frac{\sum\limits_{i} DMI_i \cdot 1000}{BW^{0.75}} + 0.0004 \cdot rough\_share^2 \qquad 7.1$$

$$r\_kpr = 0.35 + 0.022 \cdot \frac{\sum\limits_{i} DMI_i \cdot 1000}{BW^{0.75}} + 0.0002 \cdot rough\_share^2 \qquad 7.2$$

where r_kpl is the fractional passage rate of liquid out of the rumen, %/h; r_kpr is the fractional passage rate of roughage particles out of the rumen, %/h; DMI_i is the dry matter intake of the of the i=1...n'th feedstuff, kg/d; BW is the animal body weight, kg; and rough_share is the proportion of roughage in the diet, % of DM.

The passage rate of pdCP and pdST in concentrate feed particles (r_kpc) is calculated from a modified NRC equation (NRC, 2001):

$$r\_kpc = 2.504 + 0.1375 \cdot \frac{\sum\limits_{i} DMI_i \cdot 1000}{BW} - 0.02 \cdot conc\_share \qquad 7.3$$

DOI 10.3920/978-90-8686-718-9_7, © Wageningen Academic Publishers 2011

where r_kpc is the fractional passage rate of crude protein and starch in concentrate feed particles out of the rumen, %/h; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; BW is the animal body weight, kg; and conc_share is the proportion of concentrate in the diet, % of DM.

A sensitivity test and pre-evaluation of the model showed that the passage rate of pdNDF in concentrate particles had a significant effect on the estimated NDF digestibility in the rumen and that Equation 7.3 underestimated digestibility of pdNDF in concentrates. Based on these evaluations, the following modified passage rate equation was formulated:

$$r\_kpNDFc = \left(2.504 + 0.1375 \cdot \frac{\sum_i DMI_i \cdot 1000}{BW} - 0.02 \cdot conc\_share\right) \cdot 0.43 \qquad 7.4$$

where r_kpNDFc is the fractional passage rate of NDF out the rumen in concentrate particles, %/h; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; BW is the animal body weight, kg; and conc_share is the proportion of concentrate in the diet, %/DM.

The rumen evacuation technique has been used as the reference method for estimating the ruminal passage rate of NDF particles in roughage, since it has been shown to be a robust and reliable method for estimating passage kinetics of NDF fractions (Robinson *et al*., 1987b; Huhtanen and Kukkonen, 1995; Stensig *et al*., 1998). A dataset based on the rumen evacuation technique was compiled (Table 7.1) to develop an equation to predict the fractional passage rate of roughage NDF (r_kpNDFr) out of the rumen. When duodenal flow data were missing in the dataset, measurements of faecal excretion replaced ruminal outflow, assuming that digestion in the large intestine accounts for 10% of the total tract NDF digestion. Moreover, if data on pdNDF passage was not available, the kp of pdNDF was assumed to be 0.78 of the value for total NDF (Minde and Rygh, 1997; Stensig *et al*., 1998; Lund, 2002). In the experiments used for parameterization, several different marker methods were used to estimate intestinal flow and also different methods for analyzing total NDF in feed and

Table 7.1. Descriptive statistics of data used to develop the equation for predicting the passage rate of NDF in roughage.

Reference	Diets, n	DMI, g/kg BW	Concentrate proportion, %
Bosch, 1991	8	21.5-31.4	6.0-38.1
Eriksen and Ness, 2007	4	33.3	28.2
Minde and Rygh, 1997	4	25.5	50.7
Mydland, 2005	3	31,4	31.3
Prestløkken, 1999	3	30.5	59.9
Robinson *et al*., 1987a,b,c	8	8.7-37.7	61.3
Stensig and Robinson, 1997	4	35.0	37.6
Stensig *et al*., 1998	4	26.4	43.1
Volden, 1999	6	32.2 and 16.1	60.0
Volden, unpublished data	2	11.2	40.1
Volden, unpublished data	3	31.3	24.3
Volden, unpublished data	3	29.5	48.6
Volden, unpublished data	3	24.6	51.0
Volden, unpublished data	3	19.3	35.0
Volden, unpublished data	3	16.8	0
Volden, unpublished data	4	29.9	27.3

digesta. The Proc Mixed procedure in SAS software was therefore used to adjust the r_kpNDFr to account for differences in the proportion of concentrate in the diet and for methodological differences. A decrease in kp with increasing proportion of concentrate in the diet has been observed in several cases (Sauvant *et al*., 1995; NRC, 2001).

In NorFor, total NDF intake per kg BW is used as input variable for predicting r_kpNDFr. Since the NDF content is generally lower in concentrates than in roughage, the negative effect of a higher proportion of concentrate on kp is indirectly accounted for in the r_kpNDFr equation. As the substitution of roughage with concentrates generally reduces the NDF/BW ratio, the predicted value of r_kpNDFr will be lower. The r_kpNDFr is calculated from the following equation:

$$\text{r\_kpNDFr} = 0.480 + \frac{1.5106}{1 + \left(\frac{\sum_i \text{DMI}_i \cdot \text{NDF}_i}{\text{BW} \cdot 7.484}\right)^{-3.198}} \qquad 7.5$$

where r_kpNDFr is the fractional passage rate of pdNDF in roughage particles, %/h; NDF_i is the NDF content in the i=1...n'th feedstuff, g/kg DM; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; and BW is the animal body weight, kg.

An evaluation of the Equation 7.5 for use with growing cattle gave unrealistically low passage rates for rations with a low NDF intake (e.g. diets with a concentrate proportion>0.8). Thus, to obtain reliable estimates of NDF digestion in the rumen in these diets, the equation was forced through 0.5%/h as an intercept.

Figure 7.1 shows how the passage rate of different feed fractions changes with level of feed intake (DMI/kg BW), assuming a fixed ratio between roughage and concentrate in the diet (50:50) and an NDF concentration of 400 g/kg DM. There are large differences in passage rates between the

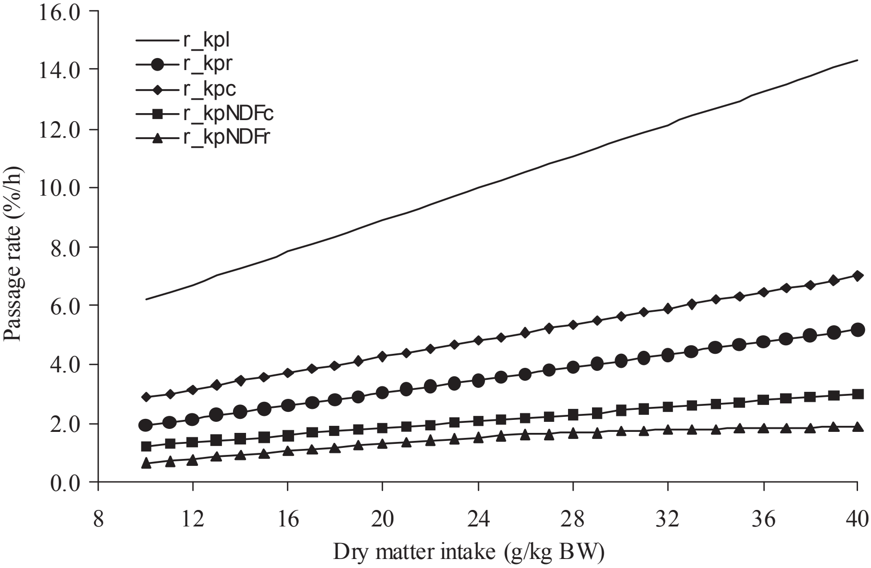

Figure 7.1. Passage rates (%/h) of liquids, r_kpl; protein and starch in roughage, r_kpr; protein and starch in concentrate, r_kpc; NDF in concentrate, r_kpNDFc; and NDF in roughage, r_kpNDFr at different dry matter intake (g/kg BW).

fractions. For example, at a DMI of 25 g/kg BW, the mean rumen retention time (MRT) of CP in concentrate particles is estimated to be 20 h (r_kpc=5.0%/h), while at the same intake level, the MRT of NDF in roughage is 64 h (r_kpNDFr=1.56%/h.).

7.1.2 Rumen degradation of crude protein

Ruminal degradation and the escape of dietary protein (the sum of sCP and pdCP) are described by a one-compartment degradation model (Ørskov and McDonald, 1979). The sCP fraction consists of both non-AA soluble N, such as NH_3N and urea-N, which are assumed to be completely degraded in the rumen, and soluble AA-N which is only partly degraded in the rumen:

$$\begin{aligned} \mathrm{rd\_sCP} = {} & \sum_i \mathrm{DMI}_i \cdot \mathrm{CP}_i \cdot \frac{\mathrm{sCP}_i}{1000} \cdot \frac{150}{150 + \mathrm{r\_kpl}} + \left(\sum_i \mathrm{DMI}_i \cdot \mathrm{CP}_i \cdot \frac{\mathrm{NH_3N}_i}{1000} \right) \\ & - \left(\sum_i \mathrm{DMI}_i \cdot \mathrm{CP}_i \cdot \frac{\mathrm{NH_3N}_i}{1000} \right) \cdot \frac{150}{150 + \mathrm{r\_kpl}} \end{aligned} \qquad 7.6$$

where rd_ sCP is the soluble crude protein degraded in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; sCP_i is the soluble crude protein content in the i=1...n'th feedstuff, g/kg CP; NH_3N_i is the ammonia and urea N content in the i=1...n'th feedstuff, g/kg CP; and r_kpl is the liquid passage rate, Equation 7.1. The fractional degradation rate of AA-N is fixed at 150%/h.

The degradation of pdCP in the rumen is calculated as:

$$\mathrm{rd\_pdCP} = \sum_i \mathrm{DMI}_i \cdot \mathrm{CP}_i \cdot \frac{\mathrm{pdCP}_i}{1000} \cdot \frac{\mathrm{kdCP}_i}{\mathrm{kdCP}_i + \mathrm{r\_kp}} \qquad 7.7$$

where rd_pdCP is the degradation of potentially degradable crude protein in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; $pdCP_i$ is the potentially degradable crude protein content in the i=1...n'th feedstuff, g/kg CP; $kdCP_i$ is the fractional degradation rate of pdCP in the i=1...n'th feedstuff, %/h; and r_kp is the fractional passage rate, %/h. If the feed used is concentrate then r_kp=r_kpc, Equation 7.3, and if the feed is roughage r_kp=r_kpr, Equation 7.2.

The total degradation of dietary CP in the rumen (g/d) is calculated as:

$$\mathrm{rd\_CP} = \mathrm{rd\_sCP} + \mathrm{rd\_pdCP} \qquad 7.8$$

where rd_CP is the total degradation of dietary crude protein in the rumen, g/d; rd_sCP is degradation of soluble protein in the rumen, Equation 7.6; and rd_pdCP is the degradation of potentially degradable protein in the rumen, Equation 7.7.

The energy for microbial growth that comes from the protein degraded in the rumen is corrected for dietary ammonia or urea and is calculated from:

$$\mathrm{rd\_CPcorr} = \mathrm{rd\_CP} - \mathrm{rd\_NH3N\_CP} \qquad 7.9$$

where rd_CPcorr is the ammonia- or urea-corrected dietary crude protein degraded in the rumen, g/d; rd_CP is the total degradation of dietary crude protein in the rumen, g/d; $rd\_NH_3\_CP$ is the dietary ammonia or urea N available in the rumen, Equation 7.10.

The variable $rd\_NH_3N\_CP$ in Equation 7.9 is:

$$\mathrm{rd\_NH3N\_CP} = \sum_i \mathrm{DMI}_i \cdot \mathrm{CP}_i \cdot \frac{\mathrm{NH_3N}_i}{1000} \qquad 7.10$$

where rd_NH3N_CP is the dietary ammonia or urea N available in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; and NH_3N_i is the ammonia or urea N content in the i=1...n'th feedstuff, g/kg CP.

7.1.3 Rumen degradation of carbohydrates

The amount of microbial OM synthesized in the rumen depends primarily upon the fermentability of the carbohydrates. A one-compartment digestion model is used to calculate ruminal degradation of ST and RestCHO in concentrate and roughage, and NDF in concentrate. Small starch granules disappearing from ruminal *in sacco* bags (30-40 µm) are assumed to flow with the liquid fraction, and their degradation is calculated as:

$$rd\_sST = \sum_i DMI_i \cdot ST_i \cdot \frac{sST_i}{1000} \cdot \frac{150}{150 + r\_kpl} \qquad 7.11$$

where rd_sST is the degradation of soluble starch in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; ST_i is the starch content in the i=1...n'th feedstuff, g/kg DM; sST_i is the soluble starch content in the i=1...n'th feedstuff, g/kg ST; and r_kpl is the ruminal liquid passage rate, Equation 7.1.The fractional degradation rate of the sST fraction is set to 150%/h for all feedstuffs.

The same type of equation is also used to calculate the degradation of the RestCHO fraction in the rumen:

$$rd\_RestCHO = \sum_i DMI_i \cdot RestCHOcorr_i \cdot \frac{kdRestCHO}{kdRestCHO + r\_kpl} \qquad 7.12$$

where rd_RestCHO is the degradation of RestCHO in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; $RestCHOcorr_i$ is the ammonia- or urea-N corrected RestCHO content (Equations 4.2 and 4.3) in the i=1...n'th feedstuff, g/kg DM; kdRestCHO is the fractional degradation rate of RestCHO, Equation 4.5; and r_kpl is the ruminal liquid passage rate, Equation 7.1.

The ruminal degradation of pdST for either roughage or concentrate is estimated as:

$$rd\_pdST = \sum_i DMI_i \cdot ST_i \cdot \frac{pdST_i}{1000} \cdot \frac{kdST_i}{kdST_i + r\_kp} \qquad 7.13$$

where rd_pdST is the degradation of potentially degradable starch in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; ST_i is the starch content in the i=1...n'th feedstuff, g/kg DM; pdSTi is the potentially degradable starch content in the i=1...n'th feedstuff, g/kg ST; $kdST_i$ is the fractional degradation rate of pdST in the i=1...n'th feedstuff, %/h; and r_kp is the fractional passage rate, %/h. If the feed is concentrate then r_kp=r_kpc, Equation 7.3, and if the feed is roughage r_kp=r_kpr, Equation 7.2.

The total degradation of dietary starch in the rumen is calculated as:

$$rd\_ST = rd\_sST + rd\_pdST \qquad 7.14$$

where rd_ST is the total degradation of dietary starch in the rumen, g/d; rd_sST is the degradation of soluble starch in the rumen, Equation 7.11; and rd_pdST is the degradation of potentially degradable starch in the rumen, Equation 7.13.

Increased levels of ST and SU in diets have a negative effect on the digestion of fibre in the rumen (Lindberg, 1981; Mould *et al.*, 1983; Khalili and Huhtanen, 1991; Huhtanen and Jaakkola, 1993; Stensig *et al.*, 1998). The decreased degradation rate of fibre with increases in the supply of non-structural carbohydrates has mainly been explained by the negative effect of a decreased ruminal pH on the activity of cellulolytic bacteria. However, the decrease in fibre degradation has also been attributed to substrate-specific stimulation of the non-fibre digesting bacteria at the expense of cellulolytic bacteria (Mould *et al.*, 1983; Huhtanen and Jaakkola, 1993; Weisbjerg *et al.* 1999). To take into account the effect of easily degradable CHO on ruminal NDF digestion, a rumen load index (RLI; the ratio of easily degradable carbohydrates to total fibre) is included in NorFor to derive a correction factor for kdNDF:

$$\mathrm{RLI} = \frac{\mathrm{rd\_ST} + \mathrm{rd\_RestCHO} - \sum_i \mathrm{DMI}_i \cdot \left(\mathrm{RestCHOcorr}_i - \mathrm{SU}_i\right)}{\sum \mathrm{DMI}_i \cdot \mathrm{NDF}_i + \sum \mathrm{DMI}_i \cdot \left(\mathrm{RestCHOcorr}_i - \mathrm{SU}_i\right)} \qquad 7.15$$

where RLI is the ratio of rapidly degraded carbohydrates to slowly degradable carbohydrates in the diet, g/g; rd_ST is the starch degraded in the rumen, Equation 7.14; rd_RestCHO is the degradation of RestCHO in the rumen, Equation 7.12; SU_i is the sugar content in the i=1...n'th feedstuff, g/kg DM; $\mathrm{RestCHOcorr}_i$ is the nitrogen-corrected RestCHO content in the i=1...n'th feedstuff, Equations 4.2 and 4.3; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; and NDF_i is the NDF content in the i=1...n'th feedstuff, g/kg DM.

The kdNDF correction factor is based on a modified equation derived from the work of Danfær *et al.* (2006):

$$\mathrm{corrNDF\_fac} = 0.4561 + \frac{0.5431}{1 + e^{\left(\frac{0.7657 - \mathrm{RLI}}{-0.1589}\right)}} \qquad 7.16$$

where corrNDF_fac is the kdNDF correction factor, 0-1; and RLI is the ratio of rapidly degraded carbohydrates to total fibre in the diet, Equation 7.15.

Figure 7.2 illustrates the relationship between corrNDF_fac and RLI. The kdNDF is multiplied by the corrNDF_fac and will thus decrease with increasing level of ruminal degraded starch and sugars in the diet. Equation 7.15 show that starch sources with a slow kdST have a less negative impact on

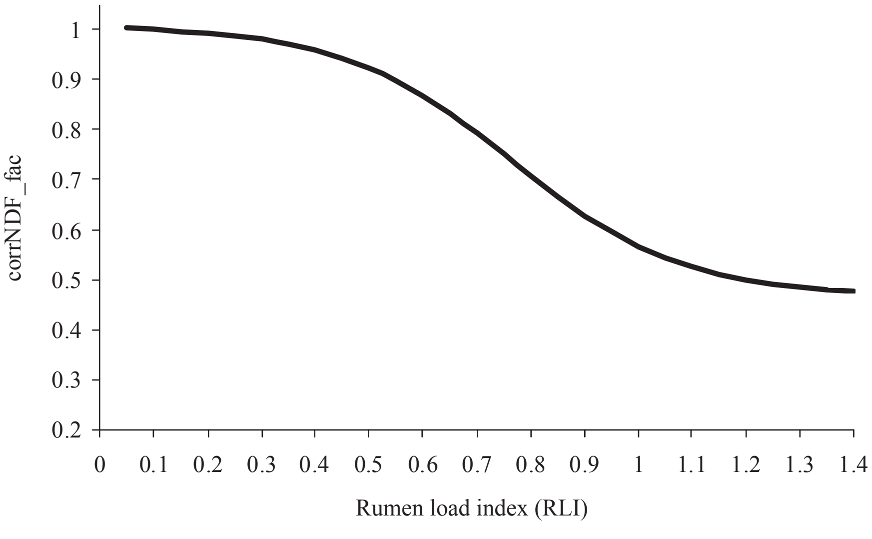

Figure 7.2. Relationship between the kdNDF correction factor (corrNDF_fac; Equation 7.16) and the rumen load index (RLI).

ruminal NDF digestion than rapidly degradable starch sources. $RestCHO_i$-SU_i is an indirect estimate of soluble fibre in the diet, and it is known that the soluble fibre fraction has a less negative impact on ruminal NDF digestibility when there are high levels of easily fermentable carbohydrates in the diet (Voelker and Allen, 2003). For further evaluation of RLI, see Section 14.5.

The ruminal degradation of NDF in concentrates (rd_pdNDFc) is estimated from a one-compartment degradation model, as follows:

$$rd\_pdNDFc = \sum_i DMI_i \cdot NDF_i \cdot \frac{pdNDF_i}{1000} \cdot \frac{kdNDF_i \cdot corrNDF\_fac}{(kdNDF_i \cdot corrNDF\_fac) + r\_kpNDFc} \qquad 7.17$$

where, rd_pdNDF is the degradation of potentially degradable NDF in concentrates in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; NDF_i is NDF content in the i=1...n'th feedstuff, g/kg DM; $pdNDF_i$ is the potentially degradable NDF content in the i=1...n'th feedstuff, g/kg NDF; $kdNDF_i$ is the fractional degradation rate of pdNDF in the i=1...n'th feedstuff, %/h; corrNDF_fac is the NDF degradation rate correction factor, Equation 7.16; and r_kpNDFc is the passage rate of NDF in concentrates from the rumen, Equation 7.4.

In NorFor ruminal degradation of NDF in roughage (rd_pdNDFr) is estimated from a two-compartment digestion model (Allen and Mertens, 1988) comprising a non-escapable and an escapable pool. The non-escapable pool represents large particles that are unable to escape from the rumen, while the escapable pool represents small particles that can pass out of the rumen. This model takes into account the selective retention of feed particles in the rumen and provides a more realistic estimate of ruminal NDF digestion than a one-compartment model (Huhtanen *et al.*, 1995; Minde and Rygh, 1997). The pdNDF passage from the non-escapable pool to the escapable pool, and subsequently from the escapable pool out of the rumen, is expressed by r_kpNDFr (Equation 7.5). The MRT of pdNDF in the non-escapable pool is assumed to be 40% of the total rumen MRT; a mean value estimated from duodenal marker profiles (Stensig, 1996; Minde and Rygh, 1997). The release factor (r_kp1) from the non-escapable to the escapable pool is calculated as:

$$r\_kp1 = \frac{100}{\frac{100}{r\_kpNDFr} \cdot 0.4} \qquad 7.18$$

where r_kp1 is the release rate of pdNDF from the non-escapable to the escapable ruminal NDF pool, %/h; and r_kpNDFr is the passage rate of pdNDF out of the rumen in roughage, Equation 7.5.

The passage of pdNDF from the escapable pool out of the rumen is:

$$r\_kp2 = \frac{100}{\frac{100}{r\_kpNDFr} \cdot 0.6} \qquad 7.19$$

where r_kp2 is the passage rate of pdNDF from the escapable pool out of the rumen, %/h; and r_kpNDFr is the passage rate out of the rumen of NDF in roughage, Equation 7.5.

From the two-compartment digestion model the rumen degradation of pdNDF in roughage is calculated as:

$$rd\_pdNDFr = \sum_i DMI_i \cdot NDF_i \cdot \frac{pdNDF_i}{1000} \cdot \left(\frac{kdNDF_i \cdot corrNDF\_fac}{(kdNDF_i \cdot corrNDF\_fac) + r\_kp1} \cdot \left(1 + \frac{r\_kp1}{(kdNDF_i \cdot corrNDF\_fac) + r\_kp2} \right) \right) \qquad 7.20$$

where rd_pdNDFr is the ruminal degradation of potentially degradable NDF in roughage, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; NDF_i is NDF content in the i=1...n'th feedstuff, g/kg DM; $pdNDF_i$ is the potentially degradable NDF content in the i=1...n'th feedstuff, g/kg NDF; $kdNDF_i$ is the fractional degradation rate of pdNDF in the i=1...n'th feedstuff, %/h; corrNDF_fac is the NDF degradation rate correction factor, Equation 7.16; r_kp1 is the release rate of pdNDF from the non-escapable to the escapable ruminal NDF pool, Equation 7.18; and r_kp2 is the passage rate of pdNDF from the escapable pool out of the rumen, Equation 7.19.

In a feed ration the total degradation of NDF in the rumen is calculated as:

$$rd\_NDF = rd\_pdNDFc + rd\_pdNDFr \qquad 7.21$$

where rd_NDF is the total degradation of NDF in the rumen, g/d; rd_pdNDF is the degradation of potentially degradable NDF in concentrate, Equation 7.17; and rd_pdNDFr is the degradation of potentially degradable NDF in roughage, Equation 7.20.

7.1.4 Rumen metabolism of crude fat and fermentation products

The CFat has a variable FA component (see Section 4.5). In concentrates, the non-fatty acid component (1000-FA) of triacylglycerols is assumed to consist of glycerol, while in roughage this component is assumed to consist of both glycerol and galactose. Since the fatty acids provide no ATP for microbial growth (Van Soest, 1994), the metabolism of CFat in the rumen is calculated from the following equation:

$$rd\_CFat = \sum_i DMI_i \cdot CFat_i \cdot \frac{1000 - FA_i}{1000} \qquad 7.22$$

where rd_CFat is the metabolism of crude fat in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; $CFat_i$ is the crude fat content in the i=1...n'th feedstuff, g/kg DM; and FA_i is the proportion of fatty acids in the i=1...n'th feedstuff, g/kg CFat.

The FPF are assumed to be completely liberated in the rumen. The VFAs do not yield ATP for microbial growth, while lactic acid (the dominating acid in silage) only provides a small amount of energy for microbial synthesis (Van Soest, 1994). The metabolism of dietary FPF in the rumen is calculated from the equation:

$$rd\_FPF = \sum_i DMI_i \cdot FPF_i \qquad 7.23$$

where rd_FPF is the liberation of dietary fermentation products in the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; and FPF_i is the fermentation product content in the i=1...n'th feedstuff, Equation 4.7.

7.1.5 Effective rumen degradability

Effective rumen degradability (erd) is used as an estimate of ruminal digestibility. The erd is also used to evaluate the effect of diet composition on ruminal digestibility. The erd values are calculated for the main nutrients, as described in Equations 7.24, 7.25, 7.26 and 7.27 for CP, ST, NDF and RestCHO, respectively:

$$erd\_CP = \frac{rd\_CP \cdot 100}{\sum_i DMI_i \cdot CP_i} \qquad 7.24$$

where erd_CP is the effective degradability of crude protein in the rumen, %; rd_CP is the degradation of crude protein in the rumen, Equation 7.8; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; and DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d.

$$erd\_ST = \frac{rd\_ST \cdot 100}{\sum_i DMI_i \cdot ST_i} \tag{7.25}$$

where erd_ST is the effective degradability of starch in the rumen, %; rd_ST is the degradation of starch in the rumen, Equation 7.14; ST_i is the starch content in the i=1...n'th feedstuff, g/kg DM; and DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d.

$$erd\_NDF = \frac{rd\_NDF \cdot 100}{\sum_i DMI_i \cdot NDF_i} \tag{7.26}$$

where erd_NDF is the effective degradability of NDF in the rumen, %; rd_NDF is the ruminal degradation of NDF, Equation 7.21; NDF_i is the NDF content in the i=1...n'th feedstuff, g/kg DM; and DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d.

$$erd\_RestCHO = \frac{rd\_RestCHO \cdot 100}{\sum_i DMI_i \cdot RestCHOcorr_i} \tag{7.27}$$

where erd_RestCHO is the effective degradability of RestCHO in the rumen, %; rd_RestCHO is the degradation of RestCHO in the rumen, Equation 7.12; $RestCHOcorr_i$ is the corrected RestCHO content in the i=1...n'th feedstuff, Equations 4.2 and 4.3; and DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d.

7.1.6 Microbial efficiency and chemical composition

The equation presented by Archimède *et al.* (1997) was used as a basis to estimate efficiency of microbial protein synthesis in the rumen (r_emCP). However, when the equation was evaluated using Norwegian data, r_emCP was overestimated at high intake levels (Figure 7.3), and the dietary proportion of easily degradable carbohydrates affected the efficiency in a curvilinear manner. This carbohydrate effect was also discussed by Archimède *et al.* (1997), who classified the carbohydrate source into rapidly degradable starch, slowly degradable starch and digestible fibre. Thus, a new equation was developed to account for the effects of carbohydrate intake on the efficiency of microbial protein synthesis.

For dairy cows, the following equation is used:

$$\begin{aligned} r\_emCP = {} & \ln\left(\frac{1000 \cdot \sum_i DMI_i}{BW}\right) \cdot 55.6 + 0.4166 \cdot \frac{\sum_i DMI_i \cdot ST_i + \sum_i DMI_i \cdot RestCHOcorr_i}{\sum_i DMI_i} - \\ & 0.0008868 \cdot \left(\frac{\sum_i DMI_i \cdot ST_i + \sum_i DMI_i \cdot RestCHOcorr_i}{\sum_i DMI_i}\right)^2 - 54.56 \end{aligned} \tag{7.28}$$

where r_emCP is the microbial protein synthesis efficiency in the rumen, g/kg organic matter actually digested in the rumen; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; BW is the animal body weight, kg; ST_i is the starch content in the i=1...n'th feedstuff, g/kg DM; and $RestCHOcorr_i$ is the nitrogen-corrected RestCHO content (Equations 4.2, 4.3) in the i=1...n'th feedstuff, g/kg DM.

Figure 7.4 illustrates how the r_emCP changes with the ST and RestCHO content of the diet (at two levels of feed intake: 18 and 36 g DMI/kg BW). There is a curvilinear effect of rapidly degradable carbohydrates on r_emCP and the efficiency is highest at 235 g/kg DM of ST + RestCHO in the diet, equivalent to 35-45% concentrate in the diet, which corresponds well to the optimum concentrate level observed by Archimède *et al.* (1997).

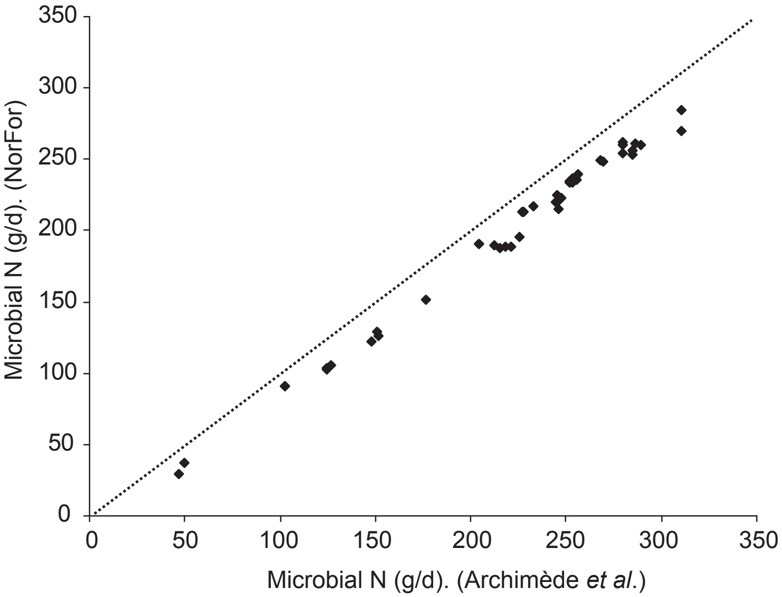

Figure 7.3. Relationship between NorFor and the Archimède et al. *(1997) estimates of microbial N supply (data from Rygh, 1997; Volden, 1999; Selemer-Olsen, 1996, Prestløkken, 1999; Mydland, 2008; Kjos, unpublished data; Volden: unpublished data).*

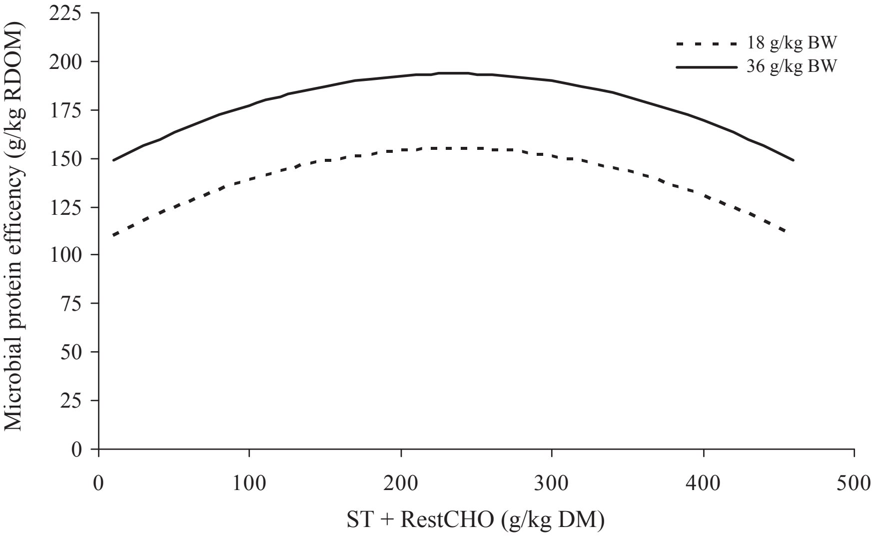

Figure 7.4. Effect of feeding level (g DMI/kg BW) and starch (ST) + residual carbohydrate (RestCHO) content of the diet on efficiency of microbial protein synthesis in the rumen (r_emCP) estimated from Equation 7.28, g/ kg rumen degraded OM (rd_OM).

Evaluation of Equation 7.28 for growing cattle showed that it yielded unrealistically low r_emCP values when proportions of ST and RestCHO in the diet were high (>400 g/kg DM, corresponding to 65-75% concentrate in the diet). To avoid this, an adjusted equation was used to calculate r_emCP in growing cattle:

$$r\_emCP = \left(\frac{3.17 + 0.248 \cdot \left(\frac{\sum\limits_i DMI_i \cdot ST_i + \sum\limits_i DMI_i \cdot \mathrm{RestCHOcorr}_i}{\sum DMI_i} \right) - 0.0004323 \cdot \left(\frac{\sum\limits_i DMI_i \cdot ST_i + \sum\limits_i DMI_i \cdot \mathrm{RestCHOcorr}_i}{\sum DMI_i} \right)^2}{1 - 0.001879 \cdot \left(\frac{\sum\limits_i DMI_i \cdot ST_i + \sum\limits_i DMI_i \cdot \mathrm{RestCHOcorr}_i}{\sum DMI_i} \right) + 0.000003548 \cdot \left(\frac{\sum\limits_i DMI_i \cdot ST_i + \sum\limits_i DMI_i \cdot \mathrm{RestCHOcorr}_i}{\sum DMI_i} \right)^2} \right) + \ln\left(\frac{1000 \cdot \sum\limits_i DMI_i}{BW} \right) \cdot 33.695 + 0.05575 \cdot \left(\frac{1000 \cdot \sum\limits_i DMI_i}{BW} \right)^2 \qquad 7.29$$

where r_emCP, DMI_i, ST_i, $\mathrm{RestCHOcorr}_i$ and BW are described in Equation 7.28.

When the ST and RestCHO content in the diet is less than 300 g/kg DM, the effect of rapidly fermentable carbohydrates on r_emCP is identical in Equations 7.28 and 7.29.

The ATP for microbial growth per unit digested OM differs between substrates (Van Soest, 1994) as the relative proportions of ATP supplied from protein and lactic acid are only 0.5 and 0.2 of those supplied from carbohydrates, respectively. This is taken into account when calculating the microbial protein supply:

$$r\_mCP = \frac{\left(r\_emCP \cdot \left(\begin{matrix} (rd\_ST + rd\_NDF + rd\_restCHO + rd\_CFat) \\ + rd\_CPcorr \cdot 0.5 + rd\_FPF \cdot 0.125 \end{matrix} \right) \right)}{1000} \qquad 7.30$$

where r_mCP is the rumen microbial protein flow out of the rumen, g/d; r_emCP is the efficiency of microbial CP, Equation 7.28 for cows and Equation 7.29 for growing cattle; rd_ST is the degradation of starch in the rumen, Equation 7.14; rd_NDF is the degradation of NDF in the rumen, Equation 7.21; rd_RestCHO is degradation of rest carbohydrates in the rumen, Equation 7.12; rd_CFat is the rumen degradation of crude fat, Equation 7.22; rd_CPcorr is the degradation of ammonia or urea corrected crude protein in the rumen, Equation 7.9; rd_FPF is the liberation of feed fermentation products in the rumen, Equation 7.23.

The r_mCP is the estimated daily flow of microbial protein out of the rumen equivalent to the microbial protein supply. When calculating the daily r_mCP, it is assumed that the proportion of lactic acid in FPF is 0.5 and, thus, 0.125 is used as a coefficient for rd_FPF in the equation. The ATP from CFat is derived from fermentation of glycerol and galactose (Equation 7.22). In NorFor, the equation for calculating r_mCP impacts also directly on the microbial synthesis of OM, starch and fat. The OM composition of rumen microbes is based on weighted averages for solid-adherent bacteria, liquid-associated bacteria and liquid-associated protozoa present in the ratio 60:30:10, estimated from data presented by Volden and Harstad (1998a) and Volden *et al.* (1999a). The chemical composition (g/kg OM) of the microbial fraction is 512 CP, 167 CFat, 51 ST and a residual fraction of 270. The amount of microbial OM supplied from the rumen is calculated from:

$$r\_mOM = \frac{r\_mCP}{0.512} \qquad 7.31$$

where r_mOM is the microbial organic matter flow out of the rumen, g/d; r_mCP is the microbial protein flow out of the rumen, Equation 7.30; and 0.512 is the proportion of CP in the microbial OM.

The equation for calculating the microbial CFat supply is:

$$r\_mCFat = r\_mCP \cdot \frac{167}{512} \qquad 7.32$$

where r_mCFat is the microbial crude fat flow out of the rumen, g/d; r_mCP is the microbial protein flow out of the rumen, Equation 7.30; and 167/512 is the CFat:CP ratio in the rumen microbial OM.

The supply of microbial ST is calculated as:

$$r\_mST = r\_mCP \cdot \frac{51}{512} \qquad 7.33$$

where r_mST is the microbial starch flow out of the rumen, g/d; r_mCP is the microbial protein flow out of the rumen, Equation 7.30; and 51/512 is the ratio of ST:CP in the rumen microbial OM.

The proportion of AAs in the microbial protein was set to 0.73 (Volden and Harstad, 1998a, b; Volden *et al*., 1999a, b) and the amount of microbial AAs flowing out of the rumen is therefore:

$$r\_mAA = r\_mCP \cdot 0.73 \qquad 7.34$$

where r_mAA is the microbial AA flow out of the rumen, g/d; r_mCP is the microbial protein flow out of the rumen, Equation 7.30; and 0.73 is the proportion of AAs in the microbial protein.

The composition of essential AAs in the microbial protein (presented in Table 7.2) was estimated from data presented by Volden and Harstad (1998b) and Volden *et al*. (1999b), based on weighted averages for solid-adherent bacteria, liquid-associated bacteria and liquid-associated protozoa in the ratio of 60:30:10.

7.1.7 Protein balance in the rumen

Low levels of degradable protein in the diet will reduce the ruminal NDF digestion and microbial protein synthesis (Hoover, 1986; Clark *et al*., 1992; Stern *et al*., 1994). In NorFor the protein balance in the rumen (PBV_N) is used to evaluate the adequacy of protein for microbial growth, and is calculated from the following equation:

Table 7.2. Essential amino acid (AA) composition (g/100 g of AA) of the rumen microbes entering the small intestine and of endogenous AAs.

Amino acid	g/100 g	
	Microbial[1]	Endogenous[2]
Arginine	5.1	4.0
Histidine	2.4	2.8
Isoleucine	5.9	3.6
Leucine	7.9	3.8
Lysine	7.4	6.3
Methionine	2.5	1.1
Phenylalanine	5.7	3,6
Threonine	5.3	5.8
Tryptophan	1.6	1.0
Valine	5.9	4.8

[1] Data from Volden and Harstad (1998b) and Volden *et al*. (1999)

[2] Data from Larsen *et al*. (2000).

$$PBV_N = rd\_CP + \left(\left(\sum_i DMI_i \cdot CP_i\right) \cdot 0.046\right) - r\_mCP \quad 7.35$$

where PBV_N is the protein balance in the rumen, g/d; rd_CP is the degradation of crude protein in the rumen, Equation 7.8; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; and r_mCP is the microbial flow out of the rumen, Equation 7.30.

The parameter 0.046 is the proportion of the dietary protein (N·6.25) recycled back to the rumen. This value is parameterized from Danish (Weisbjerg *et al.*, 1998) and Norwegian (Rygh, 1997; Prestløkken, 1999; Volden, 1999; Volden, unpublished data; Kjos, unpublished data) determinations, from a linear relationship between total N flowing into the duodenum (corrected for endogenous protein) and the dietary CP intake in trials with diets having CP contents<165 g/kg DM. Thus, this factor describes the proportion of a net duodenal flow of microbial protein from recycled N. At a dietary CP content of 162 g/kg DM, the N intake was similar to the N flow at the duodenum, while at lower N intake values the duodenal flow was higher than the N intake when corrected for endogenous excretion.

7.2. Small intestine

The OM components flowing into the duodenum are of dietary, microbial and animal origin. In the small intestine, they are subjected to enzymatic digestion. However, it is assumed that the small intestine lacks enzymes to digest NDF and microbial cell walls. The flow of OM out of the rumen is calculated as:

$$r\_outOM = \left(\sum_i DMI_i \cdot OM_i\right) - \begin{pmatrix} rd\_CPcorr + rd\_ST + rd\_NDF + rd\_NH3N\_CP \\ + rd\_CFat + rd\_FPF + rd\_RestCHO \end{pmatrix} + r\_mOM \quad 7.36$$

where r_outOM is the flow of organic material out of the rumen, g/d; OM_i is the organic matter content in the i=1...n'th feedstuff, g/kg DM; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; rd_CPcorr is ammonia- or urea-corrected dietary crude protein degraded in the rumen, Equation 7.9; rd_ST is the rumen degradation of dietary starch, Equation 7.14; rd_NDF is the rumen degradation of NDF, Equation 7.21; rd_NH3N_CP is the dietary ammonia or urea N available in the rumen, Equation 7.10; rd_CFat is the rumen metabolism of crude fat, Equation 7.22; rd_FPF is the rumen liberation of dietary fermentation products, Equation 7.23; rd_RestCHO is the rumen degradation of residual carbohydrates, Equation 7.12; r_mOM is the microbial organic matter flowing out of the rumen, Equation 7.31.

7.2.1 Digestion of dietary protein, amino acids, starch and fatty acids

The digestion of dietary protein in the small intestine is calculated from the ruminal escape fraction and the iCP fraction (see Section 4.3) as:

$$sid\_CP = \left(\sum_i DMI_i \cdot CP_i\right) - rd\_CP - \sum_i \left(DMI_i \cdot CP_i \cdot \frac{iCP_i}{1000}\right) \quad 7.37$$

where sid_CP is the digestion of dietary protein in the small intestine that has escaped from the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; rd_CP is the degradation of crude protein in the rumen, Equation 7.8; and iCP_i is the total indigestible crude protein content in the i=1...n'th feedstuff, g/kg CP.

It is assumed that the proportion of AAs in ruminal escape protein and iCP are identical to the intact feed protein. Digestion of dietary AAs in the small intestine is calculated as:

$$\text{sid\_AA} = \sum_i \text{DMI}_i \cdot \text{CP}_i \cdot \frac{\text{AA}_i}{100} \cdot \left(\begin{array}{l} 1 - \left(\frac{\text{sCP}_i}{1000} \cdot \frac{150}{150 + \text{r\_kpl}} + \frac{\text{NH}_3\text{N}_i}{1000} - \frac{\text{NH}_3\text{N}_i}{1000} \cdot \frac{150}{150 + \text{r\_kpl}} \right) \\ - \left(\frac{\text{pdCP}_i}{1000} \cdot \frac{\text{kdCP}_i}{\text{kdCP}_i + \text{r\_kp}} \right) - \frac{\text{iCP}_i}{1000} \end{array} \right) \tag{7.38}$$

where sid_AA is the digestion of total dietary AAs in the small intestine that escaped from the rumen, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; AA_i is the AA content in the i=1...n'th feedstuff, g/100 g CP; sCP_i is the soluble crude protein content in the i=1...n'th feedstuff, g/kg CP; iCP_i is total indigestible crude protein content in the i=1...n'th feedstuff, g/kg CP; NH_3N_i is the ammonia and urea N content in the i=1...n'th feedstuff, g/kg CP; r_kpl is the liquid passage rate, Equation 7.1; the fractional degradation rate of AA-N is fixed at 150%/h; $kdCP_i$ is the fractional degradation rate of pdCP in the i=1...n'th feedstuff, %/h; and r_kp is the ruminal passage rate, %/h. If the feed is concentrate then r_kp=r_kpc, Equation 7.3, and if the feed is roughage r_kp=r_kpr, Equation 7.2.

NorFor calculates the small intestine digestion of arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine. When calculating individual AA digestion, it is assumed that the AA profile of the ruminally undegraded protein and the iCP are the same as in the intact feed protein. The general equation to calculate intestinal digestion of an individual dietary AA is:

$$\text{sid\_AA}_j = \sum_i \text{DMI}_i \cdot \text{CP}_i \cdot \frac{\text{AA}_{ji}}{100} \cdot \text{H}_2\text{O}_{\text{corr}} \cdot \left(\begin{array}{l} 1 - \left(\frac{\text{sCP}_i}{1000} \cdot \frac{150}{150 + \text{r\_kpl}} + \frac{\text{NH}_3\text{N}_i}{1000} - \frac{\text{NH}_3\text{N}_i}{1000} \cdot \frac{150}{150 + \text{r\_kpl}} \right) \\ - \left(\frac{\text{pdCP}_i}{1000} \cdot \frac{\text{kdCP}_i}{\text{kdCP}_i + \text{r\_kp}} \right) - \frac{\text{iCP}_i}{1000} \end{array} \right) \tag{7.39}$$

where sid_AA_j is the intestinal digestion of the individual AA_j, g/d, j=arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan or valine; AA_{ji} is the individual AA_j content in the i=1...n'th feedstuff, g/100 g CP; H_2O_{corr} is the water correction factor for each individual AA_j; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; AAN_i is the amino acid content in the i=1...n'th feedstuff, g/100 g CP; sCP_i is the soluble crude protein content in the i=1...n'th feedstuff, g/kg CP; iCP_i is the total indigestible crude protein content in the i=1...n'th feedstuff, g/kg CP; NH_3N_i is the ammonia and urea N content in the i=1...n'th feedstuff, g/kg CP; r_kpl is the liquid passage rate, Equation 7.1; the fractional degradation rate of soluble AA-N is fixed at 150%/h; $kdCP_i$ is the fractional degradation rate of pdCP in the i=1...n'th feedstuff, %/h; and r_kp is the fractional passage rate, %/h. If the feed is concentrate then r_kp=r_kpc, Equation 7.3, and if the feed is roughage r_kp=r_kpr, Equation 7.2.

The individual AA supply is calculated as water-free AA, and H_2O correction factors (H_2O_{corr}) of 0.8966, 0.8839, 0.8627, 0.8627, 0.8767, 0.8792, 0.8910, 0.8487, 0.9118 and 0.8462 are used for arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine, respectively.

The digestion of ruminally undegraded starch in the small intestine is calculated as for protein:

$$\text{sid\_ST} = \sum_i (\text{DMI}_i \cdot \text{ST}_i) - \text{rd\_ST} - \sum_i (\text{DMI}_i \cdot \text{ST}_i \cdot \frac{\text{iST}_i}{1000} \tag{7.40}$$

where sid_ST is the digestion of ruminally undegraded dietary starch in the intestine, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; ST_i is the starch content in the i=1...n'th feedstuff, g/kg DM; rd_ST is the rumen degradation of starch, Equation 7.14; and iST_i is the indigestible starch content in the i=1...n'th feedstuff, g/kg ST.

Dietary CFat entering the small intestine is assumed to be in the form of fatty acids, and the equation by Weisbjerg *et al.* (1992) is used to calculate the digestion of dietary fatty acids in the small intestine, as follows:

$$sid\_CFat = \left(\sum_i \left(DMI_i \cdot CFat_i \right) - rd\_CFat \right) \cdot \left(\frac{93.8 - 0.0169 \cdot \left(\sum_i \left(DMI_i \cdot CFat_i \right) - rd\_CFat \right)}{100} \right) \qquad 7.41$$

where sid_CFat is the digestion of dietary crude fat in the small intestine, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; $CFat_i$ is the crude fat content in the i=1...n'th feedstuff, g kg/ DM; and rd_CFat is the degradation of crude fat, Equation 7.22.

7.2.2 Digestion of microbial protein, amino acids, starch and fatty acids

Few data are available on the small intestinal digestibility of microbial OM. However, multiple regression analyses by Tas *et al.* (1981) and Storm *et al.* (1983) indicating that 87 and 85% of bacterial AAs (which are found in both microbial cytoplasm and cell walls) are digestible in the small intestine, respectively. Similarly, Hvelplund (1985) found an average true digestibility of bacterial AAs in sheep intestines of 85%, with minor variations, while Mason and White (1971) found that AAs in the microbial cell wall are mostly indigestible in the small intestine. Nucleic acids are also efficiently digested in the small intestine. NRC (1985) showed that 75 to 90% of the nucleic acids are digested and absorbed in the small intestine. In NorFor, the following fixed digestibility coefficients for microbial CP and AAs (Storm *et al.*, 1983; Hvelplund, 1985), starch and CFat are used:

$$sid\_mCP = r\_mCP \cdot 0.85 \qquad 7.42$$

$$sid\_mAA = r\_mAA \cdot 0.85 \qquad 7.43$$

$$sid\_mST = r\_mST \cdot 0.9 \qquad 7.44$$

$$sid\_mFA = r\_mCFat \cdot 0.85 \cdot 0.65 \qquad 7.45$$

where sid_mCP, sid_mAA, sid_mST and sid_mFA are the amounts of microbial protein, amino acids, starch and fatty acids digested in the small intestine, respectively, g/d; r_mCP is the microbial protein synthesis in the rumen, Equation 7.30; r_mAA is the microbial amino acid synthesis in the rumen, Equation 7.34; r_mST is the microbial starch synthesis in the rumen, Equation 7.33; r_mCFat is the microbial crude fat synthesis in the rumen, Equation 7.32; 0.85 is the intestinal digestion coefficient; and 0.65 is the proportion of fatty acids in the microbial crude fat.

When calculating the supply of individual AAs from rumen microbes, it is assumed that the AA profile of the rumen microbes passing out of the rumen is similar to that of microbes in the rumen (Table 7.2), and that the intestinal digestibility coefficient for each individual AA is similar to that of the total microbial AAs. The microbial residual fraction, consisting mostly of microbial cell walls, is assumed to remain undigested in the small intestine.

7.2.3 Flow and digestion of endogenous protein in the small intestine

The endogenous material of animal origin emerging in the duodenum consists of epithelial cells from the rumen, the abomasum and the intestinal wall, enzymes excreted from the pancreas and the intestinal wall, and biliary excretions from the liver. In NorFor, endogenous excretion is assumed to be only protein. Based on data from Brandt *et al.* (1980), Ørskov and McLeod (1982), Hvelplund and Madsen (1985), Van Bruchem *et al.* (1985a) and Voigt *et al.* (1993), the average endogenous CP flow in the duodenum was estimated to be 30 g/kg OM flow. The endogenous proteins are digested and reabsorbed in the small intestine and a digestibility coefficient of 60% is used (Voigt *et al*., 1993, Larsen *et al*., 2000). The proportion of AAs in the total endogenous protein (N·6.25) was set to 0.5:

$$\mathrm{sid\_eAA} = \mathrm{r\_outOM} \cdot 0.03 \cdot 0.5 \cdot 0.6 \qquad 7.46$$

where sid_eAA is the amount of endogenous AAs digested in the small intestine, g/d; and r_outOM is the flow of organic material out of the rumen, Equation 7.36.

When calculating the absorption of individual AAs from the small intestine, the endogenous AA profile (Table 7.2) is based on data presented by Larsen *et al*. (2000), and it is assumed that the intestinal digestibility of individual endogenous AAs is the same as for total endogenous AAs.

7.3 Large intestine

The OM flowing into the large intestine consists of undigested feed, microbial material and endogenous material. In the large intestine, this OM is subjected to microbial fermentation.

The flow of endogenous protein into the large intestine is estimated to be three times the endogenous OM digested in the small intestine (Brandt *et al*., 1980; Voigt *et al*., 1993) and the total flow of OM into the large intestine is calculated as:

$$\begin{aligned}\mathrm{si\_outOM} = {} & \left(\sum_i (\mathrm{DMI}_i \cdot \mathrm{NDF}_i) - \mathrm{rd\_NDF}\right) + \left(\sum_i (\mathrm{DMI}_i \cdot \mathrm{ST}_i) - (\mathrm{rd\_ST} + \mathrm{sid\_ST})\right) + \\ & \left(\sum_i (\mathrm{DMI}_i \cdot \mathrm{CP}_i) - (\mathrm{rd\_CP} + \mathrm{sid\_CP})\right) + \left(\sum_i (\mathrm{DMI}_i \cdot \mathrm{CFat}_i) - (\mathrm{rd\_CFat} + \mathrm{sid\_CFat})\right) + \\ & (\mathrm{r\_outOM} \cdot 0.03 \cdot 3 \cdot 0.4) + (\mathrm{r\_mCP} \cdot 0.15) + (\mathrm{r\_mST} \cdot 0.1) + (\mathrm{r\_mCFat} \cdot 0.15) + \\ & (\mathrm{r\_mCP} \cdot 0.53)\end{aligned} \qquad 7.47$$

where si_outOM is the flow of organic matter into the large intestine, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; NDF_i is the NDF content in the i=1...n'th feedstuff, g/kg DM; rd_NDF is the degradation of NDF in the rumen, Equation 7.21; ST_i is the starch content in the i=1...n'th feedstuff, g/kg DM; rd_ST is the degradation of starch in the rumen, Equation 7.14; sid_ST is the digestion of starch in the small intestine, Equation 7.40; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; rd_CP is the degradation of crude protein in the rumen, Equation 7.8; sid_CP is the digestion of crude protein in the small intestine, Equation 7.37; CFat_i is the crude fat content in the i=1...n'th feedstuff, g/kg DM; rd_CFat is the metabolism of crude fat in the rumen, Equation 7.22; sid_CFat is the digestion of fatty acids in the small intestine, Equation 7.41; r_outOM is the flow of organic matter out of the rumen, Equation 7.36; r_mCP is the synthesis of microbial protein in the rumen, Equation 7.30; r_mST is the synthesis of microbial starch in the rumen, Equation 7.33; r_mCFat is the synthesis of microbial crude fat in the rumen, Equation 7.32; parameters 0.03·3·0.4 express the flow of undigested endogenous crude protein into the large intestine; the parameter 0.15 is the proportion of undigested microbial protein; the parameter 0.1 is the proportion of undigested microbial starch; the parameter 0.15 is the proportion of the undigested microbial crude fat; and the parameter 0.53 is the ratio of the microbial residual fraction to crude protein.

In Equation 7.47, the expression r_mCP·0.53 is an estimate of the microbial residual fraction flowing into the large intestine (0.53=270/512; see Section 7.1.6), and as discussed earlier, we assumed that this fraction is indigestible in the small intestine. The components flowing into the large intestine are subjected to microbial fermentation. However, only ruminally undegraded NDF, undigested rumen escape starch, undigested rumen microbial starch and cell walls are assumed to be substrates for microbial fermentation. A one-compartment degradation model is used to calculate NDF degradation, and fixed degradation and passage rates of 4 and 16.7%/h, respectively, are used for all feeds. The degradation of NDF in the large intestine is calculated from:

$$\text{lid\_NDF} = \left(\sum_i \left(\text{DMI}_i \cdot \text{NDF}_i \cdot \frac{\text{pdNDF}_i}{1000} \right) - \text{rd\_NDF} \right) \cdot \frac{4}{4+16.7} \qquad 7.48$$

where lid_NDF is the degradation of NDF in the large intestine, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; NDF_i is the NDF content in the i=1...n'th feedstuff, g/kg DM; pdNDF_i is the potentially degradable NDF content in the i=1...n'th feedstuff, g/kg NDF; rd_NDF is the degradation of NDF in the rumen, Equation 7.21; the parameter 4 is the degradation rate of NDF, %/h; and the parameter 16.7 is the fractional passage rate of NDF out of the large intestine, %/h.

The starch degradation in the large intestine is derived from the following equation, where, it is assumed that the digestibility coefficient of the starch fraction is 0.9:

$$\text{lid\_ST} = \left(\sum_i \left(\text{DMI}_i \cdot \text{ST}_i \right) - \text{rd\_ST} - \text{sid\_ST} \right) \cdot 0.9 \qquad 7.49$$

where lid_ST is the degradation of starch in the large intestine, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; ST_i is the starch content in the i=1...n'th feedstuff, g/kg DM; rd_ST is the degradation of starch in the rumen, Equation 7.14; and sid_ST is the digestion of starch in the small intestine, Equation 7.40.

A fixed value of 150 g/kg degraded CHO is used for the efficiency of microbial protein synthesis in the large intestine (Demeyer, 1990), and the composition of microbial OM in the large intestine is assumed to be similar to that in the rumen. Microbial protein synthesis is calculated as:

$$\text{li\_mCP} = \left(\text{lid\_NDF} + \text{lid\_ST} + \text{r\_mST} \cdot 0.1 + \text{r\_mCP} \cdot \frac{270}{512} \cdot 0.75 \right) \cdot 0.15 \qquad 7.50$$

where li_mCP is the microbial protein synthesis in the large intestine, g/d; lid_NDF is the degradation of NDF in the large intestine, Equation 7.48; lid_ST is the degradation of starch in the large intestine, Equation 7.49; r_mST is the synthesis of microbial starch in the rumen, Equation 7.33; r_mCP is the synthesis of microbial crude protein in the rumen, Equation 7.30; the parameter 270/512 is the ratio of cell wall:CP in the microbial fraction; the parameter 0.75 is the proportion of microbial cell walls digested; and the parameter 0.15 is the efficiency of microbial protein synthesis in the large intestine.

The synthesis of microbial fat in the large intestine is calculated from li_mCP as:

$$\text{li\_mCFat} = \text{li\_mCP} \cdot 0.326 \qquad 7.51$$

where li_mCFat is the microbial fat synthesis in the large intestine, g/d; li_mCP is the microbial protein synthesis in the large intestine, Equation 7.50; and the parameter 0.326 is the ratio of CFat:CP in the microbial fraction.

7.4 Total tract digestion

Apparent digestibility and energy values (based on metabolizable energy, ME) of diets are calculated from actual feed intake and composition. The energy system developed by Van Es (1978) is used to predict ME, for which estimates of total tract digestion of CP, CHO and CFat are needed. Apparent total tract digestion and digestibility of CP are calculated as:

$$\text{td\_CP} = \left(\sum_i \text{DMI}_i \cdot \text{CP}_i \right) - \left(\begin{array}{l} \left(\sum_i \text{DMI}_i \cdot \text{CP}_i \right) - \text{rd\_CP} - \text{sid\_CP} + \text{r\_mCP} \cdot 0.15 + \\ \text{r\_outOM} \cdot 0.03 \cdot 3 \cdot 0.4 + \text{si\_outOM} \cdot 0.025 + \text{li\_mCP} \end{array} \right) \qquad 7.52$$

$$\mathrm{CPD} = \frac{\mathrm{td\_CP}}{\sum\limits_i \mathrm{DMI_i} \cdot \mathrm{CP_i}} \cdot 100 \qquad 7.53$$

where td_CP is the apparent total tract digestion of crude protein, g/d; CPD is the apparent total tract digestibility of crude protein, %; $\mathrm{DMI_i}$ is the dry matter intake of the i=1...n'th feedstuff, kg/d; $\mathrm{CP_i}$ is the crude protein content in the i=1...n'th feedstuff, g/kg DM; rd_CP is the degradation of crude protein in the rumen, Equation 7.8; sid_CP is the digestion of crude protein in the small intestine, Equation 7.37; r_mCP is the synthesis of microbial protein in the rumen, Equation 7.30; r_outOM is the flow of organic matter out of the rumen, Equation 7.36; si_outOM is the flow of organic matter into the large intestine, Equation 7.47; and li_mCP is the microbial protein synthesis in the large intestine, Equation 7.50; parameter values 0.03, 3, 0.4 and 0.15 are explained in Equation 7.47; and the parameter 0.025 is the proportion of endogenous protein excreted in the large intestine per unit of OM entering the large intestine.

In Equation 7.52, 25 g protein per kg OM flowing into the large intestine is used as an estimate of endogenous protein excretion in the large intestine (van Bruchem *et al*., 1985b). Dietary ammonia and urea provide no energy for the animal although they affect the apparent total tract digestibility values of CP. Thus, ammonia- and urea-corrected protein digestion values are used in the calculation of ME:

$$\mathrm{td\_CPcorr} = \left(\sum_i \mathrm{DMI_i} \cdot \mathrm{CPcorr_i}\right) - \left(\begin{array}{l} \left(\sum\limits_i \mathrm{DMI_i} \cdot \mathrm{CP_i}\right) - \mathrm{rd\_CP} - \mathrm{jed\_CP} + \mathrm{r\_mCP} \cdot 0.15 + \\ \mathrm{r\_outOM} \cdot 0.03 \cdot 3 \cdot 0.4 + \mathrm{si\_outOM} \cdot 0.025 + \mathrm{li\_mCP} \end{array}\right) \qquad 7.54$$

Equation 7.54 is similar to Equation 7.52, except that ammonia- and urea-corrected CP ($\mathrm{CPcorr_i}$; Equation 4.4) are used as input.

The apparent total tract digestion and digestibility of CHO are calculated from:

$$\mathrm{td\_CHO} = \left(\begin{array}{l} \mathrm{rd\_NDF} + \mathrm{rd\_ST} + \mathrm{rd\_CFat} + \mathrm{rd\_FPF} + \mathrm{rd\_RestCHO} + \mathrm{sid\_ST} + \mathrm{sid\_mST} \\ -\mathrm{r\_mCP} \cdot \left(\dfrac{270}{512}\right) \cdot 0.25 + \mathrm{lid\_NDF} + \mathrm{lid\_ST} - \mathrm{li\_mCP} \cdot \left(\dfrac{270+51}{512}\right) \end{array}\right) \qquad 7.55$$

$$\mathrm{CHOD} = \frac{\mathrm{td\_CHO}}{\sum\limits_i \mathrm{DMI_i} \cdot \mathrm{OM_i} - \sum\limits_i \mathrm{DMI_i} \cdot \mathrm{CPcorr_i} - \sum\limits_i \mathrm{DMI_i} \cdot \mathrm{CFat_i} + \mathrm{rd\_CFat}} \cdot 100 \qquad 7.56$$

where td_CHO is the apparent total tract digestion of carbohydrates, g/d; CHOD is the total tract digestibility of carbohydrates, %; rd_NDF is the degradation of NDF in the rumen, Equation 7.21; rd_ST is the degradation of starch in the rumen, Equation 7.14; rd_CFat is the degradation of crude fat in the rumen, Equation 7.22, rd_FPF is the degradation of dietary fermentation products in the rumen, Equation 7.23; rd_RestCHO is the degradation of RestCHO in the rumen, Equation 7.12; sid_ST is the digestion of starch in the small intestine, Equation 7.40; r_mCP is the synthesis of microbial protein in the rumen, Equation 7.30; lid_NDF is the degradation of NDF in the large intestine, Equation 7.48, lid_ST is the degradation of starch in the large intestine, Equation 7.49; $\mathrm{DMI_i}$ is the dry matter intake of the i=1...n'th feedstuff, kg/d; $\mathrm{OM_i}$ is the organic matter content in the i=1...n'th feedstuff, g/kg DM; $\mathrm{CPcorr_i}$ is the ammonia or urea corrected crude protein content in the i=1...n'th feedstuff, g/kg DM, Equation 4.4; $\mathrm{CFat_i}$ is the crude fat content in the i=1...n'th feedstuff, g/kg DM; and the parameters 270, 512, 0.25 and 51 are the microbial cell wall content, microbial crude protein content, coefficient of undigested microbial cell walls and the microbial starch content, respectively.

Apparent total tract digestion and digestibility of CFat is calculated from the equations:

$$\mathrm{td\_CFat} = \mathrm{sid\_CFat} - \mathrm{li\_mCFat} \qquad 7.57$$

$$\mathrm{CFatD} = \frac{\mathrm{td\_CFat}}{\sum_i (\mathrm{DMI}_i \cdot \mathrm{CFat}_i) - \mathrm{rd\_CFat}} \cdot 100 \qquad 7.58$$

where td_CFat is the apparent total tract digestion of crude fat, g/d; CFatD is the total tract digestibility of crude fat, %; sid_CFat is the digestion of crude fat in the small intestine, Equation 7.41; li_mCFat is the synthesis of microbial crude fat in the large intestine, Equation 7.51; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; $CFat_i$ is the crude fat content in the i=1...n'th feedstuff, g/kg DM; and rd_CFat is the degradation of crude fat in the small intestine that came from the rumen, Equation 7.22.

The apparent total tract digestion and digestibility of OM are used for diet evaluations and also in testing and validating the system. They are calculated from:

$$\mathrm{td\_OM} = \mathrm{td\_CP} + \mathrm{td\_CFat} + \mathrm{td\_CHO} \qquad 7.59$$

$$\mathrm{OMD} = \frac{\mathrm{td\_OM}}{\sum_i \mathrm{DMI}_i \cdot \mathrm{OM}_i} \cdot 100 \qquad 7.60$$

where td_OM is the apparent total tract digestion of organic matter, g/d; OMD is the total tract digestibility of organic matter, %; td_CP is the total tract digestion of crude protein, Equation 7.52; td_CFat is the total tract digestion of crude fat, Equation 7.57; td_CHO is the total tract digestion of carbohydrates, Equation 7.55; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; and OM_i is the organic matter content in the i=1...n'th feedstuff, g/kg DM.

7.5 Implications

This chapter describes the NorFor modelling of digestion and microbial processes in the gastrointestinal tract. By separating the digestive tract into different compartments, it is possible to improve calculations and to evaluate the effects of partial digestion and metabolism on digestion and microbial processes. This can improve our understanding of the mechanisms affecting predictions of absorbed energy and AAs and, hence, facilitate optimization of the digestion efficiency and thus nutrient supply to the animal.

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8. Energy and metabolizable protein supply

H. Volden and N.I. Nielsen

Several systems are used to measure energy (Van Es, 1978; Møller *et al*., 1983; INRA, 1989; NRC, 1989; AFRC, 1993) and metabolizable protein (MP) (Madsen, 1985; NRC, 1985; Vérité *et al*., 1987; AFRC, 1992; Tamminga *et al*., 1994) supplies in cattle. Feed evaluation for cattle is in continues development and several new systems have been proposed (Sniffen *et al*., 1992; NRC, 2001; Thomas, 2004). The aim of the new systems is to refine and more carefully describe the interactions between the animal, its feed and the environment to predict performance. Also in the development of NorFor an important objective is to obtain improved estimates of the animal's dietary energy and protein supplies by taking into account the effects of feeding level and diet composition on both ration digestibility and microbial activity.

8.1 Metabolizable and net energy supply

Metabolizable energy is assumed to equal gross energy (GE) minus energy in faeces, urine and methane and NE is derived from estimates of the partial utilization efficiency (k) of ME (Van Es, 1975). The NE of diets used for maintenance, lactation and growth are calculated using coefficients, k_m, k_l and k_g, respectively. In NorFor, the energy supply and value for dairy cows is expressed in terms of NEL, based on the system developed by Van Es (1975, 1978) and for growing cattle in NEG based on a combination of the systems developed by INRA (1989) and Van Es (1975, 1978).

The starting point for predicting the NE supply is the calculation of GE. In NorFor the following equation is modified from Van Es (1978) and used to calculate GE supply:

$$\mathrm{GE} = \frac{24.1 \cdot \sum_i \left(\mathrm{DMI_i} \cdot \mathrm{CPcorr_i}\right) + 36.6 \cdot \sum_i \left(\mathrm{DMI_i} \cdot \mathrm{CFat_i}\right) + 18.5 \cdot \sum_i \left(\mathrm{DMI_i} \cdot \left(\mathrm{OM_i} - \mathrm{CPcorr_i} - \mathrm{CFat_i} - \frac{\mathrm{CP_i}}{6.25} \cdot \frac{\mathrm{NH3N_i}}{1000}\right)\right)}{1000} \tag{8.1}$$

where GE is the gross energy intake, MJ/d; $\mathrm{DMI_i}$ is the dry matter intake of the i=1...n'th feedstuff, kg/d; $\mathrm{CPcorr_i}$ is the content of ammonia- or urea-corrected crude protein of the i=1...n'th feedstuff, Equation 4.4; $\mathrm{CFat_i}$ is the crude fat content in the i=1...n'th feedstuff, g/kg DM; $\mathrm{OM_i}$ is the organic matter content of the i=1...n'th feedstuff, g/kg DM; $\mathrm{CP_i}$ is the crude protein content of the i=1...n'th feedstuff, g/kg DM; and $\mathrm{NH_3N_i}$ is the ammonia or urea N content of the i=1...n'th feedstuff, g/kg CP.

NorFor calculates ME supply from apparent total tract digestion, using a modified form of an equation for both dairy cows and growing cattle according to Van Es (1978):

$$\mathrm{ME} = \frac{18.0 \cdot \mathrm{td\_CPcorr} + 37.7 \cdot \mathrm{td\_CFat} + 14.5 \cdot \left(\mathrm{td\_CHO} - \sum_i \mathrm{DMI_i} \cdot \mathrm{SU_i}\right) + 13.9 \cdot \sum_i \mathrm{DMI_i} \cdot \mathrm{SU_i}}{1000} \tag{8.2}$$

where ME is the daily intake of metabolizable energy, MJ/d; $\mathrm{DMI_i}$ is the dry matter intake of the i=1...n'th feedstuff, kg/d; $\mathrm{SU_i}$ is the sugar content in the i=1...n'th feedstuff, g/kg DM; td_CPcorr is the total tract digestion of ammonia- or urea-corrected crude protein, Equation 7.54; td_CFat is the total tract digestion of crude fat, Equation 7.57; and td_CHO is the total tract digestion of carbohydrates, Equation 7.55.

The efficiency of ME utilization differs between maintenance and different forms of production and also due to diet composition (Blaxter, 1962). Van Es (1975) proposed the use of different efficiencies for maintenance, lactation and growth to calculate relevant NE values, and also suggested that the efficiency should be calculated as a function of the ME to GE ratio (q).

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DOI 10.3920/978-90-8686-718-9_8, © Wageningen Academic Publishers 2011

The slope of ME utilization versus q are almost similar for maintenance and lactation, and Van Es (1975) proposed that variation in maintenance NE, due to changes in q, could be accommodated by calculating it in terms of NEL, and adjusting for the difference in the intercept. The NEL supply to dairy cows is calculated as:

$$\mathrm{NEL} = 0.6 \cdot (1 + 0.004 \cdot (q - 57)) \cdot \mathrm{ME} \qquad 8.3$$

where NEL is the net energy lactation, MJ/d; q is the ratio between metabolizable energy and gross energy, %; and ME is metabolizable energy, Equation 8.2.

The calculation of NEG is more complex, because k_g and k_m differ considerably as affected by q. It is not possible to apply a constant adjustment to account for this difference, thus, the calculation of a joint efficiency, k_{mg}, is necessary (McHardy, 1966; Harkins *et al.*, 1974). To solve this problem McHardy (1966) introduced the concept of animal production level (APL), which equals the ratio of the total NE requirement (maintenance + growth) to the net energy for maintenance. In general this is calculated as:

$$\mathrm{APL} = \frac{\mathrm{NE_m} + \mathrm{NE_g}}{\mathrm{NE_m}} = \frac{\left(\mathrm{BW}^{0.75} \cdot k_m \cdot \mathrm{factor1} \cdot {}^{120}\!/\!_{88}\right) + (5.48 \cdot \mathrm{gain\_prot} + 9.39 \cdot \mathrm{gain\_fat})}{\mathrm{BW}^{0.75} \cdot k_m \cdot \mathrm{factor1} \cdot {}^{120}\!/\!_{88}} \qquad 8.4$$

where APL is the animal production level; $\mathrm{NE_m}$ is the net energy requirement for maintenance; $\mathrm{NE_g}$ is the net energy requirement for growth; BW is the body weight, kg; k_m is the partial efficiency of metabolizable energy utilization for maintenance, Equation 8.6; factor1 is 90 for heifers and steers, 91 for bulls of dairy breeds and 100 for bulls of beef breeds (Garcia *et al.*, 2007); gain_prot is the protein gain, Equation 9.8; gain_fat is the daily fat retention, Equation 9.9.

Using the APL concept, a joint efficiency of ME utilization for maintenance and growth is calculated as follows:

$$k_{mg} = \frac{k_m \cdot k_g \cdot \mathrm{APL}}{k_g + k_m \cdot (\mathrm{APL} - 1)} \qquad 8.5$$

where k_{mg} is the joint partial efficiency of metabolizable energy for maintenance and growth; k_m is the partial efficiency of metabolizable energy utilization for maintenance, Equation 8.6; and k_g is the partial efficiency of metabolizable energy utilization for growth, Equation 8.7.

The partial efficiency of ME utilization for maintenance (Van Es, 1975) and growth (Blaxter, 1974) are calculated using the following equations:

$$k_m = 0.287 \cdot \left(\frac{\mathrm{ME}}{\mathrm{GE}}\right) + 0.554 \qquad 8.6$$

$$k_g = 0.78 \cdot \left(\frac{\mathrm{ME}}{\mathrm{GE}}\right) + 0.006 \qquad 8.7$$

where k_m is the partial efficiency of metabolizable energy utilization for maintenance; k_g is the partial efficiency of metabolizable energy utilization for growth; ME is metabolizable energy, Equation 8.2; GE is gross energy, Equation 8.1.

Based on a joint k_{mg}, the NEG value of a feed ration for growing cattle is calculated as:

$$\mathrm{NEG} = k_{mg} \cdot \mathrm{ME} \qquad 8.8$$

where NEG is the net energy for growth, MJ/d, k_{mg} is the joint partial efficiency of metabolizable energy for maintenance and growth, in Equation 8.5; ME is metabolizable energy, Equation 8.2.

The NorFor system is a feed ration evaluation system rather than a single feed evaluation system, and the diet NE value for lactation and growth is calculated as:

$$NEL\_DM = \frac{NEL}{\sum_i DMI_i} \tag{8.9}$$

$$NEG\_DM = \frac{NEG}{\sum_i DMI_i} \tag{8.10}$$

where NEL_DM is the diet net energy value for lactation; MJ/kg DM; NEG_DM is the diet net energy value for growth, MJ/kg DM; NEL is net energy for lactation, Equation 8.3; NEG is net energy for growth, Equation 8.8; and DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d.

8.2 Metabolizable protein supply

The sources of digested and absorbed AAs from the small intestine are rumen microbial protein, rumen undegraded dietary protein and endogenous protein. Metabolizable protein is expressed as AAT_N:

$$AAT_N = sid\_AA + sid\_mAA + sid\_eAA \tag{8.11}$$

where AAT_N is the AAs absorbed in the small intestine, g/d; sid_AA is dietary AAs digested in the small intestine, Equation 7.38; sid_mAA is microbial AAs digested in the small intestine, Equation 7.43; sid_eAA is endogenous AAs digested in the small intestine, Equation 7.46.

The supply of AAT_N from individual AAs is calculated in the same way as for AAT and expressed in % of total AAT_N:

$$AA_j\_AAT_N = \frac{sid\_AA_j + sid\_mAA \cdot m\_Comp_j + sid\_eAA \cdot e\_Comp_j}{AAT_N} \cdot 100 \tag{8.12}$$

where $AA_j\_AAT_N$ is the individual AA $_j$ absorbed in the small intestine, g/d; j=arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan or valine; sid_AA_j is the absorption of the individual AA_j in the small intestine from rumen undegraded feed protein, Equation 7.39, sid_mAA is the absorbed AA in the small intestine from microbial protein, Equation 7.43; m_Comp_j is the AA composition of sid_mAA shown in Table 7.2; sid_eAA is the absorbed AA in the small intestine from endogenous protein, Equation 7.46, g/d; e_Comp_j is the AA composition of sid_eAA shown in Table 7.2 and AAT_N is the total absorbed AA, Equation 8.11.

8.3 Implications

NorFor uses a semi-mechanistic approach to calculate energy and amino acid supply to the animal. The ruminal and intestinal metabolism and digestion are functions of the competing processes of fermentation and passage. By taking these factors into account, more realistic and accurate diet values can be predicted. NorFor does not calculate NE from the absorbed end products of total tract digestion. The prediction of energy supply and utilization from individual absorbed VFAs, long chain FA, AAs and glucose from starch requires a much more complex model. Our ability to use this information in an applied ration evaluation system which can predict all the end products from digestion in the gastrointestinal tract, and the partitioning and efficiency of utilization in the metabolic compartments, are currently constrained by limitations of available information. Thus, as a first step we have chosen to calculate the NE supply from ME, by taking into account animal and feed interactions that occur in the ruminal and intestinal compartments.

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9. Animal requirements and recommendations

N.I. Nielsen and H. Volden

One of the challenges in developing the NorFor feed evaluation system has been to combine our sub-models with existing feed evaluation systems, i.e. combining NorFor's digestion model with systems that predict energy requirements from digested nutrients. NorFor has used existing Dutch equations to predict energy requirements for milk production, maintenance and gestation for dairy cows, while French equations have been used to predict energy demand for growth. In contrast to energy requirements, NorFor has developed its own equations to determine the AAT_N requirements for milk production and growth. The recommendations for minerals and vitamins are mainly implemented from NRC.

9.1 Energy

The net energy (NE) requirement for maintenance and growth in growing cattle is based on the French system (Robelin and Daenicke, 1980; INRA, 1989; Garcia *et al.*, 2007), while the NE requirement for maintenance and milk production in cows is based on the Dutch system by Van Es (1978). In the Dutch system the NE requirement for lactation is dependent on the production level, where the energy requirements increases with increased milk production and this effect is a compensation for reduced digestibility with increased feeding level. However, in NorFor, this effect is directly taken into account when calculating the energy value of a ration.

9.1.1 Maintenance

The NE requirement for maintenance in cows is calculated according to Van Es (1978) and for growing cattle according to Garcia *et al.* (2007) via the following equation which is illustrated in Table 9.1.

$$\text{NE\_maint} = \text{factor\_1} \cdot \text{BW}^{0.75} \cdot \text{NE\_exercise} \qquad 9.1$$

where NE_maint is the daily energy requirement for maintenance, MJ NE/d; BW is the weight of the animal, kg; NE_exercise is 1 for tied-up animals and 1.1 for loose-housed or grazing animals; and factor_1 is a constant that determines the maintenance requirement per kg metabolic weight, cows has a value of 0.29256,

for heifers and steers $\text{factor\_1} = 90 \cdot \frac{4.184}{1000} \cdot \frac{k_{mg}}{k_m}$,

for bulls of dairy breeds or crossbreed $\text{factor\_1} = 91 \cdot \frac{4.184}{1000} \cdot \frac{k_{mg}}{k_m}$,

and for bulls of beef breeds $\text{factor\_1} = 100 \cdot \frac{4.184}{1000} \cdot \frac{k_{mg}}{k_m}$,

the factor 4.184/1000 converts kcal to MJ; the k_m is used to calculate the ME requirement, Equation 8.6; k_{mg} is the combined coefficient for utilisation of ME to NE for maintenance and growth, Equation 8.5; the coefficients 90, 91, and 100 are the NE requirements in kcal per kg metabolic weight (Garcia *et al.*, 2007).

Compared with the INRA (1989) system, in which all types of growing cattle are assigned the same maintenance requirement per kg metabolic weight, the revised system (Garcia *et al.*, 2007) estimates a significantly higher maintenance requirement for bulls of beef breeds.

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DOI 10.3920/978-90-8686-718-9_9, © Wageningen Academic Publishers 2011

Table 9.1. NE requirement for maintenance in dairy cows and heifers related to BW and activity[1] (MJ/d).

Animal type	BW (kg)	Tied up	Loose
Heifer	100	10	11
Heifer	200	17	19
Heifer	300	24	26
Heifer	400	29	32
Cow	400	26	29
Cow	500	31	34
Cow	600	35	39
Cow	700	40	44

[1] In the calculation of the maintenance requirement for heifers a k_m of 0.71 and a k_{mg} of 0.62 were used.

9.1.2 Lactation

The NE requirement for the production of 1 kg ECM is 3.14 MJ NEL (Van Es, 1975; Sjaunja *et al.*, 1990):

$$NEL\_milk = ECM \cdot 3.14 \qquad 9.2$$

where NEL_milk is the daily energy requirement for production of ECM, MJ NEL/d; and ECM is the energy-corrected milk yield, Equation 3.1 and 3.2.

9.1.3 Gestation

Cows and heifers are generally pregnant for 284 days. In the first 150 days of gestation, there is practically no energy requirement for gestation, but thereafter the energy requirement increases exponentially (Figure 9.1). The energy requirement for gestation is calculated according to the equation below, which is based on tabulated values (data not shown) from Van Es (1978).

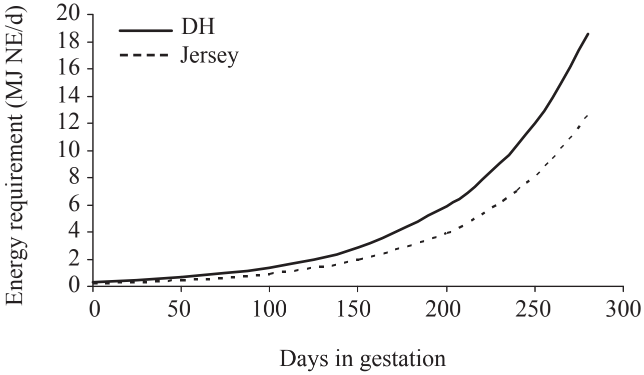

Figure 9.1. Estimated energy requirements (MJ NE/d) for pregnancy with respect to the day of gestation and mature BW. Jersey has a mature BW of 440 kg; Holstein has a mature BW of 640 kg.

$$NE\_gest = \frac{BW\_mat}{600} \cdot e^{0.0144 \cdot gest\_day - 1.1595} \qquad 9.3$$

where NE_gest is the daily NE requirement for gestation in cows and heifers, MJ/d; BW_mat is the mature weight for the breed, kg (see Table 3.2); and gest_day is the actual gestation day.

9.1.4 Growth

In the following, the terms growth and gain expresses the same physiological process and are used synonymously. The NE requirement for growth in primiparous cows is calculated using the equation below (Berg and Matre, 2001) and is illustrated in Table 9.2. NorFor does not assume growth in multiparous cows.

$$NEL\_gain = 0.00145 \cdot BW + 12.48 \cdot \frac{ADG}{1000} + 0.68 \qquad 9.4$$

where NEL_gain is the daily energy requirement for growth in primiparous cows, MJ/d; BW is the weight of the cow, kg; and ADG is the daily gain of the cow, g/d.

The NE requirement for growth in growing cattle is calculated according to the following INRA (1989) equation, which has been slightly modified to include a 10% increase:

$$NEG\_gain = \left((5.48 \cdot gain\_prot + 9.39 \cdot gain\_fat) \cdot \frac{4.184}{1000} \cdot \frac{k_{mg}}{k_{g\_corr}} \right) \cdot 1.10 \qquad 9.5$$

where NEG_gain is the daily NE requirement for gain in growing cattle, MJ NEG/d; 5.48 and 9.39 are the energy content in protein and fat, respectively, kcal/g; gain_prot is the daily protein retention, Equation 9.8; gain_fat is the daily fat retention, Equation 9.9; the factor 4.184/1000 converts kcal to MJ; k_{mg} is the combined utilisation coefficient of ME to NE for maintenance and growth, Equation 8.5 and k_{g_corr} is the utilisation coefficient of ME to NE for growth, corrected for the proportion of energy that originates from protein retention in the total daily energy retention, Equation 9.6.

The utilization coefficient k_{g_corr} takes into account the dependence of the utilization of ME for growth on the proportion of energy retained as protein. Thus, the ratio between k_{mg} and k_{g_corr} is used to adjust the NE requirement for gain to account for variations in the proportion of energy that originates from protein retention in the total daily energy retention (INRA, 1989). The 10% adjustment (factor 1.1 in Equation 9.5) in NE for growth was added because a dataset compiled from 11 Norwegian and six Swedish experiments with bulls involving 120 treatments (Homb, 1974; Hole, 1985; Olsson and Lindberg, 1985; Olsson, 1987; Johansen, 1992; Skaara, 1994; Randby, 2000a; Randby, 2000b; Berg and Volden, 2004; Volden and Berg, 2005; Berg, unpublished data; Havrevoll, unpublished data; Olsson, unpublished data) showed an underprediction of requirements (r^2=0.90 and RMSE=4.4; see Figure 9.2). Although, this modification was made, Figure 9.2 shows that there is also a slope effect indicating that the estimated energy supply is too high compared to the energy

Table 9.2. NE requirement (MJ/d) for growth in primiparous cows related to BW and daily gain.

BW, kg	Daily weight gain, g/d		
	250	500	750
400	4.4	7.5	10.6
500	4.5	7.6	10.7
600	4.7	7.8	10.9
700	4.8	7.9	11.1

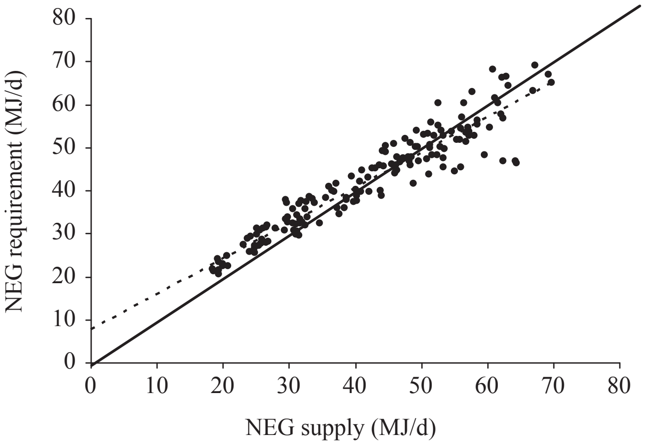

Figure 9.2. The relationship between energy supply and energy requirement after a modification of the original French system where a 10% increase in NE for growth was implemented in order to obtain a closer relationship between energy supply and energy requirements. Solid line shows Y=X and dotted line shows relationship between supply and requirement (r^2=0.90 and RMSE=4.4). The data are from the trials described in Table 9.11.

requirement in larger animals (>50 MJ NEG/d) and vice versa for small animals. However, we were not able to improve this relationship when using the described approach.

The utilisation coefficient of ME to NE for growth, corrected for the proportion of energy that originates from protein retention, is calculated according to the INRA (1989) equation:

$$k_{g\_corr} = 0.35 + 0.25 \cdot (1 - Ep)^2 \tag{9.6}$$

where k_{g_corr} is the utilisation coefficient of ME to NE for growth, corrected for the proportion of energy in the total amount of energy retained per day that originates from protein retention; and Ep is the daily NE requirement for protein retention relative to the total daily NE retention, Equation 9.7.

$$Ep = \frac{5.48 \cdot gain\_prot}{5.48 \cdot gain\_prot + 9.39 \cdot gain\_fat} \tag{9.7}$$

where Ep is the daily NE requirement for protein retention relative to the total daily NE retention; 5.48 and 9.39 are the energy content in protein and fat, respectively, kcal/g; gain_prot is the daily protein retention, Equation 9.8; and gain_fat is the daily fat retention, Equation 9.9.

The following equations are used to calculate the daily retention of protein and fat (Robelin and Daenicke, 1980) and examples of fat and protein retention in growing cattle are given in Tables 9.3 and 9.4.

$$gain\_prot = factor\_1 \cdot 1.06 \cdot (EBWG - gain\_fat) \cdot FFM^{0.06} \tag{9.8}$$

where gain_prot is the daily protein retention, kg/d; factor_1 is dependent on the type of growing cattle (Table 9.5); EBWG is the empty body weight gain, Equation 9.10; gain_fat is the daily fat retention, Equation 9.9; and FFM is fat free mass, Equation 9.11.

$$gain\_fat = \left(\left(\frac{1000 \cdot Fat\_mass}{EBW} \right) \cdot \left(\frac{(factor\_3 + 2 \cdot factor\_4 \cdot \ln(EBW)) \cdot factor\_5}{Factor\_5^{1.78}} \right) \right) \cdot (EBWG)^{1.78} \tag{9.9}$$

Table 9.3. Estimated fat and protein retention in heifers of dairy breeds related to BW and ADG.

BW, kg	800 g ADG		600 g ADG	
	Fat, g/d	Protein, g/d	Fat, g/d	Protein, g/d
200	142	134	85	105
300	207	125	124	101
400	270	114	162	95
500	333	102	199	88

Table 9.4. Estimated fat and protein retention in bulls of dairy breeds related to BW and ADG.

BW, kg	ADG, g/d	Fat, g/d	Protein, g/d
100	1,200	86	200
200	1,500	200	238
300	1,400	297	211
400	1,200	309	172
500	1,000	290	139
100	1,000	62	168
200	1,300	175	211
300	1,200	226	187
400	1000	223	151
500	800	195	120

Table 9.5. Coefficients used for calculating fat and protein retention in growing cattle.

Animal	Factor_1	Factor_2	Factor_3	Factor_4	Factor_5	Factor_6	Factor_7
Heifer or steer	0.1616	-6.311	1.811	0	0.8	1.046	-0.3939
Bull EM[1]	0.1541	-1.68	0.0189	0.1609	1.0	1.023	-0.2855
Bull LM[1]	0.1541	-5.433	1.5352	0	1.2	1.024	-0.2704
Bull CB[1]	0.1541	-5.7541	1.3708	0.0442	1.0	1.023	0.27795

[1] EM: early maturing; LM: late maturing; CB: cross breed.

where gain_fat is the daily fat retention, g/d; factor_3 to factor_5 are dependent on the type of growing cattle (Table 9.5); EBW is the empty body weight, Equation 9.12; Fat_mass is the fat content in the EBW, Equation 9.13 and EBWG is the empty body weight gain, Equation 9.10.

$$\mathrm{EBWG} = \frac{\mathrm{EBW}}{\mathrm{BW}} \cdot \mathrm{factor\_6} \cdot \mathrm{ADG} \qquad 9.10$$

where EBWG is the daily empty body weight gain, g/d; EBW is the empty body weight, Equation 9.12; BW is the weight of the animal, kg. However, BW for primiparous cows is corrected with the following term 600/BW_mat; factor_6 is dependent on the type of growing cattle (Table 9.5); and ADG is the average daily gain of live weight, g/d.

$$\mathrm{FFM} = \mathrm{EBW} - \mathrm{Fat\_mass} \qquad 9.11$$

where FFM is the fat free mass of the EBW, kg; EBW is the empty body weight, Equation 9.12; and Fat_mass is the fat content in the EBW, Equation 9.13.

$$\mathrm{EBW} = e^{(\mathrm{factor\_7} + \mathrm{factor\_6} \cdot \ln(\mathrm{BW}))} \qquad 9.12$$

where EBW is the empty body weight, kg; factor_6 and 7 are dependent on the type of growing cattle (Table 9.5); and BW is the weight of the animal, kg. However, BW for primiparous cows is corrected with the following term 600/BW_mat. BW_mat is the maturity BW (Table 3.5).

$$\mathrm{Fat\_mass} = e^{(\mathrm{factor\_2} + \mathrm{factor\_3} \cdot \ln(\mathrm{EBW}) + \mathrm{factor\_4} \cdot (\ln(\mathrm{EBW})^2))} \qquad 9.13$$

where Fat_mass is the fat content in the EBW, kg; EBW is the empty body weight, Equation 9.12; factor_2 to factor_4 are dependent on the type of growing cattle (see Table 9.5).

$$\mathrm{Protein\_mass} = \mathrm{factor\_1} \cdot \mathrm{FFM}^{1.06} \qquad 9.14$$

where Protein_mass is the protein content in the EBW, kg; factor_1 is dependent on the type of growing cattle (see Table 9.5); and FFM is the fat free mass of the EBW, Equation 9.11.

9.1.5 Mobilization and deposition

NorFor considers mobilization and deposition using BCS (see Section 3.1) for both primi- and multiparous cows. The amount of NE deposited when a cow is fed above its energy requirement and has a positive energy balance (EB>100%) is calculated as:

$$\mathrm{NEL\_dep} = \mathrm{NEL} - \mathrm{NE\_maint} - \mathrm{NEL\_gain} - \mathrm{NE\_gest} - \mathrm{NEL\_milk} \qquad 9.15$$

The amount of NE mobilized when a cow is fed EB<100% is calculated as:

$$\mathrm{NEL\_mob} = -1 \cdot (\mathrm{NEL} - \mathrm{NE\_maint} - \mathrm{NEL\_gain} - \mathrm{NE\_gest} - \mathrm{NEL\_milk}) \qquad 9.16$$

where NEL_dep is the energy deposition, MJ/d; NEL_mob is the mobilised energy, MJ/day; NEL is the energy intake, Equation 8.3; NE_maint is the energy required for maintenance, Equation 9.1; NEL_gain is the energy required for growth in primiparous cows, Equation 9.4; NE_gest is energy required for gestation, Equation 9.3; and NEL_milk is energy required for milk production, Equation 9.2.

The BCS is used as a measure for quantifying mobilization and deposition during lactation. As stated in Section 3.1, one unit of BCS corresponds to 60 kg BW except for Jersey cows which is 45 kg BW. However, large variations exist on such an estimate as reported by Nielsen *et al.* (2003), ranging from 20 to 110 kg BW per unit BCS. This large variation is related to differences in the data that have been used for estimating the relationship between these variables (including variations in e.g. breed, parity, and stage of lactation).

The NE requirement for the deposition of 1 kg body tissue is 31 MJ. A weight loss of 1 kg body tissue supplies the cow with 24.8 MJ NEL, due to 80% conversion efficiency (INRA, 1989). The amount of NE deposited or mobilized is calculated using the following equations, and examples are shown in Table 9.6.

$$\mathrm{NEL\_dep} = \mathrm{BCS\_change} \cdot \mathrm{BCS\_kg} \cdot 31.0 \qquad 9.17$$

$$\mathrm{NEL\_mob} = -1 \cdot (\mathrm{BCS\_change} \cdot \mathrm{BCS\_kg} \cdot 24.8) \qquad 9.18$$

Table 9.6. NEL requirements for deposition and mobilization in different breeds of cows.

Daily change in BCS[1]	Weight change, kg/d		NEL requirement, MJ/d	
	Large breed	Jersey	Large breed	Jersey
-0.02	-1.2	-0.9	-30	-22
-0.01	-0.6	-0.45	-15	-11
0	0	0	0	0
0.01	0.6	0.45	19	14
0.02	1.2	0.9	37	28

[1] One BCS = 60 kg for large breeds and 45 kg for Jersey, i.e. 0.01 BCS corresponds to 600 g BW for large breeds and 450 g BW for Jersey.

where NEL_dep is the energy deposition, MJ/d; NEL_mob is the mobilised energy, MJ/day; BCS_change is the change in BCS per day, units/d; and BCS_kg is the BW per unit BCS for different breeds (60 kg for large breeds and 45 kg for Jersey).

Different approaches are used in NorFor for predicting mobilization or deposition during the lactation period, depending on the breed. For NR, SH and SR the estimated changes in mobilization and deposition are modelled by a variable EB, i.e. in early lactation EB is below 100% indicating mobilization, whereas in mid and late lactation the target EB is 100%. The variable EB is calculated using the following empirical equation (Volden, unpublished data), which is illustrated in Figure 9.3.

$$\text{NEL\_variable} = \frac{100 - 35.25 \cdot \text{DIM}^{0.5} + 6.35 \cdot \text{DIM} - 0.602 \cdot \text{DIM}^{1.5} + 0.022336 \cdot \text{DIM}^{2}}{\begin{pmatrix} 1 - 0.32745 \cdot \text{DIM}^{0.5} + 0.0556 \cdot \text{DIM} - 0.005106 \cdot \text{DIM}^{1.5} \\ + 0.000177 \cdot \text{DIM}^{2} + 0.000000856 \cdot \text{DIM}^{2.5} \end{pmatrix}} \qquad 9.19$$

where NEL_variable is the recommended energy balance; and DIM is days in milk.

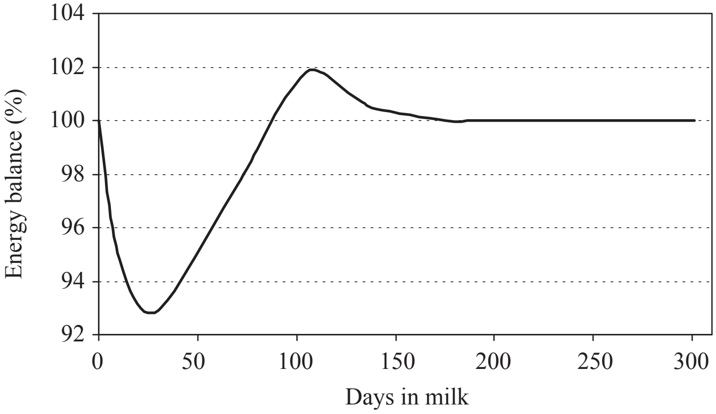

Figure 9.3. Recommended energy balance (EB) during lactation for NR, SH and SR breeds. In early lactation EB can be lower than 100% due to mobilization of energy from body reserves. In mid lactation, EB should be greater than 100% in a short period due to deposition of body reserves.

For DH, RD and JER default changes in BCS depend on the breed, parity and lactation stage. Thus, the lactation period is divided into four periods: in the first four weeks post-calving, it is assumed that 70% of body reserves are mobilized, while 30% is assumed to be mobilized in weeks 5 to 8 post-calving. In week 9-13 no mobilization or deposition is assumed. From week 14 until the end of the lactation period, a fixed energy deposition is required, which corresponds to the total energy mobilized in early lactation (Table 9.7).

The energy balance is calculated as energy supplied from the feed ration divided by the total NE requirement.

$$NEL\_bal = \frac{NEL \cdot 100}{NE\_maint + NEL\_milk + NEL\_gain + NE\_gest + NEL\_dep - NEL\_mob} \qquad 9.20$$

$$NEG\_bal = \frac{NEG \cdot 100}{NE\_maint + NEG\_gain + NE\_gest} \qquad 9.21$$

where NEL_bal and NEG_bal is the energy balancies for cows and growing cattle respectively, %; NEL and NEG is the energy supply from the ration, Equation 8.1 and 8.8 respectively; NE_maint is the energy requirement of maintenance, Equation 9.1; NEL_milk is the energy requirement of milk production, Equation 9.2; NEL_gain and NEG_gain is the energy requirement for weight gain in primiparous cows and growing cattle, Equation 9.4 and 9.5, respectively; NE_gest is the requirement of gestation in cows and heifers, Equation 9.3; NEL_dep and NEL_mob is the energy deposited and mobilised, Equation 9.17 and 9.18 respectively, NEL_dep and NEL_mob is included in the equation only if BCS change is reported.

Table 9.7. Estimated mobilization[1] and deposition[2] during lactation for the DH, RD and JER breeds.

Breed	Parity	Mobilization[1], BCS/lactation	Mobilisation, MJ NEL/d			Deposition, MJ NEL/d
			1-4 wpc	5-8 wpc	9-13 wpc	14 wpc→
DH	1	0.45	16.7	7.2	0	3.4
DH	>1	0.60	22.3	9.6	0	4.5
RD	1	0.35	13.0	5.6	0	2.6
RD	>1	0.50	18.6	8.0	0	3.7
DJ	1	0.45	12.6	5.4	0	2.5
DJ	>1	0.60	16.7	7.2	0	3.4

[1] Mobilization is assumed to take place during the first eight weeks post-calving (wpc): 70% in the first 4 wpc and 30% in 5 to 8 wpc. E.g. an older DH cow is assumed to mobilize 0.60 units of BCS in total, i.e. 0.42 BCS units during the first 4 wpc and 0.18 BCS units during 5 to 8 wpc.

[2] Deposition is assumed to take place from 14 wpc and throughout lactation with a fixed amount of energy per day. The sum of this energy corresponds to the energy lost in the first 8 wpc using a standard lactation cycle of 340 days.

9.2 Protein

While the energy requirements in NorFor are obtained from feed evaluation systems used in France and the Netherlands, NorFor has developed its own equations for the AAT_N and PBV_N requirements for the production of milk and growth, based on Nordic research data.

9.2.1 Maintenance

The AAT_N requirement for maintenance in cows and growing cattle is calculated according to NRC (1985), with modifications to account for endogenous losses, as described in Sections 7.2.3 and 7.4. The AAT_N requirement for maintenance is based on N secreted in urine, N used for hair and skin growth, and the secretion of endogenous N in the faeces. The AAT_N requirement for maintenance is illustrated in Figure 9.4 and Table 9.8, and is calculated according to Equation 9.22. The first term estimates basal AAT_N requirement, the second term the AAT_N requirement for hair and skin, and the third term estimates endogenous losses of AAT_N as an indirect function of DMI. Thus, the AAT_N requirement for maintenance increases when DMI increases.

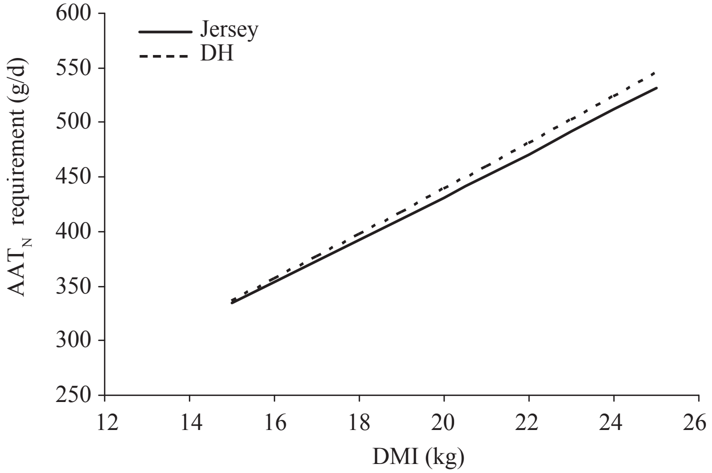

Figure 9.4. Estimated AAT_N requirement (g/d) for maintenance with respect to BW and DMI. Examples of a Jersey cow of 440 kg and a DH of 640 kg. The ration was a TMR with a fixed ratio between forage and concentrates.

Table 9.8. AAT_N requirements (g/d) for maintenance depending on BW and DMI.

BW (kg)	DMI (kg/d)		
	8 kg forage and 0 kg concentrates	8 kg forage and 8 kg concentrates	8 kg forage and 16 kg concentrates
400	199	346	499
500	203	339	490
600	207	337	484
700	210	336	478

$$\mathrm{AAT_N\_maint} = \frac{2.75 \cdot \mathrm{BW}^{0.5}}{0.67} + \frac{0.2 \cdot \mathrm{BW}^{0.6}}{0.67} + \frac{\mathrm{r\_outOM} \cdot 0.03 \cdot 0.5 \cdot 3 \cdot 0.4}{0.67} + \mathrm{si\_outOM} \cdot 0.025 \cdot 0.5 \qquad 9.22$$

where $\mathrm{AAT_N\_maint}$ is the daily $\mathrm{AAT_N}$ requirement for maintenance, g/d; BW is the weight of the animal, kg; r_outOM is the amount of OM leaving the rumen and entering the small intestine, Equation 7.36; si_outOM is the amount of OM leaving the small intestine and entering the large intestine, Equation 7.47; 0.67 is a fixed utilization coefficient of $\mathrm{AAT_N}$ for maintenance; 0.03 refers to the amount of endogenous CP, which is 3% of the OM entering the small intestine from the rumen; 3 is a multiplier to include all endogenous CP produced in the small intestine; 0.5 is the AA-N proportion of endogenous CP; 0.4 is used because 60% of endogenous CP is reabsorbed; and 0.025 refers to the amount of endogenous CP, which is 2.5% of the OM entering the large intestine from the small intestine.

9.2.2 Lactation

The $\mathrm{AAT_N}$ required for milk protein depends on milk protein yield and the utilization of the $\mathrm{AAT_N}$ available for milk protein production. The $\mathrm{AAT_N}$ required for milk production is calculated as:

$$\mathrm{AAT_N\_milk} = \frac{\mathrm{MPY}}{\mathrm{AAT_N\_Eff}/100} \qquad 9.23$$

where $\mathrm{AAT_N\_milk}$ is the $\mathrm{AAT_N}$ required for milk production, g/d; MPY is the daily milk protein yield, Equation 3.4; and $\mathrm{AAT_N\_Eff}$ is the efficiency (%) at which $\mathrm{AAT_N}$ is used in the synthesis of milk protein, Equation 9.24.

The utilization of AA for milk protein production is highly variable (MacRae *et al*., 1988; Subnel *et al*., 1994), and the Dutch DVE protein evaluation system is the only system that indirectly takes into account this variability in efficiency. Subnel *et al*. (1994) showed that the efficiency of milk protein production is dependent on the ratio of MP and NEL available for milk and milk protein production. When developing the NorFor system we also wanted to account for variations in efficiency when calculating the milk protein requirement, in order to improve the modelling of protein utilization in dairy cows (Van Straalen, 1994). Hence, a dataset compiled from 16 studies with Norwegian dairy cows including 57 treatments (Thuen, 1989; Volden, 1990; Minde and Rygh, 1997; Prestløkken, 1999; Volden, 1999; Volden and Harstad, 2002; Randby, 2003; Mydland, 2005; Schei *et al*., 2005;

Table 9.9. Descriptive statistics of the dataset[1] used for developing the equation to predict the efficiency of milk protein production.

	Average	Minimum	Maximum	SD
DMI (kg/d)	16.5	9.9	20.1	2.2
Milk (kg/d)	24.7	12.5	30.7	3.5
ECM (kg/d)	25.3	13.0	31.5	3.8
Milk protein (g/d)	783	413	1,031	120
Milk protein (%)	3.17	2.93	3.54	0.12
$\mathrm{PBV_N}$ (g/kg DM)	28	-3	68	16
$\mathrm{AAT_N}$/NEL (g/MJ)	15.7	13.5	24.7	1.7
$\mathrm{AAT_N}$ efficiency (%)	68.5	44.7	80.8	6.7

[1] (Thuen, 1989; Volden, 1990; Minde and Rygh, 1996; Prestløkken, 1999; Volden, 1999; Volden and Harstad, 2002; Randby, 2003; Mydland, 2005; Schei *et al*., 2005; Kjos, unpublished data).

Kjos, unpublished data) was used to develop an equation to predict AAT_N utilization for milk protein production (Table 9.9).

The efficiency of AAT_N (AAT_N_Eff) for milk protein production was calculated by dividing milk protein yield by the amount of AAT_N available for milk production. The AAT_N available for milk production was calculated as the total AAT_N supply minus the AAT_N requirement for maintenance and pregnancy ± AAT_N for deposition or mobilization. The ratio of AAT_N/NEL for milk production was calculated from the amount of AAT_N available for milk protein production and the NEL requirement for milk production (see Equation 9.25). The dataset showed a high correlation between AAT_N_Eff and AAT_N_NEL (r^2=0.89 and RMSE=2.3) and the relationship was curvilinear, as shown in Figure 9.5. In NorFor, the following equation is used to calculate the AAT_N_Eff:

$$AAT_{N}\_Eff = 189.4 - 11.14 \cdot AAT_{N}\_NEL + 0.2150 \cdot AAT_{N}\_NEL^2 \qquad 9.24$$

where AAT_N_Eff is the efficiency of AAT_N for milk protein production, %; and AAT_N_NEL is the ratio between AAT_N and energy available for milk production, g/MJ, Equation 9.25. The ratio between MP and energy available for milk protein production in Equation 9.24 is calculated as:

$$AAT_{N}\_NEL = \frac{Avail\_AAT_N}{NEL\_milk} \qquad 9.25$$

where AAT_N_ NEL is the ratio between AAT_N and the energy available for milk production, g/MJ; NEL_milk is the energy required for milk production, Equation 9.2; and Avail_AAT_N is the amount of AAT_N available for milk production, Equation 9.26. The amount of AAT_N available for milk protein production is calculated as:

$$Avail\_AAT_N = AAT_N - AAT_{N}\_maint - AAT_{N}\_gest + AAT_{N}\_mob - AAT_{N}\_dep \qquad 9.26$$

where Avail_AAT_N is the amount of AAT_N available for milk production, g/d; AAT_N is the AAT_N supplied from the feed ration, Equation 8.11; AAT_N_maint is the AAT_N required for maintenance, Equation 9.22; AAT_N_gain is the AAT_N requirement for growth in primiparous cows, Equation 9.32; AAT_N_gest is the AAT_N requirement for gestation, Equation 9.42; AAT_N_mob is the AAT_N

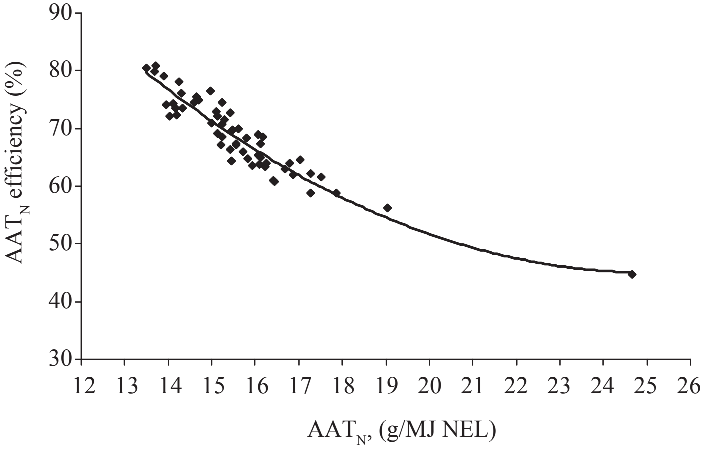

Figure 9.5. AAT_N efficiency (%) in dairy cows in relation to AAT_N supply based on the trials described in Table 9.9 (r^2=0.89 and RMSE=2.3). AAT_N supply is defined as AAT_N available for milk production per MJ NEL available for milk production.

from mobilized body mass, Equation 9.40 and AAT_N_dep is the AAT_N deposition in body mass, Equation 9.41.

The decrease in AAT_N_Eff with increases in AAT_N supports the commonly held assumption that returns diminish with increases in MP intake, as observed by MacRae *et al*. (1988) and Subnel *et al*. (1994). However, in contrast to the results of Subnel *et al*. (1994), neither the level of milk production nor the feeding level had an effect on the AAT_N_Eff. The AAT_N_Eff was closely related to AAT_N_NEL, which supports the observations of Subnel *et al*. (1994) and Van Straalen (1994), who observed a strong negative relationship between the efficiency of milk protein yield and the ratio of MP and energy available for milk protein production. These results demonstrate that the effect of extra MP supply is dependent on the amount of energy available for milk production, which also agrees with Hvelplund and Madsen (1990).

Based on the AAT_N available for milk production and the AAT_N_Eff, the milk protein production can be calculated as:

$$\text{Protein\_response} = \text{Avail\_AAT}_N \cdot \left(189.4 - 11.14 \cdot \text{AAT}_N\text{\_NEL} + 0.2150 \cdot \text{AAT}_N\text{\_NEL}^2\right) \qquad 9.27$$

The maximum milk protein production can be found by putting the first derivative of this equation to 0:

$$\frac{d\,\text{Protein\_response}}{d\text{Avail\_AAT}_N} = 189.4 - 22.93 \cdot \frac{\text{Avail\_AAT}_N}{\text{NEL\_milk}} + 0.6642 \cdot \left(\frac{\text{Avail\_AAT}_N}{\text{NEL\_milk}}\right)^2 = 0 \qquad 9.28$$

The maximum point is then obtained as:

$$\text{AAT}_N\text{\_NEL} = -\left(\frac{b}{2 \cdot a}\right) = -\left(\frac{-22.93}{2 \cdot 0.6642}\right) = 17.3 \qquad 9.29$$

This means that the maximum milk protein production is achieved at an AAT_N_NEL level of 17.3 g/MJ NEL, which corresponds to an efficiency of 61%. However, although the maximum is 17.3 g/MJ NEL, the first derivative equation is curvilinear, implying that increasing the AAT_N_NEL supply by one unit from 16.3 to 17.3 will only marginally increase milk protein production (Figure 9.6), but if AAT_N_NEL is below 15 g AAT_N/MJ NEL then the marginal response is almost linear. The optimal AAT_N supply can be described as the level at which milk protein production begins to be only marginally increased by extra AAT_N supply. Therefore, for an efficient output of milk protein it is important that the AAT_N_NEL is not lower than 15 and not higher than 17.3 g/MJ. Based on these results and assessments, the NorFor system has no fixed AAT_N requirement for milk protein production. When optimizing diets for dairy cows, a minimum value of 15 g AAT_N/MJ NEL is recommended, which corresponds to an AAT_N_Eff of 70%. This minimum recommendation is also based on the fact that it is seldom economically efficient to supply rations with high protein content, due to the relatively high cost of feed protein compared to energy.

The AAT_N balance (AAT_N_bal) can also be used as a target variable when optimizing diets in practice, using the equation:

$$\text{AAT}_N\text{\_bal} = \frac{\text{AAT}_N}{\text{AAT}_N\text{\_maint} + \text{AAT}_N\text{\_gain} + \text{AAT}_N\text{\_gest} - \text{AAT}_N\text{\_mob} + \text{AAT}_N\text{\_dep} + \text{AAT}_N\text{\_milk}} \cdot 100 \cdot R \qquad 9.30$$

where AAT_N_bal is the AAT_N balance, %; AAT_N is the AAT_N supply from the feed ration, Equation 8.11; AAT_N_maint is the AAT_N required for maintenance, Equation 9.22; AAT_N_gain is the AAT_N required for growth in primiparous cows, Equation 9.32; AAT_N_gest is the AAT_N required for gestation, Equation 9.42; AAT_N_mob is the AAT_N from mobilized body mass, Equation 9.40; AAT_N_dep is the AAT_N deposition in body mass, Equation 9.41; AAT_N_milk is the AAT_N required for milk protein, Equation 9.23; and R is the relative marginal response coefficient, Equation 9.31.

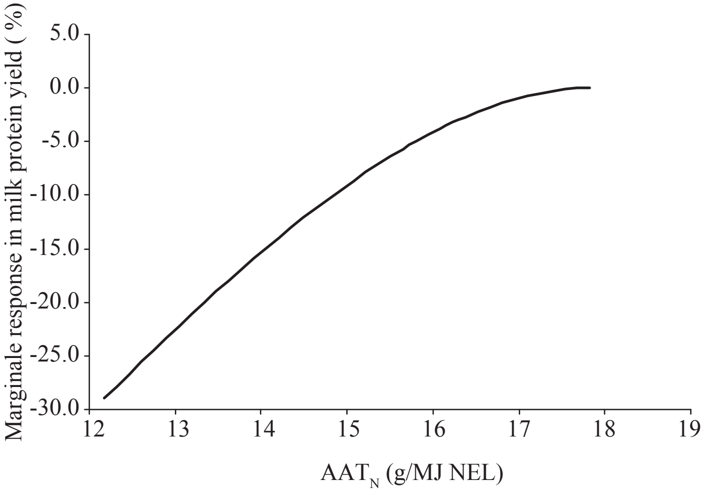

Figure 9.6. Estimated marginal response of milk protein production in relation to AAT$_N$ supply. AAT$_N$ supply is defined as the AAT$_N$ available for milk production per MJ NEL available for milk production. The data are from the trials described in Table 9.9.

In Equation 9.30 the R function describes the actual response in milk protein relative to the maximum milk protein response, which is achieved at 17.3 g AAT$_N$_NEL/MJ.

$$R = -4.165 - 0.1402 \cdot AAT_N\_NEL + 2.662 \cdot \ln(AAT_N\_NEL) \qquad 9.31$$

where R is the response factor for milk protein production, AAT$_N$_NEL is the AAT$_N$ and NEL ratio available for milk production, Equation 9.25. During the dry period R=1.

The recommended value of AAT$_N$_bal is between 95 and 103%. In theory, an AAT$_N$_bal of 100% should correspond to the maximum milk protein response, i.e. 17.3 g AAT$_N$/NEL and an AAT$_N$_bal of 95% should correspond to 15.0 g AAT$_N$/NEL. However, this is rarely the case, mainly because the AAT$_N$_bal is directly influenced by the actual protein content in milk (see Equation 9.30), which is not the case for AAT$_N$/NEL. Thus, the recommendation for AAT$_N$/NEL is based on an AAT$_N$_Eff derived from data with an average milk protein content of 31.7 g/kg. This means that in late lactation, where the protein content in milk is high, the AAT$_N$/NEL recommendation of 15.0 g AAT$_N$/NEL can easily be achieved, but AAT$_N$_bal will often be below the lower (95%) recommended limit.

9.2.3 Growth

The AAT$_N$ requirement for growth in primiparous cows is based on the requirements of growing heifers (Robelin and Daenicke, 1980). The requirement is calculated from the retention of body protein and the efficiency of AAT$_N$ utilization for growth (Volden, 2001) using the following equation:

$$AAT_N\_gain = \frac{gain\_prot \cdot 1000}{\left(104.6 \cdot e^{-0.0019 \cdot BW \cdot \frac{600}{BW\_mat}}\right) \big/ 100} \qquad 9.32$$

where AAT_N_gain is the daily AAT_N requirement for growth in primiparous cows, g/d; gain_prot is the daily protein retention, Equation 9.8; BW_mat is the mature body weight, Table 3.2; and the term beginning with 104.6·e is the utilisation equation of AAT_N for growth in primiparous cows. The AAT_N requirement for growth in primiparous cows is shown in Table 9.10.

The AAT_N required for growth in growing cattle depends on the amount of protein deposited and the efficiency with which the available AAT_N is deposited. The AAT_N required for growth is calculated using the following equation:

$$AAT_N\_gain = \frac{gain\_prot}{AAT_N\_Eff/100} \qquad 9.33$$

where AAT_N_gain is the AAT_N requirement for growth in growing cattle, g/d; gain_ prot is the daily retention of protein, Equation 9.8; and AAT_N_Eff is the efficiency at which AAT_N is used for growth, Equation 9.34.

Thus, in NorFor the AAT_N available for growth is utilized with variable efficiency, due to the diminishing returns with increases in MP intake, i.e. the same rationale that was used in relation to milk production in dairy cows (see Section 9.2.2). A dataset compiled from 11 Norwegian and six Swedish experiments with bulls involving 120 treatments (Homb, 1974; Hole, 1985; Olsson and Lindberg, 1985; Olsson, 1987; Johansen, 1992; Skaara, 1994; Randby, 2000a,b; Berg and Volden, 2005; Volden and Berg, 2005; Berg, unpublished data; Havrevoll, unpublished data; Olsson, unpublished data) was used to develop an equation to predict AAT_N efficiency for growth (Table 9.11). The variation in AAT_N efficiency could be explained with high accuracy (r^2=0.97 and RMSE=2.9) from BW, ADG and the ratio of AAT_N/NEG using the following equation:

$$AAT_N\_Eff = \begin{pmatrix} 1.88 - 0.03821 \cdot AAT_N\_NEG - 0.00176 \cdot BW - 0.2283 \cdot \frac{ADG}{1000} \\ + 0.0000019014 \cdot BW^{1.83} + 0.000000016 \cdot AAT_N\_NEG^5 \end{pmatrix} \cdot 100 \qquad 9.34$$

where AAT_N_Eff is the efficiency with which AAT_N is used for growth, %; BW is the weight of the animal, kg; ADG is the average daily live weight gain, g/d and AAT_N_NEG is the ratio between AAT_N and energy available for growth, Equation 9.35.

The ratio between MP and energy available for growth is calculated as:

$$AAT_N\_NEG = \frac{AAT_N - AAT_N\_maint - AAT_N\_gest}{NEG\_gain} \qquad 9.35$$

Table 9.10. AAT_N requirement (g/d) for weight gain in primiparous cows depending on BW and mature BW.

BW mature (kg)	BW, kg			
	400 Daily weight gain, g/d		500 Daily weight gain, g/d	
	250	500	250	500
500	106	181		
600	94	170	113	197
700	86	158	101	183

Table 9.11. Descriptive statistics of the dataset[1] used for developing the equation for predicting the AAT_N efficiency for growth in growing cattle. The dataset included trials with Norwegian and Swedish bulls involving 120 treatments.

	Average	Minimum	Maximum	SD
DMI (kg/d)	6.4	2.8	9.9	1.8
BW (kg)	322	113	568	120
ADG (g/d)	1,144	548	1,567	196
Protein retention (g/d)	173	114	226	26
PBV_N (g/kg DM)	22	-29	77	22
AAT_N/NEG (g/MJ)	16.9	9.7	29.8	4.3
AAT_N efficiency (%)	50.7	1.4	99.4	23.0

[1] (Homb, 1974; Hole, 1985; Olsson and Lindberg, 1985; Olsson, 1987; Johansen, 1992; Skaara, 1994; Randby, 2000a; Randby, 2000b; Berg and Volden, 2004; Volden and Berg, 2005; Berg, unpublished data; Havrevoll, unpublished data; Olsson, unpublished data).

where AAT_N_NEG is the ratio between AAT_N and energy available for growth, g/MJ; AAT_N is the AAT_N supplied from the feed ration, Equation 8.11; AAT_N_maint is the AAT_N required for maintenance, Equation 9.22; AAT_N_gest is the AAT_N required for gestation in heifers, Equation 9.42; and NEG_gain is the amount of energy used for growth, Equation 9.5.

The efficiency of AAT_N utilization for growth was calculated by dividing the amount of protein retained by the amount of AAT_N available for growth. The amount of protein retained was estimated using Equation 9.8 (see Section 9.1.4). The AAT_N available for growth was calculated as the total AAT_N supply minus the AAT_N required for maintenance and gestation. Some observations were omitted from the dataset due to unrealistically high AAT_N_Eff (>90%) values. The ratio of AAT_N/NEG for growth was calculated from the amount of AAT_N available for growth and the NEG requirement for growth. The relationships between AAT_N efficiency and AAT_N_NEG, BW and ADG are shown in Figures 9.7, 9.8 and 9.9.

Based on the AAT_N supply from the feed ration and the AAT_N_Eff, the amount of AAT_N retained for growth can be calculated as:

$$AAT_{Nretained} = AAT_N \cdot \begin{pmatrix} 1.88 - 0.03821 \cdot AAT_N\_NEG - 0.00176 \cdot BW - 0.2283 \cdot \dfrac{ADG}{1000} \\ + 0.0000019014 \cdot BW^{1.83} + 0.000000016 \cdot AAT_N\_NEG^5 \end{pmatrix} \tag{9.36}$$

where $AAT_{Nretained}$ is the AAT_N retained for growth, g/d; AAT_N is AAT_N supplied from the feed ration, Equation 8.11; AAT_N_NEG is the ratio between AAT_N and energy available for growth; Equation 9.35; BW is the weight of the animal, kg; and ADG is the average daily live weight gain, g/d.

The maximum retention of AAT_N in growth can be calculated by putting the derivative of this equation equal to 0, which results in:

$$AAT_N\_NEG\_Min = \frac{\left(1.88 - 0.00176 \cdot BW - 0.2283 \cdot ADG/1000 + 0.0000019014 \cdot BW^{1.83}\right)}{0.03821 \cdot 2 - 0.000000016 \cdot 5 \cdot AAT_N\_NEG^4} \tag{9.37}$$

However, the above equation is not suited for calculating the AAT_N requirement for growing cattle because it is not possible to calculate the minimum AAT_N requirement (AAT_N_NEG _Min) using AAT_N_NEG as an input, since AAT_N_NEG is a ration variable. Therefore, AAT_N_NEG was replaced

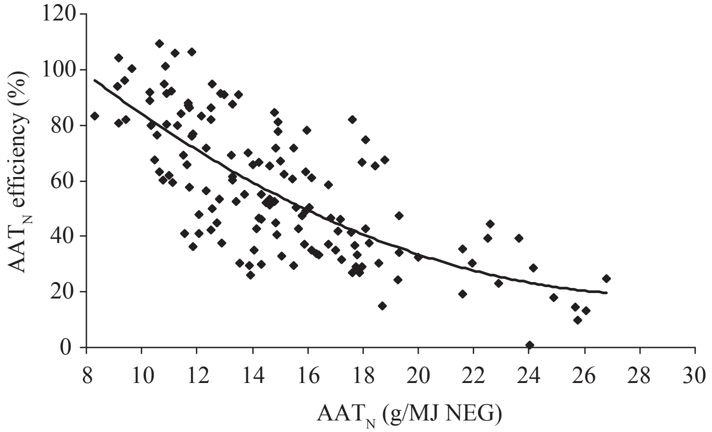

Figure 9.7. AAT_N efficiency (%) in growing cattle in relation to AAT_N supply. AAT_N supply is defined as the AAT_N available for growth per MJ NEG available for growth. A multiple regression with AAT_N supply, BW (see Figure 9.8) and ADG (see Figure 9.9) as significant explanatory variables explained the variation in AAT_N efficiency with high accuracy ($r^2=0.97$ and RMSE=2.9). The data are from the trials described in Table 9.11.

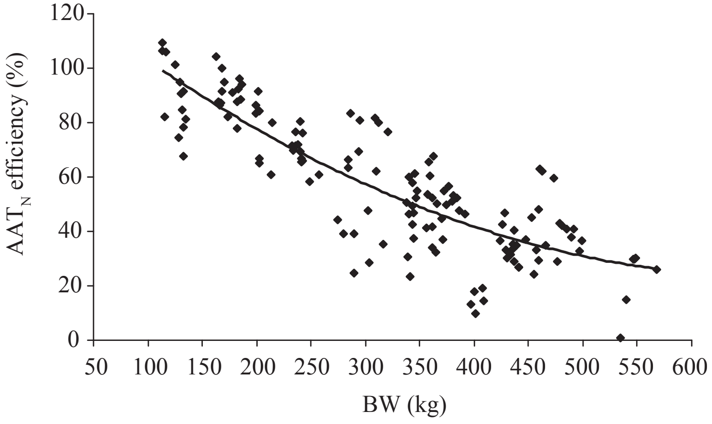

Figure 9.8. AAT_N efficiency (%) in growing cattle in relation to BW based on the trials described in Table 9.11. A multiple regression with BW, AAT_N supply (see Figure 9.7) and ADG (see Figure 9.9) as significant explanatory variables explained the variation in AAT_N efficiency with high accuracy ($r^2=0.97$ and RMSE=2.9).

with a value of 14, which corresponds to the requirement of an animal with a BW of 300 kg and an ADG of 800 g/d. Since the biological optimum is rarely the economic optimum, the biological optimum (=maximum retention of AAT_N) was lowered by 1 g AAT_N/NEG. Therefore, the following equation is a modification of Equation 9.37, in which 1 is subtracted and 14 replaces AAT_N/NEG:

$$AAT_N\_NEG\_Min = \frac{\left(1.88 - 0.00176 \cdot BW - 0.2283 \cdot ADG/1000 + 0.0000019014 \cdot BW^{1.83}\right)}{0.03821 \cdot 2 - 0.000000016 \cdot 5 \cdot 14^4} \qquad 9.38$$

where AAT_N_NEG_Min is the minimum AAT_N requirement (g/MJ NEG); BW is the weight of the animal, kg; and ADG is the average daily live weight gain, g/d.

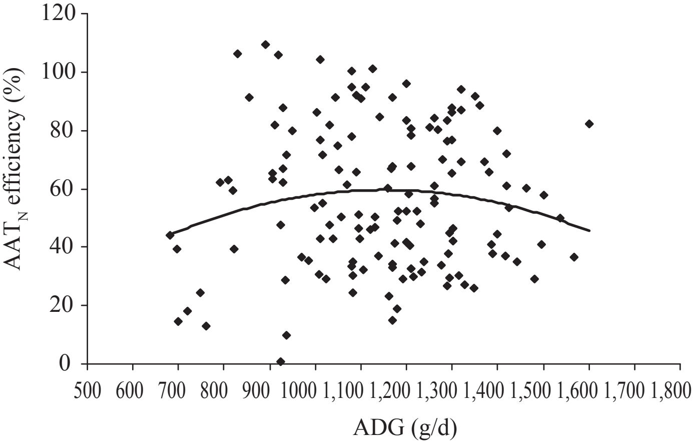

Figure 9.9. AAT_N efficiency (%) in growing cattle in relation to ADG based on the trials described in Table 9.11. A multiple regression with ADG, AAT_N supply (see Figure 9.7) and BW (see Figure 9.8) as significant explanatory variables explained the variation in AAT_N efficiency with high accuracy (r^2=0.97 and RMSE=2.9).

In contrast to the AAT_N balance for dairy cows, the AAT_N balance for growing cattle is calculated more simply:

$$AAT_N\_bal = \frac{AAT_N\_NEG}{AAT_N\_NEG\_Min} \cdot 100 \tag{9.39}$$

where AAT_N_bal is the AAT_N balance, %; AAT_N_NEG is the ratio between AAT_N and energy available for growth, Equation 9.35; and AAT_N_NEG_Min is the minimum AAT_N requirement, Equation 9.38.

9.2.4 Mobilization and deposition

In dairy cows, mobilized or deposited body protein will affect the amount of AAT_N available for milk protein production. In NorFor the AAT_N mobilization (AAT_N_mob) or AAT_N deposition (AAT_N_dep) is related to the animal's energy balance. This means that when a cow is in negative energy balance protein will be mobilized. It is assumed that body energy reserves contain 135 g protein/kg (NRC, 1985) and, based on values from INRA (1989), 24.8 MJ energy is supplied per kg mobilized body mass, and the energy requirement for deposition is 31.0 MJ/kg. The utilization of mobilized protein for milk production is assumed to be high, i.e. 80% (Tamminga *et al.*, 1994), whereas the utilization of AAT_N for deposition in adult animals has been shown to be low (INRA, 1989; NRC, 2001); it is assumed to be 50%. The amount of AAT_N originating from mobilized protein is calculated as:

$$AAT_N\_mob = \frac{135}{24.8} \cdot 0.8 \cdot NEL\_mob \tag{9.40}$$

where AAT_N_mob is the amount of AAT_N mobilized from body mass, g/d; NEL_mob is the amount of energy mobilized from body mass, Equation 9.18; 135 is the AAT_N content per kg body mass; 24.8 is the energy supplied per kg mobilized body mass, MJ NEL/kg; and 0.8 refers to the efficiency of mobilized AAT_N for milk production.

When cows are in positive energy balance the AAT_N requirement for protein deposition is calculated as:

$$AAT_N\_dep = \frac{135}{31.0} \cdot 2 \cdot NEL\_dep \qquad 9.41$$

where AAT_N_dep is the amount of AAT_N required for protein deposition, g/d; NEL_dep is the amount of energy deposited, Equation 9.17; 135 is the AAT_N content per kg body mass; 31.0 is the energy content per kg body mass, MJ NEL/kg; and 2 refers to an efficiency of 50% for AAT_N deposition. The AAT_N requirements for deposition and mobilization are illustrated in Table 9.12.

9.2.5 Gestation

The AAT_N requirement for gestation in heifers and cows depends on the stage of pregnancy and includes the AAT_N required for the development and maintenance of all conceptus tissues, including the foetus. The AAT_N requirement equation is modified from NRC (1985) and uses mature BW as a scaling factor instead of birth weight.

$$AAT_{N}\_gest = \frac{{}^{BW\_mat}\!/_{600} \cdot 34.375 \cdot e^{8.5357 - (13.1201 \cdot e^{-0.00262 \cdot gest\_day}) - 0.00262 \cdot gest\_day}}{0.5} \qquad 9.42$$

where AAT_N_gest is the daily AAT required for gestation, g/d; BW_mat is the mature BW, kg (Table 3.2 and 3.5); and gest_day is the actual day of gestation; 0.5 is the assumed AAT_N utilization for gestation.

The AAT_N requirement for gestation is illustrated in Figure 9.10.

9.3 PBV_N

The minimum PBV_N recommendation for dairy cows is related to milk yield according to the following equation, which is illustrated in Figure 9.11.

$$PBV_{N}\_DM\_Min = 10 \cdot \left(1 - e^{-0.14 \cdot ECM}\right) \qquad 9.43$$

where PBV_N_Min is the minimum recommended level of PBV_N, g/kg DM; and ECM is the daily energy-corrected milk yield, Equation 3.1 and 3.2.

Table 9.12. Weight change and AAT_N requirement for deposition and mobilization in cows depending on breed and change in BCS.

Daily change in BCS[1]	Weight change, kg/d		AAT_N requirement, g/d	
	Large breed	Jersey	Large breed	Jersey
-0.02	-1.2	-0.9	-154	-115
-0.01	-0.6	-0.45	-77	-58
0	0	0	0	0
0.01	0.6	0.45	192	144
0.02	1.2	0.9	384	288

[1] One BCS=60 kg for large breeds and 45 kg for Jersey, i.e. 0.01 BCS corresponds to 600 g BW for large breeds and 450 g BW for Jersey.

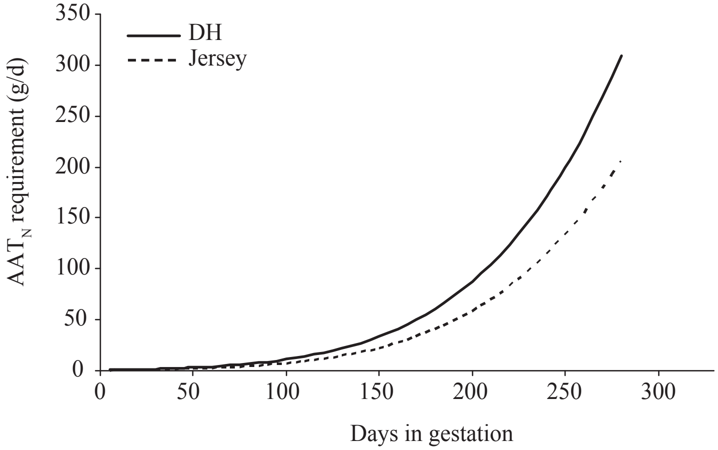

Figure 9.10. Estimated AAT_N requirement (g/d) for pregnancy depending on days of gestation and mature BW. Jersey has a mature BW of 440 kg; Holstein has a mature BW of 640 kg.

Figure 9.11 shows that for cows producing more than 20 kg ECM per day, the minimum PBV_N recommendation is 10 g/kg DM, while for cows producing less than 20 kg the minimum PBV_N is reduced to zero when the milk production is 0, i.e. for dry cows.

If recirculation of urea to the rumen is taken into account, then the minimum PBV_N should theoretically be 0, implying that the N available for microbial growth is similar to the N required for microbial growth. The NorFor PBV_N recommendation for lactating dairy cows is based on a former Danish recommendation, which was set to 0 g/d (Strudsholm *et al.*, 1999) on the basis of several production trials (Kristensen, 1997; Madsen *et al.*, 2003), but raised to 10 g/kg, for two reasons. Firstly, unlike the former Danish system, NorFor takes into account the recirculation of urea to the rumen in the calculation of PBV_N (see Equation 7.35), and secondly the feed passage rate is lower than in the former AAT/PBV system (Madsen *et al.*, 1985), which will result in a higher ruminal degradation of protein. A maximum of 40 g PBV_N per kg DM is recommended for both lactating and dry cows

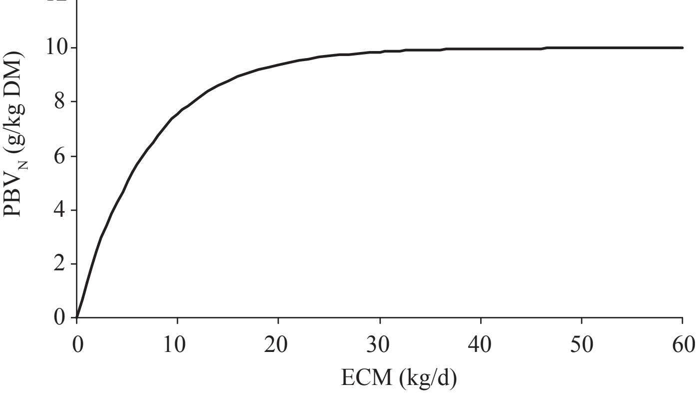

Figure 9.11. PBV_N recommendation for dairy cows as a function of ECM yield.

to avoid increased energy expenditure for the excretion of N via urine (Danfær, 1983; Reynolds, 2000) and decreased fertility (Rajala-Schultz, 2001).

For growing cattle the minimum PBV_N recommendation is 0 g/kg DM. This recommendation is not based on production trials but on a theoretical approach, i.e. that there is a balance between CP entering the rumen and CP leaving the rumen. The maximum PBV_N recommendation is set to 55 g/kg DM based on Olsson (1987). Olsson (1987) conducted several trials with intensively reared bulls and concluded a maximum recommendation of 4 g PBV/MJ ME. Assuming a 60% ME to NEG conversion efficiency, and an average content of 7.5 MJ NEG/kg DM, the maximum recommendation is 50 g PBV_N/kg DM (4/0.6=6.7 g PBV_N/MJ NEG·7.5). Since the energy content of a ration may be higher than 7.5 MJ NEG/kg DM, it was decided that NorFor has a maximum recommendation of 55 g PBV_N per kg DM.

9.4 Rumen load index

The maximum recommended RLI (see Chapter 7 and Equation 7.15 for calculation) is set to 0.6, which gives a moderate reduction of NDF degradation rate. A RLI of 0.6 corresponds to a diet with 240-280 g starch per kg DM depending on starch source. The sugar and starch content of a diet will often be 290-320 g/kg DM. These maximum levels of starch and sugar are in accordance with previous Danish recommendations (Strudsholm *et al*., 1999). The NRC (2001) recommends diets with a non-fibre carbohydrates content ranging from 360-440 g/kg DM, depending on the NDF content of the ration; 360 g/kg DM for diets with a low NDF content (250 g/kg DM), and 440 g/kg DM for diets with a high NDF content (330 g/kg DM). No health problems were reported in Danish trials with dairy cows fed diets containing 330-340 g starch/kg DM using maize silage and barley as starch sources (Hymøller *et al*., 2005).

9.5 Chewing time

Chewing time index (CI) is used for cows and growing cattle in NorFor to ensure good rumen function, see further descriptions in Chapter 11. The minimum recommendation for CI is 32 minutes per kg DM for large breeds and 30 minutes per kg DM for Jersey cows. These recommendations are based on assessments in relation to the former Danish chewing index (Nørgaard, 1986). However, in the future the recommendations will be validated against data where e.g. rumen pH and milk fat content has been measured.

9.6 Intake capacity

Calculations of the ration FV and animal IC are described in Chapter 10. The total FV of the ration should not exceed the IC of the animal. When optimising the feed ration FV should be as close to IC as possible in order to ensure the animals satiety. However for practical reasons NorFor has different minimum recommendations for IC for lactating cows, dry cows and growing cattle.

9.7 Fatty acids

The type of fat, i.e. chain length, degree of saturation and physical form, is of importance for the response in milk yield (Børsting *et al*., 2003). Too high fat content in dairy cattle diets will reduce feed intake and fibre degradation in the rumen (NRC, 2001). The NRC (2001) recommends that the CFat content in a ration should not exceed 6-7% of DM, and the Danish maximum recommendation for growing cattle is 50-60 g/kg DM (Strudsholm *et al*., 1999). A relationship was established between ECM yield and FA/kg DM, based on Danish trials with fat supplementation suggesting that the maximal ECM yield is obtained with 46 g FA/kg DM for fat with a degree of saturation of approximately 50 (Børsting *et al*., 2003). If the fat supplementation consists of FAs with a high degree of saturation then the maximum ECM yield can be achieved at 75 g FA/kg DM (Børsting *et al*., 2003). NorFor has implemented a maximum recommendation of 45 g FA/kg DM for both cows and growing cattle. This corresponds to a CFat content of 64 g/kg DM, assuming a 50/50 ratio of roughage to concentrate, and FA contents in the CFat of 650 and 750 g/kg in roughage and concentrates, respectively.

9.8 Minerals

Mineral requirements are generally based on a factorial approach in which the requirements for maintenance, milk production, growth and gestation are considered. The requirements also include a safety margin, although this margin is not quantified, but based on the lowest absorption coefficients from the literature. Furthermore, these low absorption coefficients also apply for mineral supplements, although they have higher true absorption coefficients (NRC, 2001).

9.8.1 Macro minerals

Recommendations for calcium, phosphorus, magnesium, sodium, potassium and chlorine for dairy cows and growing cattle are calculated using the following equations. Note that the absorption coefficients range from 16% for magnesium to 90% for sodium and potassium:

$$\mathrm{Ca\_intake\_Min} = \mathrm{Ca\_maint} + \mathrm{Ca\_milk} + \mathrm{Ca\_gain} + \mathrm{Ca\_gest} \tag{9.44}$$

$$\mathrm{Ca\_maint} = \mathrm{factor\_1} \cdot \mathrm{BW}/0.50 \tag{9.45}$$

$$\mathrm{Ca\_milk} = 1.22 \cdot \mathrm{ECM}/0.50 \tag{9.46}$$

$$\mathrm{Ca\_gain} = \left(\left(9.83 \cdot \left(\mathrm{BW\_mat}^{0.22}\right) \cdot \left(\mathrm{BW}^{-0.22}\right)\right) \cdot \mathrm{ADG}/1000\right)/0.50 \tag{9.47}$$

$$\mathrm{Ca\_gest} = \left(\begin{array}{l}\left(0.02456 \cdot \left(e^{(0.05581-0.00007 \cdot \mathrm{gest}) \cdot \mathrm{gest}}\right)\right) \\ -\left(0.02456 \cdot \left(e^{(0.05581-0.00007 \cdot (\mathrm{gest}-1)) \cdot (\mathrm{gest}-1)}\right)\right)\end{array}\right)\Big/0.50 \tag{9.48}$$

$$\mathrm{P\_intake\_Min} = \mathrm{P\_maint} + \mathrm{P\_milk} + \mathrm{P\_gain} + \mathrm{P\_gest} \tag{9.49}$$

$$\mathrm{P\_maint} = 1.0 \cdot \mathrm{DMI}/0.70 \tag{9.50}$$

$$\mathrm{P\_milk} = \mathrm{factor\_2} \cdot \mathrm{MY}/0.70 \tag{9.51}$$

$$\mathrm{P\_gain} = \left(\left(1.2 + \left(4.635 \cdot \mathrm{BW\_mat}^{0.22}\right) \cdot \left(\mathrm{BW}^{-0.22}\right)\right) \cdot \mathrm{ADG}/1000\right)/0.70 \tag{9.52}$$

$$\mathrm{P\_gest} = \left(\begin{array}{l}\left(0.02743 \cdot \left(e^{(0.05527-0.000075 \cdot \mathrm{gest}) \cdot \mathrm{gest}}\right)\right) \\ -\left(0.02743 \cdot \left(e^{(0.05527-0.000075 \cdot (\mathrm{gest}-1)) \cdot (\mathrm{gest}-1)}\right)\right)\end{array}\right)\Big/0.70 \tag{9.53}$$

$$\mathrm{Mg\_intake\_Min} = \mathrm{Mg\_maint} + \mathrm{Mg\_milk} + \mathrm{Mg\_gain} + \mathrm{Mg\_gest} \tag{9.54}$$

$$\mathrm{Mg\_maint} = 0.003 \cdot \mathrm{BW}/0.16 \tag{9.55}$$

$$\mathrm{Mg\_milk} = 0.15 \cdot \mathrm{ECM}/0.16 \tag{9.56}$$

$$\mathrm{Mg\_gain} = \left(0.45 \cdot \mathrm{ADG}/1000\right)/0.16 \tag{9.57}$$

$$\text{Mg\_gest} = 0.33/0.16 \tag{9.58}$$

$$\text{Na\_intake\_Min} = \text{Na\_maint} + \text{Na\_milk} + \text{Na\_gain} + \text{Na\_gest} \tag{9.59}$$

$$\text{Na\_maint} = \text{factor\_3} \cdot \text{BW}/0.90 \tag{9.60}$$

$$\text{Na\_milk} = 0.63 \cdot \text{MY}/0.90 \tag{9.61}$$

$$\text{Na\_gain} = \left(1.4 \cdot {}^{\text{ADG}}\!/_{1000}\right)/0.90 \tag{9.62}$$

$$\text{Na\_gest} = 1.4/0.90 \tag{9.63}$$

$$\text{K\_intake\_Min} = \text{K\_maint} + \text{K\_milk} + \text{K\_gain} + \text{K\_gest} \tag{9.64}$$

$$\text{K\_maint} = \left(0.038 \cdot \text{BW} + \text{factor\_4} \cdot \text{DMI}\right)/0.90 \tag{9.65}$$

$$\text{K\_milk} = 1.5 \cdot \text{MY}/0.90 \tag{9.66}$$

$$\text{K\_gain} = \left(1.6 \cdot {}^{\text{ADG}}\!/_{1000}\right)/0.90 \tag{9.67}$$

$$\text{K\_gest} = 1.0/0.90 \tag{9.68}$$

$$\text{Cl\_intake\_Min} = \text{Cl\_maint} + \text{Cl\_milk} + \text{Cl\_gain} + \text{Cl\_gest} \tag{9.69}$$

$$\text{Cl\_maint} = 0.0225 \cdot \text{BW}/0.90 \tag{9.70}$$

$$\text{Cl\_milk} = 1.15 \cdot \text{MY}/0.90 \tag{9.71}$$

$$\text{Cl\_gain} = \left(1.0 \cdot {}^{\text{ADG}}\!/_{1000}\right)/0.90 \tag{9.72}$$

$$\text{Cl\_gest} = 1.0/0.90 \tag{9.73}$$

where Ca_intake_Min is the calcium recommendation for dairy cows, g/d;Ca_maint, Ca_milk, Ca_gain, Ca_gest is a cows requirement of Ca for maintenance, milk production, gain and gestation, respectively; P_intake_Min, Mg_intake_Min, Na_intake_Min, K_intake_Min and Cl_intake_Min are recommendations of phosphorus, magnesium, sodium, potassium and chlorine for dairy cows and growing cattle, g/d; BW is the weight of the animal, kg; BW_mat is the mature weight of the animal, kg (Table 3.2 and Table 3.5); ECM is the energy-corrected milk yield, Equation 3.1 and 3.2; MY is the milk yield, kg/d; ADG is the daily weight gain of growing cattle including primiparous cows, g/d; gest is the actual day in gestation from day 190 of gestation until calving; The denominators in the equations are absorption coefficients; factor_1 is 0.031 for lactating cows and 0.0154 for non-lactating cows, g Ca/kg BW; factor_2 is 0.98 for large breeds and 1.17 for Jersey, g P/kg milk; factor_3 is 0.038 for lactating cows and 0.015 for non-lactating cows and growing cattle, g Na/kg BW; factor_4 is 6.1 for lactating cows and 2.6 for non-lactating cows and growing cattle, g K/kg DM; and DMI is dry matter intake which is set to 3.3% and 1.67% of BW for lactating and non-lactating cows, respectively. For growing cattle, DMI is calculated according to Equations 9.74 and 9.75.

The recommendations for macro minerals are from NRC (2001) with modifications for phosphorus since the phosphorus content in milk is differentiated between large breeds and Jersey based on Danish (Sehested and Aaes, 2004) and Swedish data (Lindmark-Månsson *et al.*, 2003). In NRC (2001) the coefficients for absorption of calcium and phosphorus depend on the feedstuff, but in NorFor these are fixed at 50% and 70%, respectively, based on values from NRC (2001). DMI is required to estimate the maintenance requirement of phosphorus and potassium and was set to 3.3% of BW for dairy cows according to NRC (2001). NorFor equations for DMI were developed for growing cattle, based on a subset of the data used to develop the feed intake system.

$$\mathrm{DMI}_{\mathrm{Heifer\,Steers}} = \mathrm{BW}/100 \cdot (0.000004 \cdot \mathrm{BW}^2 - 0.0049 \cdot \mathrm{BW} + 3.1033) \tag{9.74}$$

$$\mathrm{DMI}_{\mathrm{Bulls}} = \mathrm{BW}/100 \cdot (2.9 - 0.002 \cdot \mathrm{BW}) \tag{9.75}$$

where $\mathrm{DMI}_{\mathrm{HeifersSteers}}$ and $\mathrm{DMI}_{\mathrm{Bulls}}$ are estimated DMI for heifers, steers and bulls, kg DM/d; BW is the weight of the animal, kg.

The calcium recommendation for growing cattle was calculated from tabulated values in Pehrson *et al*. (1975) and is calculated using the following equation:

$$\mathrm{Ca\_intake\_Min} = \begin{pmatrix} 4.744 + 0.0361 \cdot \mathrm{BW} + 0.00000565 \cdot \mathrm{BW}^2 \\ + 0.0106 \cdot \mathrm{ADG} + 0.00000622 \cdot \mathrm{ADG}^2 \end{pmatrix} \tag{9.76}$$

where Ca_intake_Min is the calcium recommendation for growing cattle, g/d; BW is the weight of the animal, kg; and ADG is the average daily live weight gain of the animal, g/d. Heifers in late gestation require an additional Ca supply for gestation, Equation 9.48.

The recommendation for sulfur is set to 2 g/kg DM for dairy cows and growing cattle (NRC, 2001). The macro mineral recommendations for dairy cows and growing cattle that depend on the BW and ECM or ADG are illustrated in Tables 9.13 and 9.14.

9.8.2 Micro minerals

Micro mineral recommendations for dairy cows and growing cattle are shown in Table 9.15. The copper (Cu) requirement in the ration is dependent on the molybdenum and sulfur contents; the recommendation of 10 mg Cu per kg DM (Table 9.15) is valid if the ration contains less than 1 mg molybdenum (Mo) and less than 2 g sulfur per kg DM (NRC, 1989). Higher amounts of molybdenum and sulfur decrease the absorption coefficient of Cu. The ratio between Cu and Mo should not be below 4:1 (NRC, 1989). Synthesis of the hormone thyroxine in the thyroid gland is inhibited by goitrogenic substances, which are common in rape seed products that contain glucosinolates (Hermansen *et al*., 1995). Since rape seed products are commonly used in feed rations for dairy cows in Nordic countries, the recommended iodine level was set to 1.0 mg/kg DM for dairy cows, although NRC (2001) only recommends 0.6 mg/kg DM. If the ration contains substantial amounts of goitrogenic substrates, the iodine recommendation should be increased to 2.0 mg/kg DM (Strudsholm *et al*., 1999).

Table 9.13. Recommendations (g/day) for macro minerals for growing cattle gaining 750 g/day[1]*. The recommendation includes requirements for maintenance and gain.*

BW, kg	Calcium	Phosphorus	Magnesium	Sodium	Potassium
200 kg	24	12	6	5	22
400 kg	32	15	10	8	37
600 kg	40	18	13	11	52

[1] Phosphorus, magnesium, sodium and potassium recommendations are from NRC (2001). The calcium recommendation is from Pehrson *et al*. (1975).

Table 9.14. Recommendations (g/day) for macro minerals for dairy cows depending on BW and milk yield (MY) or ECM[1].

BW, kg	MY or ECM, kg/d	Calcium	Phosphorus[2]	Magnesium	Sodium	Potassium
430	17/22	80	49	29	34	151
430	24/31	102	60	37	40	166
430	31/40	124	72	46	46	181
600	25/25	109	63	35	43	201
600	35/35	136	77	44	50	218
600	45/45	163	91	53	57	235

[1] The recommendations are from NRC (2001) with a slight modification for phosphorus, for which the milk content is from Lindmark-Månsson *et al*. (2003) and Sehested and Aaes (2004).

[2] The P recommendation is dependent on breed. Jersey cows (BW=430 kg) have a content of 1.17 g P/kg milk whereas 0.98 g P/kg milk is used for large breed cows (BW=600 kg). MY and ECM yield were assumed to be equal for large breeds but for Jersey cows MY was multiplied by 1.3 to get ECM yield.

Table 9.15. Recommendations for micro minerals (mg/kg DM) for dairy cows[1] and growing cattle[2].

	Cobalt	Copper[3]	Iodine[4]	Iron	Manganese	Selenium[5]	Zinc
Dairy cows	0.1	10	1.0	50	40	0.2	50
Growing cattle	0.1	10	0.5	50	20	0.1	30

[1] The recommendations are based on NRC (2001) with the exception of selenium.

[2] The recommendations are based on NRC (2000).

[3] The recommendation is dependent on the content of molybdenum and sulfur in the ration.

[4] The recommendation considers some content of goitrogenic substrates, which are sometimes present in rape seed products (Hermansen *et al*., 1995).

[5] The recommendation is from former Swedish recommendations (Spörndly, 2003).

9.8.3 Cation anion difference

In order to reduce the risk of milk fever, the CAD has been introduced as a nutritional variable in feeding, especially for dry cows. The NorFor recommendation for CAD is -150 to 0 mEq/kg DM in the dry period, or at least for the last 3 to 4 weeks of the dry period (Horst *et al*., 1997; Moore *et al*., 2000; Kristensen, 2005). For lactating cows the recommendation is 200 to 450 mEq/kg DM since Borucki Castro *et al*. (2004) found that increasing CAD from 140 to 450 mEq/kg DM had no effect on DMI or milk yield. The CAD should never exceed 450 mEq/kg DM and this is important when adding buffer to the ration (Kristensen, 2005). Research results in the literature are equivocal about whether a reduction in dietary K and a moderate CAD in the dry period are sufficient to avert milk fever (Overton and Waldron, 2004). Potassium is therefore included in the calculation of CAD (see Chapter 6) and NorFor does not provide any recommendations for K in relation to CAD.

9.9 Vitamins

Cattle require vitamins A, D, E and K. However, the dietary requirements are only absolute for vitamins A and E, since vitamin K is synthesized by ruminal and intestinal bacteria, and vitamin D is synthesized by the action of ultraviolet radiation in the skin (NRC, 2001). NorFor has recommendations for the supply of fat soluble vitamins (A, D and E) to dairy cows and growing cattle, which are from NRC (2001) and shown in Table 9.16. The recommendations from NRC (2001) are based on supplemental vitamins and, thus, do not take into account the natural content of vitamins in feedstuffs. NorFor includes the natural content of vitamins A, D and E when calculating the supply of these vitamins from a feed ration and recommendations are therefore a total recommendation. The beta-carotene in feedstuffs is converted to vitamin A such that 1 mg beta-carotene corresponds to 400 IU of vitamin A (Strudsholm *et al*., 1999).

Table 9.16. Recommendations for vitamins A, D and E supplies (IU/kg BW) to dairy cows and growing cattle are based on NRC (2001). Requirements are expressed as total amounts, i.e. supplemental plus vitamins provided by feedstuffs.

	Vitamin A[1, 2]	Vitamin D[3]	Vitamin E[4]
Dairy cows	110	30	0.8/1.6
Growing cattle	80/110	10	0.3/1.6

[1] Beta-carotene can be converted to vitamin A and the total requirement can be met from beta-carotene. 1 mg beta-carotene corresponds to 400 IU vitamin A (Strudsholm *et al*., 1999).

[2] The requirement of 80 IU/kg BW is for bulls, steers and non-pregnant heifers, while the requirement of 110 IU/kg BW is for pregnant heifers (NRC, 2001).

[3] The requirement is from Strudsholm *et al.* (1999).

[4] The requirement of 0.8 IU/kg BW is for lactating cows, while the requirement of 1.6 IU/kg BW is for dry cows and heifers in late gestation. The requirement for growing cattle is modified from NRC (2001), which suggests a range from 0.26 to 0.8 IU/kg BW, where the lowest value refers to grazing animals and the highest value to animals fed stored forages.

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10. Prediction of voluntary feed intake

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Describing the nutrient variables in a diet and their interactions is an important part of ration formulation as productivity of the dairy cow is sensitive to the profile of the nutrients absorbed. However, the prediction of feed intake is probably the most important determinant of production. Feed intake is primarily influenced by animal and feed characteristics. The most important animal characteristics are BW and physiological state, including stage of lactation, milk production, stage of gestation, live weight gain and body condition score. Feed characteristics such as digestibility and fibre content have both a strong influence on rumen fill and, hence, feed intake (Kristensen, 1983). However, several studies (Rinne *et al*., 2002; Garmo *et al*., 2007) have shown that cows may stop eating before the fill capacity of the rumen is reached. This has been attributed to metabolic regulation (MR), which is also an important factor to consider when predicting feed intake. Physical intake regulation is related to the ruminal NDF pool (Bosch *et al*., 1992; Rinne *et al*., 2002) and is partly an indirect effect of the energy concentration of the diet because DMI declines in a curvilinear manner with increasing energy density of the diet (Mertens, 1994).

Several systems have been developed to predict DMI for practical ration formulation. These systems vary both in their complexity and choice of variables included (animal, nutritional and environmental). In the Danish (Kristensen, 1983) and French (Jarrige, 1986) systems, feed intake is predicted from dietary fill values and animal fill capacity. In the system developed by Mertens (1987), intake is regulated both physically by the diet (NDF) and metabolically by the energy demand of the animal. A similar approach is also used to predict DMI in NorFor. Each individual feed is assigned a basic fill value (FV; Section 6.2) and the animal is assigned an intake capacity (IC) expressed in the same units as the feed. When predicting DMI, the following general equation must be fulfilled:

$$IC = FV\_intake \qquad 10.1$$

where IC is the animal intake capacity and FV_intake is the total feed intake expressed in fill units, which is calculated as described in Section 6.2.

Despite this general relationship, the feed FV and thus the FV_intake is not constant; it varies with the concentrate substitution rate (SubR), which affects roughage intake. Moreover, if the energy concentration of the ration is high, relative to the animal's requirements, the above general equation will overestimate feed intake. An MR factor should therefore be included in the equation when formulating rations to meet specific animal production levels (e.g. weight gain or milk yield).

In NorFor, the IC of each animal category has been estimated from feeding experiments in which animals were fed total mixed rations *ad libitum* or fed only roughage *ad libitum* with fixed levels of concentrate. These experiments have tried to evaluate how different types of roughage are utilized and also the interaction between roughage and concentrate by different categories of animals. From each experiment, the FVs of the different feeds were calculated assuming that the FV_intake represented the IC of the animals.

10.1. Dairy cows

A database of 183 dietary treatments was compiled from Norwegian, Danish, Swedish and Icelandic production experiments. (Table 10.1) in which grass or maize silages constituted the sole or dominant forage. The breeds represented in the database were the dominant Nordic dairy breeds, i.e. DH, SR, SH, NR and IB (Table 3.2). Animal and feed characteristics for the large dairy breeds, JER and IB are presented in Table 10.2, 10.3 and 10.4, respectively. The total DMI varied from 9.7 to 32.3 kg/d

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Table 10.1. Studies used to develop the feed intake module for dairy cows in NorFor.

Bertilsson and Murphy, 2003
Bossen *et al*., 2010a
Bossen *et al*., 2010b
Hetta *et al*., 2007
Hymøller *et al*., 2005
Johansen, 1992
Kristensen, 1999
Kristensen *et al*., 2003
Kristensen *et al*., unpublished data
Misciattelli *et al*., 2003
Mo and Randby, 1986
Mould, 1996
Nordang and Mould, 1994
Randby, 1992
Randby, 1997
Randby, 1999a
Randby, 1999b
Randby, 2000
Randby, 2002
Randby, 2007
Randby and Mo, 1985
Randby and Selmer-Olsen, 1997a
Randby *et al*., 1999
Rikarðsson, 1997
Rikarðsson, 2002
Schei *et al*., 2005
Sveinbjörnsson and Harðarsson, 2008
Weisbjerg *et al*., unpublished data

Table 10.2. Descriptive statistics of data used to develop the equation for predicting intake capacity of dairy cows: large dairy breeds.

Item	Average	SD[1]	Maximum	Minimum
Days in milk	123	65	328	7
Body weight, kg	577	59	775	437
ECM[2], kg/d	29.9	5.8	48.9	15.1
Dry matter intake, kg/d	19.7	3.4	32.3	9.7
Concentrate proportion, kg/kg DM	0.42	0.101	0.84	0.14
Roughage intake, kg DM/d	11.2	2.3	19.4	3.7
Roughage basis fill value, FV/kg DM	0.51	0.031	0.76	0.42
Starch + sugars, kg/d	2.7	0.7	5.0	1.5

[1] SD=standard deviation.

[2] ECM=energy corrected milk.

Table 10.3. Descriptive statistics of data used to develop the equation for predicting intake capacity of dairy cows: Jersey cows.

Item	Average	SD[1]	Maximum	Minimum
Days in milk	119	77	294	7
Body weight, kg	458	43	598	308
ECM[2], kg/d	25.8	6.0	47.2	4.0
Dry matter intake, kg/d	16.0	2.8	23.8	5.3
Concentrate proportion, kg/kg DM	0.40	0.09	0.59	0.11
Roughage intake, kg DM/d	9.6	2.3	18.7	3.1
Roughage basis fill value, FV/kg DM	0.44	0.020	0.48	0.41
Starch + sugars, kg/d	3.6	0.7	5.9	1.2

[1] SD=standard deviation.

[2] ECM=energy corrected milk.

Table 10.4. Descriptive statistics of data used to develop the equation for predicting intake capacity of dairy cows: Icelandic cows. Data from Baldursdóttir (2010).

Item	Average	SD[1]	Maximum	Minimum
Days in milk	58	34	147	7
Body weight, kg	439	47	619	300
ECM[2], kg/d	20.4	4.7	41.0	7.6
Dry matter intake, kg/d	15.1	2.1	25.3	7.1
Concentrate proportion, kg/kg DM	0.41	0.09	0.49	0.28
Roughage intake, kg DM/d	9.0	1.8	15.6	4.0
Roughage basis fill value, FV/kg DM	0.53	0.025	0.62	0.48
Starch + sugars, kg/d	2.5	0.5	3.1	0.5

[1] SD=standard deviation.

[2] ECM=energy corrected milk.

and the concentrate intake from 2.7 to 19.8 kg DM/d. The roughage FV ranged from 0.42 to 0.76 per kg DM. A multiple regression approach was used to derive the equation for predicting animal IC.

Based on the work of Kristensen (1983, 1995), the following modified multiple regression equation was used to describe IC:

$$IC\_cow = (a \cdot DIM^{b} \cdot e^{c \cdot DIM} - DIM^{-d} + e \cdot ECM + (BW - f) \cdot g) \qquad 10.2$$

where IC_cow is the intake capacity of lactating dairy cows; DIM is days in milk; ECM is the energy corrected milk, kg/d; BW is the animal body weight, kg; and a, b, c, d, e, f, g are regression coefficients (see Table 10.5).

The Solver tool (Fylstra *et al*., 1998) in Microsoft® Excel, which employs a generalized reduced gradient non-linear optimization code (Lasdon *et al*., 1978; Sveinbjörnsson *et al*., 2006), was used to parameterize the equation and fit regression coefficients to the above model by minimizing the root mean square prediction error (RMSPE) for animal IC. The regression coefficients for predicting the IC of lactating dairy cows are presented in Table 10.5.

Table 10.5. Multiple regression coefficients used to predict dairy cow intake capacity (IC).

Cow category	Multiple regression coefficients[1]						
	a	b	c	d	e	f	g
Primiparous large dairy breeds	2.59	0.134	-0.0006	0.55	0.091	500	0.006
Multiparous large dairy breeds	2.82	0.134	-0.0006	0.55	0.091	575	0.006
Jersey primiparous cows	2.25	0.134	-0.0004	0.25	0.110	360	0.006
Jersey multiparous cows	2.40	0.134	-0.0004	0.15	0.110	405	0.006
Icelandic primiparous cows	4.07	0.087	-0.0014	0.65	0.015	400	0.002
Icelandic multiparous cows	4.77	0.071	-0.0013	0.14	0.035	523	0.0013

[1] $IC=(a \cdot DIM^{b} \cdot e^{c \cdot DIM} - DIM^{-d} + e \cdot ECM + (BW - f) \cdot g)$.

Figure 10.1 illustrates how the IC of large dairy breeds varies with lactation period, with a 305-d yield potential of between 6,000 and 10,000 kg ECM. For Icelandic cows the same approach as described above was used to parameterize the IC, and the parameter values in Table 10.5 is from the work of Baldursdóttir (2010).

The DMI is also affected by animal activity, and when cows are on pasture, or confined in a loose-house system, an IC exercise value is added (Kristensen, 1995):

$$\mathrm{IC} = (\mathrm{IC\_animal} + \mathrm{IC\_exercize}) \cdot \mathrm{factorR} \qquad 10.3$$

where IC_animal is either IC_cow described in Equation 10.2 or IC_dry described in Equation 10.5 or 10.6; IC_exercize is 0 if the cows are tied up and 0.15 if the cows are in a loose housing system or on pasture; factorR is an *ad libitum* correction factor as described in Equation 10.4.

If cows are not fed *ad libitum,* e.g. in situations where roughage intake is not optimal, due to feed shortage or feeding systems that do not allow maximal roughage intake, an adjustment factor is introduced:

$$\mathrm{factorR} = 0.0214 \cdot \left(\frac{\mathrm{roughage\_appetite}}{5} - 13 \right) + 0.8502 \qquad 10.4$$

where factorR is an adjustment factor for the intake capacity; roughage_appetite is the appetite proportion, % of expected *ad libitum* intake.

In non-lactating cows an equation based on the work of Kristensen (1995) is used to predict IC:

$$\mathrm{IC\_dry} = (5 + ((\mathrm{BW} - \mathrm{f}) \cdot 0.006)) \cdot \mathrm{factor\_h} \qquad 10.5$$

where IC_dry is the intake capacity of non-lactating cows, FV/d; BW is the body weight, kg; f is the regression factor f in Table 10.5; factor_h is the breed correction factor (large breeds=1; Jersey=0.83).

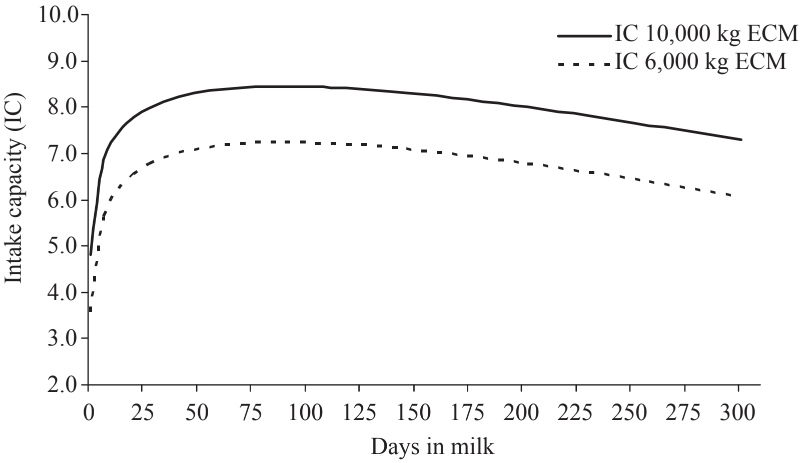

Figure 10.1. Feed intake capacity (IC) throughout a 305-d lactation period at two production levels (6,000 and 10,000 kg ECM).

When DMI is calculated, the IC is set equal to the FV_intake. Several factors affect the FV_intake and it is generally accepted that increases in concentrate supplementation decrease the roughage intake (Thomas, 1987). This is not only due to the filling effect of additional concentrate but also by the accompanying reduction in ruminal NDF digestibility (Khalili and Huhtanen, 1991; Huhtanen and Jaakkola, 1993; Stensig *et al*., 1998), which results in a higher roughage FV. However, the concentrate substitution rate is not a constant (INRA, 1989); the true roughage FV varies with ration size and composition. Moreover, MR is not related to each individual feed but instead to the entire ration. Bosch *et al*. (1992), Rinne *et al*. (2002) and Eriksen and Ness (2007) have shown that cows do not eat to a constant ruminal NDF pool size, indicating that the DMI is metabolically regulated and that dietary NDF concentration can be used as an indirect measure of MR (Mertens, 1987; 1994). The same dataset that was used in the development of animal IC was also used to establish a relationship between FV_intake and the effects of SubR and MR. When taking into account SubR and MR, the FV_intake can be calculated from the general equation:

$$\text{FV\_intake} = \sum_i \text{DMI}_i \cdot \text{FV}_i + \sum_j \text{DMI}_j \cdot \text{FV}_j \cdot \text{FV\_SubR} + \text{FV\_MR} \qquad 10.6$$

where FV_intake is the feed intake expressed in fill units; FV_i is the fill value of the i'th concentrate feed, FV/kg DM; FV_j is the basis fill value of the j'th roughage, Equation 6.10 and 6.11; FV_SubR is the substitution rate factor, 0 to1, Equation 10.7 and 10.14; FV_MR is the metabolic regulation factor, Equations 10.8 and 10.15.

Traditionally, SubR has been related to the effect of concentrate *per se*. However, it may be difficult to define a feedstuff as strictly 'roughage' or 'concentrate'. In NorFor, variations in the SubR are explained by changes in the NDF digestion in the rumen and the effect of rapidly degradable CHO's on ruminal digestion. This is similar to the effect used to explain the correction of ruminal NDF digestibility, i.e. the RLI (Equation 7.15) in Chapter 7. Therefore, the suitability of including dietary ST and SU in the estimation of the substitution factor (FV_SubR) was assessed, employing the Microsoft® Excel Solver tool to develop a SubR function based on the dietary ST and SU supply and its effect on roughage FV:

$$\text{FV\_SubR} = 0.97 + 0.562 \cdot \left(\frac{\text{ST\_SU\_DM}}{1000} - 0.2119\right) \cdot 0.1 - 0.1932 \cdot \left(\frac{\text{ST\_SU\_intake}}{1000} - 5.122\right) \cdot 0.05 \qquad 10.7$$

where FV_SubR is the roughage substitution correction factor, 0 to 1; ST_SU_DM is the proportion of starch and sugars in the diet, g/g DM; and ST_SU_intake is the starch and sugar intake, g/d.

Figure 10.2 illustrates how the FV_SubR is affected by the amount and proportion of ST + SU in the ration; an increased proportion of SU + ST in the diet has a negative effect on the roughage FV and this effect is also related to the SU + ST intake. The latter effect may explain why replacing a starchy concentrate with a soluble fibre-based concentrate has been found to have a highly variable effects on forage intake (Huhtanen, 1993; Van Vuuren *et al*., 1993; Petit and Tremblay, 1995; Huhtanen *et al*., 1995; Hymøller *et al*., 2005).

In NorFor, MR is defined as a regulatory factor causing cows to stop eating before reaching their full ruminal FV capacity. Physiologically, this is an animal related factor rather than a direct ruminal effect, and it is therefore expected to influence animal IC. However, in NorFor it is added to the feed side of the equation when calculating DMI for computational reasons. The FV_MR is calculated as:

$$\text{FV\_MR} = \left(1.453 - \frac{2.530}{1 + e^{\left(\left(0.466 - \text{FV\_r}\right)/0.065\right)}}\right) \cdot \frac{\text{IC}}{8} \qquad 10.8$$

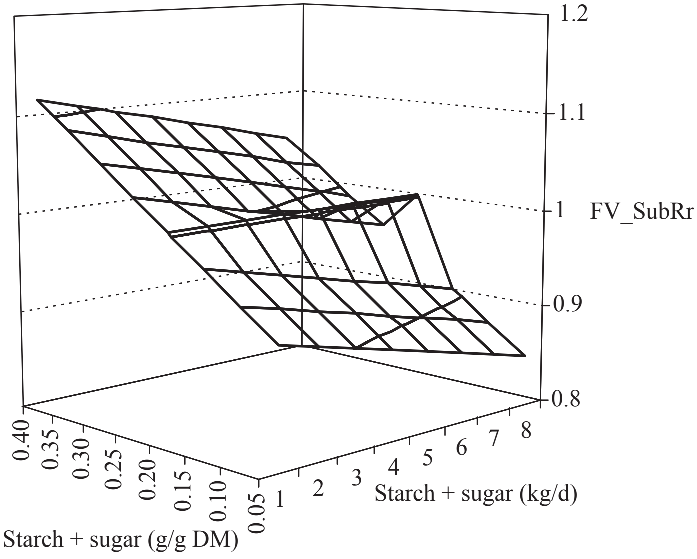

Figure 10.2. A principle figure describing the effect of starch + sugar intake and their proportion in the diet on roughage substitution rate (FV_SubR) factor.

where FV_MR is the roughage metabolic correction factor; FV_r is the mean basis roughage fill value in the diet, FV/kg DM, Equation 6.10; IC is animal intake capacity, Equation 10.3; and the IC/8 ratio is the adjustment factor for animal IC level.

Dividing IC by 8 adjusts the standard IC so that FV_MR can be used across dairy breeds. Mertens (1994) demonstrated that the threshold between an energy regulated intake and a fill limited intake was dependent on the milk yield. Maximum fill and minimum energy concentration was achieved at a higher NDF diet concentration (440 g/kg DM versus 320 g NDF/kg DM) for low-yielding cows (20 kg ECM) than for high yielding cows (40 kg ECM). Figure 10.3 shows the relationship between FV_MR and FV_r at two levels of IC (6 and 8, which represent different milk yields). At an FV_r of 0.48 the FV_MR is zero, and with a higher and increasing FV_r a low yielding cow will reach its IC relative faster than a high yielding cow. However, at low FV_r values an opposite effect is achieved, which probably is explained by a higher diet energy density and thus a metabolic regulation of the intake (Mertens, 1994).

Parameterization of Equation 10.6 showed that FV_MR makes a highly significant contribution to the prediction of roughage intake. The RMSPE was reduced by 19% when the FV_MR was introduced into the FV_intake equation. The need for this correction factor demonstrates that ruminal fill is not the only factor limiting roughage intake, as there are other important metabolic regulations (Forbes, 1995). Since FV_MR is related to roughage FV, and thus to the concentration of NDF in roughage, the rate of rumen particle size reduction may also partly explain this correction factor, since physical particle breakdown is not accounted for when calculating roughage FV. The introduction of FV_SubR and FV_MR in the prediction of DMI demonstrates that roughage FV is not a constant. Ration formulation is therefore performed by an iteration process in NorFor, using a computer program capable of solving non-linear optimization problems (see Chapter 15). The intake sub-model is further evaluated in Chapter 14.

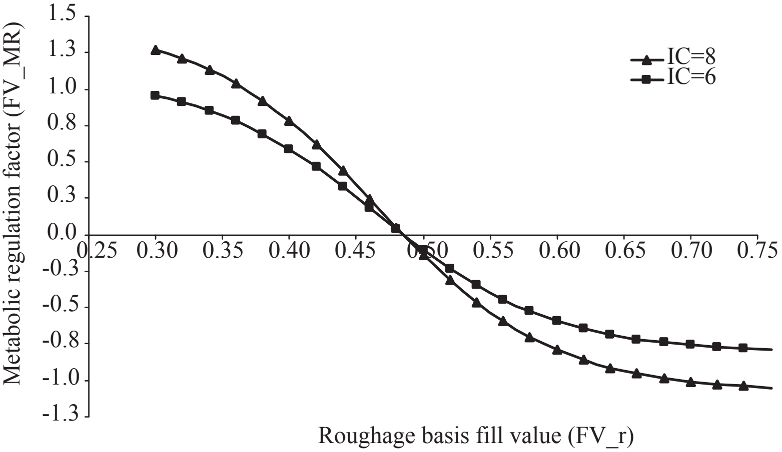

Figure 10.3. Relationship between roughage basis fill value (FV_r) and metabolic regulation factor (FV_MR) at two levels of intake capacity (IC=6 and 8).

10.2 Growing cattle

The feeding strategies used in Nordic beef production vary widely among countries, from an intensively reared beef animals fed up to 90% concentrates to an extensive system where only small amounts (0 to10%) of concentrates are used. Hence, there are substantial variations in diet composition, which makes it challenging to develop a voluntary feed intake system that is relevant to all production systems.

To develop equations for predicting the IC of bulls, steers and heifers, a database was compiled from 32 Danish, Swedish and Norwegian experiments (Table 10.6), in which cattle were fed a wide range of diets, including 145, 36 and 115 treatments for bulls, steers and heifers, respectively. Animal and feed characteristics for the bull, steer and heifer datasets are presented in Tables 10.7, 10.8 and 10.9, respectively. In the bull dataset, DMI varied from 4.5 to 11.7 kg/d (concentrate from 0 to 6.8 kg DM/d) and ADG ranged from 429 to 1,578 g, while in the heifers dataset, ADG varied from 378 to 1196 g/d and the DMI from 3.3 to 11.4 kg/d.

For all three animal categories, variations in IC were explained by changes in BW and ADG. The IC equations were parameterized using the Solver tool in Microsoft® Excel using the same approach as for the dairy cows. In bulls the IC is calculated from:

$$\mathrm{IC\_bull} = 0.006544 \cdot \mathrm{BW} + 0.0007337 \cdot \mathrm{ADG} + \frac{-20}{0.9552 \cdot \mathrm{BW}} \qquad 10.9$$

where IC_bull is the feed intake capacity of bulls; BW is the animal body weight, kg; and ADG is the average daily gain, g/d.

The steer dataset included data obtained from only 36 dietary treatments and a preliminary evaluation showed that the IC of steers and heifers were comparable. These two datasets were therefore combined in the parameterization of IC. The IC was derived from these data from:

$$\mathrm{IC\_heifer} = \left(0.007236 \cdot \mathrm{BW} + 0.0005781 \cdot \mathrm{ADG} + \frac{-3}{0.9552 \cdot \mathrm{BW}}\right) \cdot \mathrm{IC\_gest} \qquad 10.10$$

Table 10.6. Studies used to develop the feed intake module for growing cattle in NorFor.

Bulls	Steers	Heifers
Andersen *et al.*, 1993a	Matre, 1984	Andersen *et al.*, 2001
Andersen *et al.*, 1993b	Matre, 1987	Havrevoll, unpublished data
Berg, 2004	Randby, 1999c	Hessle *et al.*, 2007
Berg and Volden, 2004	Randby and Selmer-Olsen, 1997b	Ingvartsen *et al.*, 1988
Damgaard and Hansen, 1992		Mäntysaari, 1993
Jørgensen *et al.*, 2007	Rustas *et al.*, 2003	Rustas, 2009
Kirkland *et al.*, 2006	Selmer-Olsen, 1994	Sejrsen and Larsen, 1978
Matre, 1984		Olsson, unpublished data
Nadeau *et al.*, 2002		Selmer-Olsen, 1994
Olsson and Murphy, unpublished data		Vestergaard *et al.*, 1993a
Selmer-Olsen, 1994		
Therkildsen *et al.*, 1998		
Vestergaard *et al.*, 1993b		
Vestergaard *et al.*, unpublished data		
Nadeau, unpublished data		

Table 10.7. Descriptive statistics of data used to develop the equation for predicting intake capacity of bulls.

Item	Average	SD[1]	Maximum	Minimum
Age at start of experiment, d	224	109	366	83
Age at end of experiment, d	392	127	676	188
Average body weight, kg	362	130	634	178
Average live weight gain, g/d	1,165	222	1,578	429
Dry matter intake, kg/d	7.3	2.1	11.7	4.5
Concentrate intake, kg DM/d	3.0	1.9	6.8	0
Concentrate proportion, kg/kg DM	0.41	0.29	0.95	0
Roughage intake, kg DM/d	4.3	2.1	9.5	0.2
Roughage basis fill value, FV/kg DM	0.54	0.06	0.68	0.41

[1] SD=standard deviation.

where IC_heifer is the feed intake capacity of steers and heifers; BW is the animal body weight, kg; and ADG is the average daily gain, g/d. IC_gest is the intake capacity adjustments for heifers due to gestation described in Equation 10.11. The gestation correction factor is based on Kristensen and Ingvartsen (2003) and calculated as:

$$\mathrm{IC\_gest} = \frac{1}{1 + e^{\left(\frac{\mathrm{gest\_day} - 357}{36}\right)}} \qquad 10.11$$

where IC_gest is the gestation correction on the intake capacity; gest_day is the day of gestation.

Evaluation of Equations 10.9 and 10.10 showed that they were unsuitable for the Jersey breed. Therefore, the following equation was modified for Jersey young stock, irrespective of sex:

$$\mathrm{IC\_jersey} = 0.0067 \cdot \mathrm{BW} + 0.0005781 \cdot \mathrm{ADG} + \frac{-2}{0.9552 \cdot \mathrm{BW}} \qquad 10.12$$

Table 10.8. Descriptive statistics of data used to develop the equation for predicting intake capacity of steers.

Item	Average	SD[1]	Maximum	Minimum
Age at start of experiment, d	237	125	450	125
Age at end of experiment, d	349	127	555	208
Average body weight, kg	319	104	470	158
Average live weight gain, g/d	748	252	1,196	187
Dry matter intake, kg/d	6.3	1.8	9.5	4.1
Concentrate intake, kg DM/d	1.0	0.9	2.6	0
Concentrate proportion, kg/kg DM	0.21	0.18	0.54	0
Roughage intake, kg DM/d	5.3	2.5	9.5	2.2
Roughage basis fill value, FV/kg DM	0.58	0.07	0.67	0.48

[1] SD=standard deviation.

Table 10.9. Descriptive statistics of data used to develop the equation for predicting intake capacity of heifers.

Item	Average	SD[1]	Maximum	Minimum
Age at start of experiment, d	368	124	491	122
Age at end of experiment, d	468	103	634	310
Average body weight, kg	379	108	598	150
Average live weight gain, g/d	798	205	1,196	378
Dry matter intake, kg/d	7.3	1.6	11.4	3.3
Concentrate intake, kg DM/d	1.3	1.3	5.1	0
Concentrate proportion, kg/kg DM	0.19	0.20	0.75	0.0
Roughage intake, kg DM/d	6.0	2.1	11.4	1.2
Roughage basis fill value, FV/kg DM	0.54	0.04	0.67	0.49

[1] SD=standard deviation.

where IC_jersey is the feed intake capacity of Jersey young stock; BW is the animal body weight, kg; and ADG is the average daily gain, g/d.

The IC of growing cattle is also corrected for activity:

$$\mathrm{IC} = \mathrm{IC\_animal} \cdot \mathrm{IC\_exercize} \qquad 10.13$$

where IC is the intake capacity; IC_animal is either IC_bull, IC_heifer or IC_jersey described in Equation 10.9, 10.10 and 10.12, respectively.

Based on the range of animal characteristics in the datasets, it was decided that the IC equations are valid for animals of large dairy and beef breeds with body weights of ≥80 kg, and for Jersey with body weights ≥60 kg.

Figure 10.4 illustrates how the IC in growing bulls changes with BW and ADG over time up to the target slaughter weight of 300 kg at 16 months of age. The ADG changes in a curvilinear manner

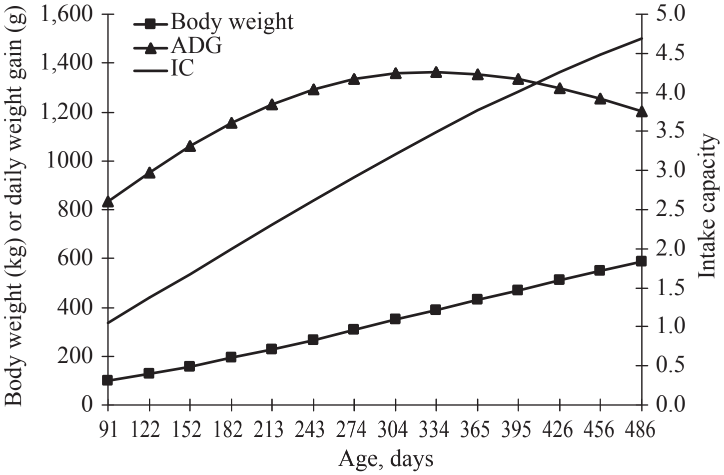

Figure 10.4. Changes in intake capacity (IC) over time for a bull with a target slaughter weight of 300 kg (587 kg body weight) at 16 months of age.

with time and the highest ADG is achieved at an age of 330 days. Since the IC is dependent on both the BW and ADG, it also changes over time in a sigmoidal fashion.

As for dairy cows, the feed intake in growing cattle is dependent on the SubR and MR effects. To parameterize these two variables for the growing cattle, the same approach was used as for lactating dairy cows. However, the concentrate characteristics available in the growing cattle datasets were incomplete, which made it difficult to develop a SubR equation based on starch and sugar information. Consequently, the SubR equation was developed from the information on the proportion of concentrate in the diet. The following equation is used for growing cattle, of all types:

$$\mathrm{FV\_SubR} = \left(\frac{0.9646 - 0.706 \cdot \frac{\mathrm{conc\_share}}{100}}{1 - 0.7512 \cdot \frac{\mathrm{conc\_share}}{100} - 0.2085 \cdot \left(\frac{\mathrm{conc\_share}}{100} \right)^2} \right)^2 \qquad 10.14$$

where FV_SubR is the roughage substitution correction factor, 0 to 1; and conc_share is the proportion of concentrate in the diet on a DM basis, %.

Figure 10.5 shows how the FV_SubR factor changes with the proportion of concentrate in the diet. The growing cattle diets vary widely in the concentrate to roughage ratio (0 to 90% concentrate on DM basis), thus, the FV_SubR correction factor must be able to correct the roughage intake over a large range of concentrate intake values. The FV_SubR factor, and consequently, the roughage FV, increase considerably when the concentrate in the diet exceeds 60%. This indicates that the voluntary roughage intake is likely to be low at high levels of concentrate.

The FV_MR significantly affected the prediction of DMI in growing cattle, and by including this variable in the prediction of FV_intake, the MSPE was reduced by 14% for the predicted roughage intake. The FV_MR was parameterized independently of animal category and is calculated as:

$$\mathrm{FV\_MR} = \left(-3.8301 + 2.6608 \cdot \mathrm{FV\_r} + \frac{1.2158}{\mathrm{FV\_r}} \right) \cdot \left(1 - e^{-0.029474088 \cdot \mathrm{BW}} \right) \cdot \left(\frac{\mathrm{IC}}{3} \right) \qquad 10.15$$

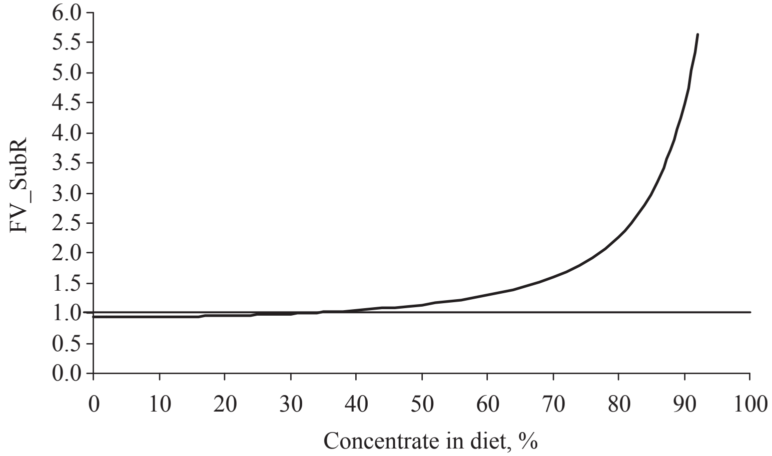

Figure 10.5. Effect of proportion of concentrate in the diet on roughage substitution rate in growing cattle.

where FV_MR is the roughage metabolic correction factor; FV_r is the diet basis roughage fill value, Equation 6.10; IC is the animal intake capacity, Equation 10.13; BW is the animal body weight, kg; and the IC/3 ratio is an adjustment factor for animal IC level.

The computer program TableCurve 2D from SYSTAT was used to resolve the equation profile and the FVL_intake equation was parameterized using the Solver tool in Microsoft$^{®}$ Excel, as described for the dairy cow model. Based on sheep data, Mertens (1994) demonstrated that the dietary NDF concentration at the intersect of metabolic and physical regulation is dependent on animal BW. This may explain why animal BW significantly affected the FV_MR in Equation 10.15. The IC/3 ratio in the equation reflects the different animal categories.

10.3 Implications

A primary objective of this work has been to develop a system that can be used to formulate diets that maximize roughage intake while meeting animals' energy requirements with a minimal dietary energy concentration. It is important to ensure that there is a high proportion of roughage in diets to maintain a favourable rumen environment. The feed intake sub-model in NorFor is complex and consists of several non-linear equations. This comprehensive approach requires DMI to be calculated iteratively by a computer program. Although the system is a simplification of numerous factors and animal-diet interactions affecting voluntary feed intake, it is applicable to diets with a wide range of roughage qualities and diverse feeding situations.

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11. Chewing index system for predicting physical structure of the diet

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An important goal in dairy cow management is, among other things, to develop a feeding strategy that ensures good rumen function, which is vitally important for efficient milk production and healthy animals. A certain intake of physically effective fibre is essential for stimulating rumination, salivation and rumen motility, and avoiding milk fat depression (Mertens, 1997; De Brabrander *et al*., 2002). A high intake of rapidly fermentable carbohydrates results in the production of a high level of volatile fatty acids in the rumen and a subsequent reduction in pH, which increases the risk of subacute ruminal acidosis (Krause and Oetzel, 2006). In addition to the structural fibre content of a feed, the length of the dietary particles is also important and affects the eating time (ET), rumination time (RT) and, thus, salivation and thereby buffering of the rumen environment (Krause and Oetzel, 2006). De Boever *et al*. (1993) observed that one kg NDF from late cut grass silage was more effective for stimulating rumination than NDF from early cut grass silage (which has low levels of lignification), demonstrating that fibre type affects chewing activity.

The formulation of diets for dairy cows with respect to the fibre content cannot be based solely on a defined roughage to concentrate ratio or a minimum amount or proportion of roughage NDF in the ration (Mertens, 1997). Balch (1971) proposed to rank the fibrousnesses of different feeds by a chewing index value that accounts for ET plus RT. In this chapter, we present a model for predicting the diet eating index (EI), rumination index (RI) and total chewing index (CI). These characteristics are used in NorFor to optimize the physical structure of the diet. The intention of this system is to characterize an additive CI for individual feeds and hence ranking feeds according to their ability to stimulate particle mastication when cows are eating and during rumination. The time spent masticating and the intensity of mastication are used to quantitatively rank the biological fibrousnesses of feeds, which is closely related to the stimulation of salivation, the frequency of rumen motility and the formation of a stable flowing layer system in the reticulo-rumen. The NorFor chewing system has been developed from the Danish chewing index system (Nørgaard, 1986) and by using new data from Nørgaard *et al*. (2010).

11.1 Predicting the chewing index from eating and rumination

Each feed is given a CI value (min/kg DM), which is estimated as the sum of EI and RI:

$$CI = EI + RI \qquad 11.1$$

where CI is the chewing index for a feedstuff, min/kg DM; EI is the eating index as described in Equation 11.2, min/kg DM; and RI is the rumination index, min/kg DM, as described in Equation 11.4.

EI and RI describe the recorded ET and RT, respectively, and in NorFor the feed EI and RI values refer to those for a standard cow of a large multiparous dairy breed with a BW of 625 kg, a NDF roughage (NDFr) intake of 0.7% of BW and a daily rumination time of 400 min. This corresponds to a daily DMI of 20 kg with a CI value of 30 min/kg DM, assuming that rumination time is equivalent to 2/3 of the total chewing time. The use of a standardized cow implies that the unit 'minutes/kg DM' reported in the practical tool refers to a standard cow and thus, does not necessarily reflects the actual mean chewing time (CT) (min/kg DM) for that particular cow. The equations for EI and RI were obtained from a meta-analysis of recorded ET and RT from cattle fed 85 different diets consisting of unchopped grass silage, grass hay or lucerne hay with or without supplementation of ground concentrates or rolled barley (Nørgaard *et al*., 2010). Based on the meta-analysis, the NorFor EI and RI values were standardized to reference values of 50 and 100 min/kg NDFr for unchopped roughage, respectively. In concentrates, the standard EI was set to 4 min/kg DM. As described in

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9_11, © Wageningen Academic Publishers 2011

Chapter 4, concentrates and roughage are defined on the basis of the most frequently measured particle length (PL) that they contain, such that feedstuffs with a PL≤6 mm are defined as concentrates while feedstuffs with a PL>6 mm are defined as roughage. Grass and maize silage are chopped at harvest and the effect of physical processing on the EI and RI values is based on the theoretical chopping length (TCL), which corresponds to the PL value (O´Dogherty, 1984). Nørgaard *et al.* (2010) observed that the mean ET and RT per kg NDFr decreased with increasing BW. Thus, the size of the cow is not taken into account when calculating the values of EI or RI (e.g. no distinctions in this respect are drawn between cows of large dairy breeds vs. small breeds or primiparous vs. multiparous breeds). This means that Jersey cows have a higher recorded mean ET and RT per kg NDFr than large breeds fed the same diet. Feeding high moisture silage containing less than 40% dry matter has been shown to increase ET (De Boever *et al*., 1993). However, in NorFor this is not reflected in a higher EI value because the DM content of a feedstuff is not taken into account when calculating the values of EI or RI.

11.2 Calculation of the eating and rumination indices

Table 11.1 presents an overview of the equations used to calculate EI and RI depending on PL. The EI describes the eating time per kg DM of a given feedstuff for the standard cow (Nørgaard *et al*., 2010). Ground, rolled or pelleted feeds are given an EI of 4 min/kg DM. The recorded ET decreases as a result of chopping (Mertens, 1997).

EI of roughage and by-products are proportional to the NDF content and a particle length factor for eating (Size_E) (Nørgaard *et al*., 2010). EI is calculated using the following equation:

$$EI = 50 \cdot \frac{NDF}{1000} \cdot Size\_E \qquad 11.2$$

where EI is the eating index, min/kg DM; NDF is the NDF content in the feedstuff, g/kg DM; Size_E is a correction factor that depends on particle length, as described in Equation 11.3; and 50 is the standardized eating time, min/kg NDF.

Table 11.1. Overview of the calculations used in the chewing index system.

Feed type	Concentrates			Roughages	
Processing	Ground		Rolled	Chopped	Long or slightly chopped
	Finely	Coarsely			
PL or TCL (mm)[1]	≤2.0	2-4	4-6	6-40	>40
Size_E				1–0.52·exp(-0.078·TCL)	1
Size_R		1–exp (-0.173·(TCL/0.7-1))			1
Hardness factor		0.75 + iNDF/1000			
Eating index (EI, min/kg DM)	4			50·NDF/1000·Size_E	
Rumination index (RI, min/kg DM)	0	100·NDF/1000·Size_R·Hardness factor			
Chewing index (CI, min/kg DM)	EI + RI				

[1] PL is the most frequent particle length in a feedstuff. TCL (theoretical chopping length) corresponds to PL in roughage (O´Dogherty, 1984).

Size_E is a correction factor for the feed particle length, which ranges from 0.67 in finely chopped feedstuffs to 1 in unchopped roughage (see Figure 11.1). Size_E is parameterized from recorded ET data in cattle fed chopped (10 or 20 mm TCL) or unchopped silage (Nørgaard, unpublished data) and is calculated using the following equation:

$$\text{Size\_E} = 1 - 0.52 \cdot e^{-0.078 \cdot \text{PL}} \qquad 11.3$$

where Size_E is the correction factor for the eating index due to the chopping or processing of the feedstuff. The Size_E factor ranges from 0.67 for fine chopped roughage to 1 for unchopped roughages; and PL is the most frequent particle length in the feedstuff, mm. PL corresponds to TCL for roughage (O´Dogherty, 1984) and is therefore used as the input for the equation.

Figure 11.1 shows how the length of feed particles affects the value of Size_E, which approaches 1 for PL values >50 mm, showing that slight chopping of roughage with TCL values higher than 50 mm does not affect the value of EI.

RI describes the associated chewing activity during rumination per kg DM of a given feedstuff in the standard cow. RI is determined from the feed NDF content, a particle length factor for rumination (Size_R) and a hardness factor, which is related to the iNDF content in the feedstuff (Nørgaard *et al.*, 2010). RI is calculated using the following equation:

$$\text{RI} = 100 \cdot \frac{\text{NDF}}{1000} \cdot \text{Size\_R} \cdot \text{Hardness\_factor} \qquad 11.4$$

where RI is the rumination index, min/kg DM; NDF is the NDF content in the feedstuff, g/kg DM; Size_R is a correction factor that depends on particle length as described in Equation 11.5; the Hardness_factor is described in Equation 11.6; and 100 is the standardized rumination time, min/kg NDF.

If the PL of the feedstuff is lower than 2.0 mm (as in finely processed concentrates), then the RI is assumed to be zero (see Table 11.1). Nørgaard and Sehic (2003) have shown that the most frequent

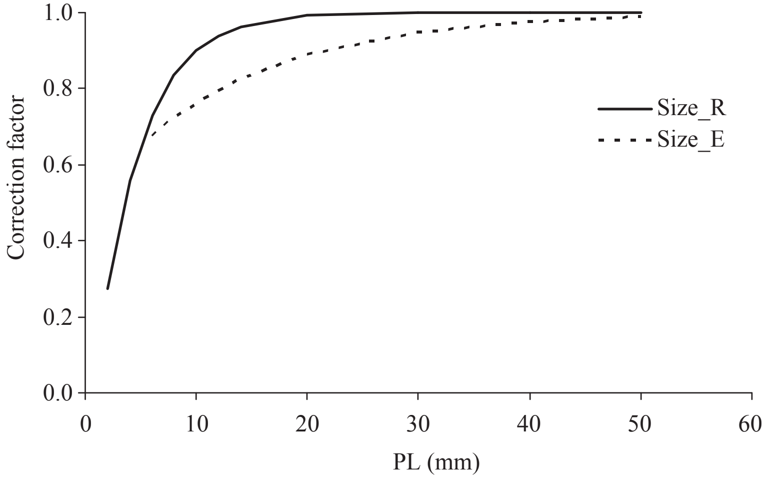

Figure 11.1. Effect of the most frequent particle length (PL) in a feedstuff on the correction factors Size_E and Size_R. Size_E and Size_R are used to adjust the eating and rumination index due to chopping or processing of feedstuffs (see Table 11.1).

particle length in the faeces of cattle fed solely roughage is 0.7 mm, consequently, feedstuffs with a PL>0.7 mm are considered to stimulate rumination. However, some concentrates have a PL>0.7 mm but are not considered to stimulate rumination. Therefore, the borderline value for PL was set to 2.0 mm to ensure that all finely ground concentrates are given an RI of zero. Thus, Size_R is zero for feeds with a PL≤2.0 mm and their CI is 4 min/kg DM corresponding to eating index (Table 11.1). Coarsely processed concentrates with a PL between 2 and 6 mm (e.g. rolled grains, coarsely ground grains, oil cakes and hulls) are considered to stimulate rumination. Several studies have shown that chopping roughage at TCL values higher than 20 mm does not decrease the recorded RT (De Boever *et al.*, 1993; Garmo *et al.*, 2008). Furthermore, Nørgaard and Sehic (2003) showed that the PL of particles in swallowed boli from cows eating grass silage chopped at 19 mm TCL was the same as the PL of boli particles from cows eating unchopped grass silage. Therefore, the RT for roughage chopped at a TCL higher than 20 mm is considered to have the same RT as unchopped roughage, and consequently Size_R at 20 mm TCL is set to 0.99. Size_R decreases exponentially when TCL is below 20 mm, as illustrated in Figure 11.1.

$$\mathrm{Size\_R} = 1 - e^{\left(-0.173 \cdot \left(\frac{\mathrm{PL}}{0.7} - 1\right)\right)} \qquad 11.5$$

where Size_R is the correction factor for the rumination index, which depends on chopping or processing the feedstuff. The Size_R factor ranges from 0 for fine processed feeds to 1 for unchopped roughage or roughage chopped with a PL higher than 20 mm. PL is the most frequent particle length (mm) in the feedstuff and for roughage PL corresponds to TCL (theoretical chopping length, mm; O'Dogherty, 1984) and can therefore be used as the input for the equation; 0.7 is the most frequent particle length in faeces from cattle, meaning that feedstuffs with a PL>0.7 stimulate rumination (Nørgaard and Sehic, 2003).

The structural NDF in immature spring grass and chopped beet pulp is soft and has relatively little resistance to physical breakdown during chewing compared with mature grass, barley straw, lucerne hay cut after blooming or whole cotton seeds. The content of iNDF in a feedstuff is closely related to the lignification of the NDF fibres (Weisbjerg and Soegaard, 2008) and lignification is known to increase resistance to physical breakdown. The resistance to physical breakdown is ranked by a hardness factor, which has been given a value of 1 for typical grass silage with an iNDF content of 250 g/kg NDF. The hardness factor increases from 0.8 for immature spring grass with an iNDF content of approximately 50 g/kg NDF to 1.25 for late cut lucerne hay with an iNDF content of approximately 500 g/kg NDF. The hardness factor is calculated as:

$$\mathrm{Hardness\_factor} = 0.75 + \left(\frac{\mathrm{iNDF}}{1000}\right) \qquad 11.6$$

where the Hardness_factor is used for calculating the rumination index and ranges from 0.8 to 1.25 for typical Nordic feedstuffs; iNDF is the iNDF content in the feedstuff, g/kg NDF.

Table 11.2 shows examples of EI, RI and CI values for some concentrates and roughages. The main reason for the much higher CI of dried beet pulp compared to barley and rape seed cake is its higher PL, which causes a higher RI. The higher CI of grass silage compared to maize silage is due to its higher TCL and NDF content, which result in higher EI and RI (Table 11.2).

The EI and RI are additive values and the CI of a total diet (min/kg DM) is considered to be the sum of the individual feed CI values:

$$\mathrm{CI\_DM} = \frac{\sum_i \mathrm{DMI_i} \cdot \mathrm{CI_i}}{\sum \mathrm{DMI_i}} \qquad 11.7$$

Table 11.2 Estimated chewing index values for different feedstuffs in the NorFor feed stuff table.

	Feed code	NDF g/kg DM	iNDF g/kg NDF	PL[1] mm	Size_E	Size_R	Hardness	EI[2] min/kg DM	RI[2] min/kg DM	CI[2] min/kg DM
Barley	001-0008	206	158	2.1		0.29	0.91	4	5	9
RSC	002-0044	268	511	2.0			1.26	4	0	4
DBP	004-0020	382	89	4.0		0.56	0.84	4	18	22
GS	006-0241	417	151	20	0.89	0.99	0.90	19	37	56
MS	006-0308	364	187	10	0.76	0.90	0.94	14	31	45

[1] PL is the most frequent particle length in concentrates and corresponds to TCL (theoretical chopping length) in roughage (O´Dogherty, 1984).

[2] See Equations 11.1 to 11.6.

RSC, rape seed cake; DBP, dried beet pulp; GS, grass silage; MS, maize silage.

where CI_DM is the chewing index for the total diet, min/kg DM; DMI_i is the dry matter intake for the i-th feedstuff, kg DM/day; and CI_i is the chewing index for the i-th feedstuff, min/kg DM as described in Equation 11.1.

11.3 Implications

The objectives of the work described in this chapter were to develop a system for ranking the structural value of different feedstuffs by calculating an additive chewing index, which could be used as a tool to minimize the risk of digestive disorders and ensure proper rumen function of a diet fed to dairy cows. The minimum recommended chewing index (32 min/kg DM) is intended to ensure a high degree of fibre digestion, a high acetate to propionate ratio and an acceptable milk fat content even at a high DMI.

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12. Prediction of milk yield, weight gain and utilisation of N, P and K

M. Åkerlind and H. Volden

NorFor predicts ECM and protein yield for dairy cows and weight gain for growing cattle. Excretion of N, P and K can also be predicted for a given diet and production level. Keep track on excreted N, P and K are of interest when estimating plant fertilising value and also evaluating the impact of excreted N and P on eutrophication of the environment.

12.1 Prediction of milk yield

Prediction of ECM yield is estimated from the total supply of NEL minus basal energy requirements corrected for any changes in BCS (see Chapter 9). Since 1 kg ECM contains 3.14 MJ (Sjaunja *et al.*, 1990), the estimated ECM production is calculated as:

$$\mathrm{ECM\_response} = \frac{\mathrm{NEL} - \mathrm{NE\_maint} - \mathrm{NEL\_gain} - \mathrm{NE\_gest} - \mathrm{NEL\_dep} + \mathrm{NEL\_mob}}{3.14} \qquad 12.1$$

where ECM_response is the predicted energy corrected milk yield, kg/day; NEL is the net energy lactation obtained from the diet, Equation 8.3; NE_maint, NEL_gain, NE_gest, NEL_dep and NEL_mob is energy required of maintenance, gestation, growth of primiparous cows, and supply of energy from mobilisation, Equation 9.1, 9.4, 9.3, 9.17 and 9.18 respectively; and 3.14 is the energy content of 1 kg ECM.

Milk protein response is calculated by multiplying available $\mathrm{AAT_N}$ by the efficiency of AA utilisation for milk protein synthesis. The available $\mathrm{AAT_N}$ is the total $\mathrm{AAT_N}$ minus basal $\mathrm{AAT_N}$ requirement. Response in milk protein production is calculated as:

$$\mathrm{Protein\_response} = (\mathrm{Avail\_AAT_N}) \cdot \frac{\mathrm{AAT_N\_Eff}}{100} \qquad 12.2$$

where Protein_response is the predicted milk protein production, g/day; $\mathrm{Avail\_AAT_N}$ is the available amino acid absorbed in the small intestine for milk production, Equation 9.26 and $\mathrm{AAT_N\_Eff}$ is the efficiency of amino acid utilization for milk protein production, Equation 9.24.

12.2 Prediction of weight gain

For growing cattle, ADG can be predicted from either the energy available for growth or the $\mathrm{AAT_N}$ available for growth. Since the energy utilization factors k_{g_corr} (Equation 9.6) and k_{mg} (Equation 8.5), both depend on BW and ADG, they cannot be used to predict daily weight gain for a given diet. Therefore, the predicted requirement for ADG was assumed to vary with animal type and BW.

For growing bulls of dairy breed weight gain is predicted from available energy:

$$\mathrm{gain\_response_{NEG}} = 1000 \cdot \frac{\mathrm{NEG - NE\_maint}}{0.0243 \cdot \mathrm{BW} + 7.7315} \qquad 12.3$$

For growing bulls of beef breed weight gain is predicted from available energy:

$$\mathrm{gain\_response_{NEG}} = 1000 \cdot \frac{\mathrm{NEG - NE\_maint}}{0.0116 \cdot \mathrm{BW} + 9.7214} \qquad 12.4$$

where $\mathrm{gain\_response_{NEG}}$ is the predicted weight gain based on the energy supply, g/d; NEG is the energy gain, Equation 8.8; NEG_maint is the energy requirement of maintenance, Equation 9.1; BW is current body weight, kg; and the numerator calculates the energy content of 1 kg of weight gain.

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9_12, © Wageningen Academic Publishers 2011

Weight gain prediction for heifers and steers are calculated from available AAT_N:

$$gain\_response_{AAT} = 1000 \cdot \frac{(AAT_N - AAT_N\_maint - AAT_N\_gest) \cdot AAT_N\_Eff / 100}{-0.1262 \cdot BW + 194.2} \quad 12.5$$

where $gain\_response_{AAT}$ is the predicted weight gain based on the amino acid supply, g/day; AAT_N is the amino acid absorbed in the small intestine, Equation 8.11; AAT_N_maint is the animal's protein requirement for maintenance, Equation 9.22; AAT_N_gest is the protein requirement of gestation for heifers, Equation 9.42; AAT_N_Eff is the efficiency of the utilisation of the available amino acids for protein gain, Equation 9.34; BW is the current BW, kg; and the numerator calculates the protein content in 1 kg of weight gain.

12.3 Prediction of N, P and K utilisation and excretion

The amount of N, P and K excreted are calculated as the difference between ingested amounts and that incorporated in milk, used in gestation and for body. The incorporation of N, P and K in milk, gain and gestation corresponds to the requirements of protein, P and K described in Chapter 9.

12.3.1 Nitrogen utilisation and excretion

The N efficiency in ruminants is low. The utilisation is higher in lactating animals than in growing cattle and non-producing animals. N efficiency is calculated as the total amount of N utilized in relation to its total intake:

$$N\_u\_pct = \frac{N\_u}{\sum DMI_i \cdot CP_i \cdot 0.16} \cdot 100 \quad 12.6$$

where N_u_pct is the N utilization as a proportion of the total intake, %; N_u is the amount of N utilized, Equation 12.7; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; and 0.16 is the N proportion in the protein.

$$N\_u = N\_milk + N\_gest + N\_gain \quad 12.7$$

where N_u is the total amount of utilised N, g/d; N_milk, N_gest and N_gain are the amount of N incorporated in milk, foetus and weight gain, Equation 12.8, 12.9 and 12.10 respectively.

$$N\_milk = MPY \cdot 0.15674 \quad 12.8$$

where N_milk is the amount of N incorporated into milk, g/d; MPY is the milk protein yield, Equation 3.4; and 0.15674 is the N content in milk protein (ISO 8968-5|IDF 020-5:2001).

$$N\_gest = AAT_N\_gest \cdot 0.16 \cdot 0.5 \quad 12.9$$

where N_gest is the N incorporated into the foetus, g/d; AAT_N_gest is the amino acid required for gestation, Equation 9.42; 0.16 is the N proportion in the protein; and 0.5 is the utilisation factor for the amino acids (NRC, 1985).

$$N\_gain = gain\_prot \cdot 0.16 \quad 12.10$$

where N_gain is the N incorporated into the BW gain, g/d; gain_prot is the protein gain, Equation 9.8; and 0.16 is the N proportion in the protein.

Total amounts of excreted N is assumed to be the difference between the N in the CP intake from the ration and N_u:

$$N\_excreted = \sum_i DMI_i \cdot CP_i \cdot 0.16 - N\_u \qquad 12.11$$

where N_excreted is the total amount of N excreted, g/day; DMI_i is the DM intake of the of the i=1...n'th feedstuff, kg DM/day; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; 0.16 is the proportion of N in CP; and N_u is the total amounts of N utilized, Equation 12.15.

Excreted N in the feaces is assumed to be the difference between N intake and apparent digested N.

$$N\_faeces = \left(\sum_i DMI_i \cdot CP_i - td\_CP \right) \cdot \qquad 12.12$$

where N_faeces is the amount of N excreted in the faeces, g/d; DMI_i is the dry matter intake of the i=1...n'th feedstuff, kg/d; CP_i is the crude protein content in the i=1...n'th feedstuff, g/kg DM; td_CP is the total digested CP, Equation 7.52; and 0.16 is the proportion of N in CP.

Overfeeding protein or pourly balanced ration increases N in the urine.The difference between total amount of excreted N and the N excreted in the faeces is assumed to be the N excreted in the urine:

$$N\_urine = N\_excreted - N\_faeces \qquad 12.13$$

where N_urine is the N excretion in urine, g/d; N_excreted is the total amount of N excreted, Equation 12.11; and N_faeces is the amount of N excreted in faeces, Equation 12.12.

$$N\_urine\_pct = \frac{N\_urine}{N\_excreted} \cdot 100 \qquad 12.14$$

where N_urine_pct is the N excreted in urine as a proportion of the total N excretion, %; N_urine is the N in urine, Equation 12.13; and N_excreted is the total amount of N excreted, Equation 12.11.

12.3.2 Phosphorus utilisation and excretion

The excessary fed P over requirement is excreted in the faeces (ARC, 1980). Therefore overfeeding P is useless.

P efficiency is calculated as:

$$P\_u\_pct = \frac{P\_u}{\sum_i DMI_i \cdot P_i} \cdot 100 \qquad 12.15$$

where P_u_pct is the P utilization as a proportion of total P intake, %; P_u is the amount of P utilized, Equation 12.16; DMI_i is the DM intake of the of the i=1...n'th feedstuff, kg DM/day; and P_i is the P content in the i=1...n'th feedstuff, g/kg DM.

$$P\_u = (P\_milk + P\_gest + P\_gain) \cdot 0.7 \qquad 12.16$$

where P_u is the total amount of utilised P, g/d; P_milk, P_gest and P_gain are the requirement of P for milk, gestation and weight gain, Equation 9.51, 9.52 and 9.53 respectively; 0.7 is the absorption coefficient.

Phosphorus excretion occurs normally in the faeces and only a minor part excretes in the urine (ARC, 1980). The excretion is estimated as the difference of total P intake and the amounts of P incorporated in milk, foetus and weight gain.

$$P\_excreted = \sum_i DMI_i \cdot P_i - P\_u \tag{12.17}$$

where P_excreted is the total amount of P excreted, g/d; DMI_i is the DM intake of the of the i=1...n'th feedstuff, kg DM/day; and P_i is the P content in the i=1...n'th feedstuff, g/kg DM; and P_u is the amount of P utilised in milk, gestation and gain, Equation 12.16.

12.3.3 Potassium utilisation and excretion

Cattle normally ingest more K than the requirement. Potassium utilisation is calculated as:

$$K\_u\_pct = \frac{K\_u}{\sum_i DMI_i \cdot K_i} \cdot 100 \tag{12.18}$$

where K_u_pct is the K utilization as a proportion of total K intake, %; K_u is the total amount of K utilized, Equation 12.19; DMI_i is the DM intake of the i=1...n'th feedstuff, kg DM/day; and K_i is the K content in the i=1...n'th feedstuff, g/kg DM.

$$K\_u = (K\_milk + K\_gest + K\_gain) \cdot 0.9 \tag{12.19}$$

where K_u is the total amount of utilised K, g/d; P_milk, P_gest and P_gain are the requirement of K for milk, gestation and weight gain, Equation 9.66, 9.67 and 9.68 respectively; 0.9 is the absorption coefficient.

The total amount of excreted K is calculated:

$$K\_excreted = \sum_i DMI_i \cdot K_i - K\_u \tag{12.20}$$

where K_excreted is the K excreted, g/day; DMI_i is the DM intake of the of the i=1...n'th feedstuff, kg DM/day; and K_i is the K content in the i=1...n'th feedstuff, g/kg DM; and K_u is the amount of K utilized in milk, gestation and gain, Equation 12.19.

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13. Standard feed value

M. Åkerlind and H. Volden

Traditional feed evaluation systems determine fixed and additive feed values of feedstuffs. The NorFor system, however, is a ration evaluation system and in principle each individual feedstuff has no fixed feed value because of the interactions in the digestion and metabolism of nutrients. Nevertheless, there is a need to compare feedstuffs for trading purposes or in the optimization of concentrate mixtures by linear programming in the feedstuff industry. Therefore, we calculate feed values based on standardized conditions, where important model variables are fixed, e.g. fractional passage rates and efficiency in the microbial protein synthesis (see Table 13.1). These fixed values represent feed rations for diets used in Denmark, Iceland, Norway and Sweden.

Standard feed values for NEL, AAT_N and PBV_N were calculated in the following way. First animal BW, DMI, concentrate proportion and content of CP, NDF, ST and RestCHO were set according to Table 13.1 to standardize the feed ration from which the standard feed value is calculated. Then values for RLI, corrNDF_fac, fractional passage rates and r_emCP are determined using Equations 13.1 to 13.8 (Table 13.1). These values substitute the corresponding equations in Chapter 7 when calculating the standard feed value of a feedstuff with specific dietary characteristics. The standard feed values of NEL, AAT_N and PBV_N (Equation 8.3, 8.11 and 13.9, respectively) receive a suffix that tells which standardised DMI, 8 or 20 kg DM, the calculations are based upon: NEL_8, NEL_{20}, PBV_{N8}, PBV_{N20}, AAT_{N8} and AAT_{N20}.

Standardised RLI, corrNDF_fac, fractional passage rates and r_emCP are calculated as:

$$RLI_{std} = \frac{280}{DMI_{std} \cdot 370} \qquad 13.1$$

where, RLI_{std} is the rumen load index; 280 is the sum of rumen degraded ST and RestCHO in the diet, g/kg DM; DMI_{std} is the standardized DM intake, which is either 8 or 20 kg DM/day; and 370 is the NDF content, g/kg DM.

Table 13.1. Fixed values for the listed parameters used for determining standard feed values.

Parameter	Equation	8 kg DMI	20 kg DMI
Current body weight, kg		600	600
Dry matter intake, kg/d		8	20
Concentrate proportion of the ration, %		50	50
CP, g/kg DM		160	160
NDF, g/kg DM		370	370
ST+RestCHO, g/kg DM		310	310
rdST+rdRestCHO, g/kg DM		280	280
Correction factor for NDF degradation rate	13.2	0.89857	0.89857
Passage rate for liquid, %/h	13.3	7.07943	12.5236
Passage rate for CP and ST in concentrate, %/h	13.4	3.33733	6.08733
Passage rate for NDF in concentrate, %/h	13.5	1.43505	2.61755
Passage rate for CP and ST in roughage, %/h	13.6	2.30177	4.47943
Passage rate for NDF in roughage, %/h	13.7	0.998465	1.64242
Efficiency of microbial CP synthesis, g/kg rd_OM	13.8	133.383	184.329

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9_13, © Wageningen Academic Publishers 2011

The NDF correction factor is calculated as:

$$corrNDF\_fac = e^{-0.24 \cdot (RLI_{std})^{2.9}} \qquad 13.2$$

where, corrNDF_fac is the correction factor for the NDF degradation rate; and RLI_{std} is the rumen load index, Equation 13.1.

$$r\_kpl = 2.45 + 0.055 \cdot \frac{DMI_{std} \cdot 1000}{600^{0.75}} + 0.0004 \cdot 50^2 \qquad 13.3$$

$$r\_kpc = 2.504 + 0.1375 \cdot \frac{DMI_{std} \cdot 1000}{600} - 0.02 \cdot 50 \qquad 13.4$$

$$r\_kpNDFc = \left(2.504 + 0.1375 \cdot \frac{DMI_{std} \cdot 1000}{600} - 0.02 \cdot 50\right) \cdot 0.43 \qquad 13.5$$

$$r\_kpr = 0.35 + 0.022 \cdot \frac{DMI_{std} \cdot 1000}{600^{0.75}} + 0.0002 \cdot 50^2 \qquad 13.6$$

$$r\_kpNDFr = 0.480339 + \frac{0.78 \cdot 1.93668}{1 + \left(\frac{DMI_{std} \cdot 370}{600 \cdot 7.48383}\right)^{-3.19822}} \qquad 13.7$$

where, r_kpl is the passage rate of the liquid phase out of the rumen; DMI_{std} is the standardized DMI, 8 or 20 kg DM; 600 is the current BW, kg; 50 is the proportion of concentrate in diet, %; r_kpc is the passage rate of protein and starch in concentrates; r_kpNDFc is the passage rate of NDF in concentrate; r_kpr is the passage rate of roughage protein and starch; r_kpNDFr is the passage rate of roughage NDF; and 370 is the NDF content in diet, g/kg DM.

The fixed r_emCP is calculated from the following equation:

$$r\_emCP = \ln\left(\frac{1000 \cdot DMI_{std}}{600}\right) \cdot 55.6 + 0.4166 \cdot 310 - 0.0008868 \cdot 310^2 - 54.56 \qquad 13.8$$

where, r_emCP is the efficiency of rumen microbial protein synthesis; DMI_{std} is the standardized DMI 8 or 20 kg DM; 600 is the standardized BW, kg; and 310 is the concentration of ST + RestCHO in the diet, g/kg DM.

The calculation of standard feed value, NEL_8, NEL_{20}, AAT_{N8} and AAT_{N20} uses the Equations 7.6 to7.14, 7.17 to 7.23. 7.30 to 7.34, 7.36 to 7.38, 7.40 to 7.51, 7.54, 7.55, 7.57, 7.59, 8.1 to 8.3 and 8.11. However, Equations 7.1 to 7.5 are changed to Equation 13.3 to 13.7, 7.16 is changed to 13.2 and 7.29 is changed to 13.8. The nutrient composition (CP_i, $CFat_i$, NDF_i, ST_i, etc.) is the composition of the specific feedstuff to which the feed values are calculated for and DMI_i is 1 kg.

The standardized value of PBV_{N8} and PBV_{N20} in Equation 13.9 assumes a fixed recirculation of urea, based on a fixed CP intake, to avoid overestimating it:

$$PBV_N = rd\_CP + (160 \cdot 0.046) - r\_mCP \qquad 13.9$$

where, PBV_N is the standard feed value for protein balance in the rumen, g/day; rd_CP is the CP degraded in the rumen of 1kg DM of the specific feedstuff, Equation 7.8; 160 is a fixed value for CP in the standardised ration (Table 13.1); 0.046 is the assumed proportion of N that is recycled back to the rumen; and r_mCP is the rumen microbial CP yielded by 1 kg DM of the specific feedstuff, Equation 7.30 (Table 13.1).

Standard feed values of some common feedstuffs are presented in Table 13.2. Note that the standard feed value AAT$_{N8}$ is lower than AAT$_{N20}$ mainly due to increased microbial efficiency with higher feed intake and therefore higher supply of AA from microbial protein. PBV$_{N8}$ is higher than PBV$_{N20}$, also due to increased microbial efficiency which incorporates more N into the microbial protein and therefore contributes less to the PBV$_N$ value. NEL$_8$ is higher than NEL$_{20}$, because increased DMI results in a higher passage rates and lowered digestibility and thus lower energy supply.

Table 13.2. Standard feed values in some feedstuffs.

Feedstuff	NorFor ID	AAT$_N$8 g/kg DM	PBV$_N$8 g/kg DM	NEL8 MJ/kg DM	AAT$_N$20 g/kg DM	PBV$_N$20 g/kg DM	NEL20 MJ/kg DM
Barley	1-16	83	-6	7.97	110	-44	7.49
Oat	1-17	66	20	7.31	87	-11	6.78
Triticale	1-15	79	-10	8.21	106	-50	7.80
Brewers grain, dried	1-68	125	97	6.99	157	55	6.38
Distillers grain, dried	1-38	92	176	7.30	127	127	6.69
Rape seed meal	2-42	102	236	6.90	144	180	6.52
Soy bean meal	2-53	154	289	8.74	218	210	8.32
Vegetable fat	2-26	17	-6	20.80	20	-11	18.98
Sugar beet pulp, dried unmolassed	4-20	70	-22	6.93	96	-63	6.26
Grass silage very high OMD	6-460	60	92	7.73	79	62	7.00
Grass silage high OMD	6-461	63	76	7.50	80	49	6.69
Grass silage low OMD	6-463	62	49	6.64	75	28	5.74
Maize silage high OMD	6-307	68	-30	7.36	87	-59	6.60
Maize silage low OMD	6-308	66	-30	7.05	84	-56	6.21
Straw, spring barley	6-386	39	-25	3.44	44	-34	2.47
Glycerin, glycerol	12-12	82	-120	8.12	109	-163	7.49
Urea	13-1	0	2,922	0.00	0	2,922	0.00

14. System evaluation

H. Volden, N.I. Nielsen, M. Åkerlind and A.J. Rygh

This chapter focuses on the evaluation of different aspects within the NorFor system. This includes sensitivity analyses with respect to feed characteristics and model tests of total tract digestion, milk production, the energy system for growing cattle, RLI, feed intake and chewing index.

14.1 Sensitivity of feed degradation characteristics to ration energy and protein values

When the NorFor system is used for on-farm ration optimization, forages are mainly analysed at commercial feed laboratories while for concentrate ingredients, values from the NorFor feed table are normally used (www.norfor.info). Within forage type, there are large variations in nutrient degradation characteristics, which affect (to varying degrees) the nutritional value of the feed ration. A sensitivity analysis is therefore useful for evaluating effects of changes in the composition of feed ingredients on the NEL and AAT_N contents of the diet. A sensitivity analysis is also advantageous for evaluating the usefulness and errors related to different routine analyses.

The sensitivity analysis presented is based on a dairy cow simulation in which a standard diet was fed and the influence of forage and concentrate degradation characteristics were tested. Effects were tested at a DM intake of 20 kg/d for a cow of 600 kg BW and 140 days in milk. The diet consisted of grass silage (50% of diet DM) with an OMD of 71.4% and the concentrate mixture consisted of barley grain (40%), dried beet pulp (12%), maize grain (10%), soybean meal (16%), rapeseed meal (9%), molasses (6%), rape seed (5%) and mineral and vitamins (2%). The diet composition was (g/kg DM): CP, 179; NDF, 347; ST, 191; CFat, 45; FPF, 56 and RestCHO, 105. Input degradation characteristics tested were: sCP, iCP, kdCP, iNDF and kdNDF, and their basal, minimum and maximum parameter values are presented in Table 14.1. When sCP and iNDF were changed, corresponding values of pdCP and pdNDF were changed simultaneously to maintain the same concentrations of CP and NDF in the diet. The input parameter of interest was changed for one characteristic at a time and correlated responses were ignored to facilitate interpretation. For example, iNDF and kdNDF are often negatively correlated within feeds but in the sensitivity test, they were changed independently. The sensitivity of diet energy and protein values to parameter variation was calculated as the change in the response variable relative to the change in parameter value:

$$\text{Sensitivity} = \left(\frac{\left(\frac{r_{min} - r_{max}}{r_{basal}} \right)}{\left(\frac{p_{min} - p_{2\,max}}{p_{basal}} \right)} \right) \cdot 100 \qquad 14.1$$

where sensitivity is calculated in %, r_{min} is the minimum response value, r_{max} is the maximum response value, r_{basal} is the basal response value, p_{min} is the minimum parameter value, p_{max} is the maximum parameter value, and p_{basal} is the basal parameter value.

Changes in diet composition, i.e. proportions of CP, ST, NDF, SU and CFat are of major importance since they affect (*inter alia*) diet energy and metabolizable protein value (Fox *et al.*, 2003). In the presented sensitivity analysis (Table 14.1), only the effects of variations in nutrient degradation characteristics were evaluated, since they may have an impact on the reliability of feed analyses.

Both NEL and AAT_N are sensitive to changes in forage iNDF and kdNDF. The pdNDF from forage constitutes a large proportion of the NDF pool, and changes in both iNDF concentration and kdNDF strongly influence the energy supply for microbial growth, and hence AAT_N from microbial protein

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9_14, © Wageningen Academic Publishers 2011

Table 14.1. Results of the sensitivity analysis in NorFor to changes in feed characteristics with a lactating dairy cow diet.

Variables	Ranges			Sensitivity, %	
	Basal	Minimum	Maximum	NEL[8] MJ/kg DM	AAT_N[9] g/kg DM
Forage					
sCP[1], g/kg CP	600	500	700	-0.1	-5.1
iCP[2], g/kg CP	38	19	57	-0.6	-1.7
iNDF[3], g/kg NDF	160	80	240	-5.3	-3.4
kdCP[4], %/h	11.0	5.5	16.0	-0.1	-3.0
kdNDF[5], %/h	4.7	2.4	7.1	7.6	5.7
Concentrate					
sCP, g/kg CP	247	124	371	-0.1	-7.5
iCP, g/kg CP	40	20	60	-0.8	-3.4
iNDF, g/kg NDF	190	80	240	-2.4	-3.0
kdCP, %/h	6.0	3.0	9.0	-0.1	-12.8
kdNDF, %/h	3.0	1.5	4.5	2.4	0.5
kdST[6], %/h	15.0	7.5	22.5	-0.9	1.5
kdRestCHO[7], %/h	150	75	225	0.3	-1.0

[1] sCP = soluble crude protein.

[2] iCP = total indigestible crude protein.

[3] iNDF = total indigestible NDF.

[4] kdCP = fractional degradation rate of potentially degradable crude protein.

[5] kdNDF = fractional degradation rate of potentially degradable NDF.

[6] kdST = fractional degradation rate of potentially degradable starch.

[7] kdRestCHO = fractional degradation rate of residual carbohydrates.

[8] NEL = net energy lactation.

[9] AAT_N = amino acids absorbed in the intestine.

and total tract digestion of OM, which provide the basis for ME predictions. The work of Nordheim *et al*. (2007) demonstrated the difficulties of using NIRS to measure kdNDF. Due to the importance of kdNDF for the nutritive value of the diet and it was, therefore, decided in NorFor to calculate the kdNDF from NIRS or *in vitro* measurements of OMD and iNDF (see Section 5.2.1; Eriksson, 2010a). The AAT_N was sensitive to the proportion of sCP in the forage, although the relative difference between the selected minimum and maximum parameter values was less than for the other variables (Table 14.1). In grass silage, sCP is the dominating protein fraction, which explains why sCP has more impact on AAT_N than kdCP (Volden *et al*., 2002). Diet NEL is not sensitive to changes in forage or concentrates sCP and kdCP. This is consistent with expectations, because the segmental digestion of degradable CP has limited effects on the total tract digestion of CP. The sensitivity analysis indicates that predicted energy values are more sensitive to the chemical composition of concentrates, (e.g. ST vs. NDF) than to degradation characteristics (data not shown). However, predictions of the AAT_N are sensitive to kdCP, sCP and iCP. Nevertheless, this sensitivity analysis demonstrates that the NorFor system is sensitive to CHO and CP degradation characteristics in both roughage and concentrates.

14.2 Evaluation of the digestive tract sub-model

Two important sub-models in NorFor are the digestive tract sub-model (which predicts the ration digestibility) and the metabolism sub-model (which predicts energy and protein supply and animal responses). When evaluating a complex model, it may be useful to evaluate several subdivisions separately, to reveal strengths and weaknesses in different parts of the system. This section summarizes the test of total tract digestion of major nutrients. Sources of data used in the evaluation of dairy cow digestion are presented in Table 14.2. The published studies were supplemented with measurements from trials conducted in connection with a student course in ruminant nutrition and physiology at the Norwegian University of Life Sciences. Total tract digestion was selected because there are minimal methodological differences between relevant studies. It is relatively simple to measure, compared to ruminal and intestinal flow measurements, which are heavily dependent on marker techniques and calculation methods used.

The model was evaluated by regressing predicted values against observed values, and several statistical measures were used to assess model adequacy and behaviour, including coefficients of correlation (r) and determination (r^2), mean square prediction error (MSPE) and the partitioning of MSPE (Bibby and Toutenburg, 1977). The MSPE was decomposed into errors due to: overall bias (deviation of the intercept from 0), line bias (deviation of the slope from unity) and disturbance (lack of correlation). The square root of the MSPE (RMSPE) expressed as a percentage of the observed mean was used as a measure of the prediction error.

High correlations (r>0.97) between predicted and observed values were found for all the digestion variables tested (td_OM, td_CP, td_NDF and td_ST) (Figure 14.1, 14.2, 14.3, 14.4). NorFor accounted for 96% of the variation in td_OM with a mean bias of 221 g/d (1.9%). Corresponding values for td_CP, td_NDF and td_ST were 68, 68 and 106 g/d (3.3, 1.6 and 3.9%), respectively. The model slightly overpredicted td_OM, td_NDF and td_ST, while td_CP was underpredicted (Table 14.2). Except for td_ST, most of the errors in the MSPE were related to disturbance. The analysis of residuals between observed and predicted td_ST indicated that the higher general bias (0.43) was largely due to an underestimation of iST in the feedstuffs. Regression statistics (Mitchell, 1997) showed that the fitted line between predicted and observed values did not differ significantly from 1, indicating that there was no systematic deviation in digestion in the interval examined. Prediction errors were generally low, with RMSPE of 560, 167, 264 and 161 g/d for td_OM, td_CP, td_NDF and td_ST, respectively. The difference between observed and predicted values for td_CP, td_NDF and td_ST and were within 5% of the observed values for 45, 58 and 70% of the observations, respectively. Deviations were less than 10% for more than 80% of the observations. This demonstrates the ability of the NorFor model to predict ration digestion over large ranges of diet composition and feed intake. This ability is crucial for calculation of energy supply, which is based on total apparent digestion of CP, CFat and CHO in NorFor. From the mean prediction error for OM, and assuming an average ME factor of 15.5 MJ/kg digestible OM, the NEL (utilization of ME=0.6) prediction error was estimated to be 5.2 MJ, corresponding to 1.7 (5.2/3.14) kg ECM.

For testing digestion in the growing cattle sub-model, a small data set from three studies (Olson and Lindberg, 1985; Olson and Lindberg, unpublished data; Wallsten, 2010) was available. The data set included results from 18 treatments, applied to both bulls (n=10) and heifers (n=8). The total apparent digestion of td_OM, td_CP, td_NDF was evaluated (Figures 14.5, 14.6 and 14.7). The coefficient of determination was high (r^2>0.96) for all digestion variables tested (Table 14.3). NorFor overpredicted td_OM (6.4%) and td_NDF (9.0), while td_CP was underpredicted (13.2%). The MSPE consisted mainly overall bias, while the proportion of MSPE related to line bias was low. The regression slope between predicted and observed digestion did not differ significantly from 1. The data set was, however, too small for further analysis of the residuals.

Table 14.2. Accuracy and precision of NorFor's ability to predict digestion in dairy cows[5].

Item	n	Digested, g/day		Regression		r^2	RMSPE	Prediction error, %	Proportion of MSPE		
		Observed	Predicted	Intercept	Slope				Overall bias	Regression	Disturbance
td_OM[1]	107	11,620	11,841	831	0.948	0.967	560	4.8	0.165	0.009	0.836
td_CP[2]	95	2061	1993	-134	1.033	0.955	167	8.1	0.168	0.100	0.732
td_NDF[3]	111	4167	4235	377	0.926	0.966	264	6.3	0.067	0.044	0.889
td_ST[4]	67	2754	2860	24	1.030	0.993	161	5.8	0.431	0.099	0.470

[1] td_OM = apparent total tract digestion of organic matter, g/day.

[2] td_CP = apparent total tract digestion of crude protein, g/day.

[3] td_NDF = apparent total tract digestion of NDF, g/day.

[4] td_ST = apparent total tract digestion of starch, g/day.

[5] The following trials were used: Alne, 2000; Aston *et al*., 1994; Bertilsson and Murphy, 2003; Eriksson *et al*., 2004; Kjos, unpublished data; Larsen *et al*. 2009b; Lund *et al*., 2004; Lund, unpublished data; Murphy *et al*., 1993; Prestløkken, 1999; Prestløkken *et al*., 2007; Rinne *et al*., 1999a, 2002; Selmer-Olsen, 1996; Tothi *et al*., 2003; Volden, unpublished data.

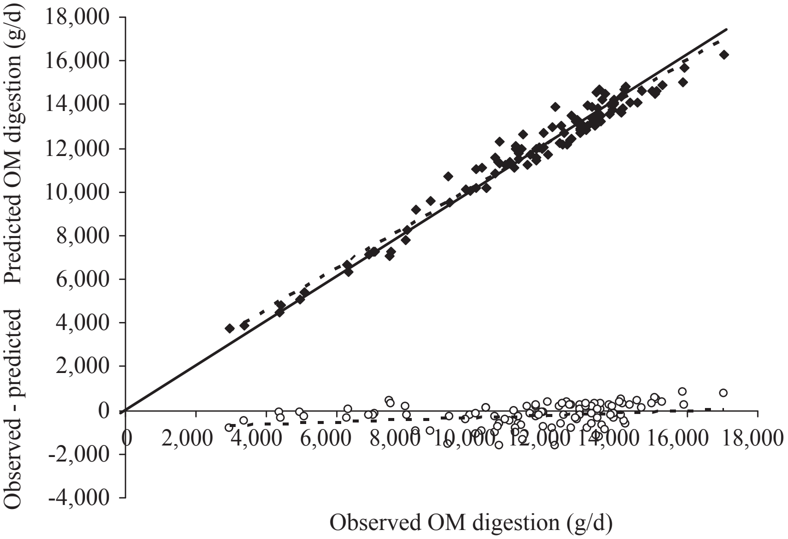

Figure 14.1. Predicted vs. observed organic matter (OM) digestion in dairy cows.

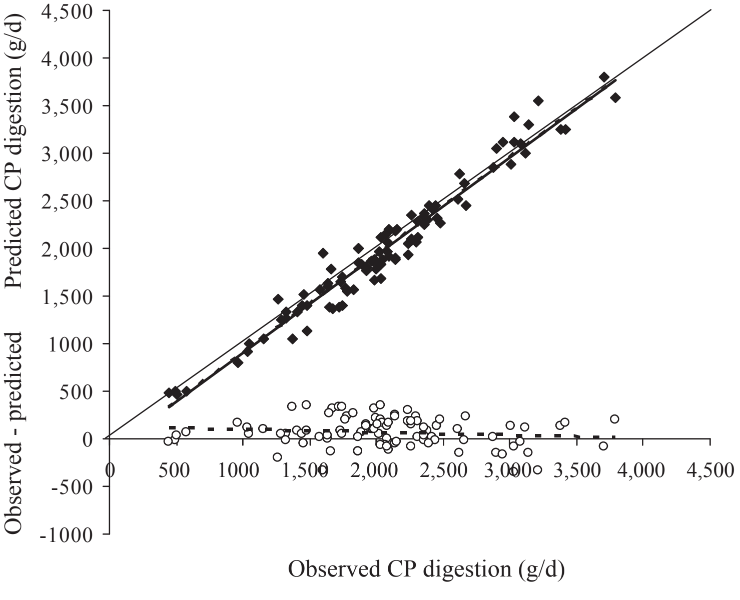

Figure 14.2. Predicted vs. observed crude protein (CP) digestion in dairy cows.

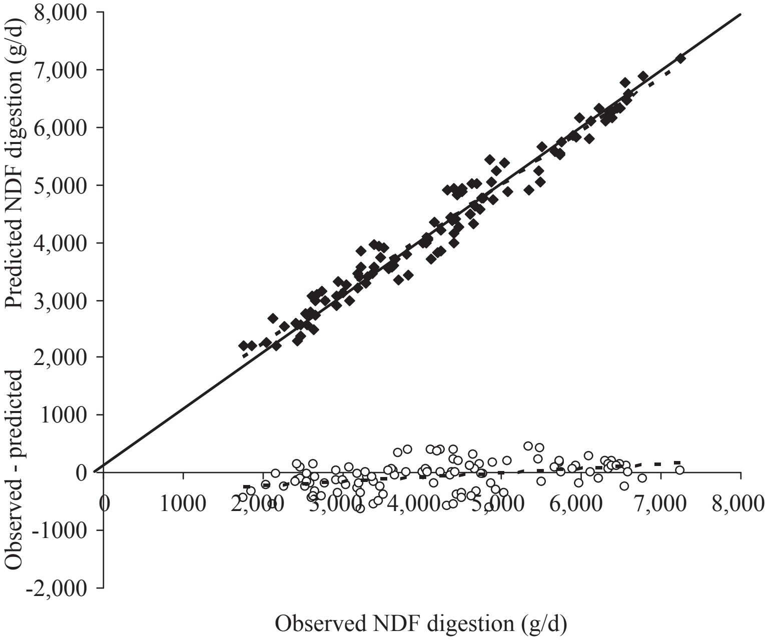

Figure 14.3. Predicted vs. observed NDF digestion dairy cow.

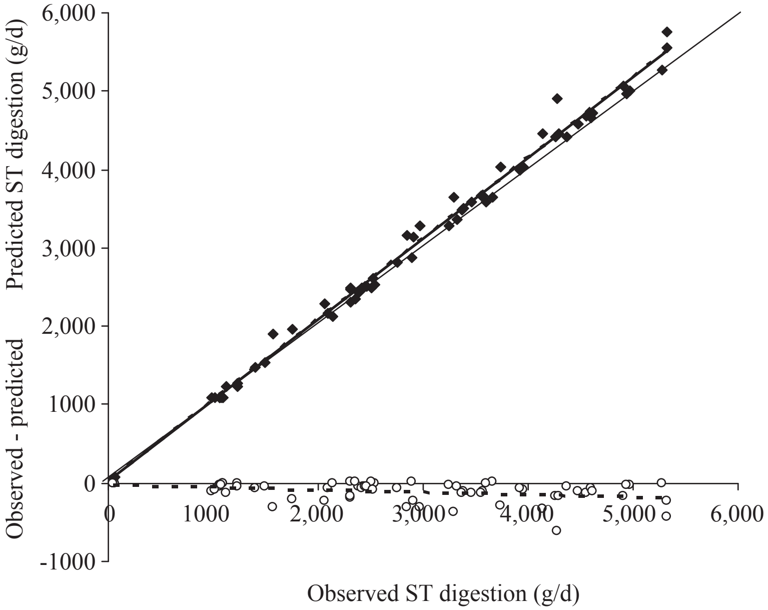

Figure 14.4. Predicted vs. observed starch (ST) digestion in dairy cows.

Table 14.3. Accuracy and precision of NorFor´s ability to predict digestion in growing cattle[4].

Item	n	Digested, g/day		Regression		r^2	RMSPE	Prediction error, %	Proportion of MSPE		
		Observed	Predicted	Intercept	Slope				Overall bias	Regression	Disturbance
td_OM[1]	18	3,090	3,290	79	1.047	0.981	230	7.5	0.753	0.035	0.212
td_CP[2]	18	445	386	-24	0.922	0.968	64	14.5	0.838	0.010	0.152
td_NDF[3]	18	958	1,044	100	0.986	0.990	62	11.1	0.657	0.001	0.342

[1] td_OM = apparent total tract digestion of organic matter, g/day.

[2] td_CP = apparent total tract digestion of crude protein, g/day.

[3] td_NDF = apparent total tract digestion of NDF, g/day.

[4] The following trials were used: Olson and Lindberg, 1985; Olson and Lindberg, unpublished data; Wallsten, 2010.

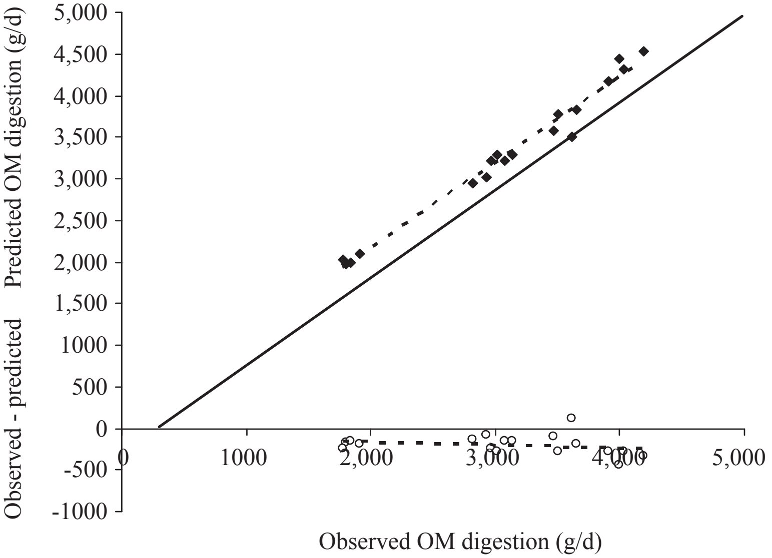

Figure 14.5. Predicted vs. observed organic matter (OM) digestion in growing cattle.

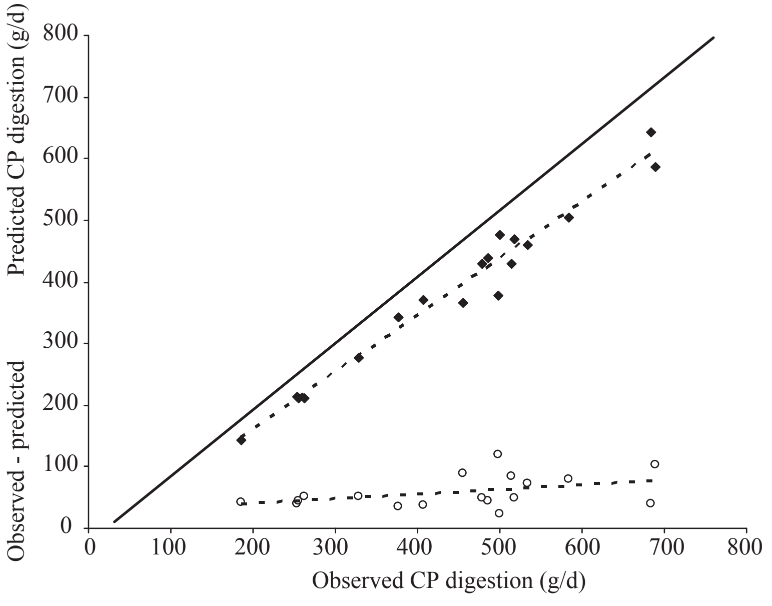

Figure 14.6. Predicted vs. observed crude protein (CP) digestion in growing cattle.

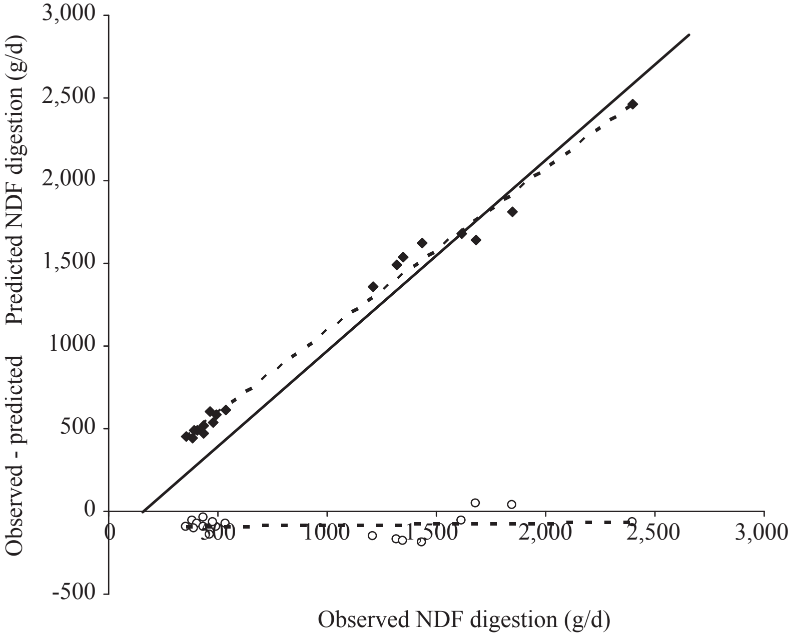

Figure 14.7. Predicted vs. observed NDF digestion in growing cattle.

14.3. Evaluation of milk production in lactating dairy cows

A Nordic dataset, which had not been used for model construction, was compiled. Data originated from published and unpublished trials performed in Denmark, Norway, Sweden, and Finland mainly from the 1990's and 2000's (Table 14.4). No selection was made among the experiments and data from all identified experiments providing information on ECM or MY, fat and protein contents, DMI and BW were included. Not all studies included information on BW or BCS changes during the trial period. Lactose content in milk was only reported in a few studies, thus a fixed content of 48 g/kg was used. The dataset included information from both long- and short-term studies, i.e. data both from continuous lactation experiments and cross-over type experiments. A further criterion was availability of data on most nutrient characteristics for each feedstuff. Experiments that only provided data on nutrient characteristics for the whole TMR were not included. Most studies did not include iNDF, sCP, kdST, kdNDF and kdCP measurements on single feedstuffs. When nutrient composition data were missing, values from the NorFor feedstuff table were used (www.norfor.info). The dataset, described in Table 14.5, consists of information from 53 trials (see Table 14.4) with five breeds (205 NRF, 77 DH, 38 SR, 5 RD and 4 JER) with a total of 329 treatments.

As described in Chapter 12, ECM is predicted from the calculated total energy intake minus the estimated energy usage for maintenance, growth (only primiparous cows), pregnancy and mobilization/deposition (see Equation 12.1). Energy usage for maintenance is estimated from BW. Information on days in gestation was often not available and was therefore set to zero. Mobilization/deposition was included via information on changes in BW or BCS. As not all studies included data on BW or BCS changes during the trial period, mobilization/deposition was assumed to be zero. Energy requirement for growth in primiparous cows was included indirectly via changes in BW or BCS. The prediction of milk protein yield is based on model estimates of AAT_N supply to the mammary gland and the efficiency of AAT_N use in synthesis of milk protein (see Equation 12.2).

Table 14.4. Studies used to evaluate the prediction of milk production, roughage intake and total dry matter intake in dairy cows.

Aaes, 1991
Aaes, 1993 [1,2]
Bertilsson, 2007
Bertilsson, 2008
Bertilsson and Murphy, 2003[1]
Eriksson, 2010b
Eriksson *et al*., 2004[1]
Hymøller *et al*., 2005[2]
Ingvartsen *et al*., 2001[1, 2]
Johansen, 1992[1]
Kjos, unpublished data
Kristensen, 1999[2]
Lund, 2002[1]
Minde and Rygh, 1997
Misciattelli *et al*., 2003[1]
Mo and Randby, 1986[1]
Mogensen and Kristensen, 2002[1,2]
Mogensen *et al*., 2008[2]
Mould, 1996[1]
Murphy *et al*., 2000
Nielsen *et al*., 2007[2]
Nordang and Mould, 1994[1]
Prestløkken, 1999
Prestløkken *et al*., 2007[1]
Randby, 1992[1]
Randby, 1997[1]
Randby, 1999a[1]
Randby, 1999b[1]
Randby, 2000a[1]
Randby, 2000b[1]
Randby, 2002[1]
Randby, 2003 [1]
Randby, 2007[1]
Randby and Mo, 1985[1]
Randby and Selmer-Olsen, 1997[1]
Rinne *et al*., 1999a[1]
Rinne *et al*., 1999b[1]
Sairanen, 2001[1]
Schei *et al*., 2005[1]
Shingfield *et al*., 2003
Steinshamn *et al*., 2006[1]
Thorhauge and Weisbjerg, 2009[2]
Thuen, 1989[1]
Volden, 1990[1]
Volden, 1999
Volden and Harstad, 2002
Wallsten and Martinsson, 2010[1]
Weisbjerg, 2007 [2]
Weisbjerg *et al*., 2008[2]
Åkerlind *et al*., 1999[2]
Österman, 2003[1, 2]

[1] The study is used for roughage intake evaluation.

[2] The study is used for total dry matter intake evaluation.

Studies marked with superscripts [1] and [2] included treatments with separate and TMR and feeding, respectively.

Table 14.5. Descriptive statistics of the 329 treatments from 53 Nordic trials used to evaluate prediction of ECM and milk protein yield.

Item	Average	SD[1]	Maximum	Minimum
Days in milk	121	44	255	31
ECM[2], kg/d	27.1	5.3	49.7	12.6
MY[3], kg/d	27.1	5.2	47.0	13.1
Fat, g/kg	41.1	4.7	58.3	26.9
Protein, g/kg	32.6	1.8	41.1	29,3
Protein yield, g/d	882	174	1,607	422

[1] SD = standard deviation.

[2] ECM = energy corrected milk.

[3] MY = milk yield.

Figures 14.8 and 14.9 illustrate the relationships between observed and predicted ECM and milk protein yields, respectively. Table 14.6 shows that across all experiments and treatments, the observed and predicted yields were similar (27.1 vs. 26.4 kg ECM/d), especially for milk protein (882 vs. 900 g protein/d). The correlation between observed and predicted milk protein values was high (r=0.97), but somewhat lower for ECM (r=0.88). Predicted ECM and milk protein values were higher than observed for 43% and 68% of the observations, respectively, with RMSE's of 2.7 kg ECM and 48 g milk protein, corresponding to prediction errors of 9.8 and 5.5%, respectively. Predicted ECM yield was within 5% of observed values for 47% of the observations and 73% of the predicted ECM yield values were within 10% of observed values. Predicted milk protein yield was within 5% and 10%

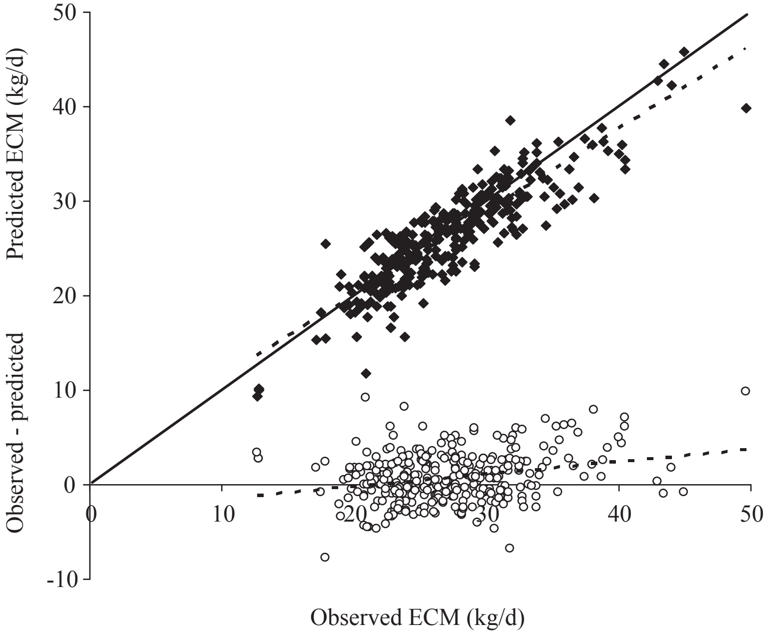

Figure 14.8. Predicted vs. observed ECM yield.

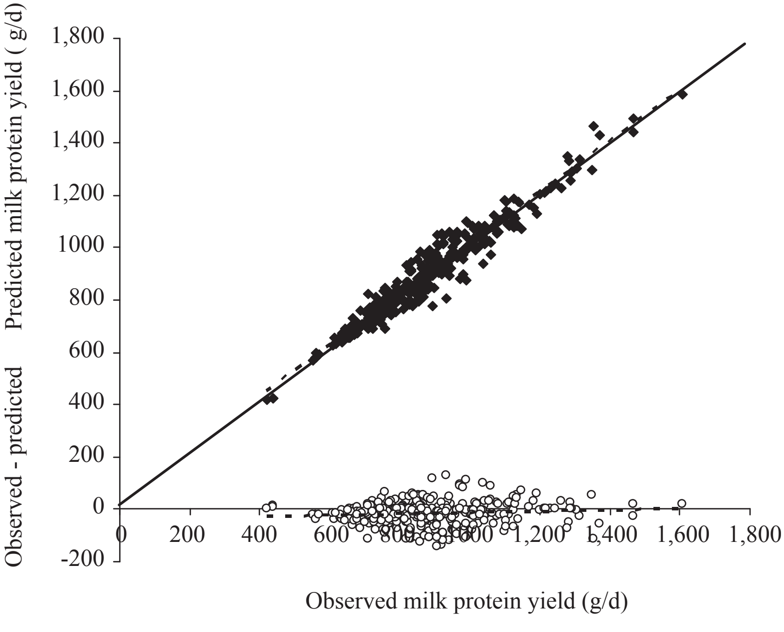

Figure 14.9. Predicted vs. observed milk protein yield.

Table 14.6. Accuracy and precision of NorFor´s ability to predict ECM and milk protein yield.

Item	n	Production		Regression		r^2	RMSPE	Prediction error, %	Proportion of MSPE		
		Observed	Predicted	Intercept	Slope				Overall bias	Regression	Disturbance
ECM[1]	329	27.1	26.4	2.6	0.88	0.78	2.7	9.8	0.07	0.05	0.88
MPY[2]	329	882	900	39	0.98	0.94	48	5.5	0.14	0.02	0.84

[1] ECM = energy corrected milk yield, kg/day.

[2] MPY = milk protein yield, g/day.

of observed values for 69% and 92% of the observations, respectively. The overall and regression biases were minor for ECM and milk protein, since more than 80% of the MSPE was characterised as disturbance. The regression slopes between predicted and observed milk production variables were not significantly different from 1.

14.4 Evaluation of the energy requirement for growing cattle

The estimated energy requirement for growing cattle is based on the French system (Chapter 9), modified with a 10% increase in the energy requirement for gain based on a dataset compiled from Nordic experiments with bulls. In order to perform an independent test of the NorFor energy system for growing cattle, an independent dataset containing heifer data from the Nordic countries and the US was used. Criteria for including data were heifers of dairy breeds and measurements of ADG, DMI and nutrient characteristics for each feedstuff. Hence, experiments where nutrient characteristics were available only for the whole diet were excluded. When nutrient composition data were missing, values from the NorFor feedstuff table were used (www.norfor.info). The reason for including US data was that a limited number of experiments from the Nordic countries were available. No selection was made among the experiments that were found in the literature. The dataset is described in Table 14.7 and consist of 9 trials with 54 treatments of which 47 include large breeds and 7 include Jersey.

Ration energy supply was calculated using NorFor and were regarded as observed values. The energy requirements were calculated from reported BW and ADG and were regarded as predicted values. The relationship between energy supply and requirement is shown in Figure 14.10. Across all experiments and treatments, the energy supply and requirement were fairly similar (31.9 vs. 33.7 MJ NEG) with an RMSPE of 3.4 MJ NEG, corresponding to a prediction error of 10.0%. The correlation (r=0.96) was stronger than that obtained from the data used to develop the energy system for growing cattle (see Figure 9.2).

14.5. Evaluation of the rumen load index (RLI)

RLI was included in the model to establish a relationship between the level of starch and sugars in the ration and their influence on digestion of NDF in the rumen (see Section 7.1.3). Therefore, RLI was evaluated against data from two studies in which rumen pH was measured (Lund, unpublished data; Larsen *et al*., 2009a) and where kdNDF was estimated on the basis of digestibility trials with lactating Holstein cows (Larsen *et al*., 2009a). The cows were fed *ad libitum* with grass-clover silage as the sole roughage and the concentrate consisted of barley, wheat, oat, maize, soybeans, faba beans, peas or lupins and most treatments also included soybean meal as a protein supplement in the ration.

Table 14.7. Descriptive statistics of the dataset[1] used for evaluating the energy system for growing cattle, including data from nine trials with heifers and 54 treatments.

Item	Average	SD[2]	Maximum	Minimum
DMI, kg/d	5.3	1.9	9.9	2.2
BW, kg	253	102	489	88
ADG, g/d	724	203	1,180	396
Concentrates (% of DMI)	35	28	92	4

[1] Olsson *et al*., 1984; Andersen *et al*., 1986; Ingvartsen *et al*., 1988; Mäntysaari, 1993; Andersen and Foldager, 1994; Van Amburgh *et al*., 1998; Andersen *et al*., 2001; Whitlock *et al*., 2002; Vestergaard, 2006.

[2] SD = standard deviation.

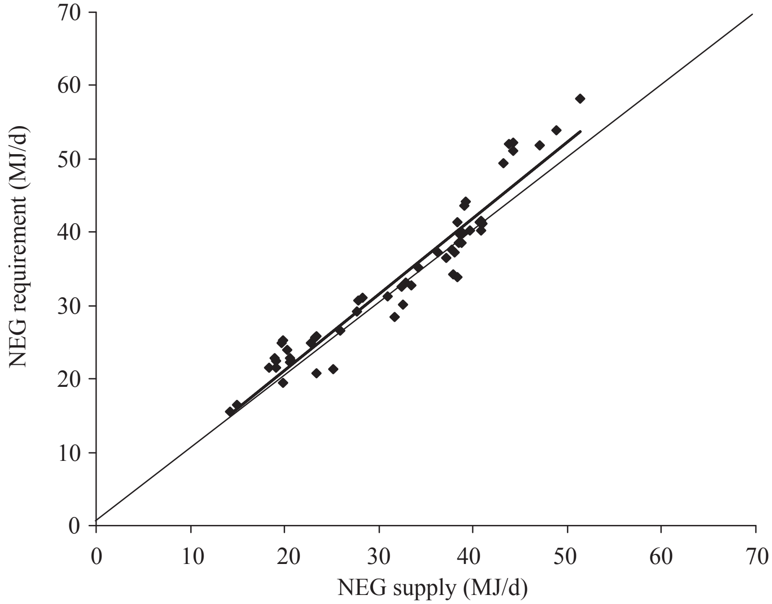

Figure 14.10. The relationship between ration energy supply calculated in NorFor and estimated energy requirement in heifers according to NorFor (r^2=0.92; RMSPE=3.4 MJ NEG; RMSPE=10.0%). The data are from the trials described in Table 14.8.

In contrast to expectations, RLI was not negatively correlated to pH in the rumen (Figure 14.11). Indeed, the data in Figure 14.11 show a positive relationship between RLI and rumen pH in the data from Lund (unpublished data) and no relationship in the data from Larsen *et al*. (2009a). As RLI was included in NorFor to estimate the effect of starch and sugars on the digestion of NDF in the rumen, the main interest is in evaluating RLI was as a predictor for kdNDF in the rumen, rather than as a predictor of rumen pH. This relationship is illustrated in Figure 14.12, where a negative correlation (r=-0.82) between RLI and kdNDF is evident. Thus, even though RLI was not correlated with rumen pH, increases in RLI were associated with reductions in kdNDF. This confirms that RLI is a useful term for correcting kdNDF, as described in Section 7.1.3, although this evaluation was only based on one study. However, the relationship shown in Figure 14.12 is supported by the findings of Danfær *et al*. (2006).

14.6. Evaluation of roughage and total dry matter intake in dairy cows

Data from Nordic experiments were used to evaluate roughage and total DMI predictions. For this purpose, the data were divided in two sub-sets (Tables 14.8 and 14.9). The first (n=226) consisted of data from studies where roughage was fed *ad libitum* and separately, and the concentrate was fed either according to MY or as fixed amounts (Table 14.8). This dataset was used to evaluate roughage intake. In the second dataset (n=62), cows were fed total mixed rations (TMR) *ad libitum* and total DMI was evaluated (Table 14.9). Both datasets showed wide variations in both DMI and diet composition, and the data were in the range of those used for parameterization of the intake sub-model. Published nutrient compositions of the individual feeds were used. When nutrient composition data were missing, values from the NorFor feedstuff table were used (www.norfor.info).

Predicted vs. observed roughage intake and the evaluation of the prediction errors are presented in Figure 14.13 and Table 14.10, respectively. Mean observed roughage DM intake was 11.0 kg/d

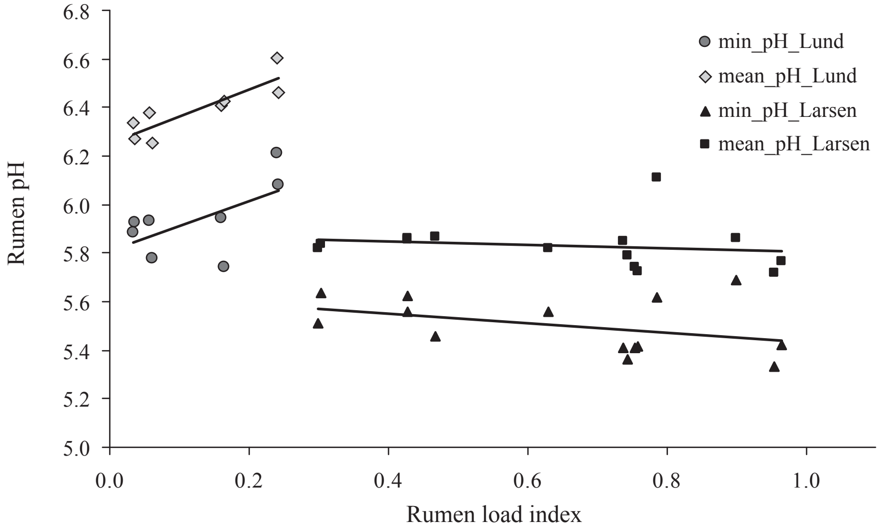

Figure 14.11. The relationship between rumen load index calculated in NorFor and mean and minimum pH measured in the rumen. The data are from Lund (unpublished data, n=8) and Larsen et al. *(2009a, n=13).*

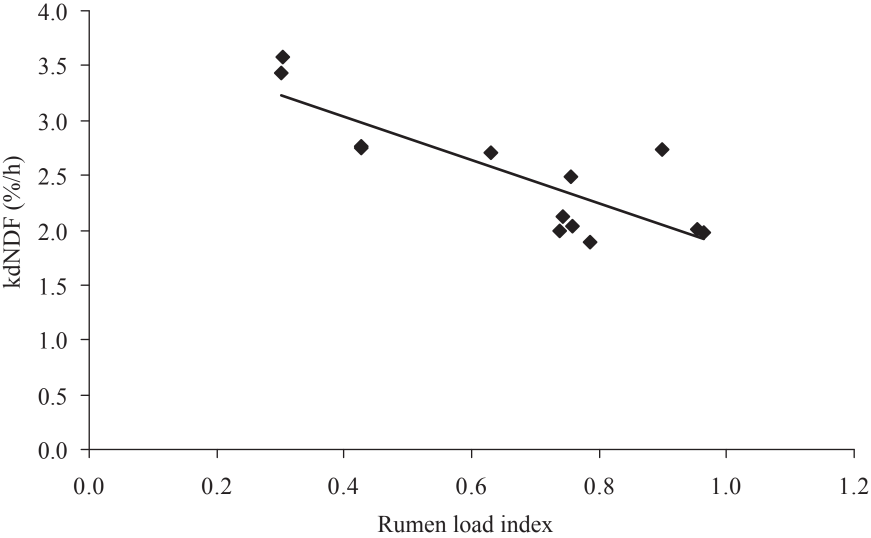

Figure 14.12. The relationship between rumen load index calculated in NorFor and trial estimates of NDF degradation rate in the rumen (kdNDF) of lactating Holstein cows (n=13; r^2=0.68; RMSPE=0.33%/h). The data are from Larsen et al. *(2009a).*

Table 14.8. Descriptive statistics of the dataset used for evaluating feed intake of cows, including data from 36 trials[3] and 226 treatments where roughage and concentrate were fed separately.

Item	Average	SD[1]	Maximum	Minimum
Days in milk	124	35	214	42
Body weight, kg	567	37	667	481
ECM[2], kg/d	25.3	4.5	45.0	17.1
Dry matter intake, kg/d	18.2	2.4	28.4	13.1
Concentrate proportion, kg/kg DM	0.40	0.12	0.80	0.14
Roughage intake, kg DM/d	10.9	2.6	18.2	3.2
Roughage basis fill value, /kg DM	0.50	0.06	0.70	0.35
Starch + sugars, g/kg DM	183	69	426	60
Starch + sugars, kg/d	3.3	1.2	6.9	0.9

[1] SD = standard deviation.

[2] ECM = energy corrected milk.

[3] The trials are listed in Table 14.5.

Table 14.9. Descriptive statistics of the dataset used for evaluating the feed intake system for cows, including data from 12 trials[3] and 62 treatments where the ration was fed as a total mixed ration.

Item	Average	SD[1]	Maximum	Minimum
Days in milk	96	43	200	31
Body weight, kg	588	48	659	441
ECM[2], kg/d	33.2	4.6	49.7	22.4
Dry matter intake, kg/d	21.2	2.1	25.1	16.6
Concentrate proportion, kg/kg DM	0.54	0.1	0.70	0.27
Roughage basis fill value, /kg DM	0.46	0.04	0.60	0.42
Starch + sugars, g/kg DM	208	59	419	94
Starch + sugars, kg/d	4.4	1.2	7.8	1.7

[1] SD = standard deviation.

[2] ECM = energy corrected milk.

[3] The trials are listed in Table 14.5.

and mean predicted intake was 10.1 kg DM/d. The regression slope was 0.88 and not significantly different from 1. The RMSPE was 1.3 kg DM/d and 0.52 of the prediction error was related to disturbance. The overall bias accounted for 0.48 of the total MSPE, and showed that the intake model underpredicts roughage intake. Predicted roughage intake was within ±10% of observed intake for 58% of the observations.

Predicted vs. observed TMR intake and results of the evaluation of the prediction error are presented in Figure 14.14 and Table 14.10, respectively. The mean observed and predicted TMR intakes were 21.2 and 21.1 kg DM/d, respectively, the regression slope was not significantly ($P<0.05$) different from 1 and 0.62 of the MSPE was explained by disturbance error. The RMSPE was 1.6 kg DM, corresponding to a prediction error of 7.7%. Predicted intake was within 10% of observed intake for 79% of the observations.

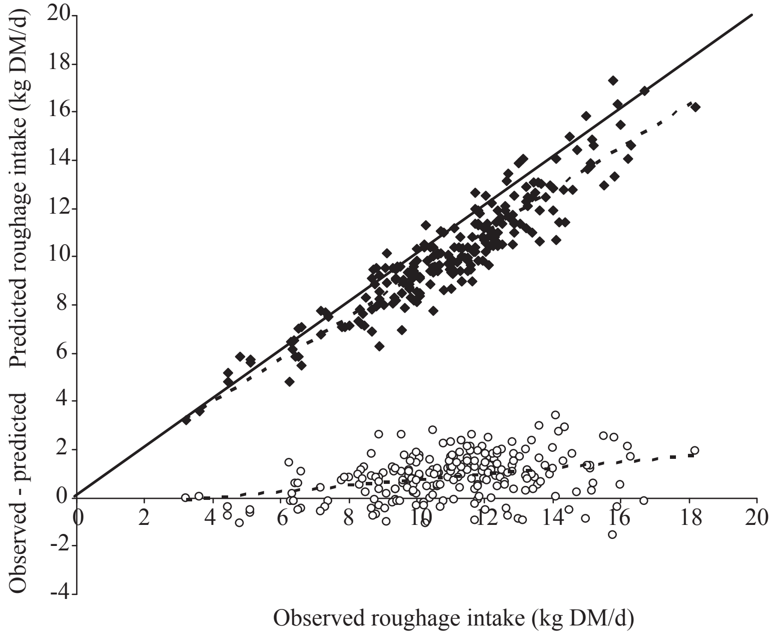

Figure 14.13. Predicted vs. observed roughage intake.

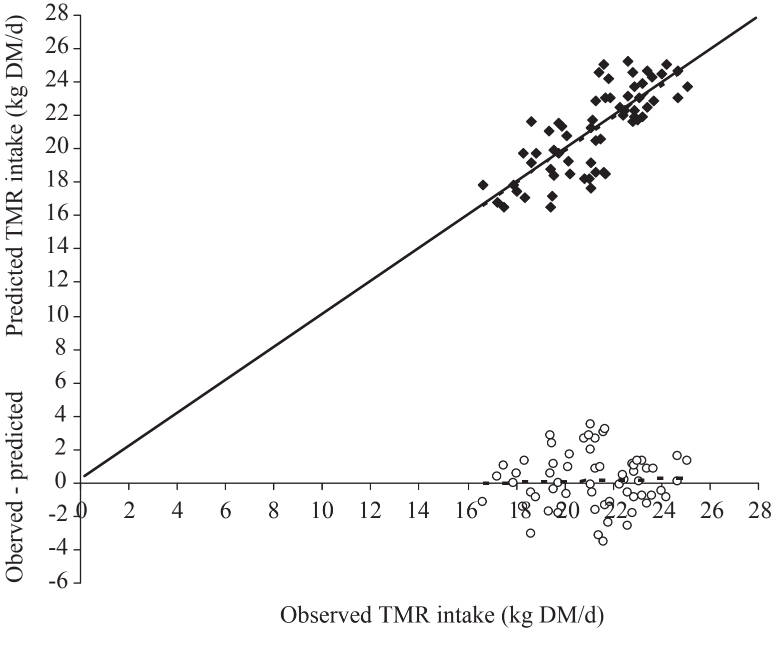

Figure 14.14. Predicted vs. observed DMI of a TMR.

Table 14.10. Accuracy and precision of NorFor´s ability to predict feed intake

Item	n	Intake, kg DM/day		Regression		r^2	RMSPE	Prediction error, %	Proportion of MSPE		
		Observed	Predicted	Intercept	Slope				Overall bias	Regression	Disturbance
Roughage[1]	229	11.0	10.1	0.49	0.876	0.866	1.3	11.6	0.468	0.001	0.531
TMR[2]	62	21.2	21.1	0.48	0.972	0.593	1.6	7.7	0.006	0.371	0.623

[1] Roughage intake in experiments where roughage and concentrate were fed separately.

[2] TMR = total mixed ration.

14.7. Evaluation of chewing index (CI)

This section describes an independent test of predicted EI, RI and CI values of various, typical Nordic roughages against recorded ET, RT and CT values. The independent test set included data from studies with dairy cows and growing steers fed grass, maize or whole crop barley silage harvested at different times with various degrees of chopping, i.e. PL. The studies included a Danish study with lactating dairy cows fed two types of maize silage (Hymøller *et al*., 2005), a Norwegian study with lactating dairy cows fed unchopped grass silage harvested at two stages of maturity (Garmo *et al*., 2008), a Swedish study with lactating dairy cows fed grass silage chopped by two different choppers (Bertilsson, 2008), and a Swedish study with growing steers fed whole crop barley silage harvested at two stages of maturity (Rustas *et al*., 2010) (Table 14.11).

The size_E value and the EI values of the roughages (listed in Table 14.11) were estimated from the content of NDF and the PL according to Equations 11.3 and 11.2, respectively. The Size_R value, Hardness factor and RI values were estimated using Equations 11.5, 11.6 and 11.4, respectively. The CI values were estimated from Equation 11.1.

The observed ET (ET_o) and RT (RT_o) per kg intake of roughage NDF (NDFIr) for each of the roughages in Table 14.11 were estimated according to the following equations:

$$ET_o = \frac{ET - 4 \cdot DMIc}{NDFr} \qquad 14.2$$

$$RT_o = \frac{RT - \sum DM_i \cdot RI_i}{NDFIr} \qquad 14.3$$

$$CT_o = ET_o + RT_o \qquad 14.4$$

where ET_o is the observed eating time, min/kg NDFr; ET is the recorded eating time of the whole ration, min/d; 4·DMIc refers to an assumed ET of 4 min/kg DMI of concentrate; NDFIr is the intake of NDF from roughage, kg/d; RT_o is the observed rumination time, min/kg NDFr; RT is the recorded RT of the whole ration, min/d; DM_i is the DMI of the i=1...n'th concentrate; RI_i is the RI value of the i=1...n'th concentrate, Equation 11.4, 11.5 and 11.6, and Table 11.1; CT_o is the observed chewing time, min/kg NDFr.

The ET_o and RT_o values were corrected to a standard cow size of 625 kg and a standard NDFIr of 0.7%/kg BW using the following equations, obtained from a meta-analysis of data from 80 dietary treatments by Nørgaard *et al.* (2010), which did not include data from the four studies listed in Table 14.11.

$$ET_{corr} = \left(ET_o + 0.21 \cdot (BW - 625)\right) \cdot \frac{NDFr}{1000} \qquad 14.5$$

$$RT_{corr} = \left(RT_o + 0.20 \cdot (BW - 625) + 52 \cdot \left(\frac{NDFIr \cdot 100}{BW} - 0.7 \right) \right) \cdot \frac{NDFr}{1000} \qquad 14.6$$

$$CT_{corr} = ET_{corr} + RT_{corr} \qquad 14.7$$

where ET_{corr} is the observed eating time corrected for BW and NDFIr, min/kg DMr; ET_o is the observed eating time, min/kg NDFr; BW is the body weight of the animal, kg; NDFr is the content of NDF in the roughage, g/kg DM; RT_{corr} is the observed rumination time corrected for BW and NDFIr, min/kg DM; RT_o is the observed eating time, min/kg NDRr; NDFIr/BW is the intake of NDF from roughage, % of BW; and CT_{corr} is the observed chewing time corrected for BW and NDFIr, min/kg DMr.

Table 14.11. Comparison of observed chewing activity (ET_{corr}, RT_{corr}, CT_{corr}) with predicted chewing index values (EI, RI, CI) in four Nordic studies with dairy cows or steers.

Experiment	Hymøller *et al.* (2005)	
Roughage	Maize silage	
Animals	Dairy cows	
Treatment	Pretti early cut	Banguy early cut
Body weight, kg	625	625
Concentrate, kg DM/d	8.4	8.9
Roughage intake, kg DM/d	11.7	12.3
NDFr intake, kg/d	5.4	5.2
NDFr intake, % of BW	0.86	0.82
NDF in roughage, g/kg DM	462	419
Particle length (PL/TCL), mm	9.3	10.3
Size_E factor[1]	0.75	0.77
Size_R factor[1]	0.88	0.91
iNDF, g/kg NDF	230	144
Hardness factor[1]	0.98	0.89
Predicted chewing index		
EI[2], min/kg DMr	17	16
RI[2], min/kg DMr	40[3]	34[3]
CI[2], min/kg DMr [2]	57	50
Observed chewing activity		
Observed ET[4], min/kg NDFr	64	67
Observed RT[4], min/kg NDFr	90^c	85^c
Observed CT[4], min/kg NDFr	154	152
Observed ET_{corr}[5], min/kg DMr	30	28
Observed RT_{corr}[5], min/kg DMr	45	38
Observed CT_{corr}[5], min/kg DMr	75	66

[1] Size_E, Size_R and Hardness factor were estimated using Equations 11.3, 11.5 and 11.6, respectively.

[2] EI, RI and CI were estimated using Equations 11.2, 11.4 and 11.1, respectively. DMr: DMI of roughage.

[3] Corrected for RI values of 10, 4 and 9 min/kg DM for rolled barley (30%), rape seed meal (50%) and pelleted beetpulp (20%), respectively.

[4] Observed ET and RT were calculated using Equations 14.1 and 14.2, respectively. NDFr: DMI of NDF from roughage.

[5] ET_{corr} and RT_{corr} are observed values corrected for BW and NDFr intake using Equations 14.4 and 14.5.

[6] In this trial only total chewing time was recorded.

Figure 14.15 shows the relationship between observed and predicted eating, rumination and chewing activity obtained from the four Nordic trials listed in Table 14.11. Across all treatments the average observed CT and predicted CI was similar (67 vs. 64 min/kg DMr). However, in the study by Hymøller *et al.* (2005), observed ET_{corr} values for the roughages were nearly twice as high as the EI values, whereas ET_{corr} values fitted well with the EI values in the study by Garmo *et al.* (2008) and Rustas *et al.* (2010). The fairly good prediction of RT compared with the less well predicted ET is in accordance with the results from the meta-analysis by Nørgaard *et al.* (2010). Predicted CI was

Garmo *et al.* (2008) Grass silage Dairy cows		Bertilsson (2008) Grass silage Dairy cows		Rustas *et al.* (2009) Whole crop barley silage Steers	
Early cut	Normal cut	Pöttinger cutter	Taarup wagon	Early cut	Late cut
618	618	625	625	350	350
5.2	5.3	8.9	10.4	0.3	0.3
16.4	14.5	15.3	17.1	7.8	7.0
7.0	7.7	6.9	7.7	3.8	3.3
1.17	1.25	1.10	1.23	1.08	0.95
427	532	450	450	486	476
>100	>100	32	25	>100	>100
1	1	0.96	0.92	1	1
1	1	1	1	1	1
113	160	120	120	192	366
0.86	0.91	0.87	0.87	0.94	1.12
21	27	22	21	24	24
37	48	39	39	46	53
58	75	61	60	70	77
51	54			99	100
70	71			130	148
121	125	113[6]	97[6]	229	248
21	28			20	20
40	52			46	51
61	80	60[6]	56[6]	66	71

within ±5% of observed CT_{corr} for six out of eight observations. The two observations with large deviations (>15%) were from the study of Hymøller *et al.* (2005) and are largely responsible for a relatively low coefficient of determination ($r^2 = 0.21$) between observed CT and predicted CI. The RMSPE was 9.2 min/kg DMr corresponding to a prediction error of 13.8%.

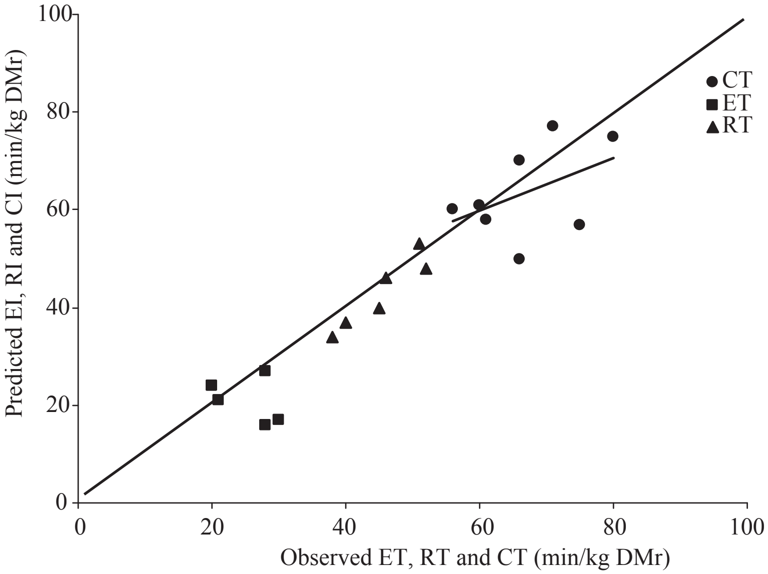

Figure 14.15. The relationship between observed eating (ET), rumination (RT) and chewing time (CT) vs. corresponding predicted indexes (EI, RI, CI). The data are from trials described in Table 14.11.

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15. The NorFor IT system, ration formulation and optimisation

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This chapter describes how we have converted a whole-animal model into a commercial computer tool to be used by advisors and farmers to formulate and optimise diets for dairy cows and growing cattle. The NorFor system is a semi-mechanistic model that has many theoretical advantages for the formulation and evaluation of feed rations. The system represents a significant development in models of nutritional formulation. It incorporates a detailed description of the protein and carbohydrate composition of the ration, which is used in the algorithms to predict degradation, digestion and metabolism in the gastro-intestinal tract and also the supply of metabolizable energy and protein. It can be used not only to estimate nutritional requirements but also provides substantial benefits for predicting nutrient utilization and the environmental impact from different diets. A complex model with semi-mechanistic algorithms and non-linear functions requires the development of a powerful, user-friendly computer tool before it can be used in practical ration formulation and optimisation.

Feed is one of the major costs in modern cattle production, so it is important to consider both nutritional and economic aspects when formulating optimal rations. A key objective in modern, computerised ration formulation is auto-balancing (Boston *et al*., 2000), i.e. identification of the least expensive combination of feed ingredients that provides all considered nutrients within specified ranges. Use of an optimisation (auto-balancing) approach in the formulation of feed rations for cattle requires detailed nutritional and economic knowledge, including information regarding available feeds, the animals and management practices. Some feeds are home-grown while others are purchased as individual ingredients or as concentrate mixtures, and knowledge of their characteristics, obtained from either analyses or tables are needed. In addition, information on feed prices is required. Important animal information includes lactation stage, lactation number, BW, gestation day and age. Management factors include housing (tied up or loose housed) and feeding system (total mixed ration or separate feeds; pasture or indoor). All of these factors affect feed requirements and it is therefore essential that all relevant information is readily available. For these reasons, NorFor has put substantial efforts and resources into the development of an effective, economic IT platform and computer tool that can be used in practical ration evaluation and optimisation.

15.1 IT platforms

NorFor is used by nutrition advisors in Denmark, Iceland, Norway and Sweden. An objective in the development of the computer tools was to use an IT platform that allows operators to access the latest version of the model. Hence, all users had to be able to access it via the same server system. Two IT platforms were developed: one web-based and one in which operators use an offline client, synchronized with the NorFor sever before starting the ration formulation. Denmark, Iceland and Norway have chosen to use an online solution, while Sweden is using an offline solution. Although, all countries use the common NorFor severs, each country, except Iceland, has developed their own national client and interface, to enable the NorFor system to be integrated with other national advisory tools. Figure 15.1 presents an overview of the common IT system, which consists of a server application, a homepage, an administration tool and Web services for dairy management software (National herd recording system), laboratories and feed companies. The NorFor servers host four web services: the feed analysis system (FAS), the feedstuff table (FST), the feed ration calculator (FRC), and the one-day feeding control (OFC) system.

15.2 The feed analysis system (FAS)

NorFor has developed a web-client that is used by linked laboratories to report results from herd level feed analyses (Figure 15.2). The laboratories connect to the system and upload analytical results,

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9_15, © Wageningen Academic Publishers 2011

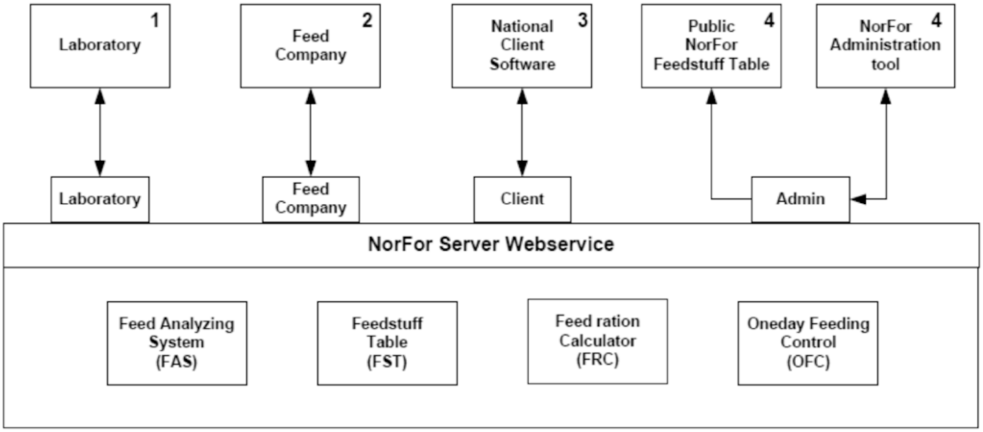


Figure 15.1. An architectural overview of the NorFor IT system.

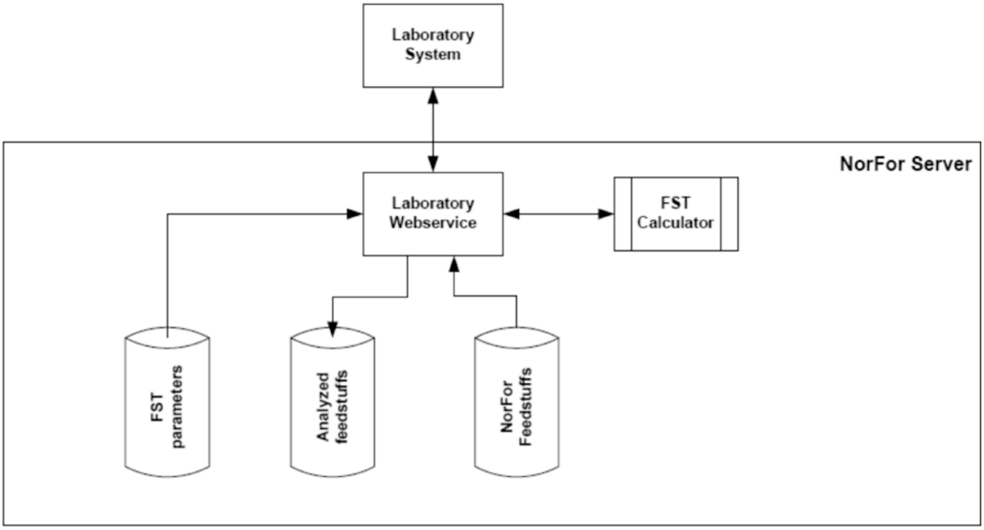


Figure 15.2. An architectural overview of the feed analysis system (FAS).

and the system calculates feed characteristics (using the FST Calculator) from other analytical data, as described in Chapter 6.

Based on the NorFor feed code system, tabulated values are added to the feed samples if absent. If the feed sample is from a herd registered in the national herd recording system (Figure 15.3), it is assigned a herd-specific id, making it automatically available for use by the FRC for ration optimisation or by the OFC for calculating herd feed efficiency. In the NorFor server, each herd has its own feedstuff table, in which the analysed feeds and those copied from the FST are saved. When roughage is analysed at the laboratory, the farmer or advisor reports additional information about the feed sample. This information included date of harvest, cutting number, botanical composition, feed additives, storage system for silage and theoretical cutting length. These additional values are stored, together with the feed characteristics, in a common feed database, which can be used for

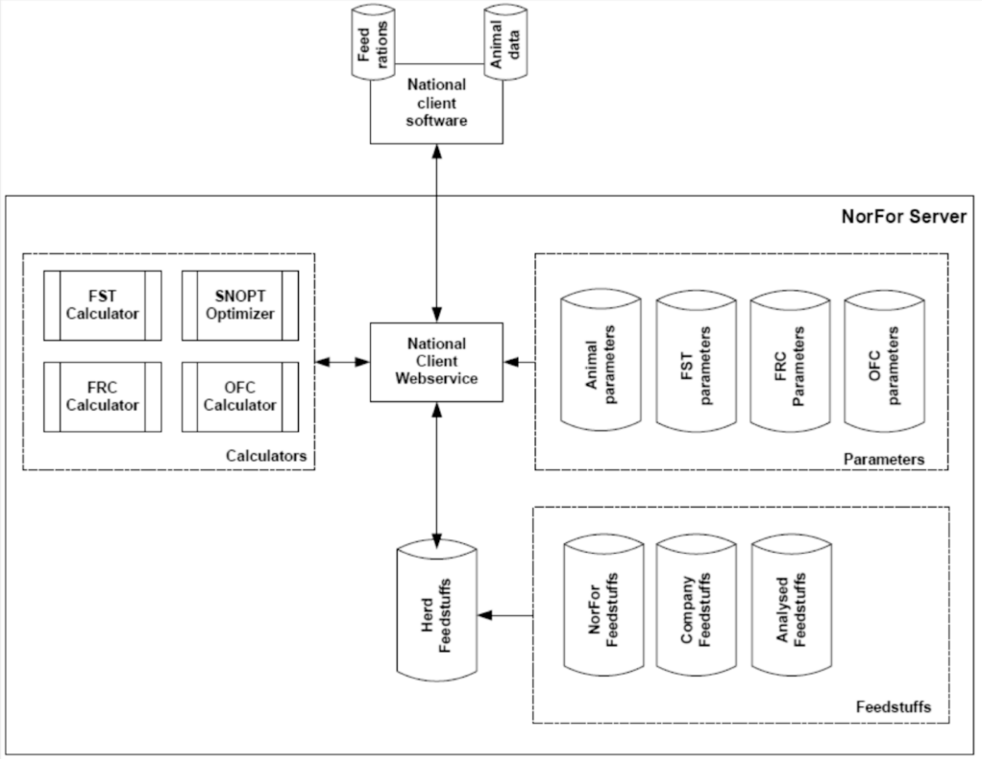


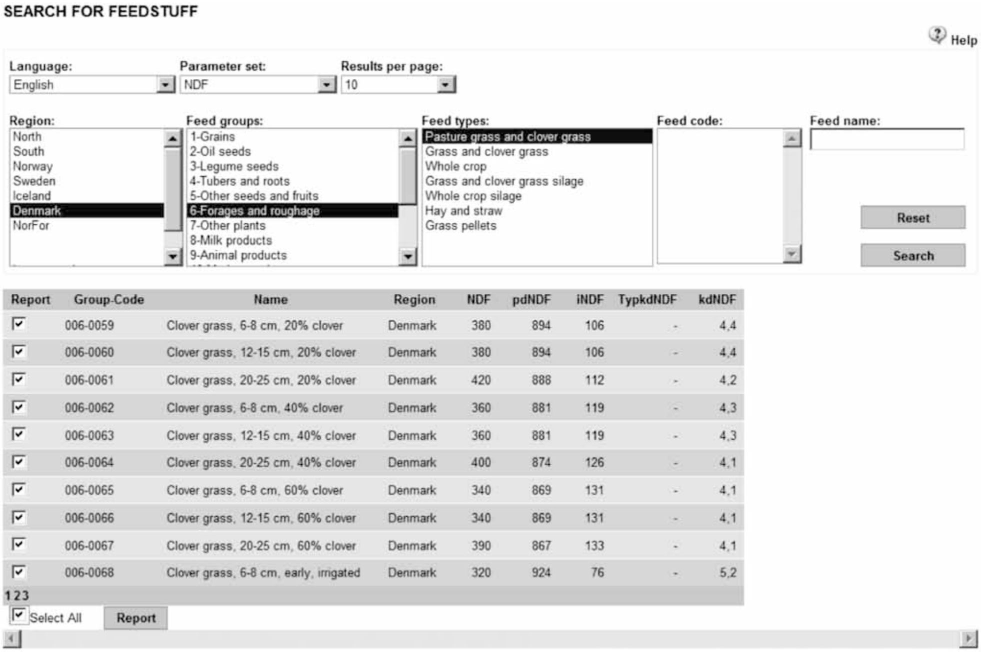
Figure 15.3. An architectural overview of the link between NorFor and the national client.

statistical evaluation of factors such as the annual roughage quality and the relationships between feed additives and silage fermentation quality. Approximately 25,000 roughage samples are analysed according to NorFor specifications annually.

15.3 Feedstuff table (FST)

NorFor has developed a comprehensive feedstuff table (FST) that is continuously updated. Updating and monitoring the FST is done by use of the NorFor administration tool. From the NorFor sever, the FST is available to each national client and when working on herd-specific feed plans, feedstuffs are copied from the FST into the herd feedstuff table for further use. For external users, the FST is available at www.norfor.info. Figure 15.4 shows an overview of the NorFor FST, which is organized in a hierarchal directory system, in which the highest level is *region*, dividing the feedstuffs into country specific and common NorFor categories. The feed directory is further divided into feed groups, by 19 sub-directories, and the feed groups are divided into feed types. For example, the feed group ‘grains, is divided into ‘grains’, ‘dry grain by-products’ and ‘wet grain by-products’. The ‘forages and roughage’ group is divided into seven feed types: ‘pasture grass and clover-grass’, ‘grass and clover-grass’, ‘whole crop’, ‘grass and clover-grass silage’, ‘whole crop silage’, ‘hay and ‘straw’, and ‘grass pellets’. Figure 15.4 also shows an example of choosing a parameter setting (‘NDF characteristics’). These settings are used to generate reports on variables such as NDF, starch, protein, amino acids fatty acids, fermentation products, minerals, vitamins or total characteristics.

A part of the feed table system is also information on commercial compound feeds including prices, reported by the feed industry (Figure 15.5). When feed rations are formulated, the operators copy



SEARCH FOR FEEDSTUFF

Language: English

Parameter set: NDF

Results per page: 10

Region: Denmark

Feed groups: 6-Forages and roughage

Feed types: Pasture grass and clover grass

Report	Group-Code	Name	Region	NDF	pdNDF	iNDF	TypkdNDF	kdNDF
☑	006-0059	Clover grass, 6-8 cm, 20% clover	Denmark	380	894	106	-	4,4
☑	006-0060	Clover grass, 12-15 cm, 20% clover	Denmark	380	894	106	-	4,4
☑	006-0061	Clover grass, 20-25 cm, 20% clover	Denmark	420	888	112	-	4,2
☑	006-0062	Clover grass, 6-8 cm, 40% clover	Denmark	360	881	119	-	4,3
☑	006-0063	Clover grass, 12-15 cm, 40% clover	Denmark	360	881	119	-	4,3
☑	006-0064	Clover grass, 20-25 cm, 40% clover	Denmark	400	874	126	-	4,1
☑	006-0065	Clover grass, 6-8 cm, 60% clover	Denmark	340	869	131	-	4,1
☑	006-0066	Clover grass, 12-15 cm, 60% clover	Denmark	340	869	131	-	4,1
☑	006-0067	Clover grass, 20-25 cm, 60% clover	Denmark	390	867	133	-	4,1
☑	006-0068	Clover grass, 6-8 cm, early, irrigated	Denmark	320	924	76	-	5,2

1 2 3

☑ Select All

Figure 15.4. Overview of the NorFor feedstuff table and example of NDF characteristics in feedstuffs from the group forages and roughage.

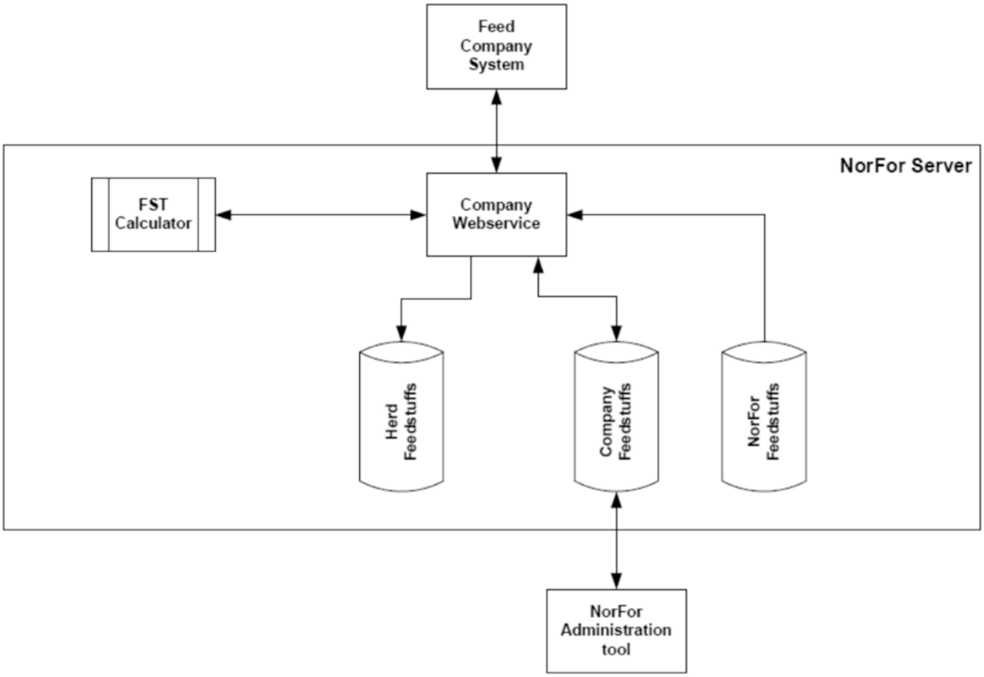


Figure 15.5. An architectural overview of the feed company web-service in NorFor.

actual company products into the herd specific feedstuff table. NorFor has developed a web-service to help the feed industry report these details to the FST.

15.4 Dairy management system

Each Nordic country has its own national herd recording system, in which both records for individual cows (e.g. lactation number, age, days in milk, milk yield, milk composition, BCS, fertility and health) and herd information (e.g. 305-d milk yield, milk composition, slaughter weight and slaughter age) are reported. When formulating diets in the NorFor system, herd information is available (Figure 15.3), which means that rations can be formulated for either individual cows or groups of cows in the herd.

15.5 Feed ration calculator (FRC)

A requirement for the NorFor IT system was that it should allow both the calculation and optimisation of rations. The chosen solution was three calculator add-inns and a black-box optimisation approach (Figure 15.6). The FRC Calculator is used to evaluate feed rations and to predict production responses when the feed input is known. The FAS/FST Calculator is used to calculate standard feed values for a single feedstuff (see Chapter 13) by combining values obtained from the FRC calculator and information from the FAS and FST.

The SNOPT™ Optimizer is used to optimise (auto-balance) a feed ration i.e. produce a ration that provides all the required nutrients at the lowest possible cost. This means that when using the optimiser individual feed prices must be reported through the herd feedstuff table. The SNOPT Optimizer is a package of software and algorithms, developed by researchers (Gill *et al*., 2005) at Stanford University and the University of California (http://www.sbsi-sol-optimize.com), for solving large-scale optimisation problems (linear and nonlinear). It is especially effective for nonlinear problems whose functions and gradients are expensive to evaluate. SNOPT was implemented in NorFor with guidance from the TOMLAB company (http://www.tomopt.com/tomlab).

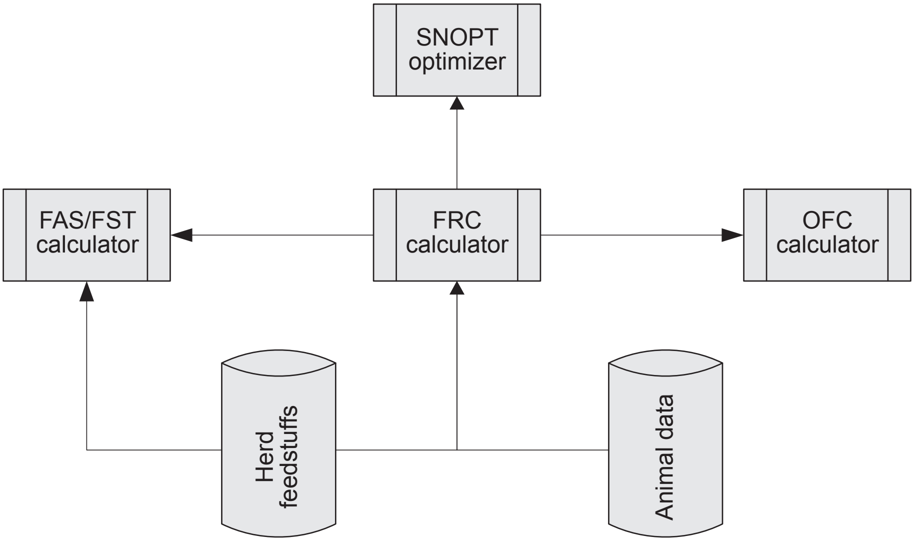


Figure 15.6. The add-inns used in the NorFor FRC calculation and optimisation.

The optimisation software module consists of a high-level interface written in C# targeting the Microsoft®.NET platform, allowing optimisation problems to be specified, and a low-level SNOPT 7 solver library built using Fortran 77 code. The functions optimized are constructed using C#-like syntax and compiled in a library called the high-level code. For nonlinear problems such as those posed in NorFor, SNOPT employs a sparse SQP algorithm, described by Gill *et al*. (2005). The nonlinear solver requires knowledge of the first derivatives of all (nonlinear) functions, and if some are unknown, they are estimated numerically. Initially, the NorFor system used numerical gradients for all nonlinear functions. However, the calculation engine applies automatic differentiation (AD). This eliminates the round-off errors normally associated with numerical estimation and yields exact derivatives down to machine precision. Tests made during the development of the AD package showed an increased robustness without significantly reducing performance by use of AD. This is important, since the operator-overloading method applied might theoretically be slower than using regular floating point expressions.

The question of whether SNOPT finds the global optimum for each problem has been raised. For the types of problem, this depends on the nature of the nonlinear constraints. If the constraint functions are known explicitly, a person might be able to deduce whether or not they define a convex region, but although doing this automatically using a computer algorithm (without a symbolic description) might be possible, it would be far from trivial. It is easier to prove non-convexity – it suffices to find two different starting points that give significantly different local optimal points, which can be done with little knowledge of the nature of the functions involved. Nevertheless, SNOPT is an industry standard nonlinear optimisation solver that often performs well even on non-convex problems. It may well find the global optimum by chance, depending on the given starting point. However, a method to increase the odds of identifying global optimality is to simply run more than one optimisation, with different starting points. If all runs give the same optimum, it is likely, although not 100% certain, that the global optimum has been found. A multi-start algorithm has been implemented in the NorFor software system, which provides an automated method for generating multiple starting points that can be used for repeated local optimisation runs. It automatically detects similar solutions according to tolerance criteria and can be used to obtain good indications of whether a particular problem is convex or not. In a test of 20 actual NorFor problems, every problem in the set was found to have a unique optimal point, although for a subset of the problems certain starting points (typically one or two of 20-50 randomly chosen points) resulted in infeasible solutions. This is not a cause for concern, since there will always be points that do not fulfil all constraints, and the multi-start algorithm can be applied in attempts to solve problems that seem to be infeasible.

The principal optimisation problem in the NorFor system is to identify the cheapest combination of feed ingredients that meets nutritional requirements. The linear cost function is simply the total cost of a ration, expressed:

$$\min_{x} f(x) = \sum_{i=1}^{n} p_i x_i \qquad 15.1$$

$$b_L \le Ax \le b_U \qquad 15.2$$

$$c_L \le c(x) \le c_U \qquad 15.3$$

$$p, x \in R^n, x \ge 0 \qquad 15.4$$

$$b_L, b_U \in R^{m_1}, A \in R^{m_1 \cdot n} \qquad 15.5$$

$$c_L, c_U, c(x) \in R^{m_2} \qquad 15.6$$

where, p_i is the price per unit of feedstuff *i*; x_i is the amount of feedstuff *i* used in the ration. R^n implies the set of real numbers with dimension n; A is a matrix with constant elements; b_L and b_U are linear constraints expressed on vector form; c_L and c_U are non-linear constraints.

The set of constraints expresses nutritional demands, which include DMI, energy, AAT_N, PBV_N and nutritional characteristics (e.g. rumen load index, fatty acids, NDF and minerals). The constraints are divided into m_1 linear and m_2 nonlinear constraints, a special case being the so-called ratio constraints that are originally nonlinear, being quotients of linear sums:

$$r(x) = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} x_i} \tag{15.7}$$

where, w_i is constant real-valued weighting values. These constraints are easily transformed into at most two linear constraints. When optimising for more than one animal simultaneously, two runs are made: first for the individual animals and then for the entire group with additional constraints. The multi-animal problem leads to a block structure in the constraint matrix. Figure 15.7 illustrates a hypothetical situation with four animals (four blocks), 10 feeds and five constraints (three of which link different animals together), and the total usage of feedstuffs 1, 2 and 3 is limited.

One of the main requirements when selecting the optimisation platform was that the execution time should be fast. A performance test was conducted with the Norwegian client involving simultaneous optimisation for 30 cows, nine constraints and five feedstuffs. The obtained optimisation time was 0.23 second per cow.

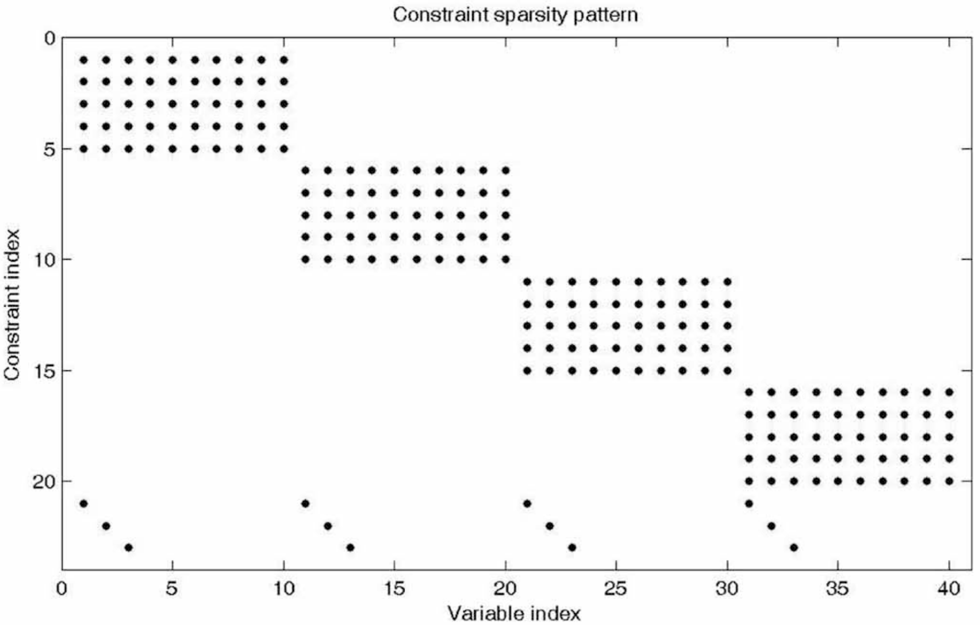


Figure 15.7. The sparsity pattern for a problem with four animals, ten feedstuffs, five constraints and three constraints limiting total usage of feedstuffs.

The goal of optimisation is to find the least costly combination of feeds that meets a set of constraints (minimum and maximum) ensuring that amounts of nutrients supplied are within specified ranges. Thus, a set of constraints is needed for both feed ingredients and nutrients. In a practical situation, the amount of home grown feed is known and feed constraints are often based on their availability. Therefore, the amount of a feed in the ration may often be adjusted by the operator to take into account a minimum or maximum that must be used from an inventory perspective. When feeds are purchased an optimisation approach is useful when the feed budget and purchasing of ingredients are planned. Nutritional constraints are based on either their direct effects on production responses, i.e. the requirements (NEL and AAT_N) of animals to meet target performance criteria or nutrient amounts and concentrations in the rations, e.g. PBV, RLI, NDF, Starch, CP, fatty acids and minerals.

It is possible to optimise from 84 nutritional variables in NorFor but not all of them have recommended constraints at present. When rations are optimised in the national clients, we start with a recommended default setting for eight nutritional constraints (Table 15.1).

Table 15.2 illustrates the process of ration optimisation with a set of diets formulated with variations in the constraints of RLI (0.6 vs. 0.45) and AAT/NEL (15 vs. 16 g/MJ). TMR rations were formulated for a target of 35 kg ECM and in addition to the standard optimisation constraints, several other nutritional variables were used to evaluate and characterise the rations. Reducing the RLI (diet 1 vs. diet 2) reduced the proportion of wheat grain in the optimal diet by 7.5% and increased the proportion of cold-pressed rapeseed by 5.8%. The change in RLI affected the starch content, which decreased by 24% when the RLI was reduced. Increasing the minimum requirement of AAT/NEL from 15 to 16 g/MJ (Diet 2 vs. Diet 3) increased the proportion of extracted soybean meal and decreased the proportion of rapeseed in the optimal diet by 3.7 and 4.6%, respectively. This change resulted in an increased CP concentration in the diet and minor changes in the AA composition. The simple examples presented in Table 15.2 demonstrate how the combination of auto-balancing and nutritional constraints changes the optimal diet composition. They also show the sensitivity of the optimisation procedure to changes in the constraints and highlight the importance of ensuring that feed rations obtained by optimisation are assessed by a trained nutritionist before they are implemented.

Table 15.1. Default optimisation constraint settings in NorFor for dairy cows.

Item	Constraint	
	Minimum	Maximum
Ration fill value	IC·0.97	IC[1]
Energy balance, %	99.5	100.5
AAT_N/NEL[2], g/MJ	15	
AAT_N response, %	95	
PBV_N[3], g/kg DM	10	40
RLI[4], g/g		0.6
Fatty acids, g/kg DM	20	45
Chewing index, min/kg DM	32	

[1] IC = animal intake capacity.

[2] AAT_N/NEL = ratio between amino acids absorbed in the small intestine (AAT_N) and net energy lactation (NEL) available for milk production.

[3] PBV = protein balance in the rumen.

[4] RLI = rumen load index.

Table 15.2. Ration optimisation with varied constraints for rumen load index and AAT/NEL for a 600 kg dairy cow producing 35 kg ECM.

	Ration		
	Diet 1	Diet 2	Diet 3
Ingredients, % of DM			
Grass silage, medium OMD[1]	16.5	16.1	16.2
Grass silage, high OMD	15.8	20.2	19.5
Maize silage, high OMD	24.8	23.3	24.8
Wheat grain	26.6	19.1	19.0
Wheat, brewers grain	6.3	6.3	6.3
Soybean meal	3.4	2.8	6.5
Rapeseed, cold pressed	5.6	11.4	6.8
Salt	0.23	0.22	0.23
Mineral and vitamin mix	0.68	0.67	0.68
Total dry matter, kg/d	22.2	22.3	22.2
Cost, NOK	29.86	29.64	30.10
Ration fill value, FV/kg DM	8.45	8.45	8.45
Energy balance, %	100	100	100
AAT_N/NEL, g/MJ[2]	15	15	16.0
AAT_N response, %	95	95	98
PBV_N, g/kg DM[3]	10	20	20
RLI, g/g[4]	0.6	0.45	0.45
Crude fat, g/kg DM	42	50	44
Chewing index, min/kg DM	41	42	42
Roughage proportion, % of DM	57.2	59.6	60.4
Crude protein, g/kg DM	154	165	170
NDF, g/kg DM	340	366	363
Starch, g/kg DM	265	202	205
Sugar, g/kg DM	33	38	36
Lysine, % of AAT_N	6.54	6.61	5.59
Methionine, % of AAT_N	2.21	2.29	2.22
Histidine, % of AAT_N	2.49	2.53	2.50
Calcium, g/kg DM	32	37	35
Phosphorus, g/kg DM	47	51	48
Magnesium, g/kg DM	28	30	29

[1] OMD = organic matter digestibility.

[2] AAT_N/NEL = ratio between amino acids absorbed in the small intestine (AAT_N) and net energy lactation (NEL) available for milk production.

[3] PBV_N = protein balance in the rumen.

[4] RLI = rumen load index.

In the system development, testing and implementation process, NorFor has developed a PC program called the NorFor Development Tool (NDT). The NDT runs off-line, incorporates all the NorFor equations and compiles the three calculator add-inns (Figure 15.8). This means that it is possible both to calculate and optimize rations with NDT. The program is used by the personnel who develop and maintain the system.

It is easy to edit existing equations and to include new equations in the program (Figure 15.9). It is also possible to both import and export data between NDT and Microsoft Excel, which makes it easy to test and evaluate experimental data. Import of feedstuff specifications into the NDT from the online NorFor feedstuff table is implemented. An essential feature of the NDT is the unit test, which allows multiple tests to be run simultaneously to ensure that changes in the equation sets do not have unexpected effects on different parts of the model. Before a new version of the NorFor system becomes available for the national clients, it is extensively evaluated in the NDT. After approval, the new/edited equations are transferred to the operative NorFor servers. This procedure ensures that the system is updated safely.

15.6 One-day feeding control (OFC)

The OFC is a ration evaluator that is used to calculate herd feed efficiency (mainly in terms of energy and nitrogen) for a specific day or period. It compiles data from the national herd recording system and from the FST and FRC. The number of animals in each category (cows, calves, heifers and bulls) and the status of individual animals (e.g. MY, milk chemical, gestation day and age) are available from the national herd recording system for the specific test day. The feed intake is measured for each animal category or groups of animals and, in combination with information from the herd feedstuff table, the FRC is used to calculate ration composition, production responses and feed efficiency. The ration evaluation and OFC are then used for optimising/adjusting the ration for the next feeding period.

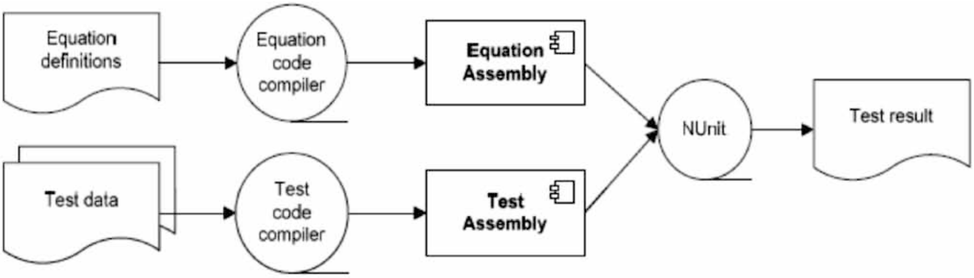
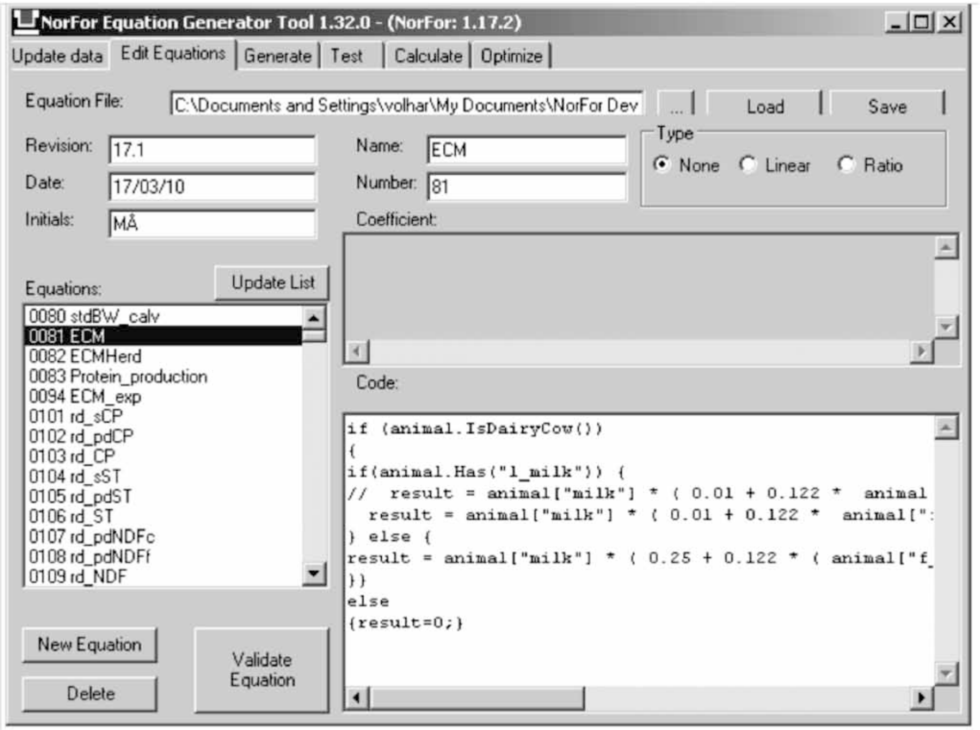


Figure 15.8. The architectural structure of the NorFor Development tool.



Equation File: C:\Documents and Settings\volhar\My Documents\NorFor Dev

Revision: 17.1

Date: 17/03/10

Initials: MÅ

Name: ECM

Number: 81

Type: ● None ○ Linear ○ Ratio

Coefficient:

Equations:

0080 stdBW_calv
0081 ECM
0082 ECMHerd
0083 Protein_production
0094 ECM_exp
0101 rd_sCP
0102 rd_pdCP
0103 rd_CP
0104 rd_sST
0105 rd_pdST
0106 rd_ST
0107 rd_pdNDFc
0108 rd_pdNDFf
0109 rd_NDF

Code:

```
if (animal.IsDairyCow())
{
if(animal.Has("l_milk")) {
//  result = animal["milk"] * ( 0.01 + 0.122 *  animal
  result = animal["milk"] * ( 0.01 + 0.122 *  animal[":
} else {
result = animal["milk"] * ( 0.25 + 0.122 * ( animal["f_
}}
else
{result=0;}
```

Figure 15.9. Example of a dialogue box in the NorFor Development Tool used to edit and test new equations.

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Keyword index

H. Volden (ed.), *NorFor–The Nordic feed evaluation system*,
DOI 10.3920/978-90-8686-718-9, © Wageningen Academic Publishers 2011