Available online at www.sciencedirect.com
SCIENCE DIRECT
Animal Feed Science and Technology
112 (2004) 29–78
ANIMAL FEED SCIENCE AND TECHNOLOGY
www.elsevier.com/locate/anifeedsci

The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion

D.G. Fox [a,*], L.O. Tedeschi [a], T.P. Tylutki [a], J.B. Russell [b], M.E. Van Amburgh [a], L.E. Chase [a], A.N. Pell [a], T.R. Overton [a]

[a] *Department of Animal Science, Cornell University, Ithaca, NY 14853, USA*
[b] *Agriculture Research Service, USDA, Department of Microbiology, Cornell University, Ithaca, NY 14853, USA*

Abstract

The Cornell Net Carbohydrate and Protein System (CNCPS) is a mathematical model that estimates cattle requirements and nutrient supply based on animal, environmental, and feed compositional information in diverse production situations. Predicted animal requirements account for different physiological states (lactation, pregnancy, and growth), body reserves and environmental effects. The CNCPS uses feed carbohydrate and protein degradation and passage rates to predict extent of ruminal fermentation, microbial protein production, post-ruminal absorption, and total supply of metabolizable energy and protein to the animal. The CNCPS has been used successfully on beef and dairy cattle farms to evaluate and formulate rations. In an evaluation with individually fed growing cattle, the CNCPS accounted for 89% of the variation in ADG with a 7.4% underprediction bias. When the CNCPS was evaluated with data from individual dairy cows where the appropriate inputs were measured and changes in energy reserves were accounted for, the CNCPS accounted for 90% of the variation in actual milk production of individual cows with a 1.3% bias. The model accounted for 76% of the variation in individual cow milk production with an 8% underprediction bias when energy was first limiting in high producing cows, and accounted for 84% of the variation with a 1.1% overprediction bias when protein was first limiting.

Keywords: Modeling; Simulation; Cattle; Nutrient; Requirement; Supply; Rumen

* Corresponding author. Tel.: +1-607-255-2855; fax: +1-607-255-9829.
E-mail address: dgf4@cornell.edu (D.G. Fox).

0377-8401/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.anifeedsci.2003.10.006

1. Introduction

Historically, nutritionists have formulated cattle rations by adding supplements to optimize production responses by using empirical prediction equations that were developed under controlled research conditions. Because these systems attempted to predict nutritional requirements and availabilities for all types of cattle, feeds and environmental or management conditions, the nutritional recommendations often contained significant "safety factors". The extra nutrients contained in these safety factors to ensure that nutrient requirements were met often increased nutrient excretion and contributed to adverse effects on water and air quality.

The Cornell Net Carbohydrate and Protein System (CNCPS) is a mathematical model to evaluate diet and animal performance that was developed from basic principles of rumen function, microbial growth, feed digestion and passage and animal physiology. By accounting for farm-specific management, environmental and feed characteristics, more accurate prediction of the growth and milk production of cattle and nutrient excretion in diverse production situations have been possible. The CNCPS has been used as a farm management tool to optimize use of "home grown" feeds, decrease the need for purchased supplements, optimize herd size and improve the annual return over feed cost (Tylutki et al., 2002).

The CNCPS was first published in 1992 and 1993 in a series of four papers (Fox et al., 1992; Russell et al., 1992; Sniffen et al., 1992; O'Connor et al., 1993), but the model has been continually refined and improved over the last 10 years (Ainslie et al., 1993; Tylutki et al., 1994; Fox et al., 1995, 1999, 2002; Pitt et al., 1996; Tylutki and Fox, 1997; Fox and Tylutki, 1998; Klausner et al., 1998; Tedeschi et al., 2000a,b,c, 2001, 2002a,b,c, 2003, 2004; Tedeschi, 2001).

The objectives of this paper are to: (1) summarize in one publication the equations and concepts currently being used in the CNCPS, (2) evaluate the CNCPS with data from individually fed lactating and growing cattle where all CNCPS inputs were determined, and (3) indicate areas that need improvement. A version of the CNCPS modified for use with sheep is also described (Cannas et al., 2004). The CNCPS software can be downloaded at http://www.cncps.cornell.edu.

2. Model development

To formulate rations with the CNCPS, information on animals, feeds, management and environmental conditions are required. We have imposed two constraints in model development. First, inputs must be routinely available on most farms and, secondly, implementation of CNCPS recommendations should not pose significant economic risk or adversely affect animal performance. The CNCPS has separate sub-models with distinctly different levels of aggregation. Some sub-models are relatively mechanistic while others are primarily empirical. Steady state conditions are assumed for the whole model and its components. The CNCPS sub-models can be classified by physiological function: (1) maintenance, (2) growth, (3) pregnancy, (4) lactation, (5) reserves, (6) feed intake and composition, (7) rumen fermentation, (8) intestinal digestion, (9) metabolism, and (10) nutrient excretion. Definitions for variable names are provided in Table 1. The following

Table 1
Description and units of the abbreviations used in the CNCPS model

Abbreviations	Units	Description
A	dmls	Intermediate constant
*a*1	Mcal/kg$^{0.75}$ per day	Fasting heat production coefficient (0.07 for *Bos taurus* beef, 0.073 for lactating dairy cow, 0.078 for non-lactating dairy, 0.064 for *Bos indicus* (except Nellore), and 0.069 for dual-purpose cows)
*a*2	Mcal/kg$^{0.75}$ per day	Maintenance adjustment for acclimatization (previous temperature)
AA		Amino acids
AAA	g per day	Total amount of the *i*th absorbed AA supplied by dietary and bacterial sources
AABCW	%	*i*th AA content of rumen bacteria cell wall protein (Table 8)
AABNCW	%	*i*th AA content of rumen bacteria non-cell wall protein (Table 8)
AAINSP	%	*i*th AA content of the insoluble protein
$AALACT_i$	g/g	Content of *i*th AA of milk protein
$AATISS_i$	g/g	Content of *i*th AA of tissue protein
ACADG	kg per day	After-calving target average daily gain
Act	Mcal per day	Physical activity factor
ADFIP or ADIN	%CP	Insoluble ADF protein in the CP
ADGPreg		Average daily gain during pregnancy
ADICP	%DM	ADF indigestible CP
ADTV	dmls	Anabolic implant factor
Af	dmls	Adjustment factor of passage rates for peNDF
AF	g/g	Proportion of empty body fat
AFBW	kg	Adjusted final BW; is the SBW at 28% EBF
AP	g/g	Proportion of empty body protein
APADG	kg per day	Post-pregnant target average daily gain
AU	dmls	Animal units (SBW/454)
BactN	g per day	Bacterial N
BactNBalance	g per day	Ruminal bacteria N balance
BactRed	g per day	Reduction in bacteria due to N deficiency
BCS	dmls	Body condition score
$BCS_{1–5}$	dmls	Body condition score in 1–5 scale
$BCS_{1–9}$	dmls	Body condition score in 1–9 scale
BFAF	dmls	Body fat adjustment factor adjusts DMI for EBF content
BI	dmls	Breed adjustment factor
BPADG	kg per day	Pre-pregnant target average daily gain
CA	%DM	CHO A fraction (sugars and organic acids)
CB1	%DM	CHO B1 fraction (starch and soluble fibers)
CB1NFC	%NFC	CHO B1 fraction (starch and soluble fibers)
CB2	%DM	CHO B2 fraction (available NDF)
CBW	kg	Calf birth weight
CC	%DM	CHO C fraction (indigestible)
CETI	°C	Current month’s effective temperature index
CHO	%DM	Carbohydrate
CI	days	Calving interval
COMP	dmls	Compensatory growth adjustment factor
CP	%DM	Crude protein
CPIA	kg per day	Crude protein intake per animal unit
CpW	kg	Conceptus weight

Table 1 (*Continued*)

Abbreviations	Units	Description
DE	Mcal/kg	Digestible energy
DIGBC	g per day	Digested bacterial carbohydrate
DIGBF	g per day	Digestible bacterial fat
DIGBNA	g per day	Digestible bacterial nucleic acids
DIGBTP	g per day	Digestible bacterial true protein
DIGC	g per day	Digestible carbohydrate
DIGF	g per day	Digestible fat
DIGFAA	g per day	Amount of the *i*th absorbed AA from dietary protein escaping rumen degradation
DIGFC	g per day	Intestinally digested feed carbohydrate
DIGFF	g per day	Digestible feed fat
DIGFP	g per day	Digestible feed protein
DIGP	g per day	Digestible protein
DIGPB1	g per day	Digestible B1 protein
DIGPB2	g per day	Digestible B2 protein
DIGPB3	g per day	Digestible B3 protein
DisappTime	h	Time required for bacteria and peptide disappearance
DLW	kg per day	Daily live weight change
DMI	kg per day	Dry matter intake
DMIA	kg per day	Dry matter intake per animal unit
DMIAF	dmls	DMI adjustment factor with night cooling
DMIFactor	dmls	Feed intake in units of intake at maintenance level minus 1
DMINC	dmls	DMI night cooling adjustment
dmls	–	Dimensionless
dTDN	%DM	Discounted TDN to level of intake about maintenance requirement intake
$EAAG_i$	g/g	Efficiency of use of the *i*th aa for growth
$EAAL_i$	g/g	Efficiency of use of the *i*th aa for lactation
$EAAM_i$	g/g	Efficiency of use of the *i*th aa for maintenance
$EAAP_i$	g/g	Efficiency of use of the *i*th aa for pregnancy
EbactRatio	g/g	Proportion of total bacteria
EBG	kg per day	Empty body gain
EBW_{BCS5}	kg	Empty body weight at BCS 5
EE	%DM	Ether extract
EFCBact	g per day	Amount of FC bacteria when energy is limiting
EFCBactRatio	g/g	Proportion of FC bacteria of total bacteria
EI	$^{\circ}$C/Mcal/m^2 per day	External insulation
EN	g per day	N in excess of rumen bacterial N and tissue needs
ENFCBact	g per day	Amount of NFC bacteria when energy is limiting
EqEBW	kg	Equivalent empty body weight
EqSBW	kg	Equivalent shrunk body weight
FBW	kg	Full body weight
FC_NH3_Avail	g per day	Amount of NH_3 available for FC bacteria usage
FC_NH3_Req	g per day	Amount of NH_3 required by FC bacteria
FCBact	g per day	Yield of fiber carbohydrate bacteria
FCBactRed	g per day	Amount of FC bacteria reduction
FCM	kg per day	Fat-corrected milk
FCRed	g per day	Amount of CHO B2 not degraded by FC bacteria
FDM	%	Dry matter of feces
FEASH	g per day	Amount of ash in feces

Table 1 (*Continued*)

Abbreviations	Units	Description
FEBACT	g per day	Amount of bacteria in feces
FEBASH	g per day	Amount of bacterial ash in feces
FEBC	g per day	Amount of bacterial carbohydrate in feces
FEBCP	g per day	Amount of fecal bacterial protein
FEBCW	g per day	Amount of fecal bacterial cell wall protein
FEBF	g per day	Amount of bacterial fat in feces
FecalN	g per day	Fecal nitrogen excretion
FecalP	g per day	Fecal phosphorus excretion
FECB1	g per day	Amount of feed starch in feces
FECB2	g per day	Amount of feed available fiber in feces
FECC	g per day	Amount of feed unavailable fiber in feces
FECHO	g per day	Amount of carbohydrate in feces
FEENGA	g per day	Amount of endogenous ash in feces
FEENGF	g per day	Amount of endogenous fat in feces
FEENGP	g per day	Amount of endogenous protein in feces
FEFA	g per day	Amount of undigested feed ash in feces
FEFAT	g per day	Amount of fat in feces
FEFC	g per day	Amount of feed carbohydrate in feces
FEFF	g per day	Amount of undigested feed fat in feces
FEFP	g per day	Amount of feed protein in feces
FEPB3	g per day	Amount of feed B3 protein fraction in feces
FEPC	g per day	Amount of feed protein fraction C in feces
FEPROT	g per day	Amount of fecal protein
FORAGE	g per day	Proportion of forage in the diet
FPN	g per day	Requirement of metabolizable protein for fecal N losses
GrowthP	g per day	Phosphorus in weight gain
GrowthTime	h	Time required for bacteria growth assuming liquid passage rate
HCCode	dmls	Hair coat code (1, dry and clean; 2, some mud on lower body; 3, wet and matted; 4, covered with wet snow or mud)
HD	cm	Hair depth
HE	Mcal per day	Heat production
HideCode	dmls	Hide depth code (1, thin; 2, average; 3, thick)
HideME	dmls	Hide thickness adjustment for external insulation
HRS	h	Hours of sunlight
IADICP	%DM	Indigestible acid detergent insoluble crude protein
IDM	g per day	Indigestible dry matter intake
Im	kg per day	DMI required for maintenance
IN	$^{\circ}$C/Mcal/m^2 per day	Total insulation
IntDigAsh	g/g	Ash intestinal digestibility (default = 0.5)
IntDigCA	g/g	A carbohydrate intestinal digestibility (default = 1)
IntDigCB1	g/g	B1 carbohydrate intestinal digestibility (default = 0.75)
IntDigCB2	g/g	B2 carbohydrate intestinal digestibility (default = 0.2)
IntDigFAT	g/g	Fat intestinal digestibility (default = 0.95)
IntDigPB1	g/g	B1 protein intestinal digestibility (default = 1)
IntDigPB2	g/g	B2 protein intestinal digestibility (default = 1)
IntDigPB3	g/g	B3 protein intestinal digestibility (default = 0.8)
K_d	%/h	Degradation rate for each fraction
KDcp	g/g	Digestibility of CP
KM1	g/(g h)	Maintenance rate of the fiber CHO bacteria, 0.05
KM2	g/(g h)	Maintenance rate of the non-fiber CHO bacteria, 0.15

Table 1 (*Continued*)

Abbreviations	Units	Description
K_p	g/(g h)	Passage rate from the rumen
K_{pc}	g/(g h)	Passage rate of concentrates
K_{pf}	g/(g h)	Passage rate of forages
K_{pl}	g/(g h)	Passage rate of liquids
LactationP	g per day	Milk phosphorus
LCT	°C	Lower critical temperature
LE	Mcal per day	Net energy required for lactation
Lig	%DM	Lignin
Lignin	%NDF	Lignin
LP	g per day	Requirement of metabolizable protein for lactation
LPAA	g per day	Metabolizable requirement of AA for lactation
ManureP	g per day	Manure phosphorus excretion
ME	Mcal/kg	Dietary content of metabolizable energy
MEmm	Mcal per day	Requirement of metabolizable energy for mammogenesis
MEPreg	Mcal per day	Metabolizable energy requirement for pregnancy
MErcs	Mcal per day	Animal requirement for ME adjusted for cold stress
MF	%	Milk fat
Milk	kg per day	Milk production
MILKA	kg per day	Milk production per animal unit
MP	g per day	Metabolizable protein
$MPAA_i$	g per day	Metabolizable requirement of *i*th AA for maintenance
MPg	g per day	Requirement of metabolizable protein for gain
MPm	g per day	Metabolizable protein required for maintenance
MPmm	g per day	Requirement of metabolizable protein for mammogenesis
MPPreg	g per day	Metabolizable protein requirement for pregnancy
Mud	cm	Mud depth
MudDMI	dmls	DMI adjustment factor for mud depth
MudME	dmls	Mud adjustment factor for external insulation
MW	kg	Mature weight
n	dmls	Week of lactation
NallowableBact	g per day	N allowable bacterial growth
NDF	%DM	Neutral detergent fiber
NDFIP or NDIN	%CP	Insoluble protein in the NDF
NDFn	%DM	NDF adjusted for protein content
NDICP	%DM	NDF indigestible CP
NE_{DLW}	Mcal/kg	Net energy for daily live weight change
NEga	Mcal/kg	Dietary content of net energy for growth
NEl	Mcal/kg	Net energy for lactation
NEma	Mcal/kg	Dietary content of net energy for maintenance
NEmr	Mcal per day	Animal requirement for net energy for maintenance
NEmrcs	Mcal per day	Animal requirement for NE for growth adjusted for cold stress
NEmrhs	Mcal per day	Animal requirement for NE for maintenance adjusted for heat stress
NetReqP	g per day	Net requirement of phosphorus
NFC	%DM	Non-fiber carbohydrate
NFC_NH3_Req	g per day	Amount of NH_3 required by NFC bacteria
NFCBact	g per day	Yield of non-fiber carbohydrate bacteria
NFCBactMass	g	Amount of NFC bacteria
NFCBactPepUp	g per day	Amount of peptide uptake by NFC bacteria

Table 1 (*Continued*)

Abbreviations	Units	Description
NH3_Bact	g per day	Amount of NH_3 from peptide uptake not used by bacteria and produced as NH_3
NH3_Diet	g per day	Amount of NH_3 from the diet
NPg	g per day	Requirement of net protein for gain
NPN	%Soluble CP	Non-protein nitrogen for each feed
PA	%DM	Protein A fraction for each feed
PB1	%DM	Protein B1 fraction for each feed
PB2	%DM	Protein B2 fraction for each feed
PB3	%DM	Protein B3 fraction for each feed
PC	%DM	Protein C fraction for each feed
peNDF	%NDF	Physical effective neutral detergent fiber
peNDFr	kg per day	peNDF required
PepBal	g per day	Balance of peptide in the rumen
PeptideAcc	g per day	Amount of peptide degraded that was used by bacteria and peptide that escaped the rumen
PeptidePass	g per day	Amount of peptide escaping the rumen
PeptideReqN	g per day	Amount of N required as peptide
PeptideUp	g per day	Actual amount of peptide uptake
PeptideUpN	g per day	Amount of N in the peptide uptake
PepUpRate	%/h	Peptide uptake rate by bacteria
PepX	g per day	Potential amount of peptide uptake
PETI	°C	Previous month's effective temperature index
PKYD	kg per day	Peak milk yield (Table 3)
PP	%	Milk true protein
PregnancyP	g per day	Phosphorus in conceptus
ProtB3Red	g per day	Reduction in protein fraction B3 that is associated with the CHO B2 fraction not degraded
Ratio	g per day	Ratio of peptides to peptide plus NFC
RDCA	g per day	Ruminally-degraded CA
RDCB1	g per day	Ruminally-degraded CB1
RDCB2	g per day	Ruminally-degraded CB2
RDPA	g per day	Ruminally-degraded PA
RDPB1	g per day	Ruminally-degraded PB1
RDPB2	g per day	Ruminally-degraded PB2
RDPB3	g per day	Ruminally-degraded PB3
RDPEPh	g per day	Rate of ruminally-degraded peptide
RDPEP	g per day	Ruminally-degraded peptides
RE	Mcal per day	Retained energy
REAA	g per day	Total amount of the *i*th AA at the duodenum
REBAA	g per day	Amount of the *i*th bacterial AA at the duodenum
REBCW	g per day	Bacterial cell wall protein at the duodenum
REBTP	g per day	Bacterial non-cell wall protein at the duodenum
REBTP	g per day	Ruminally escaped bacterial true protein
RECA	g per day	Ruminally escaped carbohydrate A
RECB1	g per day	Ruminally escaped carbohydrate B1
RECB2	g per day	Ruminally escaped carbohydrate B2
RECC	g per day	Ruminally escaped carbohydrate C
RecycledN	g per day	Amount of NH_3 recycled in the rumen
REFAA	g per day	Amount of *i*th dietary aa at the duodenum

Table 1 (*Continued*)

Abbreviations	Units	Description
REFAT	g per day	Amount of ruminally escaped fat (ether extract)
RelMilkProd	dmls	Relative milk production 1 (low) to 9 (high) scale
RelY	dmls	Relative adjustment of bacteria yield to ruminal pH
REPB1	g per day	Ruminally escaped protein B1
REPB2	g per day	Ruminally escaped protein B2
REPB3	g per day	Ruminally escaped protein B3
REPC	g per day	Ruminally escaped protein C
RHc	%	Current relative humidity
RHp	%	Previous relative humidity
RNB	g per day	Ruminal N balance
RPAA	g per day	Metabolizable requirement of AA for growth
SA	m^2	Surface area
SBW	kg	Shrunk body weight
SolCP	%CP	Soluble CP for each feed
SPA	g per day	Requirement of net protein for scurf losses
SRW	kg	Standard reference weight (default is 478 kg)
SWG	kg per day	Shrunk weight gain or average daily gain (ADG)
t	day	Days pregnant
T_{age}	day	Heifer age
T_c	°C	Current average temperature
TCA	day	Target calving age
TCW_x	kg	Target calving weight at x calving number
TDN	%DM	Total digestible nutrients
TDN_{1x}	%DM	TDN at maintenance level DMI
TDNAPP	g per day	Apparent TDN
TE	Mcal	Total empty body energy
TF	kg	Total empty body fat
TFDM	g per day	Total fecal dry matter from indigestible feed
TI	°C/Mcal/m^2 per day	Tissue (internal) insulation
TP	kg	Total empty body protein
T_p	°C	Previous month's average temperature
TPA	day	Target pregnant age
TPW	kg	Target pregnant weight
UIP	%CP	Undegraded intake protein
UPA	g per day	Requirement of net protein for urinary losses
UrinaryN	g per day	Urinary nitrogen excretion
UrinaryP	g per day	Urinary phosphorus excretion
Urine	kg per day	Urine production
WS	km/h	Wind speed
Y	g/g	Bacteria yield efficiency; g of bacteria per g of CHO digested
YE	Mcal per day	Net energy required for pregnancy
YG1	g/(g h)	Theoretical maximum yield of fiber CHO bacteria, 0.4; g of bacteria per g of CHO digested per h
YG2	g/(g h)	Theoretical maximum yield of non-fiber CHO bacteria, 0.4; g of bacteria per g of CHO digested per h
YPAA	g per day	Metabolizable requirement of aa for pregnancy

sections provide a description of each sub-model, with equations for each provided in Tables 1–16.

2.1. Maintenance

Energy available for productive functions depends on the proportion of energy consumed that must be used for meeting maintenance (NEm) requirements, and therefore is considered first in evaluating diet and animal performance. Maintenance requirements in the CNCPS (Tables 2 and 3) are determined by accounting for breed, physiological state, activity, urea excretion, heat or cold stress and environmental acclimatization effects (Fox et al., 1992; Fox and Tylutki, 1998). In growing cattle, the NEm of each breed (kcal/kg metabolic shrunk body weight: $SBW^{0.75}$) is adjusted using a 1–9 body condition scale (BCS). Because previous plane of nutrition can affect organ size, NEm is decreased or increased 5% for each BCS below or above 5 (1–9 scale), respectively, in growing cattle. The equations use the BCS of 1–9 for beef cattle and 1–5 for dairy cattle, as described in the energy reserves section. Eq. (29) in Table 2 is used to estimate the ME cost to synthesize urea N from protein in excess of requirements (7.3 kcal/g of N; Tyrrell et al. (1970)).

The National Research Council (NRC, 2000) increased the maintenance energy requirement for bulls by 15% and decreased the NEm by 10% for all types of *Bos indicus* cattle breeds. However, in a recent evaluation of three comparative slaughter experiments with Nellore cattle fed high forage diets, Tedeschi et al. (2002c) reported that the NEm of bulls ($n = 31$) and steers ($n = 66$) were similar, about 77.2 kcal/$kg^{0.75}$ EBW. For this reason, the CNCPS does not increase the NEm requirement for bulls, or reduce the NEm requirement for Nellore fed high forage diets.

The NEm requirement is adjusted for activity and energy needed to maintain normal body temperature for all classes of cattle. The impact of current temperature, animal insulation and heat loss versus heat production on NEm is computed from ME intake minus retained energy. Heat loss is calculated from temperature, wind velocity and thermal insulation of the animal (BCS, depth and condition of the hair coat). Relative humidity changes the animal's lower or upper critical temperature. Lower critical temperature is defined as the point at which fermentation and metabolism heat can no longer maintain body temperature and absorbed dietary energy must be used for this purpose. At the upper critical temperature, the animal reduces intake to decrease excess heat production in the body (Fox and Tylutki, 1998).

Heat stress is a common environmental effect in lactating dairy cows, but under normal housing, management and feeding conditions, they are not likely to experience cold stress (Fox and Tylutki, 1998; NRC, 2001). The current effective temperature index (CETI) uses current temperature and relative humidity to adjust predicted intake for temperature effects. At temperatures below 20 °C and relative humidity above 50%, the CETI is reduced. Conversely, at temperatures above 20 °C, the CETI is increased. Effects on NEm and intake are small within the range of CETI of 16–25 °C (Fox and Tylutki, 1998), but performance declines if the monthly CETI is greater than 25 °C (Fox and Tylutki, 1998).

The CNCPS assumes that protein requirements for maintenance are the sum of scurf protein, urinary protein, and metabolic fecal protein (NRC, 1984, 1985, 1989, 2000, 2001). Metabolic fecal protein is currently calculated as 9% of indigestible DM (i.e., 100 − digestible DM).

Table 2
Equations to estimate energy and protein requirements for maintenance

Equation	Variable	Constraints	Equations
(1)	NEmr		$(\mathrm{SBW}^{0.75} \times (a1 \times \mathrm{COMP} + a2) + \mathrm{Act} + \mathrm{NEmrcs}) \times \mathrm{NEmrhs}$
(2)	COMP		$0.8 + (\mathrm{BCS}_{1\text{–}9} - 1) \times 0.05$
(3)	$a2$		$((88.426 - 0.785 \times T_\mathrm{p} + 0.0116 \times T_\mathrm{p}^2) - 77)/1000$
(4)	PETI	$T_\mathrm{p} > 20\,^\circ\mathrm{C}$	$27.88 - (0.456 \times T_\mathrm{p}) + (0.010754 \times T_\mathrm{p}^2) - (0.4905 \times \mathrm{RHp}) + (0.00088 \times \mathrm{RHp}^2) + (1.1507 \times (1000/3600) \times \mathrm{WS}) - (0.126447 \times ((1000/3600) \times \mathrm{WS})^2) + (0.019876 \times T_\mathrm{p} \times \mathrm{RHp}) - (0.046313 \times T_\mathrm{p} \times ((1000/3600) \times \mathrm{WS})) + (0.4167 \times \mathrm{HRS})$
(5)	Act		$(0.1 \times$ standing H $+ 0.062 \times$ position changes $+ 0.621 \times$ flat distance $+ 6.69 \times$ vertical distance$) \times$ FBW
(6)	Im		$\mathrm{NEmr}/(\mathrm{NEma} \times \mathrm{ionophore})$
(7)	Ionophore	Growing animals	1.12 (otherwise 1)
(8)	RE	Growing cattle	$(\mathrm{DMI} - \mathrm{Im}) \times \mathrm{NEga}$
(9)	RE + YE + LE	Lactating cattle; uses NEma = Nel	$(\mathrm{DMI} - \mathrm{Im}) \times \mathrm{NEma}$
(10)	SA		$(0.09 \times \mathrm{SBW}^{0.67})$
(11)	HE		$(\mathrm{ME} \times \mathrm{DMI} - (\mathrm{RE} + \mathrm{YE} + \mathrm{LE}))/\mathrm{SA}$
(12)	MudME	HCCode ≤ 2	$1 - (\mathrm{HCCode} - 1) \times 0.2$
(13)	MudME	HCCode > 2	$0.8 - (\mathrm{HCCode} - 2) \times 0.3$
(14)	HideME		$0.8 + (\mathrm{HideCode} - 1) \times 0.2$
(15)	EI		$(7.36 - 0.296 \times \mathrm{WS} + 2.55 \times \mathrm{HD}) \times \mathrm{MudME} \times \mathrm{HideME}$
(16)	TI		$5.25 + 0.75 \times \mathrm{BCS}$
(17)	IN		$\mathrm{TI} + \mathrm{EI}$
(18)	LCT		$39 - (\mathrm{IN} \times \mathrm{HE} \times 0.85)$
(19)	MErcs	$\mathrm{LCT} > T_\mathrm{c}$	$\mathrm{SA} \times (\mathrm{LCT} - T_c)/\mathrm{IN}$
(20)	MErcs	$\mathrm{LCT} \leq T_\mathrm{c}$	0
(21)	NEmrcs	MErcs > 0	$(\mathrm{NEmr}/\mathrm{ME}) \times \mathrm{MErcs}$
(22)	CETI		$27.88 - (0.456 \times T_c) + (0.010754 \times T_\mathrm{c}^2) - (0.4905 \times \mathrm{RHc}) + (0.00088 \times \mathrm{RHc}^2) + (1.1507 \times (1000/3600) \times \mathrm{WS}) - (0.126447 \times ((1000/3600) \times \mathrm{WS})^2) + (0.019876 \times T_\mathrm{c} \times \mathrm{RHc}) - (0.046313 \times T_\mathrm{c} \times ((1000/3600) \times \mathrm{WS})) + (0.4167 \times \mathrm{HRS})$
(23)	NEmrhs	CETI > 20 °C and *Bos taurus*	$1.09857 - 0.01343 \times \mathrm{CETI} + 0.000457 \times \mathrm{CETI}^2$
(24)	NEmrhs	*Bos indicus*	1.07 (rapid shallow panting) or 1.18 (open mouth panting)
(25)	UPA		$2.75 \times \mathrm{SBW}^{0.5}/0.67$
(26)	SPA		$0.20 \times \mathrm{SBW}^{0.6}/0.67$
(27)	FPN		$0.09 \times \mathrm{IDM}$
(28)	MPm		$\mathrm{UPA} + \mathrm{SPA} + \mathrm{FPN}$
(29)[a]	UreaCost		$(\mathrm{RNB} - \mathrm{RecycledN} +$ excess N from MP$) \times 0.0073$

[a] The UreaCost (Mcal per day) is added to ME required when calculating energy balance.

Table 3
Breed maintenance requirement multipliers, birth weights, and peak milk production[a]

Breed	*a*1	Birth weight (kg)	Peak[b]			First conception weight[c]
			Milk (kg per day)	Fat (%)	Protein (%)	
Angus	0.070	31	8.0	4.0	3.8	0.60
Aryshire	0.073	32	36.0	4.0	3.4	0.55
Brown Swiss	0.073	39	37.0	3.5	3.3	0.55
Braford[d]	0.067	36	7.0	4.0	3.8	0.62
Brahman[d]	0.064	31	8.0	4.0	3.8	0.62
Brangus[d]	0.067	33	8.0	4.0	3.8	0.62
Braunvieh	0.084	39	12.0	4.0	3.8	0.57
Canchin[d]	0.067	35	8.0	4.0	3.8	0.65
Charolais	0.070	39	9.0	4.0	3.8	0.60
Chianina	0.070	41	6.0	4.0	3.8	0.60
Friesian	0.073	35	37.0	3.5	3.3	0.55
Galloway	0.070	36	8.0	4.0	3.8	0.60
Gelbvieh	0.074	39	11.5	4.0	3.8	0.57
Guernsey	0.073	32	35.0	4.7	3.7	0.55
Gir[d]	0.064	29	10.0	4.0	3.8	0.65
Guzerat[d]	0.064	32	7.0	4.0	3.8	0.65
Hereford	0.070	36	7.0	4.0	3.8	0.60
Holstein	0.073	43	43.0	3.5	3.3	0.55
Jersey	0.073	32	34.0	5.2	3.9	0.55
Limousin	0.070	37	9.0	4.0	3.8	0.55
Longhorn	0.070	33	5.0	4.0	3.8	0.60
Maine Anjou	0.070	40	9.0	4.0	3.8	0.60
Nellore[d]	0.070	32	7.0	4.0	3.8	0.65
Piedmontese	0.070	38	7.0	4.0	3.8	0.60
Pinzgauer	0.070	38	11.0	4.0	3.8	0.60
Polled Hereford	0.070	33	7.0	4.0	3.8	0.60
RedPoll	0.070	36	10.0	4.0	3.8	0.60
Sahiwal[b]	0.064	38	8.0	4.0	3.8	0.65
Salers	0.070	35	9.0	4.0	3.8	0.60
Santa Gertudis[d]	0.067	33	8.0	4.0	3.8	0.62
Shorthorn	0.070	37	8.5	4.0	3.8	0.60
Simmental	0.084	39	12.0	4.0	3.8	0.57
South Devon	0.070	33	8.0	4.0	3.8	0.60
Tarentaise	0.070	33	9.0	4.0	3.8	0.60

[a] Based on NRC (2000).
[b] *a*1, birth weight (CBW) and peak milk yield (PKYD) are used to predict cow requirements. Adjustments to *a*1 for lactation in beef breeds are the same as in the NRC (2000) (increased 20%) except high milk breeds (Simmental and Braunvieh), which are made the same as other *Bos taurus* beef breeds during lactation (0.084).
[c] Factor applied to mature weight to compute target weight at first conception.
[d] Breeds assumed to be tropical breeds (*Bos indicus*).

2.2. Growth

Energy and protein requirements for growth (Table 4) include adjustments for effects of body weight (BW), rate of body weight gain, chemical composition of gain, and mature weight (Fox et al., 1992, 1999; Tylutki et al., 1994; Tedeschi et al., 2002c), as adapted by

Table 4
Equations to estimate energy and protein requirements for growth, mammogenesis, and replacement heifer target weights

Equation	Variables	Constraints	Equations
(1)	SBW		$0.94 \times \text{FBW}$
(2)	EBW		$0.891 \times \text{SBW}$
(3)	EqSBW		$(\text{SBW} \times \text{SRW})/\text{AFBW}$
(4)	SWG		$13.91 \times \text{EqSBW}^{-0.6837} \times \text{RE}^{0.9116}$
(5)	EBG		$12.341 \times \text{EqEBW}^{-0.6837} \times \text{RE}^{0.9116}$
(6)	SWG		$\text{EBG}/0.956$
(7)	RE		$0.0635 \times \text{EqEBW}^{0.75} \times \text{EBG}^{1.097}$
(8)	NPg		$\text{SWG} \times (268 - 29.4 \times (\text{RE}/\text{SWG}))$
(9)[a]	MPg		$\text{NPg}/(0.834 - \text{EqSBW} \times 0.00114)$
(10)	MPmm		276.7
(11)	MEmm		$1/\text{NEga}$
(12)	TPW	Dual purpose and dairy	$\text{MW} \times 0.55$
(13)	TPW	*Bos taurus*	$\text{MW} \times 0.60$
(14)	TPW	*Bos indicus*	$\text{MW} \times 0.65$
(15)	TPA		$\text{TCA} - 280$
(16)	BPADG		$(\text{TPW} - \text{SBW})/(\text{TPA} - \text{T}_{\text{Age}})$
(17)	TCW1	If dairy	$\text{MW} \times 0.85$
(18)	TCW1	Otherwise	$\text{MW} \times 0.80$
(19)	TCW2		$\text{MW} \times 0.92$
(20)	TCW3		$\text{MW} \times 0.96$
(21)	TCW4		MW
(22)	APADG		$(\text{TCW1} - \text{SBW})/(280 - t)$
(23)	ACADG		$(\text{TCW}_x - \text{SBW})/(280 - (\text{CI} - t))$

[a] If $\text{EqSBW} \geq 478$ then $\text{EqSBW} = 478$.

NRC (2000, 2001). A size scaling system based on the ratio of current to mature weight is used to predict the composition of gain. Shrunk body weight (BW; SBW) is adjusted to a weight equivalent to that of a standard reference animal at the same stage of growth. This equivalent shrunk BW is calculated as follows: $\text{EqSBW} = \text{SBW} \times (\text{SRW}/\text{AFBW})$, where

Table 5
Equations to estimate weight gain, and energy and protein requirements for pregnancy

Equation	Variables	Constraints	Equations
(1)	ADG_{Preg}	Dairy	$(\text{CBW}/45) \times (\text{If } t < 190 \text{ days then } 100 \text{ otherwise } 664)$
(2)	ADG_{Preg}	Otherwise	$\text{CBW} \times (18.28 \times (0.02 - 0.0000286 \times t) \times \exp(0.02 \times t - 0.0000143 \times t^2))$
(3)	CpW	Dairy and $t > 190$ days	$(\text{CBW}/45) \times (18 + ((t - 190) \times 0.665))$
(4)	CpW	Otherwise	$(\text{CBW} \times 0.01828) \times (\exp(0.02 \times t - 0.0000143 \times t^2)$
(5)	ME_{Preg}	Dairy and $t > 190$ days	$(\text{CBW}/45) \times (2 \times 0.00159 \times t - 0.0352)/0.14$
(6)	ME_{Preg}	Otherwise	$(\text{CBW} \times (0.05855 - 0.0000996 \times t) \times \exp(0.03233 \times t - 0.0000275 \times t^2))/1000/0.13$
(7)	MP_{Preg}	Dairy and $t > 190$ days	$(\text{CBW}/45) \times (0.69 \times t - 69.2)/0.33$
(8)[a]	MP_{Preg}	Otherwise	$(\text{CBW} \times (0.001669 - 0.00000211 \times t) \times \exp(0.0278 \times t - 0.0000176 \times t^2)) \times 6.25/0.50$

[a] For beef cows the efficiency of use of MP is 50% (NRC, 1985; Wurgler and Bickel, 1987) compared to 65% (NRC, 2000).

Table 6
Equations to estimate energy and protein in the body reserves

Equation	Variables	Constraints	Equations
(1)	$BCS_{1–9}$		$(BCS_{1–5} - 1) \times 2 + 1$
(2)	AF		$0.037683 \times BCS_{1–9}$
(3)	AP		$0.200886 - 0.0066762 \times BCS_{1–9}$
(4)	EBW_r		$0.851 \times SBW$
(5)	TF		$AF \times EBW_r$
(6)	TP		$AP \times EBW_r$
(7)	TE		$9.4 \times TF + 5.7 \times TP$
(8)[a]	EBW_{BCS5}		EBW_r/adjustment factor
(9)	NE_{DLW}		$0.5381 \times BCS + 3.2855$
(10)[b]	DLW		$(\text{ME balance} \times \text{Efficiency}_{DLW})/NE_{DLW}$

[a] Adjustment factor is 0.726, 0.794, 0.863, 0.931, 1, 1.069, 1.137, 1.206, 1.274 for BCS 1–9.
[b] Efficiency_{DLW} is 0.75 for lactating dairy cow with positive energy balance or 0.785 with negative energy balance; otherwise it is 0.60.

Table 7
Equations to estimate energy and protein for lactation for beef cows

Equation	Variables	Constraints	Equations
(1)	$PKYD_{adj}$		$(0.125 \times RelMilkProd + 0.375) \times PKYD$
(2)	A		$1/(PKYD_{adj} \times (1/8.5) \times \exp(1))$
(3)	Milk		$n/(A \times \exp((1/8.5) \times n))$
(4)	$Milk_{adj}$	If age = 2 years	$0.74 \times milk$
(5)	$Milk_{adj}$	If age = 3 years	$0.88 \times milk$
(6)	$Milk_{adj}$	Otherwise	Milk
(7)[a]	LE		$Milk_{adj} \times ((0.3512 + (0.0962 \times MF))/0.644)$
(8)[a]	LP		$10 \times Milk_{adj} \times PP/0.65$

[a] LE and LP are user inputs if lactating-dairy cows.

SRW is the mature BW of the standard reference animal and AFBW is expected mature shrunk BW. In beef or dairy cows, mature BW is defined as the weight at which additional added body mass does not contain additional net protein gain, a condition assumed to occur by 4 years of age and at a BCS of 5 on a 1–9 scale for beef cows, or at BCS 3 on a 1–5 scale for dairy cows. For growing cattle to be harvested for beef, mature BW is the expected BW at the target body composition. Thus, for beef and dairy herd replacement heifers, SRW is always 478 kg, but the SRW of growing and finishing steers, heifers, or bulls is 400, 435,

Table 8
Equations to estimate amino acids requirements

Equation	Variables	Constraints	Equations
(1)	$MPAA_i$		$AATISS_i \times (FPN + ((UPA + SPA) \times 0.67)/EAAM_i)$
(2)	$RPAA_i$		$AATISS_i \times (NPg + MPmm \times 0.28908)/EAAG_i$
(3)	$LPAA_i$		$AALACT_i \times LP \times 0.65/EAAL_i$
(4)	$YPAA_i$	Dairy	$AATISS_i \times MP_{Preg} \times 0.33/EAAP_i$
(5)	$YPAA_i$	Otherwise	$AATISS_i \times MP_{Preg} \times 0.5/EAAP_i$

Table 9
Amino acid composition of tissue, milk protein, and ruminal bacteria[a]

Amino acid	Tissue[b]	Milk[c]	Ratios for milk production			Ruminal bacteria		
			CNCPS[d]	Schwab[e]	Rulquin[f]	Cell wall	Noncell wall	Mean[g]
Methionine	1.97	2.71	5.3	5.5	2.5	2.40	2.68	2.60
Lysine	6.37	7.62	16.9	16.0	7.3	5.60	8.20	7.90
Histidine	2.47	2.74	6.2	5.5	–	1.74	2.69	2.00
Phenylalanine	3.53	4.75	9.4	10.0	–	4.20	5.16	5.10
Tryptophan	0.49	1.51	2.5	3.0	–	1.63[h]	1.63	–
Threonine	3.90	3.72	9.4	8.9	–	3.30	5.59	5.80
Leucine	6.70	9.18	18.1	19.5	–	5.90	7.51	8.10
Isoleucine	2.84	5.79	11.5	11.4	–	4.00	5.88	5.70
Valine	4.03	5.89	12.5	13.0	–	4.70	6.16	6.20
Arginine	3.30	3.40	8.2	7.2	–	3.82	6.96	5.10

[a] Composition as %CP.
[b] Average of three studies summarized by whole empty body values of Ainslie et al. (1993).
[c] Waghorn and Baldwin (1984).
[d] Percent of essential amino acids.
[e] Percent of essential amino acids of the duodenum (Schwab, 1996).
[f] Percent of metabolizable protein.
[g] Average composition of 441 bacterial samples from animals fed 61 dietary treatments in 35 experiments (Clark et al., 1992). Included for comparison to the cell wall and non-cell wall values used in this model.
[h] Data were not available, therefore, content of cell wall protein was assumed to be same as non-cell wall protein (O'Connor et al., 1993).

462, or 478 kg when the harvest target is 22, 25, 27%, or 28% body fat, respectively, as described by NRC (2000, 2001). These body fat contents are associated with to devoid, trace, slight, and small degrees of marbling, respectively.

Mature cull cows sold in average body condition can be used as a starting point for estimating AFBW of breeding herd replacements. The AFBW of feedlot calves or yearlings

Table 10
Utilization of individual absorbed amino acids for physiological functions[a]

Amino acid	Maintenance ($EAAM_i$)	Pregnancy ($EAAP_i$)	Lactation ($EAAL_i$)
Methionine	0.85	0.35	1.00
Lysine	0.85	0.53	0.82
Histidine	0.85	0.32	0.96
Phenylalanine	0.85	0.48	0.98
Tryptophan	0.85	0.85	0.85
Threonine	0.85	0.57	0.78
Leucine	0.66	0.42	0.72
Isoleucine	0.66	0.32	0.66
Valine	0.66	0.32	0.62
Arginine	0.85	0.38	0.35

[a] Requirement for growth varies with stage of growth as determined by Ainslie et al. (1993). If EQSBW $<$ 478 kg then EAAG = 0.834 − (0.00114 × EQSBW), where EAAG is the efficiency of amino acid for growth factor and EQSBW is equivalent shrunk BW as described by Fox et al. (1992). Other values have been updated from O'Connor et al. (1993) by Overton (personal communication). Values are expressed as g/g.

Table 11
Equations to estimate dry matter intake

Equation	Variables	Constraints	Equations
(1)	DMI[a]	Calf (<12 momths old)	$SBW^{0.75} \times ((0.2435 \times NEma - 0.0466 \times NEma^2 - 0.1128)/NEma) \times BFAF \times BI \times ADTV \times DMIAF \times MudDMI$
(2)	DMI[a,b]	Yearling (>12 momths old)	$SBW^{0.75} \times ((0.2435 \times NEma - 0.0466 \times NEma^2 - 0.0869)/NEma) \times BFAF \times BI \times ADTV \times DMIAF \times MudDMI \times C1$
(3)	DMI[a]	Non-pregnant beef cow[c]	$SBW^{0.75} \times ((0.04997 \times NEma^2 + 0.03840)/NEma) \times DMIAF \times MudDMI + 0.2 \times Milk_{Adj}$
(4)	DMI[a]	Pregnant beef cow[d]	$SBW^{0.75} \times ((0.04997 \times NEma^2 + 0.04631)/NEma) \times DMIAF \times MudDMI + 0.2 \times Milk_{Adj}$
(5)	Lag[e]	If week in milk ≤16	$1 - \exp(-(0.564 - 0.124 \times PKMK) \times (\text{week in milk} + P))$
(6)	Lag	Otherwise	1
(7)	FCM		$0.4 \times milk + 15 \times milk \times MF$
(8)	DMI	Lactating dairy cow	$(0.0185 \times FBW + 0.305 \times FCM) \times DMIAF \times Mud \times Lag$
(9)	DMI[f]	Lactating dual purpose cow	$FBW^{0.75} \times (0.1462 \times NEma - 0.0517 \times NEma^2 - 0.0074) + 0.305 \times FCM + C2$
(10)	DMI[b]	Dry dairy cow	$0.02 \times SBW \times DMIAF \times MudDMI \times C1$
(11)	DMINC		$(119.62 - 0.9708 \times CETI)/100$
(12)	DMIAF	$T_c \leq -20\,^\circ C$	1.16
(13)	DMIAF	$-20\,^\circ C \leq T_c \leq 20\,^\circ C$	$1.0433 - 0.0044 \times T_c + 0.0001 \times T_c^2$
(14)	DMIAF	$T_c \geq 20\,^\circ C$, without night cooling	DMINC
(15)	DMIAF	$T_c \geq 20\,^\circ C$, with night cooling	$(1 - DMINC) \times 0.75 + DMINC$
(16)	MudDMI		$1 - 0.01 \times mud$
(17)	BI[g]	Holstein	1.08
(18)	BI[g]	Holstein × beef	1.04
(19)	BI[g]	Otherwise	1
(20)	BFAT[g]	EqSBW ≥ 350 kg	$0.7714 + 0.00196 \times EqSBW - 0.00000371 \times EqSBW^2$
(21)	BFAT[g]	Otherwise	1
(22)	ADTV[g]	Anabolic implant	1
(23)	ADTV[g]	No anabolic implant	0.94

[a] For diets with a NEma < 1 Mcal/kg then NEma (divisor) is 0.95. This equation is used for all dairy replacement heifers, without the BI, BFAT, or ADTV adjustments.
[b] If pregnant heifers use SBW minus CpW. If days pregnant >259 then $C1 = 0.8$ otherwise $C = 1$.
[c] Also used for first one-third of pregnancy.
[d] Used for last two-thirds of pregnancy.
[e] PKMK = 2 and $P = 2.36$.
[f] If milk production > 15 kg then $C2 = 1.7$, otherwise $C = 0$.
[g] The BI, BFAF, and ADTV adjustments are not applied for herd replacement heifers.

Table 12
Equations to estimate feed energy and protein values for level 1 predictions

Equation	Variables	Constraints	Equations
(1)	TDN_{1x}		$0.98 \times (100 - NDFn - CP - Ash - EE + IADICP) + (KDcp \times CP) + 2.70 \times (EE - 1) + 0.75 \times (NDFn - Lig) \times (1 - (Lig/NDFn)^{2/3}) - 7$
(2)	IADICP	Forages	$0.7 \times ADICP$
(3)	IADICP	Concentrates	$0.4 \times ADICP$
(4)	KDcp	Forages	$\exp(-0.0012 \times ADICP)$
(5)	KDcp	Concentrates	$1 - (0.004 \times ADICP)$
(6)	Lig	As %DM	$(Lignin/100) \times NDF$
(7)	NDFn		$NDF - (NDICP - ADICP)$
(8)	ADICP	As %DM	$(ADIN/100) \times CP$
(9)	NDICP	As %DM	$(NDIN/100) \times CP$
(10)	dTDN	Forages	$0.53 + 0.99 \times TDN_{1x} - 0.009 \times NDF + 0.00005 \times TDN_{1x} \times NDF + 8.96 \times DMIFactor - 0.1 \times TDN_{1x} \times DMIFactor - 0.13 \times NDF \times DMIFactor + 0.0005 \times TDN_{1x} \times NDF \times DMIFactor$
(11)	dTDN	Concentrates	$1.01 \times TDN_{1x} - 1.77 \times DMIFactor - 0.99$
(12)	DE		$(TDN/100) \times 4.409$
(13)	ME	Dry and lactating dairy	$(DE \times 1.01) - 0.45$
(14)[a]	ME	Beef cattle	$0.82 \times DE$
(15)	NEma		$1.37 \times ME - 0.138 \times ME^2 + 0.0105 \times ME^3 - 1.12$
(16)	NEga		$1.42 \times ME - 0.174 \times ME^2 + 0.0122 \times ME^3 - 1.65$
(17)	NEl		$ME \times 0.644$
(18)[b]	UIP		$(0.167 + a) + (1 + b) \times UIP_{1x} + (4.3 + c) \times DMIFactor + (-0.032 + d) \times UIP_{1x} \times DMIFactor$
(19)	$peNDF_{Factor}$	If peNDF < 20%	$1 - (20 - peNDF) \times 0.025$
(20)	$peNDF_{Factor}$	Otherwise	1
(21)	MP		$(dTDN \times DMI \times 1000 \times 0.13 \times 0.64 \times peNDF_{Factor}) + UIP \times CP \times DMI \times 1000 \times 0.8$
(22)	N balance		$((1 - UIP) \times DMI \times 1000 \times CP)/6.25 + RecycledN - (TDN \times DMI \times 1000 \times 0.13 \times peNDF_{Factor} \times 0.16)$

[a] Also for growing replacement dairy heifers.
[b] Coefficients *a*, *b*, *c*, and *d* are −0.07, 0.01, 0.17, and 0.09 for concentrates, otherwise zero.

should be adjusted for the use (or non-use) of various anabolic implants, using the following guidelines (NRC, 2000; Guiroy et al., 2002): (1) reduce finished BW 10–20 kg if an estrogenic implant is not used; (2) increase finished BW 30–45 kg for an aggressive implant program, which usually involves combinations of trenbolone acetate (TBA) and estrogen; (3) increase finished BW 25–45 kg for extended periods at slow rates of gain; and (4) decrease finished BW 25–45 kg for continuous use of a high energy diet from weaning.

Net energy for gain (NEg, which is RE in Eq. (7), Table 4) is based on empirical relationships described by the NRC (2000). Equivalent empty body weight (EqEBW) is 0.891 × EqSBW, where empty body gain (EBG) is 0.956 × shrunk weight gain (SWG). Across all beef cattle types, these equations accounted for 94% of the variation in energy and 91% of the protein retained with a 2% bias (NRC, 2000). Similar results were obtained with Holstein heifers (Fox et al., 1999). The CNCPS uses net energy available for gain (NEFG), corrected for NEm and BW adjusted to that of the standard reference animal to

Table 13
Equations to compute amounts and digestion and passage rates for feed carbohydrate and protein fractions for use in the level 2 rumen model

Equation	Variables[a]	Constraints	Equations
(1)	CHO_j		$100 - CP_j - EE_j - Ash_j$
(2)	CC_j		$(NDF_j \times Lignin_j \times 2.4)/100$
(3)	$CB2_j$		$NDF_j - (NDFIP_j \times CP_j)/100 - CC_j$
(4)	NFC_j		$CHO_j - CB2_j - CC_j$
(5)	$CB1_j$		$CB1NFC_j \times NFC_j/100$
(6)	CA_j		$NFC_j - CB1_j$
(7)	PA_j		$NPN_j \times (SolCP_j/100) \times (CP_j/100)$
(8)	$PB1_j$		$SolCP_j \times CP_j/100 - PA_j$
(9)	PC_j		$ADFIP_j \times CP_j/100$
(10)	$PB3_j$		$(NDFIP_j - ADFIP_j) \times CP_j/100$
(11)	$PB2_j$		$CP_j - (PA_j - PB1_j - PB3_j - PC_j)$
(12)	Kpf		$(0.38 + (0.022 \times DMI \times 1000/FBW^{0.75})$ $+ 2.0 \times FORAGE^2)/100$
(13)	Kpc		$(-0.424 + (1.45 \times Kpf \times 100))/100$
(14)	Kpl		$(4.413 + 0.191 \times DMI \times 1000/FBW)/100$
(15)	Af_j	Forage	$100/(NDF_j \times peNDF_j/100 + 70)$
(16)	Af_j	Concentrate	$100/(NDF_j \times peNDF_j/100 + 90)$
(17)	Kp_j	Forage	$Kpf \times Af_j$
(18)	Kp_j	Concentrate	$Kpc \times Af_j$
(19)	peNDFr	Growing/finishing	$0.1 \times DMI$
(20)	peNDFr	Otherwise	$0.23 \times DMI$
(21)	$RDCA_j$		$DMI_j \times CA_j \times (kd_{4j}/(kd_{4j} + kp_j))$
(22)	$RDCB1_j$		$DMI_j \times CB1_j \times (kd_{5j}/(kd_{5j} + kp_j))$
(23)	$RDCB2_j$		$DMI_j \times CB2_j \times (kd_{6j}/(kd_{6j} + kp_j))$
(24)	$RDPA_j$		$DMI_j \times PA_j$
(25)	$RDPB1_j$		$DMI_j \times PB1_j \times (kd_{1j}/(kd_{1j} + kp_j))$
(26)	$RDPB2_j$		$DMI_j \times PB2_j \times (kd_{2j}/(kd_{2j} + kp_j))$
(27)	$RDPB3_j$		$DMI_j \times PB3_j \times (kd_{3j}/(kd_{3j} + kp_j))$
(28)	$RDPEP_j$		$RDPB1_j + RDPB2_j + RDPB3_j$
(29)	$RECA_j$		$DMI_j \times CA_j \times (kp_j/(kd_{4j} + kp_j))$
(30)	$RECB1_j$		$DMI_j \times CB1_j \times (kp_j/(kd_{5j} + kp_j))$
(31)	$RECB2_j$		$DMI_j \times CB2_j \times (kp_j/(kd_{6j} + kp_j))$
(32)	$RECC_j$		$DMI_j \times CC_j$
(33)	$REPB1_j$		$DMI_j \times PB1_j \times (kp_j/(kd_{1j} + kp_j))$
(34)	$REPB2_j$		$DMI_j \times PB2_j \times (kp_j/(kd_{2j} + kp_j))$
(35)	$REPB3_j$		$DMI_j \times PB3_j \times (kp_j/(kd_{3j} + kp_j))$
(36)	$REPC_j$		$DMI_j \times PC_j$

[a] Subscript *j* means for each feed in the diet. Variable without the subscript *j* implies the sum of the variable with the subscript *j* across all feeds in the diet.

predict daily gain (Eq. (4), Table 4). After energy requirements have been determined, the amount of protein required for this gain is computed (Eq. (8), Table 4).

Recent research indicates that the growth rate of dairy herd replacement heifers affects first lactation milk production (Van Amburgh et al., 1998b; Fox et al., 1999; NRC, 2000, 2001). The NRC (2001) adopted the CNCPS approach of using target weights and daily gains to compute requirements for ADG for cattle of any mature weight (Fox et al., 1999).

Table 14
Equations to adjust carbohydrate B2 for the effect of ruminal pH

Equation	Variables[a]	Constraints	Equations
(1)	pH	peNDF < 24.5%	$5.425 + 0.04229 \times \text{peNDF}$
(2)	pH	Otherwise	6.46
(3)	Y_{1j}		$1/(\text{KM1}/(\text{kd}_{6j} - \text{KM1} \times \text{YG1}) + 1/\text{YG1})$
(4)	KM1′		$0.1409 - 0.0135 \times \text{pH}$
(5)	YG1′		$-0.1058 + 0.0752 \times \text{pH}$
(6)	RelY	pH > 5.7	$(1 - \exp(-5.624 \times (\text{pH} - 5.7)^{0.909}))/0.9968$
(7)	Y'_{ij}	pH > 5.7	$\text{RelY} \times Y_{1j}$
(8)	Kd'_{6j}	pH > 5.7	$(\text{KM1}' \times Y'_{1j} \times \text{YG1}')/(\text{YG1}' - Y'_{1j}) + \text{KM1}' \times \text{YG1}'$
(9)	RelY	pH ≤ 5.7	0
(10)	Y'_{ij}	pH ≤ 5.7	0
(11)	Kd'_{6j}	pH ≤ 5.7	0
(12)	Kd_{6j}		$\text{Min}(kd'_{6j}, \text{tabular kd}_{6j})$

[a] Subscript *j* means for each feed in the diet. Variable without the subscript *j* implies the sum of the variable with the subscript *j* across all feeds in the diet. Apostrophe indicates an intermediate calculation or adjusted variable. Eqs. (1) and (2) are used for both levels 1 and 2; all other equations are for level 2 only.

Coefficients to estimate the target weights are based on Gregory et al. (1992), Van Amburgh et al. (1998b) and NRC (2000). Target first conception weights are 55, 60, and 65% of mature BW for dairy, dual purpose and beef *Bos indicus*, and *Bos taurus* cattle, respectively. For dairy cattle, target BW after first calving is 85% of mature BW and is 80% of mature BW for all other types. Target post second and third calving BWs are 92 and 96% of expected mature BW for all cattle types.

Target BWs combined with current age and BW, age at first calving and calving interval are used to compute daily gain required to reach the next target weight. For example, for dairy heifers before conception, target BW gain to target first pregnant BW is (mature BW × 0.55 − current BW)/(days of age at first calving − 280 − current age). For first bred heifers, daily gain required to calving is (mature BW × 0.85 − current BW)/(280 − days pregnant). Conceptus daily gain is then added to the BW gain. If calving interval is extended or if there is compensatory growth, the user can increase ADG requirement by entering a shorter calving interval. Daily gain required during the first lactation (including the dry period) is (mature BW × 0.92 − current BW)/(calving interval days − days since calving). Daily gain for the second and third lactations is computed the same way, using 0.96 or 1 to compute the next target BW, respectively.

2.3. Pregnancy

The CNCPS computes pregnancy requirements and BW gain from growth of the gravid uterus based on expected calf birth weight and day of gestation (Bell et al., 1995; NRC, 2000, 2001; Table 5). For pregnant heifers, weight of fetal and associated uterine tissue is deducted from EqEBW to compute energy and protein requirements for growth, but conceptus growth then is added to ME and MP allowable ADG to compute target ADG for comparison with observed ADG.

Table 15
Equations to estimate microbial growth in the rumen

Equation	Variables[a]	Constraints	Equations
(1)	YG1	peNDF < 20%	YG1 × (1 − ((20 − peNDF) × 0.025))
(2)	YG2	peNDF < 20%	YG2 × (1 − ((20 − peNDF) × 0.025))
(3)	Y_{1j}		$1/(\text{KM1}/\text{kd}_{6j} + 1/\text{YG1})$
(4)	Y_{2j}		$1/(\text{KM2}/\text{kd}_{4j} + 1/\text{YG2})$
(5)	Y_{3j}		$1/(\text{KM2}/\text{kd}_{5j} + 1/\text{YG2})$
(6)	PepUpRate	With ionophore	7 × 2/3
(7)	PepUpRate	Without ionophore	7
(8)	Ratio		Max(RDPEP/(RDCA + RDCB1 + RDPEP), 0.18)
(9)	Imp		exp(0.404 × LN(Ratio × 100) + 1.942)
(10)	FCBact_j		$Y_{1j} \times \text{RDCB2}_j$
(11)	$\text{Adj}Y_{2j}$		$Y_{2j} \times (1 + \text{Imp}/100)$
(12)	$\text{Adj}Y_{3j}$		$Y_{3j} \times (1 + \text{Imp}/100)$
(13)	NFCBact_j		$\text{Adj}Y_{2j} \times \text{RDCA}_j + \text{Adj}Y_{3j} \times \text{RDCB1}_j$
(14)	NFCBactMass		NFCBact/(kpf × 24)
(15)	NFCBactPepUp		NDFBactMass × PepUpRate/100
(16)	RDPEPh		RDPEP/24
(17)	GrowthTime		1/(1 − kpl)
(18)	DisappTime		LN(((GrowthTime − 1) × RDPEPh)/NFCBactPepUp + 1)/LN(1 + (GrowthTime − 1)/3600)/3600
(19)	PepX		NFCBactPepUp × DisappTime
(20)	PeptideUp	PepX > RDPEPh	RDPEPh × 24
(21)	PeptideUp	Otherwise	PepX × 24
(22)	PeptidePass		RDPEP − PeptideUp
(23)	PeptideAcc		PeptideUp + PeptidePass
(24)	PeptideUpN		PeptideUp/6.25
(25)	PeptideReqN		0.66 × NFCBact × 0.1
(26)	PepBal		PeptideUpN − PeptideReqN
(27)	NFC_NH3_Req		0.34 × NFCBact × 0.625/6.25
(28)	NH3_Bact		Max(0, PepBal)
(29)	NH3_Diet		RDPA/6.25
(30)	RecycledN		$((121.7 - 12.1 \times \text{CP} + 0.3235 \times \text{CP}^2)/100) \times$ (Diet CP/6.25)
(31)	FC_NH3_Avail		Max(0, (NH3_Bact + NH3_Diet + RecycledN) − NFC_NH3_Req
(32)	FC_NH3_Req		FCBact × 0.625/6.25
(33)	BactNBalance		(PeptideUpN + NH3_Diet + RecycledN) − (PeptideReqN + NFC_NH3_Req + FC_NH3_Req)
(34)	EFCBact_j	BactNBalance < 0	FCBact_j
(35)	ENFCBact_j	BactNBalance < 0	NFCBact_j
(36)	NallowableBact	BactNBalance < 0	(PeptideUpN + NH3_Diet + RecycledN) × 0.1
(37)	EBactRatio_j	BactNBalance < 0	$(\text{EFCBact}_j + \text{ENFCBact}_j)/(\text{FCBact} + \text{NFCBact})$
(38)	NAllowableBact_j	BactNBalance < 0	$\text{NallowableBact} \times \text{EBactRatio}_j$
(39)	BactRed_j	BactNBalance < 0	$(\text{EFCBact}_j + \text{ENFCBact}_j) - \text{NallowableBact}_j$
(40)	EFCBactRatio_j	BactNBalance < 0	$\text{FCBact}_j/(\text{EFCBact}_j + \text{ENFCBact}_j)$
(41)	FCBactRed_j	BactNBalance < 0	$\text{BactRed}_j \times \text{EFCBactRatio}_j$
(42)	NFCBact_j	BactNBalance < 0	$\text{NFCBact}_j - \text{BactRed}_j \times (1 - \text{EFCBactRatio}_j)$
(43)	FCRed_j	BactNBalance < 0	$\text{FCBactRed}_j/Y_{1j}$
(44)	RDCB2_j	BactNBalance < 0	$\text{RDCB2}_j - \text{FCRed}_j$
(45)	FCRedRatio	BactNBalance < 0	(100 × FCRed)/RDCB2

Tabl 15 (*Continued*)

Equation	Variables[a]	Constraints	Equations
(46)	NFCBact	BactNBalance < 0	NFCBact
(47)	$ProtB3Red_j$	BactNBalance < 0	$FCRed_j \times (NDFIP_j - ADFIP_j) \times CP_j$
(48)	$RDPB3_j$	BactNBalance < 0	$Max(0, RDPB3_j - ProtB3Red_j)$
(49)	$AdjRDPB1_j$		$Max(0, RDPB1_j - PeptidePass \times RDPB1_j/RDPEP)$
(50)	$AdjRDPB2_j$		$Max(0, RDPB2_j - PeptidePass \times RDPB2_j/RDPEP)$
(51)	$AdjRDPB3_j$		$Max(0, RDPB3_j - PeptidePass \times RDPB3_j/RDPEP)$
(52)	$AdjREPB1_j$		$REPB1_j + (PeptidePass \times RDPB1_j/RDPEP)$
(53)	$AdjREPB2_j$		$REPB2_j + (PeptidePass \times RDPB2_j/RDPEP)$
(54)	$AdjREPB3_j$		$REPB3_j + (PeptidePass \times RDPB3_j/RDPEP) + ProtB3Red_j$
(55)	$AdjRECB2_j$		$RECB2_j + FCRed_j$
(56)	BactN		$(FCBACT + NFCBACT) \times 0.625/6.25$
(57)	EN		$PeptideUpN + NH3\_Diet + RecycledN - BACTN + (MP_{Avail} - MP_{Req})/6.25$
(58)	$REBTP_j$		$0.625 \times 0.6 \times Min(NAllowableBact_j, ENFCBact_j + EFCBact_j)$
(59)	$REBCW_j$		$0.625 \times 0.25 \times Min(NAllowableBact_j, ENFCBact_j + EFCBact_j)$
(60)	$REBNA_j$		$0.625 \times 0.15 \times Min(NAllowableBact_j, ENFCBact_j + EFCBact_j)$
(61)	$REBCA_j$		$0.211 \times 0.80 \times Min(NAllowableBact_j, ENFCBact_j + EFCBact_j)$
(62)	$REBCB1_j$		$0.211 \times 0.20 \times Min(NallowableBact_j, ENFCBact_j + EFCBact_j)$
(63)	$REBCHO_j$		$REBCA_j + REBCB1_j$
(64)	$REBFAT_j$		$0.12 \times Min(NAllowableBact_j, ENFCBact_j + EFCBact_j)$
(65)	$REBASH_j$		$0.044 \times Min(NAllowableBact_j, ENFCBact_j + EFCBact_j)$

[a] Subscript *j* means for each feed in the diet. Variable without the subscript *j* implies the sum of the variable with the subscript *j* across all feeds in the diet.

2.4. Body reserves

The CNCPS reserves model uses BCS rather than BW to compute energy reserves because most beef and dairy producers monitor BCS to manage energy reserves (Table 6). Further, since there are significant exchanges in body water and fat throughout lactation (Andrew et al., 1994), BW does not adequately account for changes in energy balance. After reaching maturity, BW changes reflect use or deposition of energy reserves (Fox et al., 1999; NRC, 2000, 2001). The BW gain and loss after maturity has nearly the same composition as BW gain during growth (Otto et al., 1991; Fox et al., 1999; NRC, 2000). The CNCPS uses the reserves model developed for the NRC (2000) and adapted for dairy cattle (NRC, 2001) as described by Fox et al. (1999). In the database used to develop this sub-model, mean SBW was 642 kg (BCS 5 on the 1–9 scale), the average BW change per BCS change was 44 kg (6.85% of the mean BW), and EBW was 85.1% of SBW. NRC (2000) computes BW

Table 16
Equations to estimate intestinal digestibility, fecal output, total digestible nutrients and energy values of feedstuffs, and supply of amino acids

Equation	Variables[a]	Constraints	Equations
(1)[b]	$DIGPB1_j$		$IntDigPB1_j \times REPB1_j$
(2)	$DIGPB2_j$		$IntDigPB2_j \times REPB2_j$
(3)	$DIGPB3_j$		$IntDigPB3_j \times REPB3_j$
(4)	$DIGFP_j$		$DIGPB1_j + DIGPB2_j + DIGPB3_j$
(5)	$DIGBTP_j$		$REBTP_j$
(6)	$DIGBNA_j$		$REBNA_j$
(7)	$DIGP_j$		$DIGFP_j + DIGBTP_j + DIGBNA_j$
(8)	$DIGFC_j$		$IntDigCA_j \times RECA_j + IntDigCB1_j \times RECB1_j + IntDigCB2_j \times RECB2_j$
(9)	$DIGBC_j$		$0.95 \times REBCHO_j$
(10)	$DIGC_j$		$DIGFC_j + DIGBC_j$
(11)	$REFAT_j$		$I_j \times Ee_j$
(12)	$DIGFF_j$		$IntDigFAT_j \times REFAT_j$
(13)	$DIGBF_j$		$0.95 \times REBFAT_j$
(14)	$DIGF_j$		$DIGFF_j + DIGBF_j$
(15)	$FEPB3_j$		$(1 - IntDigPB3_j) \times REPB3_j$
(16)	$FEPC_j$		$REPC_j$
(17)	$FEFP_j$		$FEPB3_j + FEPC_j$
(18)	$FECB1_j$		$(1 - IntDigCB1_j) \times RECB1_j$
(19)	$FECB2_j$		$(1 - IntDigCB2_j) \times RECB2_j$
(20)	$FECC_j$		$RECC_j$
(21)	$FEFC_j$		$FECB1_j + FECB2_j + FECC_j$
(22)	$FEFA_j$		$I_j \times ASH_j \times (1 - IntDigAsh_j)$
(23)	$FEFF_j$		$REFAT_j \times (1 - IntDigFAT_j)$
(24)	$FEBCW_j$		$REBCW_j$
(25)	$FEBCP_j$		$FEBCW_j$
(26)	$FEBC_j$		$(1 - 0.95) \times REBCHO_j$
(27)	$FEBF_j$		$(1 - 0.95) \times REBFAT_j$
(28)	$FEBASH_j$		$(1 - 0.50) \times REBASH_j$
(29)	$FEBACT_j$		$FEBCP_j + FEBC_j + FEBF_j + FEBASH_j$
(30)	$FEENGP_j$		$0.09 \times IDM_j$
(31)	$FEENGF_j$		$0.0119 \times DMI_{gj}$
(32)	$FEENGA_j$		$0.017 \times DMI_{gj}$
(33)	$FEPROT_j$		$FEFP_j + FEBCP_j + FEENGP_j$
(34)	$FECHO_j$		$FEFC_j + FEBC_j$
(35)	$FEFAT_j$		$FEBF_j + FEFF_j + FEENGF_j$
(36)	$FEASH_j$		$FEFA_j + FEBASH_j + FEENGA_j$
(37)	IDM_j		$(FEFP_j + FEBCP_j + FECHO_j + FEFAT_j + FEASH_j)/0.91$
(38)	$TDNAPP_j$		$PROT_j - FEPROT_j + CHO_j - FECHO_j + 2.25 \times (FAT_j - FEFAT_j)$
(39)	ME_j	Lactating dairy	$(0.001 \times TDNAPP_j \times 4.409 \times 1.01) - 0.45$
(40)	ME_j	Otherwise	$0.001 \times TDNAPP_j \times 4.409 \times 0.82$
(41)	NEl		$ME_j \times 0.644$
(42)	$NEga_j$		$1.42 \times ME_j - 0.174 \times ME_j^2 + 0.0122 \times Me_j^3 - 1.65$
(43)	$NEma_j$		$1.37 \times ME_j - 0.138 \times ME_j^2 + 0.0105 \times ME_j^3 - 1.12$
(44)	MP_j		$DIGP_j - DIGBNA_j$
(45)[c]	$REBAA_i$		$AABCW_i \times REBCW_j/100 + AABNCW_i \times REBTP_j/100$
(46)[c]	$DIGBAA_i$		$AABNCW_i \times 0.01 \times REBTP_j$

Table 16 (*Continued*)

Equation	Variables[a]	Constraints	Equations
(47)[c]	$REFAA_i$		$AAINSP_{ij} \times (REPB1_j + REPB2_j + REPB3_j + REPC_j)/100$
(48)[c]	$REAA_i$		$REBAA_i + REFAA_i$
(49)[c]	$DIGFAA_i$		$AAINSP_{ij} \times (IDPB1 \times REPB1_j + IDPB2 \times REPB2_j + IDPB3 \times REPB3_j)/100$
(50)[c]	AAA_{si}		$DIGBAA_i + DIGFAA_i$

[a] Subscript *j* means for each feed in the diet. Variable without the subscript *j* implies the sum of the variable with the subscript *j* across all feeds in the diet.

[b] Recommended intestinal digestibilities to use for carbohydrate fraction B1 in grain are as follows. For growing beef steers and lactating dairy cows consuming feed at two to three times maintenance level of intake: whole corn, 30–50%; cracked corn, 50–70%; dry rolled corn, 70–80%; corn meal, 80–90%; whole high moisture corn, 80–90%; high moisture ground corn, 85–95%; steam flaked corn, 92–97%; dry rolled sorghum, 60–70%; dry ground sorghum, 70–80%; and steam flaked Sorghum, 90–95%. For high producing dairy cows (above 45 kg milk): whole corn, 30–40%; cracked corn, 40–60%; corn meal, 70–90%; rolled high moisture corn, 75–85%; and processed small grains (wheat, barley, oats), 90%.

[c] Subscript *i* means for each amino acid.

change per condition score as 6.85% for each BCS on either side of the BW at BCS 5. The NRC (2000) model was adapted for dairy cattle (Fox et al., 1999) by converting dairy BCS of 1–5 to the 1–9 score ((dairy BCS − 1) × 2 + 1), with one condition score resulting in a 13.5, 7.54, and 1.33% change in SBW, fat and protein.

Change in BCS is subtracted or added to the current BCS to compute energy and protein gain or loss. In the reserves model, 0.75 is the efficiency of use of ME for reserves in lactating cows and 0.644 is the efficiency of use of ME for lactation. The evaluations described by Fox et al. (1999), using the data of Otto et al. (1991), indicate that this model accounts for 96% of the variation in body fat of dairy cattle with a 1.6% bias, and the predicted change per BCS was 80 versus the observed value of 84.6 kg.

2.5. Lactation

Energy and protein required for lactation are calculated from actual milk production and components (Table 7). Crude milk protein is adjusted to true milk protein (crude protein (%) × 0.93) to compute requirements. If protein and fat are not entered, the CNCPS calculates lactation energy and protein from default values. Metabolizable energy required for lactation is computed from milk energy with an efficiency of 64.4% (Moe, 1981). Metabolizable protein requirements are computed from milk yield and milk protein content and MP is converted to milk protein with an efficiency of 65% (NRC, 1985). Since actual milk production of beef cows usually is not measured, lactation requirements are estimated from age of cow, time of lactation peak, expected peak milk yield based on breed and calf weaning weights, day of lactation, duration of lactation, milk fat content, milk solids not fat, and protein as described by NRC (2000).

2.6. Amino acid (AA) requirements

Equations used to compute amino acid (AA) requirements are provided in Table 8, as described and discussed by Fox and Tedeschi (2003). Table 9 lists the AA composition of tissue and milk, recommended ratios of methionine and lysine for milk production, and ruminal bacteria, and Table 10 includes the efficiencies of utilization of AAs for each physiological stage. Coefficients for the efficiency of individual AAs use for pregnancy and lactation have been updated from the original values in O'Connor et al. (1993). The revised coefficients for use of individual AAs for pregnancy were calculated based upon uptake/output of individual AAs by the gravid uterus in sheep (Chung et al., 1998). The revised coefficients for the efficiency of individual AAs use for lactation were calculated from summarized data for uptake/output of individual AAs by the mammary gland in experiments using dairy cattle (Spires et al., 1975; Clark et al., 1977; Erickson et al., 1992; Hanigan et al., 1992; Cant et al., 1993; Guinard and Rulquin, 1995; Metcalf et al., 1996; Lykos and Varga, 1997; Mackle et al., 2000). The high value for methionine (100%) reflects the arithmetic mean of the experimental observations. The datasets above indicate that there is little net use of methionine for processes other than milk protein synthesis in the mammary gland. The AA requirements for gain or milk production are compared to AAs that would be supplied from the chemical and physical characteristics of the feed, the AA composition of the insoluble protein that escapes the rumen, the AA composition of bacterial protein and efficiency of use (O'Connor et al., 1993; Rulquin and Vérité, 1993; NRC, 2000, 2001). NRC (2001) recommends that MP supply contain 7.2% LYS and 2.4% MET. These ratios have not been evaluated, or developed, for other classes of cattle. The lack of a protected lysine product makes it difficult to attain the high lysine values suggested by the French workers.

2.7. Dry matter (DM) intake

The CNCPS computes supply of nutrients from actual dry matter (DM) intake (DMI). However, empirical equations are provided to predict DMI when intake is not known and for comparison with measured intakes. Equations (Table 11) specifically developed for beef cattle (NRC, 2000), dual purpose cattle (Traxler, 1997), and dairy cattle (Milligan et al., 1981; Roseler et al., 1997a,b) are used. For all cattle types, DMI is adjusted for the effect of temperature, and the predicted DMI is adjusted for lot mud depth because animals become increasingly reluctant to go the feed bunk as mud depth increases.

2.8. Levels 1 and 2 for predicting supply of energy and protein

The CNCPS has two levels of solution to accommodate the needs of different types of users. Level 1 is intended for conditions where feeds cannot be well characterized or the user is not knowledgeable enough to use the CNCPS rumen model with confidence. Level 2 is intended for users who have adequate information on feed composition and DMI and an understanding of how to use the level 2 rumen model. Both levels use TDN and NRC (2000) equations to predict DE, ME, NEm and NEg while NE_l is computed using equations from NRC (1989).

Level 1 computes TDN and MP values with empirical equations (Table 12) based on those developed by Weiss et al. (1992), Weiss (1993, 1999) and NRC (2001). Once TDN is computed at an energy maintenance level of intake (Eq. (1), Table 12), it is adjusted for other levels of intake (Tedeschi, 2001). The MP from microbial protein, which is assumed to be 64% true protein, is calculated as 13% of TDN, the same equation used in the dairy NRC (2001) and level 1 of the beef NRC (2000). The TDN discounted for level of DMI is used by NRC (2001) and CNCPS level 1, whereas NRC (2000) level 1 uses undiscounted TDN. Undegraded protein from feed is calculated from CP intake and ruminally undegraded CP (%UIP) and has an intestinal digestibility of 80%.

In level 2 of the CNCPS, ruminally available TDN and MP are derived mechanistically from digestion (K_d) and passage (K_p) rates (Russell et al., 1992; Sniffen et al., 1992) using the simple relationship, $K_d/(K_d+K_p)$. Feed not digested in the rumen will pass undegraded to the intestines where it may or may not undergo further digestion. Each feed component (NDF, CP, soluble CP, NDFIP and ADIP, lignin, fat, ash (Fox et al., 2003)) is assigned its own K_d, and this value can be modified to accommodate variations in feed processing. The K_p values depend on factors such as intake, particle size, lignification and the ratio of forage to concentrate. Sugars usually have a high K_d (>60%) and are almost completely digested in the rumen, but many carbohydrates and proteins (e.g., B fraction components) have a low K_d and are not completely digested by ruminal microorganisms. This system of calculating ruminal disappearance assumes that: (1) K_d is a simple first order rate, (2) each feed component operates as a single pool, (3) ruminal microorganisms are always in excess, (4) there is no time lag before initiation of fermentation, and (5) K_p depends only on intake and physically effective NDF (peNDF). While one might argue that these assumptions are not always valid, this simplification has allowed practical application of this concept in describing feeds and validating the overall model.

The CNCPS has several outputs that can be used to assess whether protein or energy is the first limiting nutrient for milk production or gain. Two of the N outputs (rumen N balance and peptide balance) show the N status of the ruminal bacteria, but the peptide balance is not a requirement per se. The peptide balance is the amount of peptide needed to stimulate protein production from NFC bacteria. A negative peptide balance indicates that yield of microbial protein from NFC bacteria could be increased by adding ruminally-degraded true protein to the diet. If the total flow of microbial protein, or ruminal escape protein, exceeds the protein needs of the animal, production will not increase. The remaining two N outputs (MP balance and AA allowable milk or gain) reflect the needs and supply of protein and essential AAs to the animal. Scrutiny of all four N balances is essential in diet evaluation.

2.9. Physically effective NDF (peNDF)

When cattle are fed diets deficient in fiber and rich in grain, ruminal pH can decline significantly. Davis et al. (1964) noted that cows fed grain-based diets produced less saliva than those fed forage, and other workers have shown that they often have a slower fluid dilution rate (Allen, 1997). If the dilution rate is rapid, VFA can pass out of the rumen in the fluid phase and be absorbed from the abomasum where the pH is lower and passive diffusion more rapid, but this avenue of VFA removal is depressed in animals fed grain-based rations (Russell, 2002). The effectiveness of the NDF in stimulating saliva flow and ruminal fluid dilution rate is manifested in its ability to stimulate chewing, rumination and rumen motility. The CNCPS uses the NDF content of the ration and the physical properties of the NDF to predict ruminal pH and the impact of acidic pH on ruminal fermentation (Table 14). The peNDF is the percent of the NDF that is retained on a 1.18 mm screen as described by Mertens (1997). Default NDF and physically effective NDF values are provided in the CNCPS feed library (Fox et al., 2003).

2.10. Describing feeds for level 2 of the CNCPS

The pool sizes of carbohydrate and protein fractions needed to predict rumen fermentation and escape are computed as shown in Table 13 and default chemical composition values are provided in the feed library (Fox et al., 2003). In level 2 of the CNCPS, carbohydrates are defined as fiber carbohydrates (FC) or non-fiber carbohydrates (NFC). The FC is equal to the NDF and NFC is total DM minus NDF (adjusted for NDIP), CP, fat, and ash. Carbohydrates (CHO) are further categorized into A, B1, B2 and C fractions. The CHO A fraction is a very rapidly fermented, water soluble, pool that is largely composed of sugars, although it also contains organic acids and short oligosaccharides. The CHO B1 fraction, with a slower K_d than CHO A, is primarily starch and pectin. The CHO B2 pool is composed of available NDF. The CHO C pool is an indigestible fraction, and it is computed as NDF $\times$ Lignin $\times$ 2.4 (%DM). The assumption that the CHO A fraction is largely sugar is an oversimplification, and does not account for the fact that forages and silages can have a significant amount of organic acids. Organic acids are not utilized as efficiently for microbial growth as sugars (Doane et al., 1997a; Molina, 2002). Microbial growth from the organic acid fraction of CHO A of silages in the feed library is reduced by 50% to adjust this overestimation of microbial growth (Fox et al., 2003).

Protein fractions (as a percentage of CP) are described using a scheme similar to that used for carbohydrates. Protein fraction A (PROT A) of CP is NPN that enters the ruminal ammonia pool directly. PROT B1 is true protein that has a rapid K_d and is nearly completely degraded in the rumen. The PROT C fraction is acid detergent insoluble protein (ADIP) and is assumed to be unavailable. The PROT B3 or slowly degraded protein fraction is determined by subtracting the value determined for ADIP from the value determined for neutral detergent insoluble protein (NDIP). The PROT B2 fraction, which is partly degraded in the rumen, is then estimated as the difference between CP and the sum of soluble + B3 + C where the soluble protein equals A + B1. Intestinal digestibility of the amino acids is assumed to be 100% for B1 and B2 and 80% for B3 protein pools, as described by O'Connor et al. (1993).

The assumption that PROT A fraction protein is NPN that enters the ruminal ammonia pool directly can be a problem with high quality alfalfa silages (Makoni et al., 1997; Aquino et al., 2003; Ross and Van Amburgh, 2003). As much as two-thirds of the NPN can be peptides and AAs that are forms of N that stimulate growth of NFC bacteria to a greater extent than ammonia (see microbial growth below). If alfalfa silage is high quality and has been ensiled properly, as much as two-thirds of the NPN should be included in the PROT B1 fraction.

Estimates of K_d values for common feeds were developed (Sniffen et al., 1992) and have been expanded to over 150 feedstuffs (Tedeschi et al., 2001; Tedeschi et al., 2002b; Fox et al., 2003). The K_d values were in most cases extrapolated from in vitro studies or in situ experiments. Protein K_d degradation rates have also been estimated from enzymatic studies. Many of the values in the original feed library (Sniffen et al., 1992) have been updated for the current feed library (Fox et al., 2003), based on recent studies with a gas production system

(Pell and Schofield, 1993; Schofield et al., 1994; Schofield and Pell, 1995a,b; Stefanon et al., 1996; Pell et al., 1998; Schofield, 2000; Molina, 2002), including evaluations of Doane et al. (1997b), Chen et al. (1999), Juarez Lagunes et al. (1999), Cerosaletti (1998), Kolver et al. (1998), and Tedeschi et al. (2002b). The use of the terms A, B and C to describe feed carbohydrate and proteins is a convenient method of classification, but it does not circumvent the need for independent measurements of K_d. Some organic acids have a slow K_d and can also escape the rumen (Doane et al., 1997a; Molina, 2002). The K_p rate is computed as a function of level of intake, percent forage, and peNDF value (Table 13).

2.11. Microbial growth in level 2 of the CNCPS

In level 2 of the CNCPS, ruminal microorganisms are categorized as bacteria that ferment FC and NFC (Russell et al., 1992; NRC, 2000). Generally, FC bacteria degrade cellulose and hemicellulose, grow more slowly, and utilize ammonia as their primary N source for microbial protein synthesis. The NFC bacteria that utilize starch, pectin, and sugars usually grow more rapidly than FC bacteria and can utilize ammonia or AAs as N sources. The rate of NFC and FC bacterial growth (μ) is dictated by the amount of carbohydrate that is digested in the rumen and the rate of carbohydrate digestion (K_d) so long as adequate N sources and other essential nutrients are available (Tables 14 and 15). The CNCPS assumes that bacterial growth rate (μ) is proportional to K_d, and this assumption is, in turn, based on the hypothesis that the rumen operates as a substrate-limited, enzyme (microbial mass) excess system. Critics have argued that fermentation rate is at times limited by microbial mass (Dijkstra et al., 2002), but it should be realized that most feedstuff components are insoluble and have a K_d value that is significantly lower than maximum μ of ruminal microorganisms. Given these observations, the assumption that μ and K_d are usually proportional is justified. However, factors such as energy spilling mechanisms (Van Kessel and Russell, 1993) might affect relationships between μ and K_d.

Dijkstra et al. (2002) concluded that there was little experimental "agreement" on the theoretical maximum growth yield (Y_g) of mixed ruminal bacteria, but many of the cited studies used batch culture techniques that selected for rapidly growing bacteria (e.g., *S. bovis*), did not account for changes in cell composition and did not consider that energy sources can be the source of cell carbon if AAs are not available (Russell and Strobel, 1993). The CNCPS assumes that NFC and FC bacteria both have a theoretical maximum growth yield (Y_g) of 50 g cells/100 g of carbohydrate fermented, an identical value to that reported by Isaacson et al. (1975) in continuous cultures of mixed ruminal bacteria. If it is assumed that ruminal bacteria can derive approximately 3.75 mmol of ATP/mole of hexose, the ATP yield would be 25 g of cells per mol. This value is lower than the hypothetical value (32 g cells/mol ATP) proposed by Stouthamer (1973), but it is within the range of values reported for pure cultures of ruminal and other anaerobic bacteria (Russell and Wallace, 1997).

Protozoa can comprise as much as 50% of the microbial mass in the rumen, but the rumen sub-model of the CNCPS does not have a protozoal pool per se. This simplification is based on the work of Weller and Pilgrim (1974). They noted that protozoa lyse easily, recycle themselves, and contribute little microbial protein to the animal. The impact of protozoa on ruminal fermentation is addressed by adjusting the theoretical maximum growth yield of bacteria. Although FC and NFC bacteria have the same theoretical maximum growth yield (Y_g) (40 g of cells/100 g of carbohydrate fermented), this value has been decreased by 20% to account for the presence of protozoa. The CNCPS does not specifically address defaunation, but Y_g could be increased to accommodate this effect. Ruminal fungi account for less than 8% of rumen microbial mass and they are ignored in the model.

It has long been recognized that bacteria must devote a fraction of their ATP to non-growth functions, and this expenditure is analogous to the maintenance energy of animal cells (Russell and Cook, 1995). Because bacteria must use energy to maintain cell integrity, yield declines particularly at slow growth rates. The CNCPS uses the double reciprocal plot of Pirt (1965) to correct the yield (Y) for maintenance energy (m): $1/Y = (m/\mu) + (1/Y_g)$. The CNCPS assigns different maintenance coefficients to the FC and NFC bacteria (0.05 and 0.15 g carbohydrate/(g microorganism h), respectively). In recent years, it has become apparent that most bacteria have another avenue of non-growth energy dissipation that is distinctly different from maintenance energy, and this dissipation has been called "energy spilling" (Russell and Wallace, 1997). The impact of maintenance on cell yield is most apparent when energy is limiting, but bacteria are more apt to spill energy when it is in excess. The energy status of bacteria can be envisioned as a balance of anabolic and catabolic rates, and most bacteria grow twice as fast if they are supplied with preformed AAs. The CNCPS does not have an energy spilling function per se, but it has a peptide stimulation algorithm that increases yield by as much as 18% if peptides and AAs are available (Russell and Sniffen, 1984).

Partitioning of ruminal bacteria into those that use FC and those that use NFC is consistent with distinctly different patterns of N utilization. The CNCPS assumes that FC bacteria use ammonia as a N source for growth, but NFC bacteria can use either ammonia, peptides or AAs (Russell et al., 1992). Atasoglu et al. (2001) examined the ability of pure cultures of ruminal cellulolytic bacteria to use ammonia versus amino N, and they found that "a mean of 80% of the cell N was from NH_3." The assumption that fiber is only digested by cellulolytic bacteria is clearly an oversimplification, and this may partly explain why some researchers have been able to stimulate fiber digestion by adding ruminally-degraded protein (Dijkstra et al., 2002). Another reason is the availability of branched chain VFA (BCVFA; see 'model improvement for future CNCPS' versions).

The CNCPS provides the user with a "rumen N balance", a parameter that is based on both the amount of N that is incorporated in bacterial cells and the amount of feed N that is converted to ammonia. Nitrogen incorporated is based on in vitro experiments with mixed ruminal bacteria that were fed a mixture of soluble carbohydrates (NFC) on an hourly basis so growth rate could be controlled (approximately 7%/h), and the ammonia pool was labeled with ^{15}N ammonia so the relative contribution of ammonia and amino N could be determined (Russell et al., 1983). These experiments indicated that NFC bacteria prefer amino N if both ammonia and amino N are available. Under these conditions, two-thirds of their N is derived from the peptide and AA pools. If amino N is not available, all NFC bacterial N is derived from ammonia. Because cellulolytic bacteria do not utilize amino N well (Bryant, 1973; Russell et al., 1992; Atasoglu et al., 2001), FC bacteria derive all of their N from the ammonia pool.

In the CNCPS, AA deamination is a function of NFC (but not FC) bacteria, and amino N status of the NFC bacteria can be assessed by examining the ruminal peptide pool balance. If this pool is negative, the NFC bacteria lack amino N, and addition of ruminally-degraded protein should have a positive impact on bacterial protein flow from the rumen (see section on energy spilling above). However, as noted above, the growth of NFC bacteria is dependent on the amount and rate of NFC fermentation (Russell et al., 1983). If the peptide balance is positive, the NFC bacteria have more amino N than they can incorporate into protein, and the excess will be converted to ammonia. Because fate of amino N is determined by the balance of NFC growth and deamination rates, rate of amino N uptake into NFC bacteria is also defined by a rate (K_{up}). The K_{up} rate is currently assigned a fixed value of 30 nmol/mg bacterial protein/min until the amino N pool is exhausted, but recent work indicated that this value may be diet dependent with lower values for animals consuming grain-based rations (Lana et al., 1998).

The rumen sub-model was constructed before the isolation and characterization of obligate AA (OAA) fermenting bacteria (Paster et al., 1993). These bacteria ferment AAs, but not carbohydrates, and can contribute significantly to the ammonia production of cattle fed forage (Yang and Russell, 1993; Rychlik and Russell, 2000). The OAA fermenting bacteria violate the assumption that all ruminal bacteria need carbohydrates (or possibly organic acids) to grow, but they have very low growth yields and contribute little bacterial protein to the animal. The OAA fermenting bacteria are currently part of the NFC bacterial pool, a categorization that is not ideal. They are more sensitive to ionophores than true NFC bacteria that can also deaminate AAs.

Early versions of the CNCPS, noted that "if ammonia becomes limiting, yield should theoretically decline, but the CNCPS does not make any provision for this type of limitation" (Russell et al., 1992). Version 4.0 of the CNCPS, and subsequent releases, account for effects of ruminal N deficiency (Tedeschi et al., 2000a; Tedeschi et al., 2000b). Fiber digestion rate and microbial yield are reduced proportional to the ammonia deficiency. If the rumen N balance is negative, microbial yield and fiber escaping the rumen are adjusted as: (1) the sum of rumen available peptides and ammonia is divided by microbial N content to determine the N allowable microbial growth, (2) this value is subtracted from the energy allowable total microbial growth to obtain the reduction in yield, (3) this yield reduction is allocated between FC and NFC bacteria based on their proportions in the energy allowable total bacterial growth, and (4) the loss in fiber digested is computed as the loss in FC yield divided by its growth rate, which is added to FC escaping the rumen. These calculations do not account for inefficiency of microbial N utilization of ruminally-degraded dietary N. In the NRC (2001), this inefficiency is addressed by assuming bacteria capture 85% of ruminally-degraded N. In the current version of the CNCPS, the NRC (1985) equation is used to estimate recycled N added to the rumen supply of N to account for the effects of this inefficiency.

Acidic pH can have a dramatic effect on the growth of some ruminal bacteria (Russell and Dombrowski, 1980; Strobel and Russell, 1986). In early versions of the CNCPS, yields of FC and NFC bacteria were reduced 2.5% for each reduction in peNDF, if forage NDF was less than 20% of DM (Russell et al., 1992). In the 1990s, equations were added to predict ruminal pH and adjust microbial yield (Pitt et al., 1996). However, it has now become apparent that these equations are not always accurate. Pitt et al. (1996) assumed that the maintenance energy of FC bacteria increased when pH declined, but there is now strong evidence that pH only causes a metabolic inhibition (Russell and Wilson, 1996). Because yields of FC and NFC bacteria already have been discounted by effects of peNDF, the pH-dependent increase in maintenance leads to "double accounting" for the decrease in FC bacteria. Ruminal pH is not currently sensitive to the rate of starch fermentation nor the fluid dilution rate that would carry VFA out of the rumen. When VFA are washed out of the rumen in fluid, they can be absorbed from the abomasum where the pH is lower and rate of passive dilution is faster.

The rumen sub-model was evaluated with experiments that measured bacterial N and undergraded feed protein from flow from the rumen (Russell et al., 1992; O'Connor et al., 1993). These evaluations indicated that the CNCPS accounted for 93, 95, 76, and 79% of actual N, non-ammonia N, bacterial N and dietary non-ammonia N flows from the rumen, respectively, and 81–90% of the variation in essential AAs was also explained. However, it should be noted that these validations included a wide range of duodenal flows. Other workers have had less success in evaluating the CNCPS rumen sub-model, but the range of diets and animal performance was much narrower and most of the feed information was from the feed library rather than measured values (Zinn and Shen, 1997; Kohn et al., 1998). True tests the CNCPS should be based on descriptions of the feeds that were actually offered, not those listed in the glossary.

2.12. *Intestinal digestion*

The equations that are used to predict intestinal digestion and fecal losses for feed fractions escaping ruminal degradation and microbial mass are in Table 16. The CNCPS uses experimentally measured digestibility coefficients to predict intestinal digestibilities and fecal losses (Sniffen et al., 1992; Knowlton et al., 1998). The accuracy of these estimates depends on how well ruminally undegraded carbohydrate and protein fractions are predicted. For most feeds, over 75% of total tract digestion occurs in the rumen.

The small intestine is assumed to lack the enzymes to digest cellulose and hemicellulose, but the colon has fibrolytic bacteria. To account for hindgut fiber digestion, intestinal digestion of CHO B2 is assigned a digestibility of 20%, based on Sniffen et al. (1992). Intestinal CHO B1 digestibility depends on type of grain, degree and type of processing, and level of intake above maintenance (Sniffen et al., 1992; Knowlton et al., 1998). Guidelines for intestinal digestion of the CHO B1 for growing beef steers and lactating dairy cows consuming feed at 2–3 times energy maintenance level of intake are: whole corn, 30–50%; cracked corn, 50–70%; dry rolled corn, 70–80%; corn meal, 80–90%; whole high moisture corn, 80–90%; high moisture ground corn, 85–95%; steam flaked corn, 92–97%; dry rolled sorghum, 60–70%; dry ground sorghum, 70–80%; and steam flaked Sorghum, 90–95%. Guidelines for intestinal digestion of the CHO B1 fraction for high producing dairy cows (above 45 kg milk) are: whole corn, 30–40%; cracked corn, 40–60%; corn meal, 70–90%; and rolled high moisture corn, 75–85% (Knowlton et al., 1998). Use of 90% for intestinal digestion of the CHO B1 fraction in processed small grains (i.e., wheat, barley and oats) is recommended. Protein B1, B2 and B3 are assumed to have an intestinal digestibility of 100, 100, and 80%, respectively.

2.13. *Prediction of feed energy values*

Equations to compute feed energy, metabolizable protein and metabolizable AA values are in Table 16. The equations used to calculate net energy derived from feeds are empirical,

Table 17
Equations to estimate manure production and N and P excretion for dairy cattle

Equation	Variables	Constraints	Equations
(1)	TFDM		IDM/FDM
(2)	FDM	Milk $\leq$ 45.4 kg per day	$(-0.102 \times \text{Milk} + 21.487)/100$
(3)	FDM	Otherwise	0.1685
(4)	Urine		$(3.55 + 0.16 \times \text{DMIA} + 6.73 \times \text{CPIA} - 0.35 \times \text{MilkA}) \times \text{AU}$
(5)	FecalN		$(\text{FEPB3} + \text{FEPC} + \text{FEBCP} + \text{IDM} \times 0.09)/6.25$
(6)	UrinaryN		$((\text{PA} + \text{PB1} + \text{PB2} + \text{PB3} + \text{PC}) - (\text{SPA} + \text{Milk} \times \text{MilkCP} \times 10/0.93 + \text{MP}_{\text{Preg}} + \text{MP}_{\text{g}} + \text{FecalN}))/6.25$
(7)	UrinaryP		$2 \times \text{FBW}/1000$
(8)	LactationP		$1 \times \text{milk}$
(9)	PregnancyP	Pregnancy > 190 days	$0.02743 \times \exp(((0.05527 - 0.000075 \times \text{DaysPreg}) \times \text{DaysPreg})) - 0.02743 \times \exp(((0.05527 - 0.000075 \times (\text{DaysPreg} - 1)) \times (\text{DaysPreg} - 1)))$
(10)	GrowthP		$(1.2 + 4.635 \times \text{MW}^{0.22} \times \text{FBW}^{-0.22}) \times \text{ADG}/0.96$
(11)	NetReqP		LactationP + PregnancyP + GrowthP
(12)	FecalP		DietP − (UrinaryP + NetReqP)
(13)	ManureP		FecalP + UrinaryP

but the validations below indicate they have represented the complexity of energy and protein metabolism reasonably well in predicting animal responses in combination with the rumen model. Apparent TDN is the sum of total tract digestible nutrients (Table 16). The DE values for each feed are based on the assumption that 1 kg of TDN is equal to 4.409 Mcal of DE. Because K_p increases as the intake increases, apparent TDN is adjusted for level of intake. The CNCPS uses NRC (1989, 2000) equations to predict ME and NE. Variations in ME are in part due to variations in ruminal methane production. The NEl values are based on the respiration chamber data of Moe (1981). Evaluation of the predicted NEma and NEga values for growing cattle demonstrated little bias across a wide range of diet ME (NRC, 2000).

2.14. Manure production and nutrient excretion

Recently, it has become evident that animal agriculture can adversely affect the environment, so the CNCPS has been modified to assess nutrient excretion (Table 17). Because the CNCPS predicts manure production and N and P excreted (Fox et al., 2002), it can be used in the development of whole farm nutrient management plans (Tylutki and Fox, 1997; Fox et al., 2002). When predictions of total N excretion, which is partitioned into N excretion from feces and urine, are compared to experimental data, there is good correlation (Tylutki and Fox, 1997). Phosphorus excretion is described in an input/output model, and manure P is residual P after excretion via products (milk, tissue, and pregnancy) are subtracted (Tylutki, 2002). The CNCPS uses the P equations developed by Kirchgeßner (1993) to predict the sum of fecal and urinary P because these equations performed better than those adopted by NRC (2000, 2001) or INRA (1989).

2.15. The CNCPS model for sheep

The CNCPS was modified for use with sheep (CNCPS-S), and has been published by Cannas et al. (2004). Equations were added to predict energy and protein requirements of sheep, with special emphasis on dairy sheep. The CNCPS for cattle (CNCPS-C) equations used to predict nutrient supply from each feed were modified to include new solid and liquid ruminal passage rates for sheep and revised equations were included to predict metabolic fecal N (MFN) more correctly. Equations were added to predict fluxes in body energy and protein reserves from BW and BCS in sheep. When evaluated with data from seven published studies (19 treatments), the CNCPS-S predicted OM digestibility, which is used to predict feed ME values, without any mean bias (1.1%; $P > 0.1$) and a low root mean squared prediction error (RMSPE; 3.6 g 100/g DM).

3. Model evaluations

The accuracy of several sub-models (e.g., growth, body reserves, and rumen) was discussed in the previous sections. For a model to be useful on-farm, the combination of model equations must accurately predict animal responses. This section summarizes CNCPS evaluation studies that have been conducted with animal response as the evaluation criteria when appropriate CNCPS inputs have been measured.

The CNCPS was evaluated by regressing observed on model-predicted values, in which observed is the *Y*-variate, as described by Mayer and Butler (1993). Several statistical measures were used to assess model adequacy including the regression coefficients of correlation (r) and determination (r^2), mean square error (MSE), mean square prediction error (MSPE; Bibby and Toutenburg, 1977), partition of MSPE (Haefner, 1996), intercept and slope confidence intervals (Mitchell, 1997; Mitchell and Sheehy, 1997), rank analysis (Agresti, 2002), and residual analysis (Neter et al., 1996). The random effect of studies was also analyzed using PROC Mixed methodology as described by Littell et al. (1991, 1999).

3.1. Milk production of lactating dairy cows

Kolver et al. (1998) and ADAS (1998) assessed the ability of the CNCPS to predict lactation performance in cows fed TMRs and those that were grazing. In both studies, actual feed composition, animal BCSs and environmental factors were used. In the studies of Kolver et al. (1998), the CNCPS under-predicted ME allowable milk by 2.5 and 6.8% in TMR and pasture fed groups, respectively. In a study on 10 dairy farms in the UK, ADAS (1998) reported that the CNCPS predicted milk yield when either ME or MP was limiting to within 2.5 and 5%, respectively, using actual DMI and feed composition, and these differences were not statistically different from actual milk yields. The CNCPS intake model predicted DMI to within 2% of actual values.

We evaluated the ability of the CNCPS to predict the performance of individually fed animals. Since studies had no effect on the slope and intercept of the overall regression (lactating cows column in Table 18), the data was pooled and analyzed together. With nearly all of the CNCPS inputs measured (Stone, 1996; Ruiz et al., 2002), the CNCPS

Table 18
Summary of statistical measures to assess model adequacy using regression between observed on model predicted values

Statistical measures	Scenarios	
	Lactating dairy cows (Fig. 1)	Growing steers (Fig. 2)
Study as random effects		
Intercept ($H0$: $\beta0 = 0$)	$P > 0.32$	$P > 0.27$
Slope ($H0$: $\beta1 = 1$)	$P > 0.32$	$P > 0.27$
Overall intercept ($H0$: $\beta0 = 0$)	1.73 ± 1.16 ($P = 0.14$)	0.146 ± 0.022 ($P < 0.01$)
Overall slope ($H0$: $\beta1 = 1$)	1.00 ± 0.035 ($P = 0.98$)	0.954 ± 0.017 ($P < 0.01$)
Mean square error (MSE)	17.85	0.014
Coefficient of correlation (r)	0.936	0.945
Coefficient of determination (r^2)	0.875	0.893
Mean bias (MB)	1.76	0.0896
Percentage of mean predicted	5.56	7.43
Percentage of mean observed	5.26	6.92
Mean square prediction error (MSPE)	20.6	0.0224
Square root of MSPE (RMSPE)	4.54	0.150
Partition of MSPE[a]		
Error due to mean bias (%)	14.9	35.8
Error due to slope not equal to 1 (%)	0	1.24
Error due to lack of correlation (%)	85.1	62.9
Ranking analysis[b]		
Spearman's r	0.933 ($P < 0.001$)	0.935 ($P < 0.001$)
Kendall's τ	0.782 ($P < 0.001$)	0.781 ($P < 0.01$)

[a] The partition of MSPE was done based on Haefner (1996).

[b] The Spearman's r is a non-parametric coefficient of correlation that measures the rank of the data values and the kendall's τ is a non-parametric coefficient that measures the association based on the number of concordances and discordances in paired observations (Agresti, 2002).

accounted for 88% of the variation with a mean bias of 1.8 kg per day or 5.5% (Table 18 and Fig. 1). When energy was first limiting for high producing cows, the r^2 was 76% and the mean bias was 3 kg per day (8% underprediction bias; Table 18). If protein was first limiting, the r^2 was 84% and the mean bias was −0.2 kg per day (1.1% overprediction bias; Table 18). When the CNCPS reserves model was used to adjust supply of energy to account for changes in BCS, the model accounted for 90% of the variation in milk production with a mean bias of 1.3% (not shown). Table 18 also indicates that most of the errors in the MSPE are related to lack of correlation (85.1%) between observed and predicted values, but shows no error due to the slope differing from unity. This agrees with our analysis, in which slope is not different than unity ($P > 0.9$) and there is a low error due to mean bias (14.9%). The non-parametric analysis indicated a good agreement via Spearman's and Kendall's statistics (Agresti, 2002) between observed and predicted values.

Two published evaluations of the CNCPS (Kohn et al., 1998; Alderman et al., 2001a,b,c) were helpful in identifying areas for improvement in representations of biology in the CNCPS. Since those assessments, extensive debugging and refinement of both the model and the feed library have occurred. The Kohn et al. (1998) evaluation relied heavily on

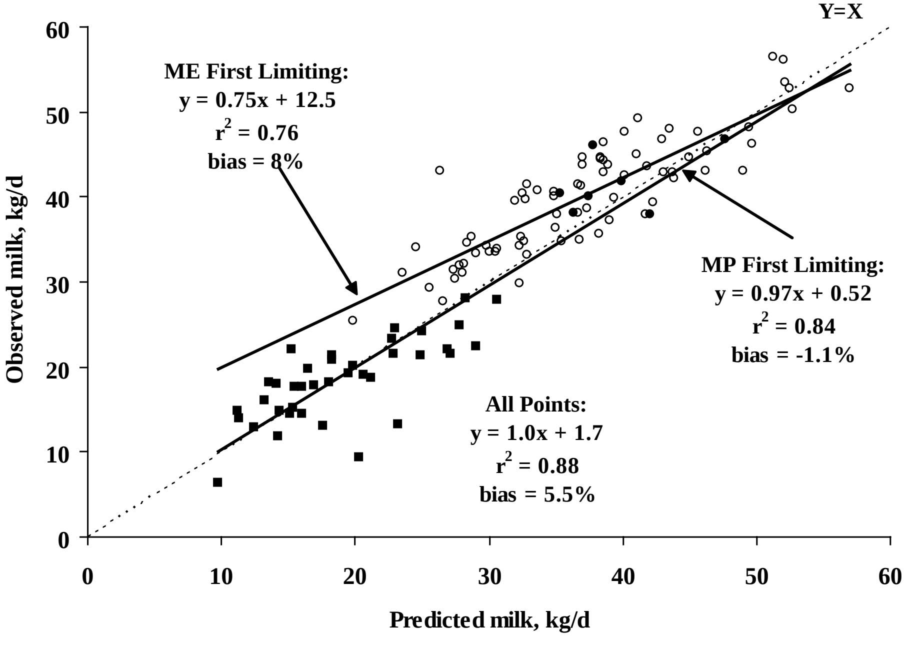

Fig. 1. Relationship between observed and predicted first limiting metabolizable energy (ME (○)) or metabolizable protein (MP (■, ●)) milk production using (■) and (○, ●) data from Ruiz et al. (2002) and Stone (1996), respectively.

feed library values. To accurately evaluate the CNCPS biological model however, feed composition values based on actual chemical analysis and digestion rates must be used, as demonstrated by Juarez Lagunes et al. (1999) and Ruiz et al. (2001). Alderman et al. (2001a,b,c) critiqued the level of aggregation of the scientific knowledge in the rumen, post-rumen digestion, and animal requirements models of the CNCPS, but did not evaluate them with data. Some of the limitations of earlier CNCPS versions have been addressed in this version (e.g., accounting for effects of a ruminal N deficiency, more accurate coefficients used to compute efficiency of use of ME for milk production, revised calculation of body reserves). Others (e.g., improved carbohydrate degradation and liquid and solid passage rates, prediction of VFA and methane production; a more mechanistic prediction of rumen pH) are being addressed as information becomes available and will be incorporated into future versions of the CNCPS (see last section).

3.2. Prediction of growth of dairy replacement heifers

The CNCPS has been used successfully to assess BW gain of growing cattle. When Van Amburgh et al. (1998a) evaluated the CNCPS with Holstein replacement heifers ($n = 273$), ME allowable ADG accounted for 86% of variation with a bias of 5.7%, and target BWs and daily gains to minimize production costs agreed with published studies (Van Amburgh et al., 1998b).

Table 19
Evaluation of the CNCPS prediction of ADG (kg per day) in growing cattle fed high forage diets when either ME or MP are first limiting

	ADG (kg per day)			Regression statistics[a]			RMSPE
	Minimum	Mean ± S.E.	Maximum	r^2	MSE	Bias (%)	
ME first limiting (n = 19)							
Observed	0.80	1.11 ± 0.04	1.44	–	–	–	–
Tabular	0.73	1.25 ± 0.06	1.78	0.61	0.01	−11.4	0.23
CNCPS level 1	0.74	1.13 ± 0.06	1.62	0.73	0.01	−2.2	0.14
CNCPS level 2	0.79	1.10 ± 0.05	1.48	0.80	0.01	0.4	0.10
MP first limiting (n = 28)							
Observed	0.12	0.78 ± 0.07	1.36	–	–	–	–
Tabular	0.11	0.81 ± 0.09	1.78	0.80	0.03	−4.3	0.21
CNCPS level 1	0.13	0.78 ± 0.09	1.73	0.79	0.03	−0.5	0.22
CNCPS level 2	0.12	0.77 ± 0.07	1.45	0.92	0.01	1.9	0.11

[a] Observed values (Y) were regressed on predicted ADG (X) using tabular TDN or TDN predicted by CNCPS level 1 or level 2. MSE is the mean square error from the regular regression, S.E. is the standard error, and RMSPE is the root of the mean square prediction error.

3.3. Weight gain with pen-fed growing cattle fed high forage diets

Studies with pen-fed growing cattle consuming high forage diets indicated that the NRC (2000) tabular system had an overprediction bias because intake effects were not considered and the carbohydrate and protein fractions were not adequately described (Table 19; Tedeschi, 2001). The MSE were similar in all evaluations (tabular, and levels 1 and 2), but the CNCPS level 2 had the highest accuracy (lowest RMSPE) followed by level 1. The CNCPS level 2 accounted for more of the variation in animal performance because variables such as digestion rates, effects of level of intake, microbial growth on cell wall and non-cell wall carbohydrate fractions, rate of passage, rumen pH, and ruminal nitrogen deficiency, on feed ME and MP values were considered.

3.4. Weight gain with growing cattle individually fed high grain diets

Fig. 2 shows the prediction of ADG using a version of the CNCPS growth model described by Tedeschi et al. (2004) using mean BW. The Tedeschi et al.'s (2004) model is based on the CNCPS and uses the same approach to compute ADG. In this simulation, the ADG was predicted based on dietary ME predicted by the CNCPS and actual DMI. The model accounted for 89% of the variation with mean bias of 90 g per day (7.4% underprediction bias; Table 18). Table 18 also shows that, similar to the lactating cow scenario, most of the errors in the MSPE relate to lack of correlation (62.9%) between observed and predicted values, with nearly no error attributed to the slope differing from unity (1.24%), but with an appreciable amount due to mean bias (35.8%). This agrees with the observation that the mean bias (as % of predicted mean) is higher in growing steers than in lactating cows. Analysis of the regression between observed and model-predicted values indicated that the intercept and slope differed from zero ($P < 0.05$) and unity ($P < 0.05$), respectively.

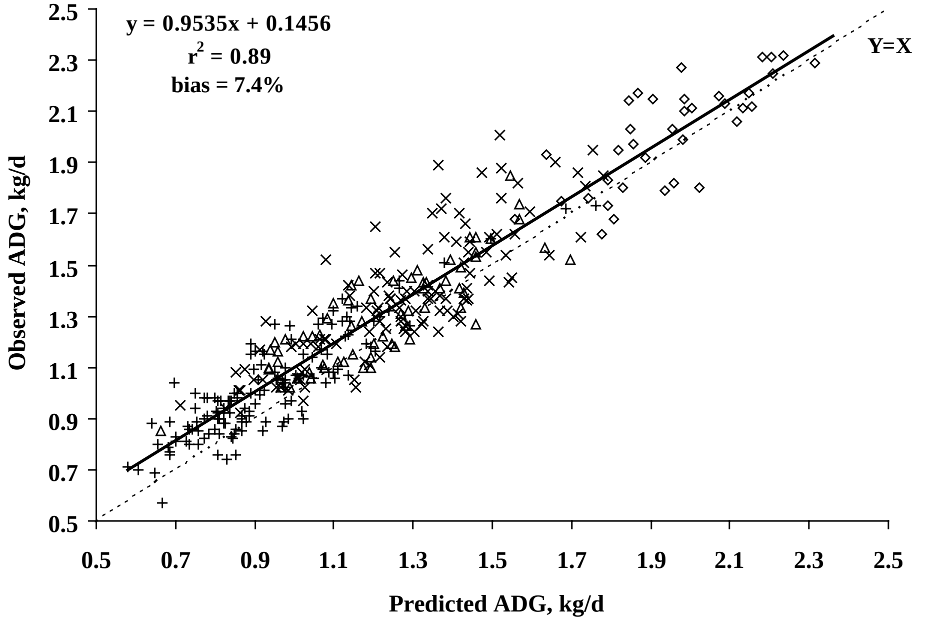

Fig. 2. Prediction of average daily gain (ADG, kg per day) using the growth model simulation when dry matter intake is known. The data points are from Nour and Thonney (1987) (+); Perry and Fox (1997) (△); Perry et al. (1991) (×); Guiroy (2001) (◇).

Likewise, the non-parametric analysis indicated a good agreement using Spearman's and Kendall's statistics (Agresti, 2002) between observed and predicted values.

3.5. Prediction of the effects of a ruminal nitrogen deficiency on animal performance

Five studies with adequate information were used to evaluate the effect of added dietary N on fiber digestion and microbial growth (Tedeschi et al., 2000a). Evaluations comparing observed and CNCPS-predicted ADG indicated that N adjustment decreased the overprediction of ADG from 19.2 to 4.7% and the mean bias declined from 0.16 to 0.04 kg per day. The r^2 of the regression ME or MP allowable ADG increased from 0.83 to 0.88.

3.6. Nutrient management on dairy farms

Klausner et al. (1998) evaluated the ability of the CNCPS to reduce diet and manure N and P on a dairy farm in New York State (USA), and results indicated that milk production increased from 11,000 kg to over 12,000 kg per cow per year, feed costs were reduced US$ 42,000 per year, and manure N and P excretion were reduced approximately 33%. In another study, the CNCPS underpredicted total manure excretion by 16%, but this difference was largely due to incorrect accounting for nutrients in bedding (Tylutki and Fox, 1997). Predicted N excretion was 10% higher than measured values, but other researchers using a similar manure handling system showed that 10% of N was lost due to volatilization (Hutson et al., 1998). The predicted P excretion was only 2% higher than measured values, within measurement error, and agreed with studies of Cerosaletti et al. (2002). Predicted *K* excretion was 16% higher than actual values. The CNCPS has been linked to a crop, soil, and manure nutrient management program (Cornell Cropware; Rasmussen et al., 2002) to evaluate its potential to improve environmental and economic sustainability of a 650 cow commercial dairy (Tylutki et al., 2002). A summary of the last 5 years indicated that the precision nutrient management system developed resulted in a 26% increase in animal numbers, a 9% increase in milk/cow, a 45% increase in total milk, a 48% decrease in purchased feed, a 52% decrease in feed cost/kg of milk sold, and 17 and 28% decreases in total manure N and P, respectively. These improvements could be explained by better forage production, quality, and storage (38% increases in proportion of feeds grown on-farm) and the ability of CNCPS to use these high forage diets efficiently.

4. Sensitivity analysis of the CNCPS

This sensitivity analysis is based on the case study of Tylutki (2002) in which the CNCPS model has been used on a 650 cow dairy farm for 5 years. Results of two types of sensitivity analysis are presented; (1) how a change in a feed composition input variable changes pools and responses in the rumen model, and (2) how changes in farm-observed CNCPS model inputs affect priorities set in obtaining inputs to apply the CNCPS.

4.1. Sensitivity of the rumen model to changes in feed composition

This sensitivity analysis (Table 20) is based on the high cow group on the case-study farm. The diet is based on feeds typically used on dairy farms in the Northeastern USA (alfalfa and corn silage, ground corn, whole cottonseed, soybean meal, wet brewers grains and a protein-mineral mix). The standard deviations (S.D.) of the measured forage composition from a 2 years feed sampling project at the case-study *farm were used to evaluate* effects of changes in the composition of feed ingredients on CHO and PROT pool sizes, ruminal balances, microbial yield, and ME and MP allowable milk production (ME and MP milk, respectively). Inputs evaluated include NDF, lignin, CP, and protein solubility. Other feed characteristics (physically effective NDF, starch degradation rate and intestinal digestibility, and ruminal degradation rate of available NDF) were varied based on observed field variation (reduction in corn silage NDF digestion rate from 8 to 3%/h, reduction in corn silage CHO B1 digestion rate by 50% and intestinal digestion rate by 50% to reflect the effect of hard corn kernels that appear in the manure). The input of interest was changed for one feed (corn silage) and correlated responses were ignored for ease of explanation. This type of sensitivity analysis allows for evaluation and discussion regarding model directionality; however correlations (i.e., CP and soluble protein decreases when NDF increases, etc.) must be considered when discussing biological appropriateness and field implementation. Specific changes in pools and responses due to changes in feed characteristics are summarized below.

Table 20
Sensitivity analysis of the CNCPS with a lactating dairy cow diet[a]

	Balanced ration (g)[b]	DMI[c]	NDF[d]	Lignin[e]	CP[f]	Protein solubility[g]	CHO B1 kd[h]	CHO B2 kd[i]	pef[j]
Percentage change in pool size when composition of indicated forage changed									
CHO A[k]	1767	4.1	−7.8	0	−6.8	0	0	0	0
CHO B1[k]	8469	4.2	−5.2	0	−0.2	0	0	0	0
CHO B2[k]	4427	4.2	10.7	−8.7	−0.7	0	0	0	0
CHO C	1989	4.3	5.0	19.3	0	0	0	0	0
PROT A[k]	866	4.3	0	0	10.6	12.7	0	0	0
PROT B1[k]	370	4.1	0	0	1.1	1.6	0	0	0
PROT B2[k]	2148	4.2	0	0	3.5	−5.4	0	0	0
PROT B3	447	4.3	0	0	3.8	0	0	0	0
PROT C	245	4.1	0	0	5.3	0	0	0	0
Percentage change when composition of indicated forage changed									
NFC bacteria	2986	3.5	−5.0	0	−0.2	−0.3	−7.5	−0.1	−9.0
FC bacteria	819	2.8	13.7	−9.9	−0.7	0	0	−32.8	−11.6
Bacteria MP	1427	3.3	−1.0	−2.2	−0.4	−0.3	−5.9	−7.1	−9.6
Diet ME	2.78	−0.4	−1.1	−1.8	0	0	−1.8	−3.2	0
Feed MP	1361	5.3	−0.4	−0.3	1.5	−2.9	−0.1	−0.3	0.6
ME milk	40.5	5.4	−1.7	−2.7	−0.7	0	−3.2	−5.2	−1.0
MP milk	42.0	4.5	−1.7	−2.9	1.0	−2.1	−5.5	−7.1	−6.4
Rumen balances (g) after changing composition of indicated forage									
Rumen N balance	65	68	69	73	87	72	87	92	100
Peptide balance	40	40	50	40	46	28	54	40	56
peNDF balance	−300	−300	200	−300	−300	−300	−300	−300	−1600
Rumen pH	6.35	6.35	6.44	6.35	6.35	6.35	6.35	6.35	6.11

[a] Based on case study of Tylutki (2002).
[b] Amount in balanced ration. Actual milk is 40.8 kg.
[c] DMI increased 1 kg.
[d] Corn silage NDF increased 2 S.D. (NDF S.D. = 3.75 percentage units).
[e] Corn silage lignin increased 2 S.D. (Lignin S.D. = 2.63 percentage units).
[f] Alfalfa silage CP increased 2 S.D. (S.D. = 2.43 percentage units).
[g] Alfalfa silage protein solubility increased 2 S.D. (S.D. = 7.28 percentage units).
[h] Corn silage CHO B1 kd reduced 50% (28–14%/h) and intestinal digestibility reduced 50% (75–37.5%) to account for appearance of corn in the feces.
[i] CHO B2 kd of corn silage reduced to 3%/h.
[j] physically effective fiber (pef) of corn silage reduced 50% (90–45%).
[k] The percent that is degraded in the rumen is: CHO A, 51.3; CHO B1, 81.5; CHO B2, 59.5; CHO C, 0; PROT A, 100; PROT B1, 95.4; PROT B2, 51.3; PROT B3, 8.7 PROT C, 0.

(I) *Increase in DMI*:
  (a) All pools and responses are affected by a change in DMI, demonstrating the importance of having accurate estimates of DMI.
  (b) Diet ME is reduced due to increased rate of passage.

(II) *Increase in corn silage NDF*:
(a) CHO B2 pool increases and CHO A and B1 pools decrease because they are displaced by NDF.
(b) CHO C increases, because of the increase in NDF and associated lignin.
(c) FC bacteria increase due to increased CHO B2 and NFC bacteria decrease due to decreased CHO A and B1. Bacterial MP is decreased due to the loss in NFC bacteria not being offset by the increase in FC bacteria.
(d) Diet ME and ME milk are decreased because of the increase in CHO C and the lower digestibility of CHO B2 (less microbial growth from NFC and lower intestinal digestibility of escaped CHO B2) compared with the CHO A and B1 that it replaced.
(e) MP milk is decreased due to less bacterial protein produced and an increase in the MP maintenance requirement. MP maintenance increases due to higher CHO C (increasing metabolic fecal DM as a result of increased indigestible DM).
(f) Peptide balance increases because of fewer NFC bacteria, which utilize both peptides and ammonia.
(g) PeNDF balance and rumen pH increase because of the increased concentration of NDF in the diet.

(III) *Increase in corn silage lignin* (*%NDF*):
(a) The CHO B2 pool is reduced because the CHO C pool increased.
(b) FC bacteria decrease because of the decrease in CHO B2 pool size.
(c) Diet ME and ME milk decrease because assumed zero digestibility of CHO C results in decreased TDN.
(d) MP milk decreases due to lower FC bacteria production and increased MP maintenance (increased indigestible DM).
(e) Rumen N balance increases because of less FC bacteria growth.

(IV) *Increase in alfalfa silage CP*:
(a) The CHO A pool decreases because CP displaces NFC (CHO A + B1) and nearly all NFC in alfalfa silage is CHO A.
(b) All protein pools increase, but fraction A increases the most because of the high proportion of NPN in the total N in alfalfa silage. As a result, the rumen N balance increases, which also increases the urea cost.
(c) ME milk decreases due to increased ME maintenance requirement (urea cost) and less CHO A and B1 supply (also decreases microbial flow).
(d) MP milk increases because of the increase in feed MP flow.

(V) *Increase in solubility of the CP in alfalfa silage*:
(a) PROT A fraction increases because the increased solubility results in increased NPN.
(b) PROT B2 decreases because a higher proportion of this fraction is now NPN and is therefore shifted to the PROT A fraction, resulting in a decrease in the peptide balance.
(c) MP milk decreases due to a lower MP feed flow.

(VI) *Decrease in corn silage CHO B1 digestion rate and intestinal digestibility*:
(a) NFC bacteria are decreased because less CHO B1 was degraded in the rumen (resulting in higher CHO B1 flow to small intestine).

(b) Diet ME and ME milk decreased because of the low intestinal digestibility of the CHO B1.
(c) MP milk decreased because of less bacterial MP, due to fewer NFC bacteria and increased MP maintenance requirements.
(d) Rumen N and peptide balances increased because of lower NFC bacterial growth.

(VII) *Decrease in corn silage CHO B2 digestion rate*:
(a) FC bacteria and bacterial MP decreased because less of the CHO B2 pool was degraded in the rumen.
(b) Diet ME and ME milk decreased because less of the CHO B2 was degraded in the rumen.
(c) Rumen N balance increased because of less FC bacterial growth.

(VIII) *Decrease in corn silage peNDF*:
(a) Both NFC and FC bacteria are reduced (as a result of rumen pH adjustment to bacterial yield), which reduces microbial MP and MP milk.
(b) CHO B2 ruminally degraded (not shown) decreases due to rumen pH adjustment of CHO B2 degradation rate.

These results are generally consistent with those of Alderman et al. (2001b), who found that the rumen model was not sensitive to CHO A and PROT A and B1 digestion rates. This is expected because digestion rates of these pools result in nearly 100% of these pools being ruminally degraded (except in silages, where CHO A is nearly all organic acids). The rumen model was not sensitive to changes in PROT B3 in the Alderman et al. (2001b) analysis because the K_d is significantly slower than the rate of passage, thus almost all of the B3 protein escapes ruminal degradation. Collectively, the sensitivity analyses that have been conducted (including those presented below) indicate that the rumen model is sensitive to all of the CHO and protein pools under some conditions.

4.2. *Sensitivity analysis based on implementation of the CNCPS*

For lactating dairy cattle, the CNCPS was sensitive to changes in variables in the following order (Tylutki, 2002): (1) animal characteristics (BW, milk production, milk fat, and milk protein), (2) environmental factors (temperature, relative humidity, and wind speed), (3) feed DM content, (4) feed chemical composition, and (5) ruminal digestion rates for feeds. This order of sensitivity illustrates the need to accurately describe the animal and its environment if accurate animal requirements are to be calculated for the specific situation (Tylutki, 2002). By accounting for more of the on-farm variation, variation in production can be decreased, demonstrating that a complex model can be useful under field conditions.

4.3. *Sensitivity analyses with other classes of cattle*

Other published sensitivity analyses of the CNCPS demonstrate that CNCPS sensitivity to various inputs depends on the class of cattle and their requirements relative to the variation in feed composition. Juarez Lagunes et al. (1999) evaluated the sensitivity of CNCPS predicted milk production in dual purpose cows fed high forage diets to changes in the protein and carbohydrate fractions and digestion rates, using measured values. Their results were consistent with those in Table 20, except the magnitude of responses to changes in forage NDF and lignin were much higher because of their greater dependency on NDF as a source of fermentable CHO and ME. In the feedlot case study reported by Fox and Tedeschi (2002), forage ME and microbial MP were more sensitive to changes in peNDF, because rumen pH was always in a sensitive range (5.6–5.8) because of the low forage, high grain diet being fed.

Fox et al. (1995), in a study of Holstein calves fed high forage diets, demonstrated that ME allowable ADG was sensitive to BW (affects energy requirement) and BCS (affects maintenance requirement). Both ME and MP allowable ADG were sensitive to dietary NDF and CHO B2 digestion rate. In addition, MP allowable ADG was sensitive to diet CP, protein solubility, and CHO B1 digestion rate. Tedeschi et al. (2000a) evaluated the sensitivity of the rumen model to a ruminal N deficiency, which decreases NDF digestion rate and microbial protein production. Fox and Tylutki (1998) evaluated the sensitivity of the environmental model for both growing and lactating dairy cattle. The sensitivity of milk production or ADG depended on interaction of temperature, wind, humidity, housing and diet type. Generally, the ADG of growing replacement heifers (generally fed high forage diets) is more sensitive to cold stress than that of lactating cows because of their lower heat production. Lactating dairy cows were more sensitive to heat stress than other classes of dairy cattle because of their higher heat production.

5. Applications of the CNCPS

The CNCPS has been used as a teaching tool to improve skills of students to evaluate the interactions of feed composition, feeding management and animal requirements and to design and interpret experimental results. The CNCPS has also been used to refine conventional diet formulation programs by developing more precise values for feed NE and MP so that the impact of dietary change on total N, peptide and AA balances can be more accurately assessed. The CNCPS predictions of nutrient excretion can be used in whole farm nutrient management planning. The utility of the CNCPS is supported by the observation that various components have been adapted by the NRC (2000, 2001) and in commercial computer programs (e.g., DALEX). The CNCPS was used to develop a version for consulting dairy nutritionists through a collaborative effort by scientists at Cornell University, University of Pennsylvania and Miner Institute (CPM Dairy). The CNCPS and CPM Dairy computer programs are being routinely used by both nutritional consultants and feed companies. Use of these models is reported by users to permit reduction of ration CP by 1–2% units and lower feed costs while maintaining or improving animal performance.

The CNCPS was designed for both temperate and tropical regions. With collaborators in Brazil, Mexico, Honduras, South Africa and Kenya (Nicholson et al., 1994; Lanna et al., 1996; Traxler et al., 1998; Juarez Lagunes et al., 1999; Molina, 2002; Reynoso-Campos et al., in press; Rueda-Maldonato, 2002), work is underway to ensure that the model accurately reflects tropical environments and that the feed library includes tropical forages (Tedeschi et al., 2002b).

6. Model improvements for future versions of the CNCPS

Practical experience and validations indicate that the CNCPS accurately predicts nutrient balances and animal performance (milk and growth). It is apparent that specific aspects of the model should be revised to better reflect a specific biological function and improve the accuracy and utility of the model. This section describes needed modifications that have been identified.

6.1. Feed digestion rates

The values in the current feed library (Fox et al., 2003) represent average expected values and have performed reasonably well in most situations. However, recent studies indicate these values are variable and procedures are needed for determining feed specific digestion rates. The K_d values for NDF from high quality alfalfa silages were too low to account for observed milk production (Aquino et al., 2003) in agreement with previous work on NDF digestion rates (Doane et al., 1997a). The current fiber digestion rates are based on the data of Mertens (1973). However, in the CNCPS the indigestible pool is calculated as NDF × lignin × 2.4 (U, %DM) as described by Chandler et al. (1980). The rate data of Mertens (1973) are dependent on prediction of U, but his calculations were conducted prior to the development of the 2.4 value. Thus, there is discontinuity in the two approaches since they are applied independently in the model. This is currently being resolved. Current work is exploring the possibility that NDF digestion rate of forages may be predicted from chemical composition and adjusted for unavailable NDF (U, %NDF) at 240 h (Van Soest et al., 2000). In the future, it is possible that digestion rates could be determind from near-infrared spectroscopy.

6.2. Rumen model

As noted above, the ability of the CNCPS to predict ruminal pH and subsequent effects on bacterial growth and fiber digestion have limitations. The CNCPS does not attempt to integrate ruminal pH with the rate or amount of NFC digestion, and effects of ruminal fluid dilution rate on VFA removal from the rumen are not considered. Forage fed cattle often have a relatively slow rate of carbohydrate fermentation and a high rumen fluid dilution rate, but the same is not true for cattle fed grain based rations (Russell, 1999, 2002). When cattle are fed large amounts of grain, ruminal VFA production is rapid, but fluid dilution rate is relatively slow. Because VFA absorption from the rumen is a passive process, the absorption rate does not increase until pH declines (Allen, 1997). Absorption of VFA from the rumen is further complicated by changes in viscosity. When fluid dilution is slow, the rumen has a higher viscosity and movement of VFA to the epithelium is slowed (Russell, 2002). These general concepts are illustrated by experiments in vitro and in vivo. When Meng et al. (1999) increased the dilution rate of fermenters from 2.5 to 20%/h, pH increased from 5.78 to 6.91, and Allen (1997) noted that feed processing affected water intake, saliva flow and the amount of ruminal VFA that is washed out of the rumen.

Our approach to improving this aspect of the CNCPS is two-fold: (1) we are modifying the steady state version so that it can estimate total VFA production in the rumen, the amount of VFA that passes out of the rumen in the fluid, the amount VFA that must truly be absorbed from the rumen and ruminal pH and (2) we are developing a dynamic ruminal sub-model so the impact of feeding behavior (feeding frequency, time spent chewing and ruminating, and oscillations in the eating pattern (Dado and Allen, 1994), and K_p and K_d of carbohydrates can be integrated to provide within day variations in ruminal pH. By developing a rumen model that has a dynamic pH function, and using fermentation balance similar to that of Wolin (1960), it is possible to predict the ratio of VFA, CO_2, and CH_4 stoichiometrically. It then should be possible to select appropriate ration ingredients and feeding strategies to minimize CH_4 and N excretion.

It has long been recognized that ruminal cellulolytic bacteria have a requirement for branched chain VFA, and these acids are derived from fermentation of branched chain AA (Bryant, 1973). If the supply of ruminally-degraded protein to the rumen is low and N is supplied as NPN, BCVFA can limit the rate of FC digestion. This aspect of ruminal fermentation has not been incorporated into this version of the CNCPS, but a prototype model of BCVFA deficiency has been developed by Tedeschi et al. (2000b). Hungate and Stack (1982) showed that the cellulolytic ruminal bacterium, *Ruminococcus albus*, has a requirement of phenylpropionate and phenylacetate in addition to BCVFA, but it is not clear whether this requirement could or should be added to the CNCPS in the BCVFA sub-model. Other species of cellulolytic bacteria do not have a similar requirement, an in vivo stimulation of fiber digestion by these acids has never been demonstrated, and it is not clear if these acids are derived solely from phenolic AA (tyrosine and phenylalanine).

6.3. *Nutrient excretion*

Currently, the CNCPS predicts total N excretion acceptably, but the ratio of urinary to fecal N is under-predicted. Because of the need to accurately predict the route (fecal or urinary) and form (e.g., potentially volatilized to ammonia) of N excretion for nutrient management planning, a new N excretion model for the CNCPS is being developed. Urinary N is calculated by difference between N intake and the sum of N accretion, milk N, N retained as conceptus, scurf N and fecal N. Endogenous urinary N (EUN) will be also computed to estimate N required for maintenance.

Several approaches have been used to compute metabolic fecal N, but the most common is the regression of apparently digested N on N intake in which the slope indicates the true digestibility of N and the intercept indicates the MFN. Current and past versions of the NRC and CNCPS have relied on the values obtained by Swanson (1977), but this data has severe shortcomings requiring a re-evaluation of this approach. It is now apparent that the current fecal N loss (Table 17) equations may result in “double accounting”. Because some of the MFN and undigested feed ash is excreted as microbial mass, N excretion is overpredicted which results in an underestimation of TDN. In regions with low grain prices, nutritionists often recommend feeding large quantities of grain, and some of this grain is fermented in the hindgut. The result is that the amount of fecal N excretion that is of bacterial origin is increasing. We foresee that a mechanistic hindgut sub-model will be required to accurately predict the fermentative processes occurring in the large intestine, including the production and absorption of VFA, the capture of N by hindgut bacteria, N recycling of urea and the absorption of ammonia from the lower tract.

6.4. Dairy replacement heifer growth

The growth model is based on body composition studies with beef cattle beginning at 150–200 kg. Although we have evaluated the equations for use with dairy replacement heifers, extrapolation below the range in BW used to develop the equations is not adequate to compute requirements for calves (Diaz et al., 2001). Current adjustment for size scaling accounts for some of the variation in body composition at light BWs and in dairy breeds. In a comparison of model predictions with slaughter data from Holstein heifers, mature BWs of Holsteins had to be set at 580 kg or less, an unrealistically low value based on BWs of the mature animals in the herd, to account for the greatest amount of variation in retained energy and protein (Fox et al., 1999). This apparent bias is most likely due to genotypic differences and extrapolation outside the equation ranges. A calf growth model, under development, will be in future CNCPS versions and new slaughter data for Holstein heifers will be used to refine the current growth model.

6.5. Energy and protein metabolism

The current empirical equations used to represent metabolism of energy and protein are inadequate to predict effects of nutrients absorbed on milk and meat composition or substrate adequacy for synthesis of products. Thus, equations are needed that account for fluctuations in the end products of ruminal fermentation and other absorbed nutrients on milk and meat composition. Because a metabolic model depends on the rumen model for its substrates, our first priority has been to develop a robust rumen model that can accurately predict quantities of end products of fermentation that are available for absorption. Further research is needed to improve the predictions of AA balances, including AA intestinal availability, identification of AA limitations, efficiency of use of absorbed AAs, and requirements for branched-chain AAs (Fox and Tedeschi, 2003). When known shortcomings in the ruminal sub-model have been addressed, future versions of the CNCPS may contain a metabolism sub-model. This sub-model will predict heat increment and efficiency of absorbed nutrient utilization (carbohydrates, VFA, lipids and AA). Furthermore, this metabolic sub-model will predict whether individual substrates are adequately supplied for energy use and product synthesis by tissues. The ultimate goal of this metabolic sub-model will be to permit metabolic troubleshooting on-farms.

7. Implications

The CNCPS as presented here accurately predicts nutrient requirements, feed utilization and nutrient excretion in a variety of production settings. These predictions enable nutritionists to identify sources of variation and can be used to formulate more economical and environmentally friendly rations. By more accurately formulating diets in each unique production situation, the need for expensive, and often environmentally detrimental, nutritional safety factors can be minimized.

References

ADAS, 1998. On farm validation of the Cornell Net Carbohydrate and Protein System. ADAS Bridgets Research Centre Research Report. Martyr Worthy, Winchester, Hampshire, England.

Agresti, A., 2002. Categorical Data Analysis, second ed. Wiley, New York.

Ainslie, S.J., Fox, D.G., Perry, T.C., Ketchen, D.J., Barry, M.C., 1993. Predicting amino acid adequacy of diets fed to Holstein steers. J. Anim. Sci. 71, 1312–1319.

Alderman, G., France, J., Kebreab, E., 2001a. A critique of the Cornell Net Carbohydrate and Protein System with emphasis on dairy cattle. 1. The rumen model. J. Anim. Feed Sci. 10, 1–24.

Alderman, G., France, J., Kebreab, E., 2001b. A critique of the Cornell Net Carbohydrate and Protein System with emphasis on dairy cattle. 2. The post-rumen digestion model. J. Anim. Feed Sci. 10, 203–221.

Alderman, G., France, J., Kebreab, E., 2001c. A critique of the Cornell Net Carbohydrate and Protein System with emphasis on dairy cattle. 3. The requirements model. J. Anim. Feed Sci. 10, 361–383.

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

Andrew, S.M., Waldo, D.R., Erdman, R.A., 1994. Direct analysis of body composition of dairy cows at three physiological stages. J. Dairy Sci. 77, 3022–3033.

Aquino, D.L., Tedeschi, L.O., Lanzas, C., Lee, S.S., Russell, J.B., 2003. Evaluation of CNCPS predictions of milk production of dairy cows fed alfalfa silage. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. New York State College of Agriculture and Life Sciences, Cornell University, 137–180.

Atasoglu, C., Newbold, C.J., Wallace, R.J., 2001. Incorporation of [^{15}N]ammonia by the cellulolytic ruminal bacteria Fibrobacter succinogenes BL2, *Ruminococcus albus* SY3, and Ruminococcus flavefaciens 17. Appl. Environ. Microbiol. 67, 2819–2822.

Bell, A.W., Slepetis, R., Enrhardt, R.A., 1995. Growth and accretion of energy and protein in the gravid uterus during late pregnancy in Holstein cows. J. Dairy Sci. 78, 1954–1961.

Bibby, J., Toutenburg, H., 1977. Prediction and Improved Estimation in Linear Models. Wiley, Berlin, Germany.

Bryant, M.P., 1973. Nutritional requirements of the predominant rumen cellulolytic bacteria. Fed. Proc. 32, 1809–1813.

Cannas, A., Tedeschi, L.O., Fox, D.G., Pell, A.N., Van Soest, P.J.,2004. A mechanistic model to predict nutrient requirements and feed biological values for sheep. J. Anim. Sci., in press.

Cant, J.P., DePeters, E.J., Baldwin, R.L., 1993. Mammary amino acid utilization in dairy cows fed fat and its relationship to milk protein depression. J. Dairy Sci. 76, 762–774.

Cerosaletti, P.E., 1998. Application of the Cornell Net Carbohydrate and Protein System on a Pasture-based Dairy Farm. M.S. Thesis, Cornell University, Ithaca, NY.

Cerosaletti, P.E., Fox, D.G., Chase, L.E., 2002. Phosphorus Reduction Through Precision Animal Feeding. Final Technical Report of the Phosphorus Reduction Through Precision Animal Feeding Project. Cornell Cooperative Extension of Delaware Country, Hamden, NY.

Chandler, J.A., Jewell, W.J., Gossett, J.M., Van Soest, P.J., Robertson, J.B., 1980. Predicting methane fermentation biodegradability. In: Proceedings of the Biotechnology and Bioengineering Symposium, vol. 10. Wiley, New York, pp. 93–107.

Chen, Y.K., Pell, A.N., Chase, L.E., Schofield, P., 1999. Rate and extent of digestion of the ethanol-soluble and neutral detergent-insoluble fractions of corn grain. J. Anim. Sci. 77, 3077–3083.

Chung, M., Teng, C., Timmerman, M., Meschia, G., Battaglia, F.C., 1998. Production and utilization of amino acids by ovine placenta in vivo. Am. J. Physiol. (Endocrinol. Metab.) 274, E13–E22.

Clark, J.H., Klusmeyer, T.H., Cameron, M.R., 1992. Microbial protein synthesis and flow of nitrogen fractions to the duodenum of dairy cows. J. Dairy Sci. 75, 2304–2323.

Clark, J.H., Spires, H.R., Derrig, R.G., Bennink, M.R., 1977. Milk production, nitrogen utilization, and glucose synthesis in lactating cows infused postruminally with sodium caseinate and glucose. J. Nutr. 107, 631–644.

Dado, R.G., Allen, M.S., 1994. Variation in and relationships among feeding, chewing, and drinking variables for lactating dairy cows. J. Dairy Sci. 77, 132–144.

Davis, C.L., Brown, R.E., Beitz, D.C., 1964. Effect of feeding high-grain restricted-roughage rations with and without bicarbonates on the fat content of milk produced and proportions a of volatile fatty acids. J. Dairy Sci. 47, 1217–1226.

Diaz, M.C., Van Amburgh, M.E., Smith, J.M., Kelsey, J.M., Hutten, E.L., 2001. Composition of growth of Holstein calves fed milk replacer from birth to 105 kg body weight. J. Dairy Sci. 84, 830–842.

Dijkstra, J., Mills, J.A.N., France, J., 2002. The role of dynamic modelling in understanding the microbial contribution to rumen function. Nutr. Res. Rev. 15, 67–90.

Doane, P.H., Pell, A.N., Schofield, P., 1997a. The effect of preservation method on the neutral detergent soluble fraction of forages. J. Anim. Sci. 75, 1140–1148.

Doane, P.H., Schofield, P., Pell, A.N., 1997b. Neutral detergent fiber disappearance and gas and volatile fatty acids production during the in vitro fermentation of six forages. J. Anim. Sci. 75, 3342–3352.

Erickson, P.S., Murphy, M.R., Clark, J.H., 1992. Supplementation of dairy cow diets with calcium salts of long-chain fatty acids and nicotinic acid in early lactation. J. Dairy Sci. 75, 1078–1089.

Fox, D.G., Tylutki, T.P., 1998. Accounting for the effects of environment on the nutrient requirements of dairy cattle. J. Dairy Sci. 81, 3085–3095.

Fox, D.G., Tedeschi, L.O., 2002. Application of physically effective fiber in diets for feedlot cattle. In: Proceedings of the Plains Nutrition Conference. pp. 67–81.

Fox, D.G., Tedeschi, L.O., 2003. Predicting dietary amino acid adequacy for ruminants. In: D'Mello, J.P.F. (Ed.), Amino Acids in Animal Nutrition. CABI Publishing, Cambridge, MA, pp. 389–410.

Fox, D.G., Van Amburgh, M.E., Tylutki, T.P., 1999. Predicting requirements for growth, maturity, and body reserves in dairy cattle. J. Dairy Sci. 82, 1968–1977.

Fox, D.G., Sniffen, C.J., O'Connor, J.D., Russell, J.B., Van Soest, P.J., 1992. A net carbohydrate and protein system for evaluating cattle diets. III. Cattle requirements and diet adequacy. J. Anim. Sci. 70, 3578–3596.

Fox, D.G., Barry, M.C., Pitt, R.E., Roseler, D.K., Stone, W.C., 1995. Application of the Cornell net carbohydrate and protein model for cattle consuming forage. J. Anim. Sci. 73, 267–277.

Fox, D.G., Tylutki, T.P., Albrecht, G.L., Cerosaletti, P.E., Tedeschi, L.O., 2002. Environmental protection and the Cornell University nutrient management planning system: Future perspectives. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. New York State College of Agriculture and Life Sciences, Cornell University. pp. 79–98.

Fox, D.G., Tylutki, T.P., Tedeschi, L.O., Van Amburgh, M.E., Chase, L.E., Pell, A.N., Overton, T.R., Russell, J.B., 2003. The Net Carbohydrate and Protein System for Evaluating Herd Nutrition and Nutrient Excretion: Model Documentation. Mimeo No. 213, Animal Science Department, Cornell University, Ithaca, NY.

Gregory, K.E., Cundiff, L.V., Koch, R.M., 1992. Composite Breeds to Use in Heterosis and Breed Differences to Improve Efficiency of Beef Production. U.S. Department of Agriculture, Washington, DC.

Guinard, J., Rulquin, J., 1995. Effects of graded amounts of duodenal infusions of methionine on the mammary uptake of major milk precursors in dairy cows. J. Dairy Sci. 78, 2196–2207.

Guiroy, P.J., 2001. A system to improve local beef production efficiency and consistency in beef quality and its implementation through the creation of a strategic alliance. Ph.D. Dissertation, Cornell University, Ithaca, NY.

Guiroy, P.J., Tedeschi, L.O., Fox, D.G., Hutcheson, J.P., 2002. The effects of implant strategy on finished body weight of beef cattle. J. Anim. Sci. 80, 1791–1800.

Haefner, J.W., 1996. Modeling Biological Systems: Principles and Applications, first ed. Kluwer Academic Publishers, Dordrecht.

Hanigan, M.D., Calvert, C.C., DePeters, E.J., Reis, B.L., Baldwin, R.L., 1992. Kinetics of amino acid extraction by lactating mammary glands in control and sometribove-treated Holstein cows. J. Dairy Sci. 75, 161–173.

Hungate, R.E., Stack, R.J., 1982. Phenylpropanoic acid: growth factor for *Ruminococcus albus*. Appl. Environ. Microbiol. 44, 79–83.

Hutson, J.L., Pitt, R.E., Koelsch, R.K., Houser, J.B., Wagenet, R.J., 1998. Improving dairy farm sustainability. II. Environmental losses and nutrient flows. J. Prod. Agric. 11, 233–239.

INRA, 1989. Ruminant Nutrition. Recommended Allowances and Feed Tables. Institut National de la Recherche Agronomique, John Libbey Eurotext, Montrouge, France.

Isaacson, H.R., Hinds, F.C., Bryant, M.P., Owens, F.N., 1975. Efficiency of energy utilization by mixed rumen bacteria in continuous culture. J. Dairy Sci. 58, 1645–1659.

Juarez Lagunes, F.I., Fox, D.G., Blake, R.W., Pell, A.N., 1999. Evaluation of tropical grasses for milk production by dual-purpose cows in tropical Mexico. J. Dairy Sci. 82, 2136–2145.

Kirchgeßner, M., 1993. Mitteilungen des ausschusses fur bedasfsnormen der gesselchaft fur ernahrungsphysiologie. Proc. Soc. Nutr. Physiol. 1, 108–112.

Klausner, S.D., Fox, D.G., Rasmussen, C.N., Pitt, R.E., Tylutki, T.P., Wright, P.E., Chase, L.E., Stone, W.C., 1998. Improving dairy farm sustainability. I. An approach to animal and crop nutrient management planning. J. Prod. Agric. 11, 225–233.

Knowlton, K.F., Glenn, B.P., Erdman, R.A., 1998. Performance, ruminal fermentation, and site of starch digestion in early lactation cows fed corn grain harvested and processed differently. J. Dairy Sci. 81, 1972–1984.

Kohn, R.A., Kalscheur, K.F., Hanigan, M., 1998. Evaluation of models for balancing the protein requirements of dairy cows. J. Dairy Sci. 81, 3402–3414.

Kolver, E.S., Muller, L.D., Barry, M.C., Penno, J.W., 1998. Evaluation and application of the Cornell Net Carbohydrate and Protein System for dairy cows fed diets based on pasture. J. Dairy Sci. 81, 2029–2039.

Lana, R.P., Russell, J.B., Van Amburgh, M.E., 1998. The role of pH in regulating ruminal methane and ammonia production. J. Anim. Sci. 76, 2190–2196.

Lanna, D.P.D., Fox, D.G., Boin, C., Traxler, M.J., Barry, M.C., 1996. Validation of the CNCPS estimates of nutrient requirements of growing and lactating Zebu germplasm in tropical conditions. J. Anim. Sci. 74, 287.

Littell, R.C., Freund, R.J., Spector, P.C., 1991. SAS System for Linear Models, thirrd ed. SAS Institute Inc., Cary, NC.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1999. SAS System for Mixed Models. SAS Institute, Cary, NC.

Lykos, T., Varga, G.A., 1997. Varying degradation rates of total nonstructural carbohydrates: effects on nutrient uptake and utilization by the mammary gland in high producing dairy cows. J. Dairy Sci. 80, 3356–3367.

Mackle, T.R., Dwyer, D.A., Ingvartsen, K.L., Chouinard, P.Y., Ross, D.A., Bauman, D.E., 2000. Effects of insulin and postruminal supply of protein on use of amino acids by the mammary gland for milk protein synthesis. J. Dairy Sci. 83, 93–105.

Makoni, N.F., Broderick, G.A., Muck, R.E., 1997. Effect of modified atmospheres on proteolysis and fermentation of ensiled alfalfa. J. Dairy Sci. 80, 912–920.

Mayer, D.G., Butler, D.G., 1993. Statistical validation. Ecol. Model. 68, 21–32.

Meng, Q., Kerley, M.S., Ludden, P.A., Belyea, R.L., 1999. Fermentation substrate and dilution rate interact to affect microbial growth and efficiency. J. Anim. Sci. 77, 206–214.

Mertens, D.R., 1973. Application of theoretical mathematical models to cell wall digestion and forage intake in ruminants. Ph.D. Dissertation, Cornell University, Ithaca, NY.

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

Metcalf, J.A., Wray-Cahen, D., Chettle, E.E., Sutton, J.D., Beever, D.E., Crompton, L.A., MacRae, J.C., Bequette, B.J., Backwell, F.R.C., 1996. The effect of dietary crude protein as protected soybean meal on mammary metabolism in the lactating dairy cow. J. Dairy Sci. 79, 603–611.

Milligan, R.A., Chase, L.E., Sniffen, C.J., Knoblauch, W.A., 1981. Least-cost Balanced Dairy Rations. Anim. Sci. Mimeo No. 54. Cornell University, Ithaca, NY.

Mitchell, P.L., 1997. Misuse of regression for empirical validation of models. Agric. Syst. 54, 313–326.

Mitchell, P.L., Sheehy, J.E., 1997. Comparison of predictions and observations to assess model performance: a method of empirical validation. In: Kropff, M.J., Teng, P.S., Aggarwal, P.K., Bouma, J., Bouman, B.A.M., Jones, J.W., Van Laar, H.H. (Eds.), Applications of Systems Approaches at the Field Level. Kluwer Academic Publishers, Boston, MA, pp. 437–451.

Moe, P.W., 1981. Energy metabolism of dairy cattle. J. Dairy Sci. 64, 1120–1139.

Molina, D.O., 2002. Prediction in intake of lactating cows in the tropics and of the energy value of organic acids. Ph.D. Dissertation, Cornell University, Ithaca, NY.

Neter, J., Kutner, M.H., Nachtsheim, C.J., Wasserman, W., 1996. Applied Linear Statistical Models, fourth ed. McGraw-Hill Publishing Co., Boston.

Nicholson, C.F., Blake, R.W., Urbina, C.I., Lee, D.R., Fox, D.G., Van Soest, P.J., 1994. Economic comparison of nutritional management strategies for Venezuelan dual-purpose cattle systems. J. Anim. Sci. 72, 1680–1696.

Nour, A.Y.M., Thonney, M.L., 1987. Carcass soft tissue and bone composition of early and late maturing steers fed two diets in two housing types and serially slaughtered over a wide weight range. J. Agric. Sci. 109, 345–356.

NRC, 1984. Nutrient Requirements of Beef Cattle, sixth ed. National Academy Press, Washington, DC.

NRC, 1985. Ruminant Nitrogen Usage. National Academy Press, Washington, DC.

NRC, 1989. Nutrient Requirements of Dairy Cattle, sixth ed. National Academy Press, Washington, DC.

NRC, 2000. Nutrient Requirements of Beef Cattle, seventh ed. (updated). National Academy Press, Washington, DC.

NRC, 2001. Nutrient Requirements of Dairy Cattle, seventh ed. National Academy Press, Washington, DC.

O'Connor, J.D., Sniffen, C.J., Fox, D.G., Chalupa, W., 1993. A net carbohydrate and protein system for evaluating cattle diets. IV. Predicting amino acid adequacy. J. Anim. Sci. 71, 1298–1311.

Otto, K.L., Ferguson, J.D., Fox, D.G., Sniffen, C.J., 1991. Relationship between body condition score and composition of ninth to eleventh rib tissue in Holstein dairy cows. J. Dairy Sci. 74, 852–859.

Paster, B., Russell, J.B., Yang, C.M.J., Chow, J.M., Woese, C.R., Tanner, R., 1993. Phylogeny of ammonia-producing ruminal bacteria, *Peptostreptococcus anaerobius*, *Clostridium sticklandii* and *Clostridium aminophilum* sp. nov. Int. J. Sys. Bacteriol. 43, 107–110.

Pell, A.N., Schofield, P., 1993. Computerized monitoring of gas production to measure forage digestion in vitro. J. Dairy Sci. 76, 1063–1073.

Pell, A.N., Pitt, R.E., Doane, P.H., Schofield, P., 1998. The development, use and application of the gas production technique at Cornell University, USA. In vitro Techniques for Measuring Nutrient Supply to Ruminants No. 22. British Soc. Anim. Sci., Penicuik, U.K.

Perry, T.C., Fox, D.G., 1997. Predicting carcass composition and individual feed requirement in live cattle widely varying in body size. J. Anim. Sci. 75, 300–307.

Perry, T.C., Fox, D.G., Beermann, D.H., 1991. Effect of an implant of trenbolone acetate and estradiol on growth, feed efficiency, and carcass composition of Holstein and beef steers. J. Anim. Sci. 69, 4696–4702.

Pirt, S.J., 1965. The maintenance energy of bacteria in growing cultures. Proc. R. Soc. London Ser. B 163, 224–231.

Pitt, R.E., Van Kessel, J.S., Fox, D.G., Pell, A.N., Barry, M.C., Van Soest, P.J., 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. J. Anim. Sci. 74, 226–244.

Rasmussen, C.N., Ketterings, Q.M., Albrecht, G.L., 2002. Cornell Cropware version 1.0, a CuNMPS Software Program, Developing and Applying Next Generation Tools for Farm and Watershed Nutrient Management to Protect Water Quality. Cornell Animal Science Department Mimeo 220 and Crop and Soil Science Research Series E-02-1, pp. 13–29.

Reynoso-Campos, O., Fox, D.G., Blake, R.W., Barry, M.C., Tedeschi, L.O., Nicholson, C.F., Kaiser, H.M., Oltenacu, P.A, 2004. Predicting nutritional requirements and lactation performance of dual-purpose cows using a continuous model. Agric. Syst., in press.

Roseler, D.K., Fox, D.G., Pell, A.N., Chase, L.E., 1997a. Evaluation of alternative equations for prediction of intake for Holstein dairy cows. J. Dairy Sci. 80, 864–877.

Roseler, D.K., Fox, D.G., Chase, L.E., Pell, A.N., Stone, W.C., 1997b. Development and evaluation of equations for prediction of intake for lactating Holstein dairy cows. J. Dairy Sci. 80, 878–893.

Ross, D.E., Van Amburgh, M.E., 2003. Amino acid composition of ruminant feeds and feed fractions. J. Anim. Sci. 81 (Suppl. 1), 217 (Abstr.).

Rueda-Maldonato, B., 2002. Nutrient dynamics and productivity potentials of pasture-based cattle systems in the western Amazon of Brazil. Ph.D. Dissertation, Cornell University, Ithaca, NY.

Ruiz, R., Albrecht, G.L., Tedeschi, L.O., Jarvis, G., Russell, J.B., Fox, D.G., 2001. Effect of monensin on the performance and nitrogen utilization of lactating dairy cows consuming fresh forage. J. Dairy Sci. 84, 1717–1727.

Ruiz, R., Tedeschi, L.O., Marini, J.C., Fox, D.G., Pell, A.N., Jarvis, G., Russell, J.B., 2002. The effect of a ruminal nitrogen (N) deficiency in dairy cows: evaluation of the Cornell net carbohydrate and protein system ruminal N deficiency adjustment. J. Dairy Sci. 85, 2986–2999.

Rulquin, H., Vérité, R., 1993. Amino acid nutrition of dairy cows: productive effects and animal requirements. In: Garnsworthy, P.C., Cole, D.J.A. (Eds.), Recent Advances in Animal Nutrition. Nottingham University Press, Nottingham, pp. 55–77.

Russell, J.B., 1999. Excessive grain feeding acid-resistant bacteria and their impact on cattle. Recent Adv. Anim. Nutr. Austr. 73–79.

Russell, J.B., 2002. Rumen Microbiology and Its Role in Ruminant Nutrition. J.B. Russell Publishing Co., Ithaca, NY.

Russell, J.B., Dombrowski, D.B., 1980. Effect of pH on the efficiency of growth by pure cultures of rumen bacteria in continuous culture. Appl. Environ. Microbiol. 39, 604–610.

Russell, J.B., Sniffen, C.J., 1984. Effect of carbon-4 and carbon-5 volatile fatty acids on growth of mixed rumen bacteria in vitro. J. Dairy Sci. 67, 987–994.
Russell, J.B., Strobel, H.J., 1993. Microbial energetics. In: Forbes, J.M., France, J. (Eds.), Quantitative Aspects of Ruminant Digestion and Metabolism. CAB International, Oxon, UK, pp. 165–186.
Russell, J.B., Cook, G.M., 1995. Energetics of bacterial growth: balance of anabolic and catabolic reactions. Microbiol. Rev. 59, 48–62.
Russell, J.B., Wilson, D.B., 1996. Why are ruminal cellololytic bacteria unable to digest cellulose at low pH? J. Dairy Sci. 79, 1503–1509.
Russell, J.B., Wallace, R.J., 1997. Energy yielding and consuming reactions. In: Stewart, P.N.H.a.C.S. (Ed.), The Rumen Microbial Ecosystem. Blackie Academic & Professional, London, England, pp. 246–282.
Russell, J.B., Sniffen, C.J., Van Soest, P.J., 1983. Effect of carbohydrate limitation on degradation and utilization of casein by mixed rumen bacteria. J. Dairy Sci. 66, 763–775.
Russell, J.B., O'Connor, J.D., Fox, D.G., Van Soest, P.J., Sniffen, C.J., 1992. A net carbohydrate and protein system for evaluating cattle diets. I. Ruminal fermentation. J. Anim. Sci. 70, 3551–3561.
Rychlik, J.L., Russell, J.B., 2000. Mathematical estimations of hyper-ammonia producing ruminal bacteria and evidence for bacterial antagonism that decreases ruminal ammonia production. FEMS Microbiol. Ecol. 32, 121–128.
Schofield, P., 2000. Gas production methods. In: D'Mello, J.P.F. (Ed.), Farm Animal Metabolism and Nutrition. CAB International, Wallingford, Oxon, U.K., pp. 209–232.
Schofield, P., Pell, A.N., 1995a. Validity of using accumulated gas pressure readings to measure forage digestion in vitro: a comparison involving three forage. J. Dairy Sci. 78, 2230–2238.
Schofield, P., Pell, A.N., 1995b. Measurement and kintetic analysis of the neutral detergent-soluble carbohydrate fraction of legumes and grasses. J. Anim. Sci. 73, 3455–3463.
Schofield, P., Pitt, R.E., Pell, A.N., 1994. Kinetics of fiber digestion from in vitro gas production. J. Anim. Sci. 72, 2980–2991.
Schwab, C.G., 1996. Amino acid nutrition of the dairy cow: current status. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. New York State College of Agriculture and Life Sciences, Cornell University, pp. 184–198.
Sniffen, C.J., O'Connor, J.D., Van Soest, P.J., Fox, D.G., Russell, J.B., 1992. A net carbohydrate and protein system for evaluating cattle diets. II. Carbohydrate and protein availability. J. Anim. Sci. 70, 3562–3577.
Spires, H.R., Clark, J.H., Derrig, R.G., Davis, C.L., 1975. Milk production and nitrogen utilization in response to postruminal infusion of sodium caseinate in lactating cows. J. Nutr. 105.
Stefanon, B., Pell, A.N., Schofield, P., 1996. Effect of maturity on digestion kinetics of water-soluble and water-insoluble fractions of Alfalfa and Brome hay. J. Anim. Sci. 74, 1104–1115.
Stone, W.C., 1996. Applied topics in dairy cattle nutrition. 1. Soyhulls as either a forage or concentrate replacement in early lactation Holstein dairy cattle. 2. Evaluation of the Cornell Net Carbohydrate and Protein System's metabolizable protein requirement as supply in Holstein dairy cattle. 3. In vitro effects of lipids on fermentation systems. Ph.D. Dissertation, Cornell University, Ithaca, NY.
Stouthamer, A.H., 1973. A theoretical study on the amount of ATP required for synthesis of microbial cell material. Antonie van Leeuvenhoek. 39, 545–565.
Strobel, H.J., Russell, J.B., 1986. Effect of pH and energy spilling on bacterial protein synthesis by carbohydrate-limited cultures of mixed rumen bacteria. J. Dairy Sci. 69, 2941–2947.
Swanson, E.W., 1977. Factors for computing requirements of protein for maintenance of cattle. J. Dairy Sci. 60, 1583–1593.
Tedeschi, L.O., 2001. Development and evaluation of models for the Cornell Net Carbohydrate and Protein System. 1. Feed libraries. 2. Ruminal nitrogen and branched-chain volatile fatty acid deficiencies. 3. Diet optimization. 4. Energy requirement for maintenance and growth. Ph.D. Dissertation, Cornell University, Ithaca, NY (Chapter 2).
Tedeschi, L.O., Fox, D.G., Russell, J.B., 2000a. Accounting for the effects of a ruminal nitrogen deficiency within the structure of the Cornell net carbohydrate and protein system. J. Anim. Sci. 78, 1648–1658.
Tedeschi, L.O., Fox, D.G., Russell, J.B., 2000b. Accounting for ruminal deficiencies of nitrogen and branched-chain amino acids in the structure of the Cornell net carbohydrate and protein system. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. New York State College of Agriculture and Life Sciences, Cornell University, pp. 224–238.

Tedeschi, L.O., Fox, D.G., Chase, L.E., Wang, S.J., 2000c. Whole-herd optimization with the Cornell net carbohydrate and protein system. I. Predicting feed biological values for diet optimization with linear programming. J. Dairy Sci. 83, 2139–2148.

Tedeschi, L.O., Pell, A.N., Fox, D.G., Llames, C.R., 2001. The amino acid profiles of the whole plant and of four residues from temperate and tropical forages. J. Anim. Sci. 79, 525–532.

Tedeschi, L.O., Baker, M.J., Ketchen, D.J., Fox, D.G., 2002a. Performance of growing and finishing cattle supplemented with a slow-release urea product and urea. Can. J. Anim. Sci. 82, 567–573.

Tedeschi, L.O., Fox, D.G., Pell, A.N., Lanna, D.P.D., Boin, C., 2002b. Development and evaluation of a tropical feed library for the Cornell Net Carbohydrate and Protein System model. Scientia Agricola. 59, 1–18.

Tedeschi, L.O., Boin, C., Fox, D.G., Leme, P.R., Alleoni, G.F., Lanna, D.P.D., 2002c. Energy requirement for maintenance and growth of Nellore bulls and steers fed high-forage diets. J. Anim. Sci. 80, 1671–1682.

Tedeschi, L.O., Fox, D.G., Tylutki, T.P., 2003. Potential environmental benefits of ionophores in ruminant diets. J. Environ. Qual. 31, 1591–1602.

Tedeschi, L.O., Fox, D.G., Guiroy, P.J., 2004. A decision support system to improve individual cattle management. 1. A mechanistic, dynamic model for animal growth. Agric. Syst., in press.

Traxler, M.J., 1997. Predicting the effect of lignin on the extent of digestion and the evaluation of alternative intake models for lactating cows consuming high NDF forages. Ph.D. Dissertation, Cornell University, Ithaca, NY.

Traxler, M.J., Fox, D.G., Van Soest, P.J., Pell, A.N., Lascano, C.E., Lanna, D.P.D., Moore, J.E., Lana, R.P., Vélez, M., Flores, A., 1998. Predicting forage indigestible NDF from lignin concentration. J. Anim. Sci. 76, 1469–1480.

Tylutki, T.P., 2002. Improving herd nutrient management on dairy farms: 1) Individual cow milk production variance. 2) Developing a quality management program on a commercial dairy farm: a six sigma approach. 3) Variation in nutrient content of feeds on a commercial dairy farm. 4) Predicting phosphorus excretion by dairy cattle. 5) Incorporating risk in managing dairy cattle nutrition. PhD Dissertation, Cornell University, Ithaca, NY.

Tylutki, T.P., Fox, D.G., 1997. Application of the cornell nutrient management planning system: optimizing herd nutrition. In: Proceedings of the Cornell Nutrition Conferencce for Feed Manufacturers. New York State College of Agriculture and Life Sciences, Cornell University, pp. 54–65.

Tylutki, T.P., Fox, D.G., Anrique, R.G., 1994. Predicting net energy and protein requirements for growth of implanted and nonimplanted heifers and steers and nonimplanted bulls varying in body size. J. Anim. Sci. 72, 1806–1813.

Tylutki, T.P., Fox, D.G., McMahon, M., 2002. Implementation of the cuNMPS: development and implementation of alternatives. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. Cornell University, Ithaca, NY, pp. 57–70.

Tyrrell, H.F., Moe, P.W., Flatt, W.P., 1970. Influence of excess protein intake on energy metabolism of the dairy cow. In: Schurch, A., Wenk, C. (Eds.), Energy Metabolism of Farm Animals, fifth ed. EAAP, pp. 69–72.

Van Amburgh, M.E., Fox, D.G., Galton, D.M., Bauman, D.E., Chase, L.E., 1998a. Evaluation of National Research Council and Cornell Net Cabohydrate and Protein Systems for predicting requirements of Holstein heifers. J. Dairy Sci. 81, 509–526.

Van Amburgh, M.E., Galton, D.M., Bauman, D.E., Everett, R.W., Fox, D.G., Chase, L.E., Erb, H.N., 1998b. Effects of three prepubertal body growth rates on performance of holstein heifers during first lactation. J. Dairy Sci. 81, 527–538.

Van Kessel, J.S., Russell, J.B., 1993. Energy spilling in mixed ruminal bacteria. In: Proceedings of the Conference on Rumen Function, vol. 27.

Van Soest, P.J., Van Amburgh, M.E., Tedeschi, L.O., 2000. Rumen balance and rates of fiber digestion. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. New York State College of Agriculture and Life Sciences, Cornell University, pp. 150–166.

Waghorn, G.C., Baldwin, R.L., 1984. Model of metabolite flux within mammary gland of the lactating cow. J. Dairy Sci. 67, 531–544.

Weiss, W.P., 1993. Predicting energy values of feeds. J. Dairy Sci. 76, 1802–1811.

Weiss, W.P., 1999. Energy prediction equations for ruminant feeds. In: Proceedings of the Cornell Nutrition Conference for Feed Manufacturers. New York State College of Agriculture and Life Sciences, Cornell University, pp. 176–185.

Weiss, W.P., Conrad, H.R., St. Pierre, N.R., 1992. A theoretically-based model for predicting total digestible nutrient values of forages and concentrates. Anim. Feed Sci. Technol. 39, 95–110.

Weller, R.A., Pilgrim, A.F., 1974. Passage of protozoa and volatile fatty acids from the rumen of the sheep and from a continuous in vitro fermentation system. Br. J. Nutr. 32, 341–351.

Wolin, M.J., 1960. A theoretical rumen fermentation balance. J. Dairy Sci. 43, 1452–1459.

Wurgler, F., Bickel, H., 1987. The partial efficiency of energy utilization in steers of different breeds. In: Moe, P.W., Tyrrell, H.F., Reynolds, P.J. (Eds.), Proceedings of the Energy Metabology, vol. 10. Rowman & Littlefield, pp. 32, 90–93.

Yang, C.M.J., Russell, J.B., 1993. The effect of monensin supplementation on ruminal ammonia accumulation in vivo and the number of amino acid-fermenting bacteria. J. Anim. Sci. 71, 3470–3476.

Zinn, R.A., Shen, Y., 1997. Factorializing postruminal protein supplies for feedlot cattle: assessment of 1996 NRC beef metabolizable protein concepts. In: Huber, J.T. (Ed.), Proceedings of the Southwest Nutrition and Management Conference, vol. 12. University of Arizona, Arizona, pp. 35–43.