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Cornell Net Carbohydrate and Protein System: A model for precision feeding of dairy cattle

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Abstract

The Cornell Net Carbohydrate and Protein System (CNCPS) predicts cattle requirements and nutrient supply for site-specific situations. This paper describes the CNCPS version 6 (CNCPSv6), which represents a re-engineering and updating of CNCPS version 5 with the following objectives: (1) improve the organization of the model and user interface to improve speed and accuracy in formulating diets for a herd of dairy cattle, (2) expand the carbohydrate pools to include sugars, soluble fibers, and organic and volatile fatty acids, (3) integrate a fat model to account for ruminal lypolization and biohydrogenation, and absorption of fatty acids in the small intestine, and (4) update the computational sub-models with new information. The CNCPSv6 model was re-designed using object-oriented programming in which physiological functions (*e.g.* growth, lactation, pregnancy) and anatomical compartments (*e.g.* rumen, intestines) were programmed as objects. The interface uses farm, location, and group flow, which decreases the number of inputs required per cattle group and allows for more rapid evaluation of diets, feed requirements, and nutrient excretion by location, group, and herd. The revised implementation of the body reserves sub-model allows accounting for fluxes in energy reserves when formulating diets. Updated equations and coefficients include the prediction of rumen ammonia balance and feed passage rates, indigestible DM, MP lactation efficiency, and DMI. The CNCPSv6 was evaluated with data from individually fed lactating dairy cows from three independent studies. As implemented, CNCPSv6 accounted for a similar proportion of the variation

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(86%) in first limiting (ME or MP) milk production as CNCPSv5 but with a lower bias (1% *versus* 4%, respectively). We concluded the re-designing and updating of the CNCPS improved its ability to formulate and evaluate a feeding program for a herd of dairy cattle with greater accuracy and efficiency.

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

1. Introduction

The Cornell Net Carbohydrate and Protein System version 5 (CNCPSv5) is a model designed to evaluate diets and animal performance for all classes of cattle in unique production situations, using science-based principles of rumen function, microbial growth, feed digestion and passage, and physiological state (Fox et al., 2004). By accounting for farm-specific animal, feed, and environmental characteristics, more accurate prediction of dietary nutrient requirements for maintenance, growth and milk production of cattle and nutrient excretion in diverse production situations is possible. The CNCPSv5 model was used as the biological structure for developing a computer program for consulting dairy nutritionists to use in formulating rations for individual groups in a herd through a collaborative effort by scientists at Cornell University, University of Pennsylvania, and Miner Institute. The result of this collaboration was the development of the CPM Dairy model (Boston et al., 2000). The CNCPS version 5 and CPM Dairy version 3 software are being routinely used by both nutritional consultants and feed companies. The CNCPS has been used as a farm management tool to optimize use of farm-specific feeds, decrease the need for purchased supplements, optimize herd size, predict the manure nutrients that will have to be managed, and improve the annual return over feed cost (Tylutki et al., 2004; Fox et al., 2004). However, the software interface was not designed for efficient routine use in developing whole herd feeding plans. The United States Department of Agriculture National Resource Conservation Service (USDA-NRCS) identified the need to improve herd feed management to reduce manure nutrients, and to address this issue has developed a Feed Management Standard for use in nutrient management planning on farms. The purposes of the USDA-NRCS 592 standard are (1) to supply the quantity of nutrients required by livestock in the diet while reducing the quantity of nutrients excreted, and (2) to improve net farm income by feeding nutrients more efficiently (USDA-NRCS, 2003).

The objective of this paper is to describe the re-designed CNCPSv5 and to evaluate its prediction in meeting the USA NRCS Feed Management Standard objective of more accurately supplying the quantity of energy and protein required in the diets of dairy cattle on USA dairy farms for milk production.

2. Model development

This model must predict the following for each animal group (and the whole herd) when accounting for nutrient management: (1) accurately predict the nutrient requirements and supply for each group in each production unit (*e.g.* barn, pen, paddock) from inputs currently available on the farm, (2) evaluate the adequacy of each diet accurately and quickly, (3) predict nutrient excretion for the herd for a designated period of time, (4) predict feed requirements for the same period of time, and (5) have an efficient interface that minimizes inputs that must be made manually for each group of animals.

The CNCPS version 6 (CNCPSv6) represents an evolution of the model that was first published by Russell et al. (1992), Sniffen et al. (1992), and Fox et al. (1992). The object-oriented programming structure was used in the development of CNCPSv6 in which each object was designed to represent specific physiological or structural functions as shown in Fig. 1.

Each of the following sections describes changes made to CNCPSv5 resulting in CNCPSv6. Definitions for variable names used in the equations are provided in Table 1 for acronyms used in equations presented in the text and tables.

2.1. Growth requirements

Energy and protein requirements for growth are predicted in the CNCPS from body weight, rate of body weight gain, chemical composition of gain, and mature weight. The basic equations for the growth model were provided in Table 4 of Fox et al. (2004). A size scaling system based on the ratio of current to mature weight is used to predict the composition of gain. Shrunk body weight (SBW) is adjusted to a weight equivalent to that of a standard reference animal at the same stage of growth. This equivalent SBW (EqSBW) is calculated as SBW × (SRW/AFBW), in which SRW is the mature SBW of the standard reference animal and AFBW is the expected mature SBW. In beef or dairy cows, mature SBW 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

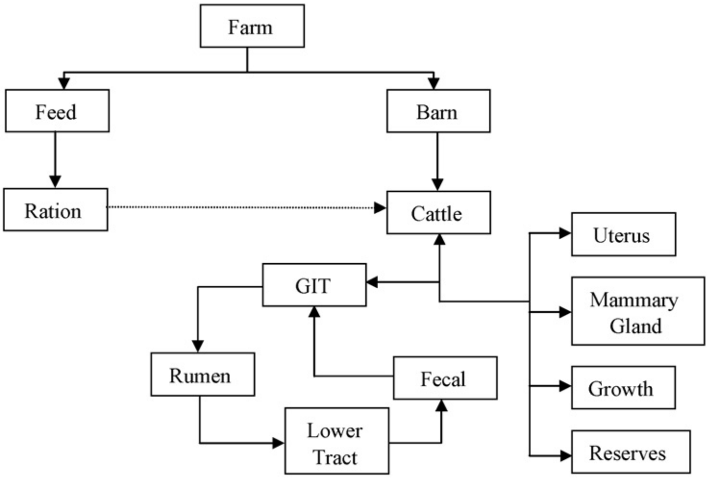

Fig. 1. Diagram of the object-oriented programming structure of the Cornell Net Carbohydrate and Protein System, version 6.0. GIT is gastrointestinal tract.

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Table 1
Description and units of the abbreviations used in this paper

Abbreviations	Units	Description
AA	None	Amino acids
$AATISS_i$	g/g	Content of *i*th AA of tissue protein
ADGPreg	kg/day	Average daily gain during pregnancy
ADICP	%DM	ADF indigestible CP
ADFIP	% DM	ADF insoluble protein
Af	None	Adjustment factor of passage rates for peNDF
Afbiohyd	None	Adjustment factor for biohydrogenation of FFA
AfLip	None	Adjustment factor for lipolysis rate
Adj	None	Adjustment
AGE	Days	Age of animal
BCS	None	Body condition score
$BCS_{1–5}$	None	Body condition score, 1–5 scale
$BCS_{1–9}$	None	Body condition score, 1–9 scale
BioHydKb	%/h	Adjusted rate of biohydrogenation
CA1	% DM	CHO A1 fraction (acetate + propionate + butyrate)
CA2	% DM	CHO A2 fraction (lactate)
CA3	% DM	CHO A3 fraction (other organics)
CA4	% DM	CHO A4 fraction (sugars)
CB1	% DM	CHO B1 fraction (starch)
CB2	% DM	CHO B2 fraction (soluble fiber)
CB3	% DM	CHO B3 fraction (available NDF)
CBW	kg	Calf birth weight
CC	% DM	CHO C fraction (lignin × 2.4)
CHO	% DM	Carbohydrate
CpW	kg	Conceptus weight
DE	Mcal/kg	Digestible energy
Denovo	None	Fatty acid synthesis in the rumen
DMI	kg/d	Dry matter intake
EBEnergy	Mcal	Empty body energy
EBFat	kg	Empty body fat
EBProtein	kg	Empty body protein
EBG	kg/d	Empty body gain
EBW	kg	Empty body weight
EBWBCS5	kg	Empty body weight at BCS 5
EBW_r	kg	Empty body weight for computing energy reserves
EE	% DM	Ether extract
EqEBW	kg	Equivalent empty body weight
EqSBW	kg	Equivalent shrunk body weight
FBF	kg	Final body fat
FC	% DM	Fiber carbohydrates
FA	g/d	Fatty acids
FAID		Fatty acids intestinal digestibility
FEFA	g/d	Amount of undigested feed ash in feces
FFA	% DM	Free fatty acids
FFADig		Free fatty acids intestinal digestibility
Ft	None	Fermentable
HP	Mcal/d	Heat production
IntDigAsh	g/g	Ash intestinal digestibility (default = 0.5)
KbA	%/h	Rate of biohydrogenation

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Table 1 (*Continued*)

Abbreviations	Units	Description
K_d	%/h	Degradation rate for each fraction
K_p	h^{-1}	Passage rate from the rumen
K_{pc}	h^{-1}	Passage rate of concentrates
K_{pf}	h^{-1}	Passage rate of forages
K_{pl}	h^{-1}	Passage rate of liquids
LE	Mcal/d	Metabolizable energy required for lactation
LP	g/d	Requirement of metabolizable protein for lactation
ME	Mcal	ME required
ME	Mcal/d	Metabolizable energy intake
MEmm	Mcal/d	Requirement of metabolizable energy for MAMMOGENESIS
MEPreg	Mcal/d	Metabolizable energy requirement for pregnancy
MF	%	Milk fat
Milk	kg/d	Milk production
ML	% of milk	Milk lactose
MP	g/d	Metabolizable protein
MPmm	g/d	Requirement of metabolizable protein for mammogenesis
MPPreg	g/d	Metabolizable protein requirement for pregnancy
MTP	% of milk	Milk true protein
NDF	% DM	Neutral detergent fiber
NDFIP or NDIN	% CP	Insoluble protein in the NDF
NDICP	% DM	NDF indigestible CP
NEL	Mcal	Net energy lactation
NFC	% DM	Non-fiber carbohydrate
NPl	g/d	Requirement of net protein for lactation
NPmm	g/d	Requirement of net protein for mammogenesis
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
pEBF	dmls	Proportion of empty body fat
pEBP	dmls	Proportion of empty body protein
peNDF	% NDF	Physical effective neutral detergent fiber
peNDFr	kg/d	peNDF required
PepBal	g/d	Balance of peptide nitrogen in the rumen
RDCA1	g/d	Ruminally degraded CA1
RDCA2	g/d	Ruminally degraded CA2
RDCA3	g/d	Ruminally degraded CA3
RDCA4	g/d	Ruminally degraded CA4
RDCB1	g/d	Ruminally degraded CB1
RDCB2	g/d	Ruminally degraded CB2
RDCB3	g/d	Ruminally degraded CB3
RDGlycerol	g/d	Rumen degraded glycerol
RDP	% DM	Ruminally degraded protein
RDPA	g/d	Ruminally degraded PA
RDPB1	g/d	Ruminally degraded PB1
RDPB2	g/d	Ruminally degraded PB2
RDPB3	g/d	Ruminally degraded PB3
RDPEP	g/d	Ruminally degraded peptides
RE	Mcal/d	Retained energy

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Table 1 (*Continued*)

Abbreviations	Units	Description
REAA	g/d	Total amount of the *i*th AA at the duodenum
RECA1	g/d	Ruminally escaped carbohydrate A1
RECA2	g/d	Ruminally escaped carbohydrate A2
RECA3	g/d	Ruminally escaped carbohydrate A3
RECA4	g/d	Ruminally escaped carbohydrate A4
RECB1	g/d	Ruminally escaped carbohydrate B1
RECB2	g/d	Ruminally escaped carbohydrate B2
RECB3	g/d	Ruminally escaped carbohydrate B3
RECC	g/d	Ruminally escaped carbohydrate C
Recycled N	g/d	Amount of NH_3 recycled in the rumen
REFAA	g/d	Amount of *i*th dietary AA at the duodenum
REFAT	g/d	Amount of ruminally escaped fat (ether extract)
REPB1	g/d	Ruminally escaped protein B1
REPB2	g/d	Ruminally escaped protein B2
REPB3	g/d	Ruminally escaped protein B3
REPC	g/d	Ruminally escaped protein C
RFC18:0	g/d	Rumen free C18:0 fatty acids
RNB	g/d	Rumen N balance
RTFC18	g/d	Free C18 produced in the rumen by lipolysis
SBW	kg	Shrunk body weight
SolCP	% CP	Soluble CP for each feed
SRW	kg	Standard reference weight (default is 478 kg)
t	d	Days pregnant
TDN	% DM	Total digestible nutrients
TFA	g/d	Total long chain fatty acids
TI	°C Mcal/m^2/d	Tissue (internal) insulation

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 SBW is the expected SBW at the target body composition. 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, 462, or 478 kg when the harvest target is 22, 25, 27, or 28 kg body fat/100 kg SBW, respectively, as described by NRC (2000, 2001). These body fat contents are equivalent to devoid, trace, slight, and small degrees of marbling, respectively.

A continuous equation (Eq. (1)) was developed to compute standard reference weight (SRW) for growing and finishing cattle based on final body fat (FBF) as recommend by NRC (2000).

$$\mathrm{SRW} = 399.9 - (1019.5 \times \mathrm{FBF}) + (4621.1 \times \mathrm{FBF}^2) \tag{1}$$

where SRW is standard reference weight (kg) and FBF is final body fat (kg/100 kg FBW).

The requirement for metabolizable protein (MP) for mammary growth is based on the values reported by VandeHaar and Donkin (1999). This new version computes MP for mammary growth using Eq. (2) instead of using a fixed value of 276.7 g/d as proposed by Fox et al. (2004). This allows a continuous calculation of MP required for mammary growth

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as EqSBW changes.

$$MP_{mm} = \frac{80}{0.834 - 0.00114 \times EqSBW} \quad (2)$$

where MP_{mm} is metabolizable protein for mammary growth (g/d) and EqSBW is equivalent shrunk body weight (kg).

Thus, a heifer with an EqSBW of 380 kg will have a mammary growth requirement of 200 g (80/0.40) *versus* 276 g for a heifer with an EqSBW of 478 kg (80/0.29).

2.2. Pregnancy requirements

The CNCPS computes pregnancy requirements and SBW gain from growth of the gravid uterus based on expected calf birth weight and day of gestation. Requirements for pregnancy were summarized in Table 5 of Fox et al. (2004). For dairy cattle, we decided to modify Eqs. (1), (3), (5) and (7) in Fox et al. (2004) to be consistent with NRC (2001), which begins accounting for pregnancy starting at 190 d pregnant. Eqs. (3)–(6) show those modifications.

$$ADG_{preg} = \left(\frac{CBW}{45}\right) 665 \quad (3)$$

$$CpW = \left(\frac{CBW}{45}\right) (18 + (t - 190)0.665) \quad (4)$$

$$ME_{preg} = \left(\frac{CBW}{45}\right) \frac{(2 \times 0.00159 \times t - 0.0352)}{0.14} \quad (5)$$

$$MP_{preg} = \left(\frac{CBW}{45}\right) \frac{(0.69 \times t - 69.2)}{0.33} \quad (6)$$

where ADG_{preg} is average daily gain during pregnancy (kg/d); CBW the calf birth weight (kg); CpW the conceptus weight (kg); t the days pregnant; ME the metabolizable energy (Mcal/d); and MP is metabolizable protein (g/d).

Since most requirement predictions (*e.g.* maintenance energy) were originally determined with non-pregnant animals, CNCPSv6 subtracts the predicted conceptus weight from inputted body weight to determine SBW for pregnant cattle.

2.3. Lactation requirements

Energy and protein required for lactation are calculated from actual milk production and components. Requirements for lactation were summarized in Table 7 in Fox et al. (2004). NRC (2001) developed new coefficients and equations to compute lactation requirements, based on an extensive review of the literature. We decided to update the CNCPS with these equations. The following Eqs. (7) and (8) were added to compute lactation requirements for dairy cows as suggested by NRC (2001). Eq. (7) uses a default of 4.85 g lactose/100 g milk when this value is not available. Eq. (8) was updated from CNCPSv5 to use efficiency

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of MP to net protein for lactation (NPl) of 0.67 as suggested by NRC (2001).

$$\mathrm{LE} = \mathrm{Milk}(0.0929 \times \mathrm{MF}) + \left(\frac{0.0547 \times \mathrm{MTP}}{0.93}\right) + (0.0395 \times \mathrm{ML}) \tag{7}$$

$$\mathrm{LP} = \mathrm{Milk}\left(\frac{(\mathrm{MTP}/100)}{0.67}\right) \times 1000 \tag{8}$$

where LE is net energy for lactation (Mcal/d); Milk the milk production (kg/d); MF the milk fat (g/100 g milk); MTP the milk true protein (g/100 g milk); ML the milk lactose (g/100 g milk); and LP is metabolizable protein for lactation (g/d).

2.4. Maintenance requirements

Maintenance requirements in the CNCPS are determined by accounting for breed, physiological state, activity, urea excretion, heat or cold stress and environmental acclimatization effects. The equations used to compute maintenance requirements were summarized in Table 2 in Fox et al. (2004), and Table 3 in that publication provided default values for use in computing maintenance requirements. In CNCPSv6, conceptus weight is subtracted from SBW to compute maintenance requirements. An additional change was made to use the previous effective temperature index when the previous temperature is greater than 20 °C; otherwise the previous temperature is utilized.

Heat production calculations were modified to be a function of energy utilization *versus* dietary energy values as follows.

$$\mathrm{HP} = \mathrm{MEI} - (\mathrm{RE} + \mathrm{LE} + \mathrm{PE})$$

where HP = heat production (Mcal/d), MEI = metabolizable energy intake (Mcal/d), RE = retained energy (Mcal/d), LE = lactation energy (Mcal/d) and PE = pregnancy (conceptus) energy (Mcal/d).

The age adjustment for TI (tissue insulation, Eq. (16) in Table 2 of Fox et al., 2004) was differentiated for different age groups as recommended by NRC (2000).

$$\mathrm{TI} = 5.25 + 0.75 \times \mathrm{BCS} \quad \text{for} \quad \mathrm{AGE} > 364\,\mathrm{d} \tag{9}$$

$$\mathrm{TI} = 2.5 \quad \text{for} \quad \mathrm{AGE} < 31\,\mathrm{d} \tag{10}$$

$$\mathrm{TI} = 6.5 \quad \text{for} \quad \mathrm{AGE} > 31 < 184\,\mathrm{d}, \tag{11}$$

and

$$\mathrm{TI} = 5.1875 + (\mathrm{BCS} \times 0.03125) \quad \text{for} \quad \mathrm{AGE} > 184 < 364\,\mathrm{d} \tag{12}$$

where TI is tissue insulation ($^{\circ}$C/Mcal/m^2/d) and BCS is body condition score (scale 1–9).

In Table 3 in Fox et al. (2004), hide thickness codes were added for each breed for use as defaults; hide code is 1 for dairy and *Bos indicus* breeds, 3 for Hereford, and 2 for all other breeds.

In Eq. (29) in Table 2 in Fox et al. (2004), a conditional statement was added that only includes recycled nitrogen in computing urea cost when rumen N balance is greater than recycled N calculation as shown in Eqs. (13) and (14).

$$\text{Urea cost} = (\text{RNB} - \text{recycled N} + \text{excess N from MP}) \times 0.0073 \quad \text{if} \quad \text{RNB} > \text{recycled N} \tag{13}$$

$$\text{Urea cost} = \text{excess N from MP} \times 0.0073 \quad \text{if} \quad \text{RNB} < \text{recycled N} \tag{14}$$

where RNB is rumen nitrogen balance (g/d), and recycled N is nitrogen recycled to the rumen (g/d).

2.5. *Body reserves*

After reaching maturity, body weight changes reflect use of energy reserves to either supplement ration deficiencies or to store energy consumed above requirements. The CNCPS energy reserves model uses BCS at a particular BW to compute energy reserves changes with changes in animal dietary energy deficiencies or surpluses. Table 6 in Fox et al. (2004) summarized the equations used to compute body reserves. The CNCPS uses the reserves model developed for NRC (2000) and adapted for dairy cattle (NRC, 2001) as described by Fox et al. (1999). In the database used to develop this submodel, mean SBW was 642 kg (BCS 5 on the 1–9 scale), the average SBW change per BCS change was 44 kg (6.85 kg/100 kg mean SBW), and EBW was 85.1 kg/100 kg SBW. NRC (2000) computes SBW change per condition score as 6.85 kg/100 kg SBW for each BCS on either side of the SBW at BCS 5. 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 kg change in SBW, fat and protein/100 kg SBW.

Because of the large number of equations added for this revision, Table 2 provides all of the equations for the body reserves model as implemented in CNCPSv6. The following changes were made for CNCPSv6, to compute contributions of body reserves to ME supply and replenishment of body reserves from the diet, as described by Reynoso-Campos et al. (2004), Tedeschi et al. (2006); (1) adjustment factors used to predict SBW at BCS 3 were converted to an equation, (2) equations were added to compute daily ME and MP required from the diet to reach a user entered target BCS gain in a user entered number of days, and (3) equations were added to compute daily ME and MP provided by reserves for user entered BCS loss in a user entered number of days. This allows the user to define or understand where the additional energy is being partitioned relative to energy allowable milk.

2.6. *Amino acid requirements*

Amino acid requirements in the CNCPS are computed from tissue and milk protein content of amino acids. Tables 8–10 in Fox et al. (2004) provided the equations used to compute amino acid requirements. The values for amino acid composition of tissue (g/100 g of CP) were revised, based on recent analyses of dairy heifer soft tissue (M.E. Van Amburgh, personal communication): Methionine, 1.79; Lysine, 6.26; Histidine, 2.41; Phenylalanine,

Table 2
Equations to estimate energy and protein in the body reserves

Variables	Equations	
BCS_{1-9}	$(BCS_{1-5} - 1) \times 2 + 1$	(20)
EBW_r	$0.851 \times SBW$	(21)
pEBFat	$0.037683 \times BCS9$	(22)
pEBProtein	$0.200886 - (0.0066762 \times BCS9)$	(23)
EBFat	$EBW \times pEBFat$	(24)
EBProtein	$EBW \times pEBProtien$	(25)
EBEnergy	$(9.4 \times EBFat) + (5.7 \times EBProtein)$	(26)
EBWBCS5[a]	$\frac{EBW}{0.657167 + (BCS9 \times 0.068567)}$	(27)
BCS9_Diff	$Target\_BCS9 - BCS9$	(28)
Target_BCS5	$\frac{Target\_BCS9 - 1}{2} + 1$	(29)
Target_BCS_EBW	$EBWBCS5 \times (0.657167 + Target\_BCS9 \times 0.068567)$	(30)
Target_BCS_Fat_Prop	$0.037683 \times Target\_BCS9$	(31)
Target_BCS_Protein_Prop	$0.200886 - (0.0066762 \times Target\_BCS9)$	(32)
Target_BCS_Fat	$Target\_BCS\_EBW \times Target\_BCS\_Fat\_Prop$	(33)
Target_BCS_Protein	$Target\_BCS\_EBW \times Target\_BCS\_Protein\_Prop$	(34)
Target_BCS_Energy	$(9.4 \times Target\_BCS\_Fat)$	(35)
Target_BCS_EBW_Diff	$\frac{Target\_BCS\_EBW - EBW\_at\_BCS5}{Days}$	(36)
Target_BCS_Fat_Prop_Diff	$\frac{Target\_BCS\_Fat\_Prop - EB\_Fat\_Prop}{Days}$	(37)
Target_BCS_Protein_Prop_Diff	$\frac{Target\_BCS\_Protein\_Prop - EB\_Protein\_Prop}{Days}$	(38)
Target_BCS_Fat_Diff	$\frac{Target\_BCS\_Fat - EB\_Fat}{Days}$	(39)
Target_BCS_Protein_Diff	$\frac{Target\_BCS\_Protein - EB\_Protein}{Days}$	(40)
Target_BCS_Energy_Diff	$\frac{Target\_BCS\_Energy - (9.4 \times EB\_Fat)}{Days}$	(41)
Target_BCS_MP_Diff	$\frac{Target\_BCS\_Protein\_Diff \times 1000}{NP\_to\_MP}$	(42)
$Target\_BCS\_AA_j$	$AA\_Tissue_j \times Target\_BCS\_MP\_Diff$	(43)

[a] Adjustment factors used to develop equation are 0.726, 0.794, 0.863, 0.931, 1, 1.069, 1.137, 1.206 and 1.274 for BCS 1–9.

3.65; Tryptophan, 1.18; Threonine, 3.83; Leucine, 6.96; Isoleucine, 2.94; Valine, 4.28; and Arginine, 6.75.

2.7. Dry matter intake (DMI)

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. Table 11 in Fox et al. (2004) provides the equations used to predict DMI. NRC (2001) developed new equations to predict DMI of all classes of dairy cattle, and we decided to update the CNCPS with these equations. The following changes were made to make CNCPS equations consistent with NRC (2001): (1) NRC

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(2001) equations were added for open and pregnant dairy heifers, (2) NRC (2001) equation for lactating cows was added, and (3) the dry cow equation was changed to NRC (2001) equation.

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

The CNCPS has two levels of solution to predict supply of energy and protein 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 1 computes TDN and MP values with empirical equations. 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. In level 2 of the CNCPS, rumen outflow of TDN and MP are derived mechanistically from digestion (K_d) and passage (K_p) rates, using the simple relationship, $K_d/(K_d + K_p)$.

Table 12 in Fox et al. (2004) provided the equations used to compute level 1 solution as published by Tedeschi et al. (2005). The intent of level 1 remains to provide a more empirical system that predicts feed energy and the ratio of rumen degradable protein (RDP) to rumen undegradable protein (RUP) values from feed carbohydrate and protein fractions that are consistent with the CNCPS level 2 when limited information and/or knowledge is available to use level 2. The equations to adjust both TDN and RUP for level of intake were developed from values obtained with level 2 as described in Tedeschi et al. (2005). The resulting level 1 gives feed energy values that are consistent with level 2 and compared very favorably with level 2 when evaluated with growing cattle performance data (Tedeschi et al., 2005) and lactating dairy cows.

2.9. Carbohydrate and protein fractionation and feed passage rates

Feed composition in the CNCPS is described by carbohydrate and protein fractions and their digestion rates, which are used to compute the amount of SC and NSC available for each of these two microbial pools in the rumen submodel. Digestion and passage rates have been developed for common feeds, based on data in the literature. Table 13 in Fox et al. (2004) provided the equations used to compute carbohydrate and protein pools. Because of the large number of equations added, Table 3 provides all of the equations for the prediction of feed carbohydrate and protein pools as implemented in CNCPSv6. The complete feed library containing feed carbohydrate and protein fractions and their digestion rates used by the model to compute these pools is available on the CNCPS website (http://www.cncps.cornell.edu).

The carbohydrate (CHO) pools have been expanded to eight fractions: CA1 (acetic, propionic and butyric acids), CA2 (lactic acid), CA3 (organic acids), CA4 (sugars), CB1 (starch), CB2 (soluble fiber), CB3 (available NDF) and CC (unavailable NDF) to calculate rumen degradation and escape, as described by Lanzas et al. (2007). In previous versions of the CNCPS, carbohydrate fractions were categorized into four fractions: A, B1, B2 and C (Fox et al., 2004). The previous CNCPS fractionation system resulted in sugars, organic acids, and oligosaccharides in the CHO A, and starch and soluble fiber compounds in the

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Table 3
Equations to compute feed carbohydrate and protein fractions available and degraded in the rumen for use in the level 2 rumen model

Variables[a]	Constraints	Equations	
CHO_j		$100 - CP_j - EE_j - Ash_j$	(44)
CC_j		$\frac{NDF_j \times Lignin_j \times 2.4}{100}$	(45)
$CB3_j$		$NDF_j - CC_j$	(46)
NFC_j		$CHO_j - NDF$	(47)
$CB2_j$		$NFC_j - CA1 - CA2 - CA3 - CA4 - CB1$	(48)
PA_j		$NPN_j \times \left(\frac{SolCP_j}{100}\right) \times \left(\frac{CP_j}{100}\right)$	(49)
$PB1_j$		$\frac{SolCP_j \times CP_j}{100 - PA_j}$	(50)
PC_j		$\frac{ADFIP_j \times CP_j}{100}$	(51)
$PB3_j$		$\frac{(NDFIP_j - ADFIP_j) \times CP_j}{100}$	(52)
$PB2_j$		$CP_j - (PA_j - PB1_j - PB3_j - PC_j)$	(53)
K_{pf}		$2.365 + (0.214 \times FpBW) + (0.734 \times CpBW) + (0.069 \times FDMI)$	(54)
K_{pc}		$1.169 + (1.375 \times FpBW) + (1.721 \times CpBW)$	(55)
K_{pl}		$4.524 + (0.223 \times FpBW) + (2.046 \times CpBW) + (0.344 \times FDMI)$	(56)
peNDFr	Growing/finishing	$0.1 \times DMI$	(57)
peNDFr	Otherwise	$0.23 \times DMI$	(58)
$RDCA_{1j}$		$DMI_j \times CA1_j \times \left(\frac{kdCA1_j}{(kdCA1_j + kp_j)}\right)$	(59)
$RDCA_{2j}$		$DMI_j \times CA2_j \times \left(\frac{kdCA2_j}{(kdCA2_j + kp_j)}\right)$	(60)
$RDCA_{3j}$		$DMI_j \times CA3_j \times \left(\frac{kdCA3_j}{(kdCA3_j + kp_j)}\right)$	(61)
$RDCA_{4j}$		$DMI_j \times CA4_j \times \left(\frac{kdCA4_j}{(kdCA4_j + kp_j)}\right)$	(62)

Table 3 (*Continued*)

Variables[a]	Constraints	Equations	
$RDCB1_j$		$DMI_j \times CB1_j \times \left(\frac{kdCB1_j}{(kdCB1_j + kp_j)}\right)$	(63)
$RDCB2_j$		$DMI_j \times CB2_j \times \left(\frac{kdCB2_j}{(kdCB2_j + kp_j)}\right)$	(64)
$RDCB3_j$		$DMI_j \times CB3_j \times \left(\frac{kdCB3_j}{(kdCB3_j + kp_j)}\right)$	(65)
$RDPA_j$		$DMI_j \times PA_j \times \left(\frac{kdPA_j}{kdPA_j + kp_j}\right)$	(66)
$RDPB1_j$		$DMI_j \times PB1_j \times \left(\frac{kdPB1_j}{(kdPB1_j + kp_j)}\right)$	(67)
$RDPB2_j$		$DMI_j \times PB2_j \times \left(\frac{kdPB2_j}{(kdPB2_j + kp_j)}\right)$	(68)
$RDPB3_j$		$DMI_j \times PB3_j \times \left(\frac{kdPB3_j}{(kdPB2_j + kp_j)}\right)$	(69)
$RDPEP_j$		$RDPB1_j + RDPB2_j + RDPB3_j$	(70)
$RECA1_j$		$DMI_j \times CA1_j \times \left(\frac{kp_j}{(kdCA1_j + kp_j)}\right)$	(71)
$RECA2_j$		$DMI_j \times CA2_j \times \left(\frac{kp_j}{(kdCA2_j + kp_j)}\right)$	(72)
$RECA3_j$		$DMI_j \times CA3_j \times \left(\frac{kp_j}{(kdCA3_j + kp_j)}\right)$	(73)
$RECA4_j$		$DMI_j \times CA4_j \times \left(\frac{kp_j}{(kdCA4_j + kp_j)}\right)$	(74)
$RECB1_j$		$DMI_j \times CB1_j \times \left(\frac{kp_j}{(kdCB1_j + kp_j)}\right)$	(75)
$RECB2_j$		$DMI_j \times CB2_j \times \left(\frac{kp_j}{(kdCB2_j + kp_j)}\right)$	(76)
$RECB3_j$		$DMI_j \times CB3_j \times \left(\frac{kp_j}{(kdCB3_j + kp_j)}\right)$	(77)
$RECC_j$		$DMI_j \times CC_j$	(78)
$REPB1_j$		$DMI_j \times PB1_j \times \left(\frac{kp_j}{(kdPB1_j + kp_j)}\right)$	(79)

Table 3 (*Continued*)

Variables[a]	Constraints	Equations	
$REPB2_j$		$DMI_j \times PB2_j \times \left(\frac{kp_j}{(kdPB2_j + kp_j)}\right)$	(80)
$REPB3_j$		$DMI_j \times PB3_j \times \left(\frac{kp_j}{(kdPB3_j + kp_j)}\right)$	(81)
$REPC_j$		$DMI_j \times PC_j$	(82)

Equations will be added to mathematically describe how the fat model of Moat et al. (2004) is implemented.
[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.

CHO B1. Organic acids, which can be quite high in forages, are used less efficiently for microbial growth compared to sugars, and lactate can be quite high in silages and, contrary to VFA, produces microbial protein (Doane et al., 1997; Molina, 2002). Lanzas et al. (2007) used published information to develop degradation rates for the CHO A fractions, soluble fiber, and starch, which varies with type of grain and processing method, which are used in CNCPSv6. Lanzas et al. (2007) reported that the expanded CHO scheme provides a more biologically correct and appropriate feed description that more closely relates to rumen fermentation characteristics to account for variation in changes in silage quality and diet NFC composition.

The passage rate equations were replaced with those developed by Seo et al. (2006). Seo et al. (2006) equations accounted for more variation and had lower mean bias in predicting forage, concentrate and liquid passage rates than other passage rate equations, including those used in Fox et al. (2004). An important difference between the CNCPSv5 and CNCPSv6 passage rate equations is in Seo et al. (2006) equations the physical effective NDF (peNDF) adjustment factor is not used. This adjustment was removed due to potential double accounting, as discussed by Seo et al. (2006). For example, the peNDF adjustment previously used increases soybean meal hourly passage rate by 8 g/100 g in a typical lactating dairy cow ration. However, it was already in meal form in the database used to develop the passage rate equations; thus applying the peNDF adjustment to K_p was double accounting for the small particle size of soybean meal.

2.10. Ruminal pH

The CNCPS reduces microbial growth for the effects of acidic pH. The CNCPS predicts rumen pH from physical characteristics of feeds as related to their effectiveness in stimulating chewing, rumination and increased rumen motility based on their total cell wall content and particle size within classes of feeds (physically effective NDF; peNDF). Table 14 in Fox et al. (2004) provided the equations used to compute rumen pH. In order to use a non-linear optimizer more efficiently, the equation to predict pH and to adjust the degradation rate of available CHO NDF are replaced by those developed for use with the optimizer in CPM

Dairy version 3 (Boston et al., 2000).

$$\text{Ruminal pH} = (1 - g) \times (5.418454 + 4.26014 \times \text{peNDF concentration} + (g \times 6.459806)), \tag{15}$$

where

$$g = \frac{1}{1 + \mathrm{e}(-282.7726 \times (\text{peNDF concentration} - 0.2429614))} \tag{16}$$

Fox et al. (2004) discussed limitations of the CNCPS approach to predicting rumen pH, which were not addressed in this revision. 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. The development of a more integrated rumen model is underway, in which microbial growth is more integrated with digestion and passage and rumen concentrations of VFA are used to predict pH.

2.11. *Microbial growth*

In level 2 of the CNCPS, ruminal microorganisms are categorized as bacteria that ferment fiber carbohydrate (FC) and non-fiber carbohydrate (NFC). The FC bacteria degrade cellulose and hemicellulose, grow more slowly, and utilize ammonia as their primary N source for microbial protein synthesis. The NFC bacteria utilize starch, pectin, and sugars and grow more rapidly than FC bacteria and can utilize ammonia or AA's 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. 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.

Table 15 in Fox et al. (2004) listed the equations used to compute microbial growth, which were implemented in CNCPSv6 as presented in that table except for Eqs. (17) and (18), which were revised as shown below.

$$\text{NFC NH}_3\text{ required} = 0.333 \times \text{NFC bacteria} \times \frac{0.625}{6.25} + \text{if (peptide balance} < 0,\ \text{absolute (peptide balance), 0)} \tag{17}$$

$$\text{If bacteria N balance} < 0,\ \text{nitrogen allowable bacteria} = \frac{\text{peptide uptake N} + \text{NH}_3\text{ diet} + \text{recycled N}}{0.1} \tag{18}$$

This represents a better accounting for ruminal N balance. This correction increases the ammonia requirement of the NFC microbes when the peptide N balance is negative ensuring adequate N availability whereas previously, if rumen degraded peptides were deficient in meeting the NFC peptide requirement, no additional ammonia was required.

In the CNCPS, peptides are considered stimulatory to NFC bacteria. In accounting for peptides as N sources, previous versions did not properly default to ammonia N requirements

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for NFC bacteria when peptides were not available as N sources for this pool of bacteria. This has been corrected and in doing so, the ammonia N requirement increases to meet the N requirements of the NFC bacteria as the peptide supply drops.

2.12. Intestinal digestion and the prediction of feed energy values

The CNCPS uses experimentally measured digestibility coefficients to predict intestinal digestibilities and fecal losses. Table 16 in Fox et al. (2004) summarized the equations used to compute intestinal digestion, fecal output, and feed energy values. Modifications for CNCPSv6 were as follows.

It was discovered that fecal ash was being miscalculated, since the ash content of bacteria was not subtracted from intake ash. In correcting this error, it was determined that bacterial ash could not be partitioned back to individual feeds as the CHO substrate utilized by bacteria may not represent the ash source for bacteria. This resulted in an equation that calculates ash flow (feed and bacterial) for the entire diet as described below.

$$\text{Dietary FEFA} = (\text{DMI} \times \text{ASH} - \text{REBASH})(1 - \text{IntDigAsh}) \tag{19}$$

where FEFA is fecal escape of feed ash (g/d); DMI the dry matter intake, ASH the ash content of DM (g/g); REBASH the rumen escape bacterial ash, (g/d); and IntDigAsh is intestinal digestibility of ash (g/g).

As a result, the model computes apparent TDN and fecal composition for the total diet in predicting diet ME supply. However, individual feed metabolizable energy values can be computed by adding 0.1 kg of the feed to the diet, then using the diet change in ME supply due to that amount of feed to compute its ME value.

Implementing the 2001 Dairy NRC equation to compute NEL of feeds from ME (NELp (Mcal/kg) = 0.703 × MEp − 0.19) was considered. However, this equation, which is based on Moe et al. (1972) does not predict efficiencies consistent with those developed by Moe et al. (1970) and Moe (1981). The average ME from the diets (2.58 Mcal/kg) fed to 332 lactating cows (Moe et al., 1972) used to derive that equation gives an average efficiency of 0.629. The equation proposed by Moe et al. (1972) was developed after extensive energy adjustments for maintenance, excess dietary nitrogen, pregnancy, and tissue gain or loss. As a result the average predicted efficiency (Moe et al., 1972) does not agree with the average efficiency of the unadjusted data (Moe et al., 1970). Therefore, we decided to continue using the efficiency constant of 0.644 for MEl to NEl that Moe et al. (1970) determined by direct caloric measurements across all 350 lactating dairy cows in their studies.

2.13. Fatty acids absorbed

The CNCPS version 5 assumed all fat escapes the rumen undegraded, and has an intestinal digestibility efficiency of 0.95. To improve this aspect of the model, equations were developed (Table 4) to incorporate the fatty acid model as published by Moate et al. (2004). These equations compute intake of individual fatty acids, and predict the *de novo* synthesis of fatty acids by rumen microbes, the biohydrogenation of mono- and poly-unsaturated fatty acids in the rumen, passage of individual fatty acids to the small intestine, and intestinal digestion

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Table 4
Equations to predict long chain fatty acid rumen *de novo* synthesis, biohydrogenation, and intestinal digestion[a]

Variables	Constraints	Equations	
AdjFactor_i	Concentrates	$\dfrac{100}{((\text{NDF}_i \times \text{peNDF}_i)/100) + 90}$	(83)
AdjFactor_i	Forages	$\dfrac{100}{((\text{NDF}_i \times \text{peNDF}_i)/100) + 70}$	(84)
AfLip_i		$e^{((-\text{Adj.Factor}_i \times (\text{TFA}_i/\text{DMI})/10))}$	(85)
AdjLipolysis_i		$\text{AfLip} \times \text{LipolysisRate}_i$	(86)
$\text{Lipolysis}_{i,j}$		$\left(\dfrac{\text{AdjLipolysis}_i}{\text{AdjLipolysis}_i + 100 \times \text{kp}_i}\right) \times \text{FA}_{j,i}$	(87)
LipolysisFFA_i		$\sum_{j=1}^{10} \text{Lipolysis}_{j,i}$	(88)
LipolysisRTFC18_i		$\sum_{j=5}^{9} \text{Lipolysis}_{j,i}$	(89)
FermentableCHO_i		$\text{RDCA1}_i + \text{RDCA2}_i + \text{RDCA3}_i + \text{RDCA4}_i + \text{RDCB1}_i + \text{RDCB2}_i + \text{RDCB3}_i + \text{RDCC}_i$	(90)
TotalLipolysis_j		$\sum_{i=1}^{n} \text{Lipolysis}_{j,i}$	(91)
TotalLipolysisFFA		$\sum_{i=1}^{n} \text{LipolysisFFA}_i$	(92)

Table 4 (*Continued*)

Variables	Constraints	Equations
TotalLipolysisRFTC18		$\sum_{i=1}^{n} \text{LipolysisRTFC18}_i$ (93)
TotalFermentableCHO		$\sum_{i=1}^{n} \text{FermentableCHO}_i$ (94)
Afbiohyd_j	For $j=4$, 6, 7, 8, and 9	$e^{\left(\frac{-\text{KbB}_{j,i} \times 0.1 \times \text{TotalLipolysisFFA}}{\text{DMI}}\right)}$ (95)
BioHydKb_j	For $j=4$, 6, 7, 8, and 9	$\text{Kba}_{j,\text{I}} \times \text{Afbiohyd}_{j,i}$ (96)
Denovo_j	For $j=3$, 4, and 10	$\frac{\text{FermentableCHO}}{1000} \times \text{DenovoFtCHO}_{j(3,4,10),i} \times e^{(-\text{DenovoRumenFA}_{j(3,4,10),i} \times \text{TotalLipolysis}_{j(3,4,10),i}/\text{DMI})}$ (97)
$\text{Denovo}_{j,i}$	For $j=5$	$\frac{\text{FermentableCHO}}{1000} \times \text{DenovoFtCHO}_{j=5,i} \times e^{(-\text{DenovoRumenFA}_{j=5,i} \times \text{TotalLipolysis}_{j=5,i}/\text{DMI})}$ (98)
BioHyd_j	For $j=1$ and 2	$\text{Lipolysis}_{j,i}$ (99)
BioHyd_j	For $j=3$	$\text{Lipolysis}_{j=3,i} + \left(\frac{\text{BioHydKb}_{j=4,i}}{\text{kp}_i + \text{BioHydKb}_{j=4,i}}\right) \times \text{Lipolysis}_{j=4,i} + \text{Denovo}_{j=3,i}$ (100)
BioHyd_j	For $j=4$	$\left(\frac{\text{BioHydKb}_{j=4,i}}{\text{kp}_i + \text{BioHydKb}_{j=4,i}}\right) \times \text{Lipolysis}_{j=4,i} + \text{Denovo}_{j=4,i}$ (101)
BioHyd_j	For $j=5$	$\text{DenovoRFC18} : 0_i + \text{Denovo}_{j=5,i}$ (102)

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BioHyd_j	For $j=6$	$\left(\dfrac{\mathrm{BioHydKb}_{j=6,i}}{\mathrm{kp}_i+\mathrm{BioHydKb}_{j=6,i}}\right)\times \mathrm{Lipolysis}_{j=6,i} + \left(\dfrac{\mathrm{BioHydKb}_{j=8,i}}{\mathrm{kp}_i+\mathrm{BioHydKb}_{j=8,i}}\right)\times \mathrm{Lipolysis}_{j=8,i} + \left(\dfrac{\mathrm{BioHydKb}_{j=9,i}}{\mathrm{kp}_i+\mathrm{BioHydKb}_{j=9,i}}\right)\times \mathrm{Lipolysis}_{j=9,i}$ (103)
BioHyd_j	For $j=7$	$\left(\dfrac{\mathrm{BioHydKb}_{j=7,i}}{\mathrm{kp}_i+\mathrm{BioHydKb}_{j=7,i}}\right)\times \mathrm{Lipolysis}_{j=7,i}$ (104)
BioHyd_j	For $j=8$	$\left(\dfrac{\mathrm{BioHydKb}_{j=8,i}}{\mathrm{kp}_i+\mathrm{BioHydKb}_{j=8,i}}\right)\times \mathrm{Lipolysis}_{j=8,i} + \left(\dfrac{\mathrm{BioHydKb}_{j=9,i}}{\mathrm{kp}_i+\mathrm{BioHydKb}_{j=9,i}}\right)\times \mathrm{Lipolysis}_{j=9,i}$ (105)
BioHyd_j	For $j=9$	$\left(\dfrac{\mathrm{BioHydKb}_{j=8,i}}{\mathrm{kp}_i+\mathrm{BioHydKb}_{j=9,i}}\right)\times \mathrm{Lipolysis}_{j=9,i}$ (106)
BioHyd_j	For $j=10$	$\mathrm{Lipolysis}_{j=10,i}+\mathrm{Denovo}_{j=10,i}$ (107)
$\mathrm{DenovoRFC18{:}0}_i$		$\mathrm{LipolysisRFTC18}_i-\sum_{j=6}^{9}\mathrm{BioHyd}_{j,i}$ (108)
$\mathrm{BioHydTotalTFA}_i$		$\sum_{j=1}^{10}\mathrm{BioHyd}_{j,i}$ (109)
RDGlycerol		$\left(\dfrac{\mathrm{GlycerolKd}_i}{\mathrm{GlycerolKd}_i+\mathrm{kp}_i}\right)\times \mathrm{Glycerol}_i$ (110)
$\mathrm{FADuodenal}_{j,i}$		$\dfrac{\mathrm{kp}_i}{\mathrm{kp}_i+\mathrm{Lipolysis}_{j,i}}\times \mathrm{FAIntake}_{j,i}$ (111)
$\mathrm{FAAbsorbed}_{j,i}$		$\mathrm{FADuodenal}_{j,i}\times \mathrm{FAID}_{j,i}+\mathrm{FFADuodenal}_{j,i}\times \mathrm{RumenFFADig}_{j,i}$ (112)

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Table 4 (*Continued*)

Variables	Constraints	Equations
Apparent TDN		$(\text{ProteinIntake} - \text{FecalProtein}) + (\text{CHOIntake} - \text{FecalCHO}) + 2.25 \times \sum_{i,j}^{n,10} \text{FAAbsorbed}_{i,j}$ (113)
ProteinDE		$4.409 \times (\text{ProteinIntake} - \text{FecalProtein})$ (114)
CHODE		$4.409 \times (\text{CHOIntake} - \text{FecalCHO})$ (115)
FatDE		$4.409 \times 2.25 \times \sum_{i,j}^{n,10} \text{FAAbsorbed}_{i,j}$ (116)
ME	Lactating, dairy cow	$(1.01 \times (\text{ProteinDE} + \text{CHODE} + 1.23 \times \text{FatDE}) - 0.45 + +0.0046 \times (\text{DietEE} \times 100 - 3)) \times \text{DMI}$ (117)
ME	Otherwise	$0.82 \times (\text{ProteinDE} + \text{CHODE} + 1.23 \times \text{FatDE}) \times \text{DMI}$ (118)

[a] *i* is the *i*th feed and *j* is the *j*th fatty acid in which C12:0 ($j=1$), C14:0 ($j=2$), C16:0 ($j=3$), C16:1 ($j=4$), C18:0 ($j=5$), C18:1t ($j=6$), C18:1c ($j=7$); C18:2 ($j=8$), C18:3 ($j=9$), and others ($j=10$).

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of individual lypolized and unlypolized fatty acids (assigned variable intestinal digestibility coefficients). When the fatty acid model is used, diet energy values are computed as shown in Table 4 Eqs. (114)–(118). The major difference between these equations and those used when the fatty acid model is not used is in the apparent TDN computation for fat. When the fatty acid model is not used, the apparent TDN from fat is 2.25(fat intake − fecal fat), which includes microbial and endogenous fat. When the fat model is used, glycerol is added to the absorbed feed CHO pool and only the absorbed fatty acids derived from feed are used in the apparent TDN computations. Pigment and waxes from ether extract (EE) are assumed undigested and excreted via feces. The rumen degraded CHO is used to calculate microbial *de novo* fat synthesis. The CPM model (Boston et al., 2000) does not calculate bacterial fatty acids and therefore does not include them in the absorbed fat pool. On the other hand, the CPM model does not discount digested fat for endogenous fat because their regression analysis indicated that there is no endogenous fat to be accounted for. These two effects are offsetting in calculating apparent TDN. As in the CNCPS, the CPM model uses fecal EE from feed and bacteria in the calculation of indigestible dry matter (IDM), which is used to estimate MP allowable milk. The fatty acid model provides flows of individual fatty acids, and indicates that a digestibility efficiency for EE of 0.95 is not feasible. Also it indicates not removing bacteria CHO from degraded feed CHO results is double accounting. However, this approach does not allow direct calculation of apparent TDN from fatty acid flows and fecal content of fat. Further work is required to improve this aspect of the fatty acid model.

3. Model evaluation

The CNCPSv6 model was evaluated for precision and accuracy in predicting milk production of lactating dairy cows with data from three published studies with lactating dairy cows described by Ruiz et al. (2001, 2002) and Stone (1996). A second evaluation was conducted with data from an experiment conducted at the Brazilian Agricultural Research Corporation (EMBRAPA in Coronel Pacheco, MG, Brazil) with lactating Holstein cows (Fernando C.F. Lopes, unpublished) to test the adequacy of the CNCPSv6 for tropical conditions. A third evaluation was conducted with data from a study (Recktenwald and Van Amburgh, 2006) to evaluate model predictions with diets formulated to be nitrogen deficient in the rumen or deficient in supply of MP for the energy allowable milk production. In this study, 89 multiparous Holstein cows were individually fed three different diets: (1) control diet to provide adequate rumen N and MP balances, (2) diet to be deficient in MP, and (3) diet to be deficient in rumen N. Body weight and BCS changes were accounted for in the evaluations including the expanded carbohydrate scheme and new passage rate equations (Seo et al., 2006). Methods for testing model adequacy described by Tedeschi (2006)[1] were used for all evaluations.

The comparisons made in the first evaluation were: (1) CNCPS v5, (2) the re-engineered CNCPSv6 with CNCPSv5 passage rates, CHO fractions, and fat accounting, (3) CNCPSv6 with the new passage rate equations, (4) CNCPSv6 with the new fatty acids model, and (5)

[1] http://nutritionmodels.tamu.edu.

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CNCPSv6 with the expanded CHO pools. The evaluation of level 1 was done by assigning values for RUP values for each feed similarly to what was done in the evaluations of CNCPSv5 (Fox et al., 2004). The evaluation of the new fractionation of CHO was performed assuming the current NFC content of the feeds and allocating the NFC into CHO A1, A2, A3, A4, B1, and B2 based on the their proportion in the NFC of similar feeds (based on DM, CP, and NDF values) from the CPM Dairy feed dictionary[2]. Table 5 lists the feed CHO fractions content and degradation rates that were used for this evaluation. Other organic acids (*i.e.* malic and citric acids), sugars (*i.e.* glucose), and starch were assigned to be 30.3, 52.5, and 17.2 g/100 g of NFC for fresh forage based on information from the DairyOne[3] database. Lactate and acetate was assumed to be 63 and 37 g/100 g of the total acids for corn silage; 59.5 and 40.5 g/100 g of the total acids for alfalfa haylage; and 76.4 and 23.6 g/100 g of the total acids for high-moisture shelled corn, respectively. The degradation rates of CHO A2, A3, A4, and B2 shown in Table 4.5 were changed to match those reported by Molina (2002), who reported fractional hourly rates of 0.068 for lactic acid (A2), 0.055 for other organic acids (A3), 0.398 for sugars (A4), and 0.156 for pectin (arabinose) (B2). The degradation rates for starch (B1) varied accordingly to the degree of processing of the feed.

Table 6 lists the mean bias (bias), the r^2 of the linear regression between observed (*Y*-axis) and model-predicted (*X*-axis) values, the simultaneous probability to test for intercept = 0 and slope = 1, the linear regression mean square error (MSE), the mean square error of prediction (MSEP), the concordance correlation coefficient (CCC), and the MSEP decomposition for all evaluations as described by Tedeschi (2006).

The CNCPSv6 level 1 (run 8 in Table 6) to predict feed energy and protein developed by Tedeschi et al. (2005) based on Weiss et al. (1992) had the greatest precision (measured by the r^2, 89%) and greatest accuracy (measured by the CCC = 0.943 and MSEP = 14.6) in predicting milk production across the three studies analyzed. Tedeschi et al. (2005) found no difference between the CNCPSv6 levels 1 and 2 in predicting average daily gain of high-grain and high-forage fed beef cattle, and similar predictions of feed energy and protein biological values were obtained by both levels of solution when evaluating the beef NRC (2000) feed library. More mechanistic models (*e.g.* CNCPSv6 level 2) tend to have lower accuracy than simple theoretical or empirical models due to increased complexity and numbers of inputs required (France et al., 2000). It should also be noted that level 1 rumen degraded protein (RDP) values were calculated using level 2, thus level 1 feed energy and protein values are auto-correlated with level 2 predictions. Under certain circumstances, CNCPSv6 level 1 can be used to formulate diets and be more accurate, especially when detailed feed analysis (carbohydrate and protein fractions and their digestion rates) is lacking.

The comparison between runs 1 (CNCPSv5) and 2 (CNCPSv6) (Table 6) shows improved accuracy for the CNCPSv6, with similar precision. Implementing the new passage rate equations and expanded CHO scheme had little effect on the precision but bias was decreased four units in predicting milk production with CNCPSv6 (Table 6, runs 2–5). Additionally, the MSEP partitioning was improved such that all error (run 5) is random, a 9.3 unit improvement over version 5. The prediction improvements were primarily due to the re-engineering and bacterial ash adjustments. Lanzas et al. (2007) performed an extensive

[2] http://www.cpmdairy.com.
[3] http://www.dairyone.com.

Table 5
Composition of organic acids, sugar, starch, and pectin of several feeds in the CNCPSv6 feed dictionary (modified from the CPM Dairy feed dictionary (Boston et al., 2000))

Reference	Feed	%NFC						Degradation rates of CHO (%/h)						
		VFA	Lac	OA	Sugar	Starch	Pectin	A1	A2	A3	A4	B1	B2	B3
1	Pasture	0	0	30.3	52.5	17.2	0	0	6.8	5.0	39.8	–	–	–
1	CS	7.03	12.0	0	2.0	77.0	2.0	0	6.8	5.0	39.8	35.0	15.6	6.0
1	HMSC	0.472	1.53	0	2.4	94.0	1.6	0	6.8	5.0	39.8	35.0	15.6	6.0
2	AS	10.1	14.9	0	12.0	5.0	58.0	0	6.8	5.0	39.8	30.0	15.6	7.5
2	CS	6.29	10.7	0	4.0	79.0	0	0	6.8	5.0	39.8	32.0	15.6	5.1
2	HMSC	0.472	1.53	0	2.4	94.0	1.6	0	6.8	5.0	39.8	30.0	15.6	6.0

References: 1, Ruiz et al. (2001, 2002) and 2, Stone (1996). VFA is volatile fatty acids, Lac is lactate, OA is organic acids, NFC is non-fiber carbohydrate, CHO is carbohydrate, CS is corn silage, AS is alfalfa silage, and HMSC is high-moisture shelled corn.

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Table 6
Model adequacy statistics of the predictions of the CNCPSv6[a]

Simulations	Linear regression[b]			r^2 (%)	MSE	CCC[a]	Bias[c] (%)	MSEP	MSEP partition[d] (%)		
	a	*b*	P						U^M	U^R	U^D
(1) CNCPS version 5 (v5)	1.23	1.00	0.001	86.1	18.3	0.918	4.31	19.9	9.3	0.0	90.7
(2) v6 + kp_{Fox}	0.49	0.98	0.91	85.4	19.4	0.922	−0.03	19.1	0.0	0.10	99.9
(3) v6 + kp_{Seo}	0.57	0.99	0.89	84.7	20.3	0.918	0.32	20.0	0.10	0.10	99.8
(4) v6 + kp_{Fox} + expanded CHO	0.45	0.98	0.88	86.2	18.3	0.927	−0.24	18.0	0.04	0.16	99.8
(5) v6 + kp_{Seo} + expanded CHO	0.52	0.99	0.91	85.6	19.0	0.920	0.15	18.8	0.0	0.10	99.9
(6) v6 + kp_{Fox} + fatty acid (FA) model	0.21	1.00	0.75	85.3	19.4	0.920	0.88	19.2	0.40	0.0	99.6
(7) v6 + kp_{Seo} + expanded CHO + FA model	0.30	1.00	0.67	85.4	19.2	0.92	1.04	19.1	0.60	0.0	99.4
(8) v6 + level 1 solution for energy and protein	1.50	0.97	0.22	89.0	14.5	0.943	1.38	14.6	1.4	0.9	97.7

[a] MSE = mean square error, MSEP = mean square error of prediction, and CCC = concordance correlation coefficient.

[b] *a* = intercept, *b* = slope, and P=simultaneous probability of *a* = 0 and *b* = 1.

[c] Mean bias as a percent of the model-predicted mean (*X*-axis values). A negative value indicates overprediction and a positive value indicates underprediction. Mean of observed milk production was 32.845 kg/d for 134 lactating dairy cows.

[d] U^M = percentage of errors due to mean bias, U^R = percentage of errors due to systematic bias, and U^D = percentage of errors due to random errors. The sum of $U^M + U^R + U^D = 100$.

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evaluation and sensitivity analysis and found little effect on ME and MP allowable milk production due to the expanded CHO pools. Implementation of Moate et al. (2004) fatty acid model had little effect on precision and accuracy of predicting ME and MP allowable milk production. Further evaluations with the fat model are required since the diets in the evaluation data set did not contain added fat.

The evaluation of the CNCPSv6 using the tropical experiment data was performed using the rate of passage equation described by Seo et al. (2006) and the expanded carbohydrate scheme, similar to simulation 5 in Table 6. Fig. 3 shows the relationship between observed and model-predicted milk production with and without adjustment for changes in BCS. The prediction with the adjustment for BCS changes (Fig. 3B) resulted in lower mean bias (3.2% *versus* 14.2%), greater CCC (0.9 *versus* 0.85; likely due to a greater accuracy, Cb of 0.98 *versus* 0.92), and lower MSEP (4.58 kg/d *versus* 7.9 kg/d) compared to without adjustment for BCS changes (Fig. 3A), respectively. The precision of the prediction with and without adjustments for BCS changes was identical based on the correlation of determination (r^2 of 85%).

Based on these evaluations, we concluded the predictions of CNCPSv6 level 2, with the new passage rates, expanded carbohydrate fractions, and fatty acid model were improved (Figs. 2 and 3), suggesting the re-engineering of the CNCPSv5 to meet the objectives of CNCPSv6 was successfully completed.

However, the model evaluations with the Recktenwald and Van Amburgh (2006) data with CNCPSv6 indicated the predictions of the model were inconsistent among the diets fed in this study. In all evaluations, MP was predicted to be first limiting. Across all diets, the precision was low (r^2 of 29%) even though the mean bias was low and the accuracy was high (−0.49 and 0.96, respectively). There was substantial systematic bias (48.3% of MSEP) which is sustained by the low slope (0.39), and 51.6% of the MSEP being due to random errors. With the control and MP-deficient diets, accuracy was good (Cb of 0.79 and 0.94, respectively) but the model was imprecise (r^2 of 15 and 16%, respectively). The causes of the problem were diverse. In the MP-deficient diet, the source of errors in the MSEP were mean bias (25.7%), systematic error (37.6%), and random error (36.6%), meaning the model was not able to explain the variation in the data. This suggested to us the CNCPS was not able to account for the variation in supply of MP due to offsets in N transactions not currently accounted for in the rumen submodel. For example, Ouellet et al. (2002) demonstrated that endogenous protein in the form of peptides could supply the microbial population with N at levels equal to recycled urea. This would over-estimate the requirement for rumen available protein as indicated by the variation. For the positive control, even though the mean bias was only −3.26% of the model-predicted values, the precision was very low (r^2 of 16%) and most of the source of variation in the MSEP was random error. For the diet deficient in rumen N, the model had a better precision (r^2 of 57%) and high accuracy (Cb of 0.94), but mean bias was high (10.8% underprediction). The evaluations of the CNCPS recycled N equation with the model of Lanzas (2006) suggested recycled N was underpredicted for this treatment. Cannas et al. (2004) found that in sheep with very low rumen N balance, the model underpredicted performance, likely because animals with ruminal N deficiency recycled more N than the model accounts for. This evaluation indicated the CNCPS needs equations to account for the effects of monensin, and models to account for recycled N and unexplained differences in protein supply based on microbial turnover, endogenous protein re-absorption, and rates of protein degradation and passage when MP is predicted to be deficient.

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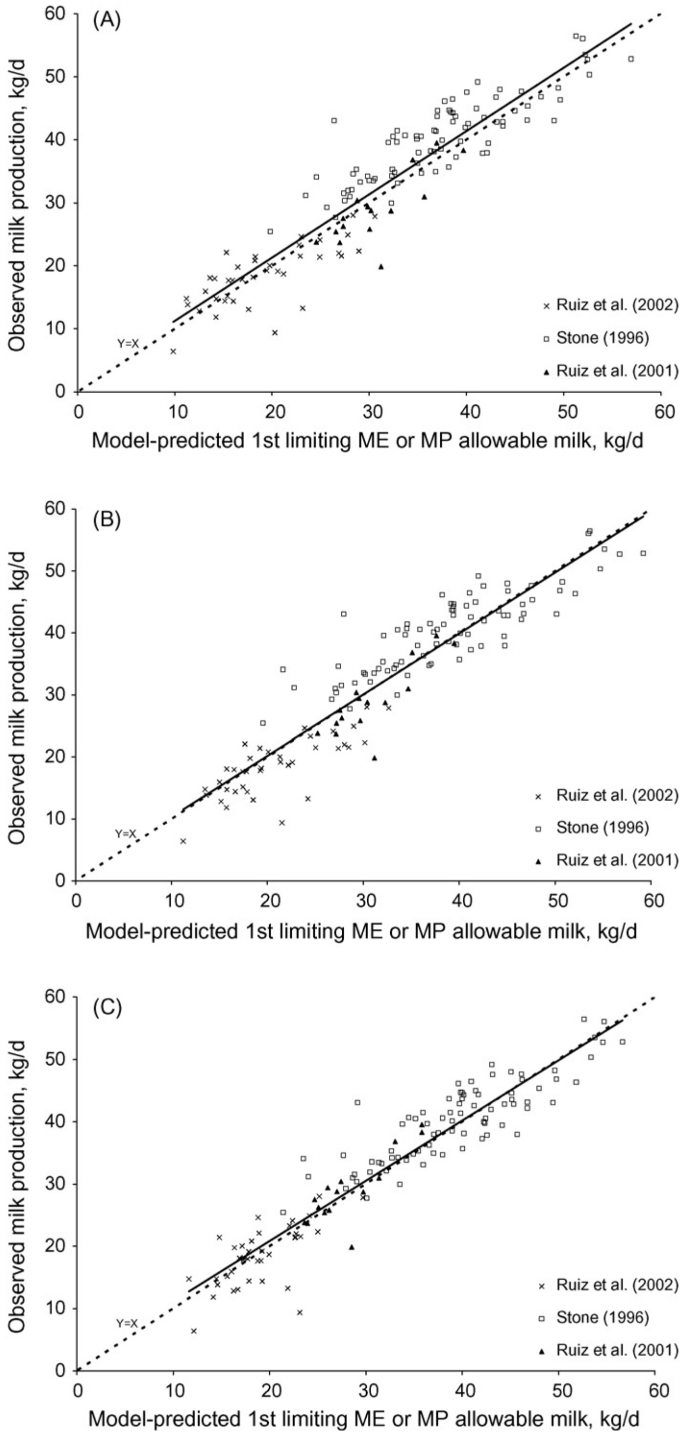

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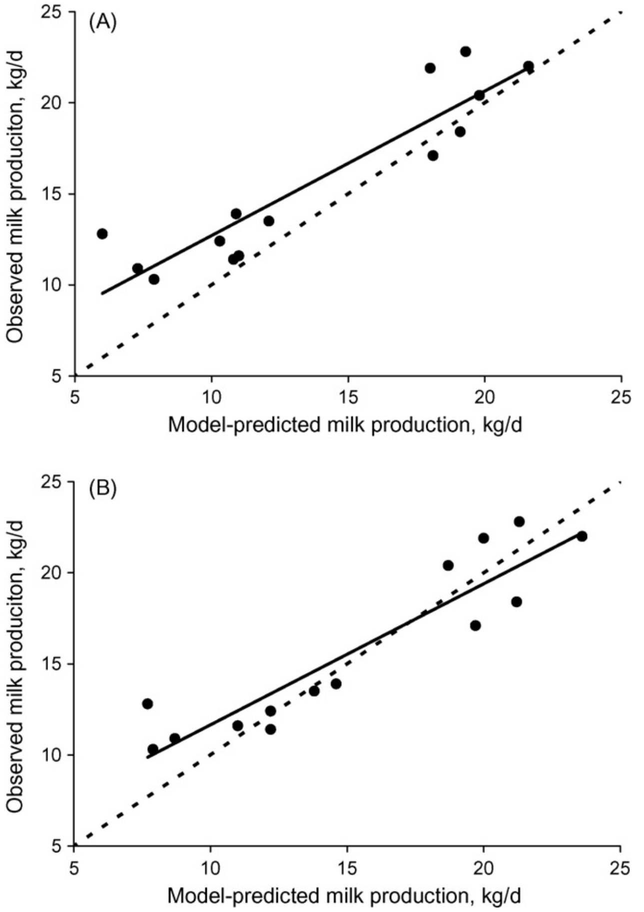

Fig. 3. Relationship between observed and model-predicted first-limiting metabolizable energy or metabolizable protein allowable milk production of the tropical experiment with lactating Holstein cows without (A) and with (B) adjustment for changes in body condition score.

4. Implications

The evolution of the CNCPS is a continuous process as our biological understanding improves and user needs evolve. The latest version (CNCPSv6) was developed primarily to meet user needs for more accurate formulation of dairy rations given the increased focus on precision feeding in the United States. It represents a re-engineering process including object-oriented programming approaches and improvements in the user interface to assist in

Fig. 2. Relationship between observed and model-predicted milk production using (A) the level 2 solution of CNCPSv5 (run 1 in Table 6), (B) the level 2 solution of CNCPSv6 (run 2 in Table 6), and (C) the level 1 solution of the CNCPSv6 (run 8 in Table 6).

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herd level nutrient management planning. Through this process, ease of use, speed of data input, and software stability were concerns that were addressed. Based on these changes, our on farm experience with CNCPS version 6 indicates it can be utilized in day-to-day formulation and nutrient management planning with improved prediction accuracy than CNCPS version 5 with increased user efficiency.

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