Development of Mathematical Models to Estimate Animal Performance and Feed Biological Values

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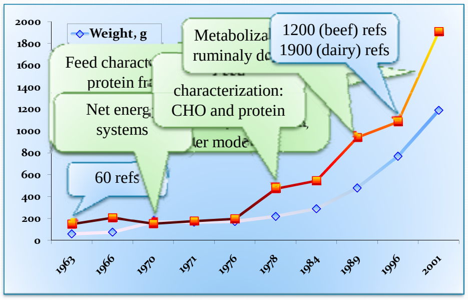
Why Nutrition Models ?

Integrate accumulated knowledge

- Account for factors affecting performance on each farm
- Improve ruminants nutrition and productivity
- Minimize costs of production
- Reduce environmental impact
- Integrate economics with biological responses

Knowledge in the NRC pubs



Feeds and feeding


Bell Ranch, NM, USA

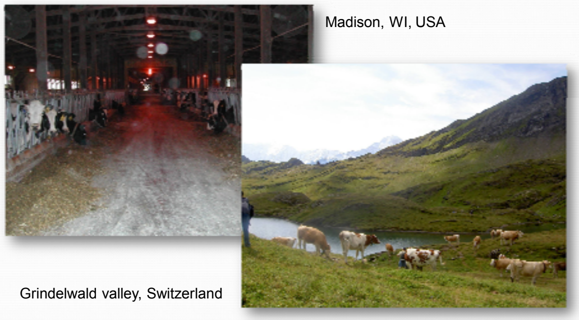
Pernambuco, BRA

Environmental (clime) effects


Torréon, Mexico (Farm 1)

Torréon, Mexico (Farm 2)

Production systems (dairy)


Madison, WI, USA

Grindelwald valley, Switzerland

Production systems (beef)

São Paulo, BRA

Amarillo, TX, USA

Application of models

- Teaching tools for students and consultants
- Design and interpret experiments
- Apply and model research results
- Develop table of nutrient requirements
- Evaluate and improve feeding programs
- Nutrient management planning

Mathematical Models are tools for understanding ruminant nutrition, to stimulate our intellect, building our intuition and improving our mental simulation capability

Objectives of the presentation

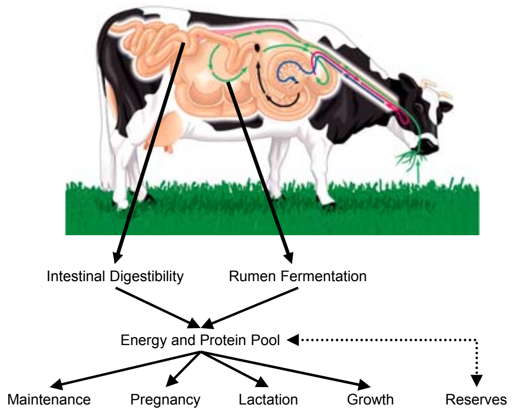
- Summarize structure of CNCPS framework for computing requirements and supply of nutrients to meet requirements
- Review details of how the rumen model uses knowledge about rumen fermentation to predict feed digestion
- Provide information on future structures of the CNCPS model

Step 1 – Predicting requirements

- Predicts maintenance requirements for breed type and environmental conditions
- Computes growth requirements for any mature size for optimum lifetime production
- Predicts requirements for days pregnant
- Predicts requirements for target milk amount
- Predicts energy reserves fluxes to account for positive or negative energy balance

Step 2 – Estimating supply

- Computes carbohydrate and protein fractions available for rumen fermentation from each feed
- Uses a mechanistic rumen model to predict microbial growth and energy and protein absorbed from each feed
- Computes intestinal digestibility, TDN, and MP



Intestinal Digestibility

Rumen Fermentation

Energy and Protein Pool

Maintenance

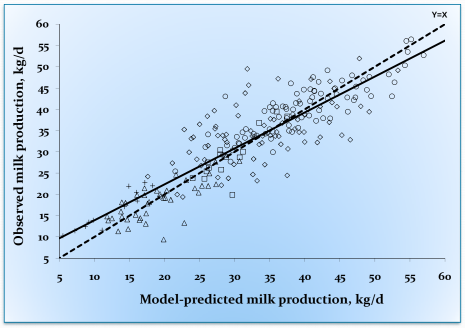
Pregnancy

Lactation

Growth

Reserves

Models must accurately predict current animal performance before using it to identify diet changes that will improve performance



N	r^2	Bias	Cb	CCC	RMSEP	U_M	U_S	U_R
228	0.80	0.52	0.997	0.89	5.14	1.0	11.7	87.3

Tedeschi et al. (2007, submitted)

Predicting Animal Requirements

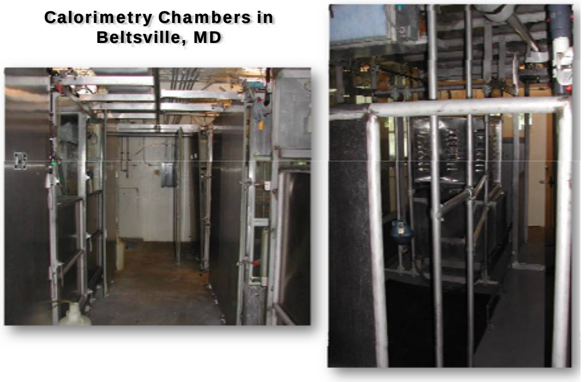
1. Maintenance

Factors affecting maintenance

- Body weight
- Physiological State
  - Dry
  - Lactating
  - Compensating
- Acclimatization
  - Previous temperature
- Heat or Cold stress
  - External Insulation
    - Coat Condition
    - Wind speed
    - Hide Thickness
  - Internal Insulation
    - Condition Score
    - Age

USDA ars United States Department Of Agriculture Agricultural Research Service

Calorimetry Chambers in Beltsville, MD



Maintenance requirements

- Dairy Heifers = $SBW^{0.75}$ x 0.086, Mcal/d
- Dairy Cows = $SBW^{0.75}$ x 0.080, Mcal/d
- Beef = $SBW^{0.75}$ x 0.077, Mcal/d

- Include basal metabolism + 10% for physical activity

Fox et al. (2004)

Environmental (clime) effects

MARC, NE, USA

Homer, NY, USA

Predicting Animal Requirements

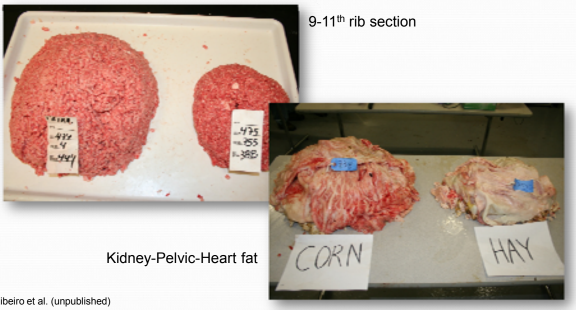
2. Growth

NEg required in the US

- Genotype - over 80 types have been identified
- Sex
  - Feedlot steers, heifers & bulls
  - Replacement heifers
  - Bulls
  - Cows
- Implant combinations
- Feeding systems

Breeds effect

Nutrition & feeding levels



9-11th rib section

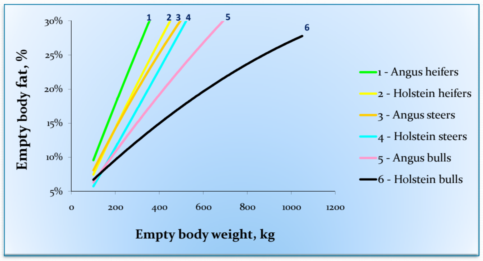
Kidney-Pelvic-Heart fat

Ribeiro et al. (unpublished)

Setting target body fat

Marbling Score	% Body Fat	USDA Grade	Canadian Grade
Trace	25%	Standard	A
Slight	27%	Select	AA
Small	28%	Choice	AAA

Breed type vs. body fat

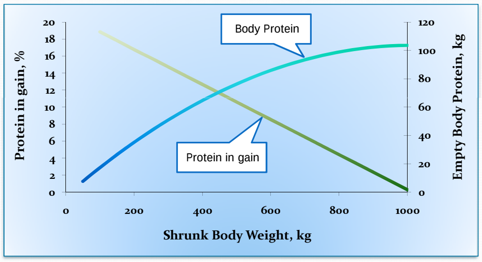


NRC (2000)

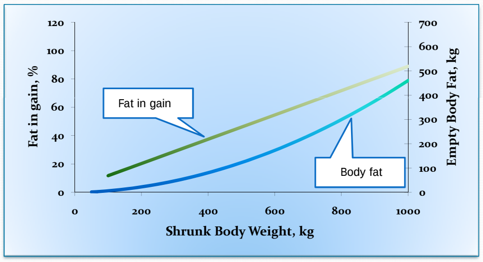
Predicting growth requirement

- 1984 NRC medium frame steer equations described the growth curve of cattle based on 20 years of body composition data at University of California
- Modern cattle have different body size, composition, and conformation
- Adjust base system for widely varying body sizes utilizing an scaling approach

Protein composition



Fat composition



Calculation of EqSBW to a SRW

EqSBW = Actual SBW x (SRW / FW)

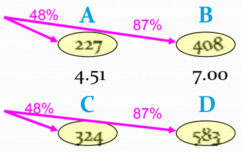
SRW:

435 kg @ 25% EBF
462 kg @ 27% EBF
478 kg @ 28% EBF

Calculation of NEg required

NEg = $0.0635 \times EQEBW^{0.75} \times EBG^{1.097}$

Net energy requirement



	A	B
Final weight: 478 kg		
Weight, kg	227	408
NEm, Mcal/d	4.51	7.00
Final weight: 667 kg	C	D
Weight, kg	324	583
NEm, Mcal/d	5.89	9.15
NEg, Mcal/d		
0.68 kg/d	2.14	3.32
1.59 kg/d	5.42	8.42

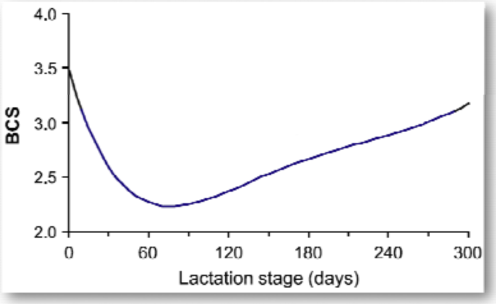
Predicting Animal Requirements

3. Body Reserves

Changes in body reserves

- Predict supplements needed to reach target condition score
- Predict feed replaced by reserves
- Adjust predicted ME and MP milk production

Changes in BCS during lactation



Mao et al. (2004)

Energy reserves @ different BCS

		Mature weight at BCS 3		
		400 kg	600 kg	800 kg
BCS	% of BCS 3 weight	Mcal NE in 1 BCS change		
2	86	134	201	251
3	100	164	246	307
4	114	193	290	362
5	127	222	333	417

Body fat changes 7.54% per dairy body condition score: 1 Mcal replaces 0.82 Mcal NEL and 1 Mcal diet NEL provides (1/0.644) x 0.75 = 1.16 Mcal NE for reserves

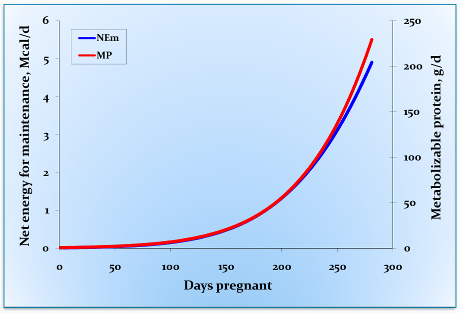
Predicting Animal Requirements

4. Pregnancy and Lactation

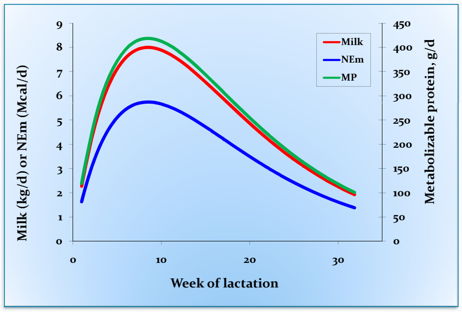
Pregnancy and lactation

- Pregnancy requirements are computed for expected birth weight and days pregnant
- For dairy, lactation requirements are computed from amount and composition of milk
- For beef, lactation requirements are computed from standard composition of milk and milk production curves based on peak milk

Requirements for pregnancy



Requirements for lactation



Predicting Supply of Energy and Nutrients

1. Rumen: Fractionation

CHO and protein fractionation

A = Rapidly Degraded in the Rumen

- Sugars, soluble protein

B = Slowly Degraded in the Rumen

- Starch, available NDF

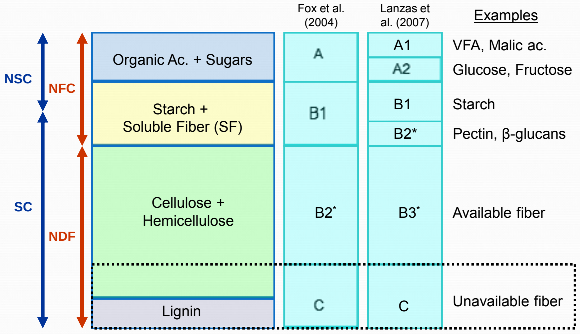
C = Unavailable to ruminal digestion

- Lignin, ADF protein

Chemical feed analysis

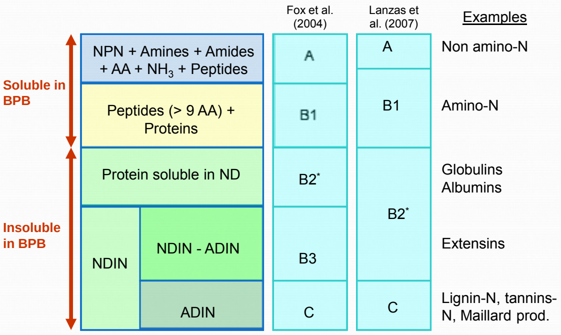
- Dry matter (DM)
- Ash
- NDF
- Ether extract (EE)
- Lignin
- Starch
- Crude protein (CP)
- Soluble CP (SolCP)
- Non-protein N (NPN)
- NDF Protein (NDIN)
- ADF Protein (ADIN)

CHO fractions



			Fox et al. (2004)	Lanzas et al. (2007)	Examples
NSC	NFC	Organic Ac. + Sugars	A	A1	VFA, Malic ac.
				A2	Glucose, Fructose
		Starch + Soluble Fiber (SF)	B1	B1	Starch
				B2*	Pectin, β-glucans
SC	NDF	Cellulose + Hemicellulose	B2*	B3*	Available fiber
		Lignin	C	C	Unavailable fiber

Protein fractions



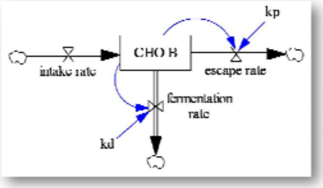
			Fox et al. (2004)	Lanzas et al. (2007)	Examples
Soluble in BPB	NPN + Amines + Amides + AA + NH_3 + Peptides		A	A	Non amino-N
	Peptides (> 9 AA) + Proteins		B1	B1	Amino-N
Insoluble in BPB	Protein soluble in ND		B2*	B2*	Globulins Albumins
	NDIN	NDIN - ADIN	B3		Extensins
		ADIN	C	C	Lignin-N, tannins-N, Maillard prod.

Predicting Supply of Energy and Nutrients

2. Rumen: Degradation

Rumen degradation

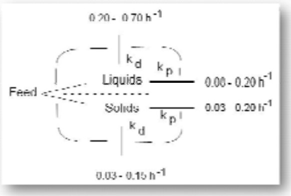
- Assumptions in the model:
  - Steady-state condition (dCHO B/dt = o)
  - Linear relationship between flows and stocks

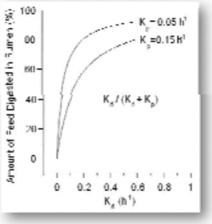


$$RDCHO\ B = \frac{kd}{kd + kp}$$

$$RECHO\ B = \frac{kp}{kd + kp}$$

Feed dynamics in the rumen





Kp = 5%/h and Kd = 5%/h

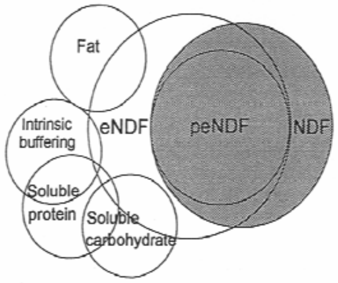
Ruminal digestibility = 5/(5 + 5) = 5/10 = 50%

Russell (2002)

Predicting Supply of Energy and Nutrients

3. Rumen: Effective NDF

Concept of effective NDF (eNDF)



Mertens (2002); PNC

Physically effective NDF (peNDF)

That portion of the total cell wall that is effective in increasing rumination and rumen motility, based on:

- particle size
- degree of lignification of NDF

Measured as % of feed NDF retained on a 1.18 mm screen after vertical shaking (Mertens, 1997)

Physical effectiveness of forages

Physical form	length cm	Grass hay	Grass silage	Corn silage	Alfalfa hay	Alfalfa silage
	% of NDF that is physically effective					
Long		100			95	
Coarse chopped	4.8 to 8	95	95	90		85
Med chopped	1.2 to 2.0	90	90	85	85	80
Fine chopped	0.3 to 0.5	85	85	80	80	70
Ground	0.15 to 0.25	40			40	

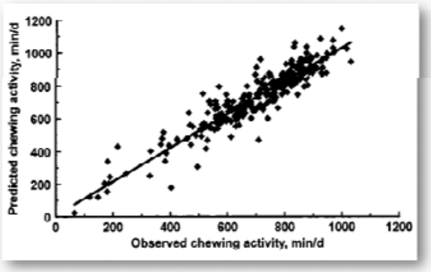
Mertens (1997)

Physical effectiveness of grains

	HMC	Barley	Cracked corn	Ground corn	Meal/ pellet
	% of NDF that is physically effective				
Rolled	80	70			
Coarse			60		
Medium				40	
Fine					30

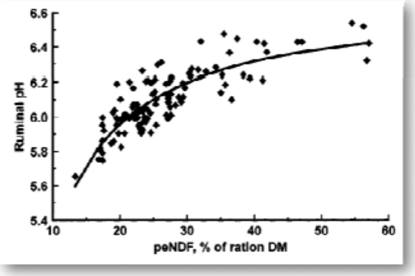
Mertens (1997)

Observed vs. predicted chewing



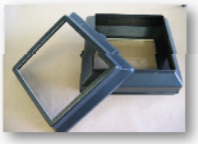
Mertens (1997)

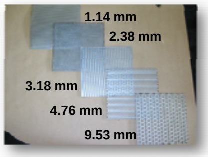
Ruminal pH vs. peNDF



Mertens (1997)

Z-Box particle separator design


Z-Box original design (Miner Institute, 2000)



Cotanch and Grant (2006)

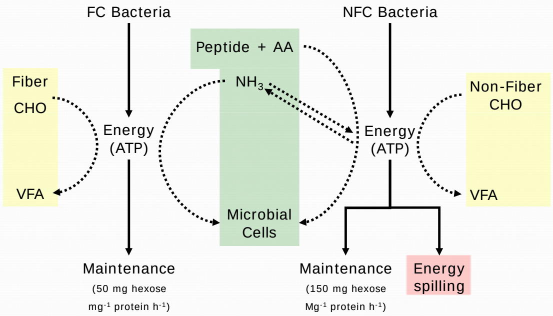
Using Z-Box to predict peNDF

- Z-Box system promising for determination of pef of “as fed” samples
  - Vigorous vertical shaking
  - 150 g/sample (3 - 50 g/replicates)
  - pef Z-Box similar to pef$_{1.18}$
  - CS and TMR: 3.18-mm sieve
  - Haylage: 4.76-mm sieve
  - Use different sieves for different feed types

Predicting Supply of Energy and Nutrients

4. Bacteria

Modeling ruminal bacteria growth


FC Bacteria

NFC Bacteria

Peptide + AA

Fiber CHO

NH$_3$

Non-Fiber CHO

Energy (ATP)

Energy (ATP)

VFA

Microbial Cells

VFA

Maintenance (50 mg hexose mg^{-1} protein h^{-1})

Maintenance (150 mg hexose Mg^{-1} protein h^{-1})

Energy spilling

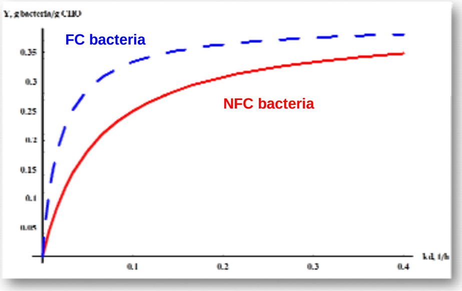
Modeling ruminal bacteria growth

- Depends on requirement of CHO for maintenance (km), maximum yield (Y_g), and kd
- Km$_1$ (FC bacteria) = 0.05 g FC/g bact/h
- Km$_2$ (NFC bacteria) = 0.15 g NFC/g bact/h
- Y_g affected by peNDF < 20%; 0.4 g bact/g CHO

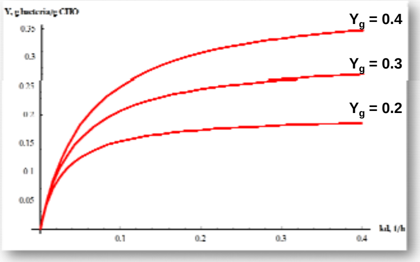
$$\frac{1}{Y}=\frac{km}{kd}+\frac{1}{Y_g}\Rightarrow Y=\frac{kd\times Y_g}{kd+km\times Y_g}$$

$$Y_g = Y_g\times\left(1-0.025\times\left(20-peNDF\right)\right)$$

Bacteria yield: FC x NFC



NFC bacteria yield



Predicting Supply of Energy and Nutrients

5. Intestine

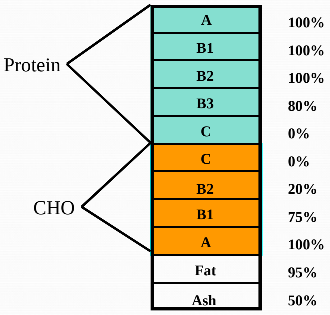
Intestinal digestibility coefficients

- Based on Sniffen et al. (1992) and Knowlton et al. (1998)
- Protein
  - A, B1 and B2 = 100%
  - B3 = 80%
  - C = 0%
- Carbohydrate
  - B2 (NDF) = 20% due to lack of proper enzymes
  - B1 (Starch) based on observation of the feces and in adjusting inputs to account for predicted and actual animal performance

Starch (B1) Intestinal Digestibility

Process	Corn	Sorghum
Whole	30 to 50%	
Cracked	50 to 70%	
Dry rolled	70 to 80%	60 to 70%
Meal or dry ground	80 to 90%	70 to 80%
Whole high moisture	80 to 90%	
High moisture ground	70 to 80%	
Steam flaked	92 to 97%	90 to 95%

Intestinal digestibilities



Protein	A	100%
	B1	100%
	B2	100%
	B3	80%
	C	0%
CHO	C	0%
	B2	20%
	B1	75%
	A	100%
	Fat	95%
	Ash	50%

Future Modeling Research

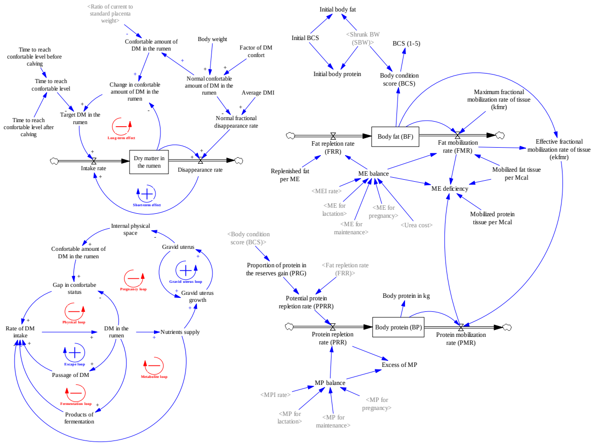
Future modeling research

Dynamic body reserves model
- Adjust predicted ME or MP allowable milk

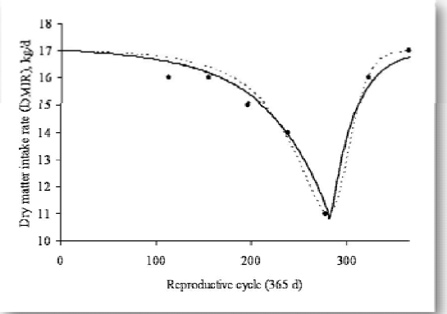
Dynamic rumen model
- Predict methane production

Passage rate model
- Robust prediction of passage

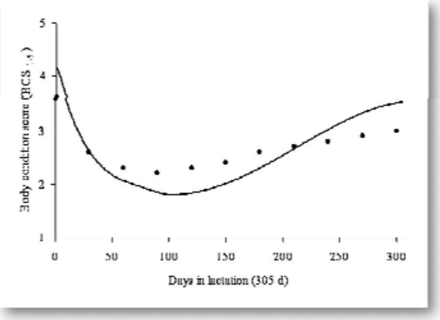
Fermentation rate model
- Neural network technique to estimate kd



Pattern of DMI

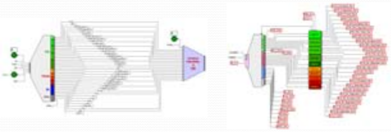


Fluxes of body reserves

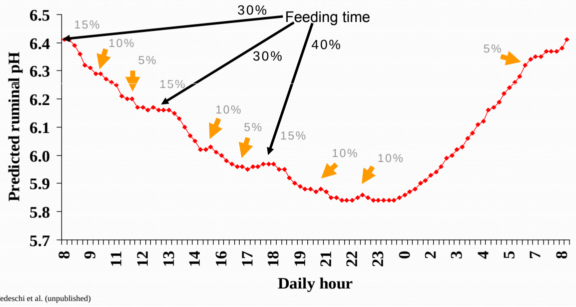


2. Dynamic rumen model

- Basis for VFA and AA system
- Synchronization of energy-protein
- Methane production
- Pool size

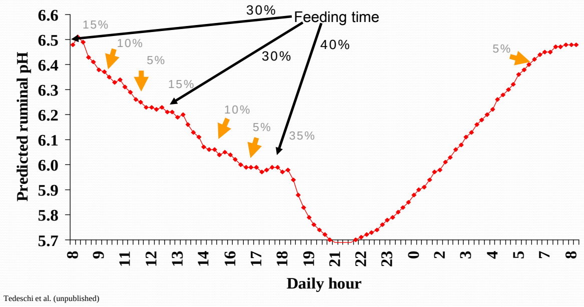


Beef cattle ruminal pH



Tedeschi et al. (unpublished)

Beef cattle ruminal pH



Tedeschi et al. (unpublished)

3. Ruminant dry matter intake

- DMI indirectly dictates the profile of VFA produced in the rumen via acid load and pH
- DMI is not controlled by one specific mechanism, but by a multifactorial system, which seeks for a balance
- Need to understand the behavior of DMI

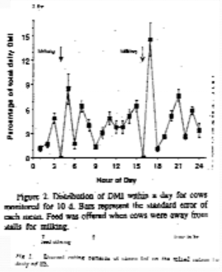
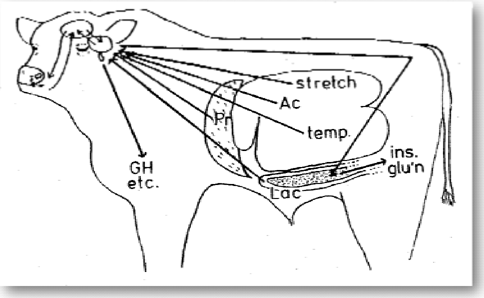
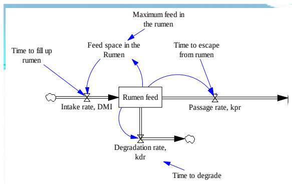


Figure 2. Distribution of DMI within a day for cows monitored for 10 d. Bars represent the standard error of each mean. Feed was offered when cows were away from stalls for milking.

Scheme of feed intake control





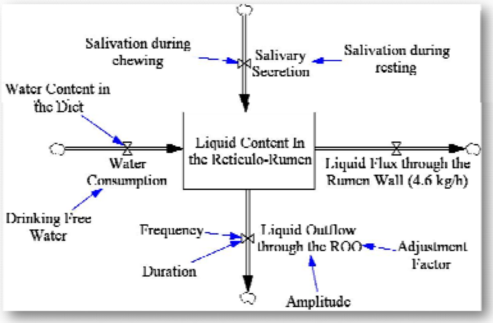
4. Passage rate model

- Seo et al. (2006) equations were the best among a total of 8 tested equations
- However, the predictability was still low
  - Forage passage
    - $R^2 = 39\%$
    - RMSPE = 0.011 h^{-1}
  - Liquid passage
    - $R^2 = 25\%$
    - RMSPE = 0.033 h^{-1}

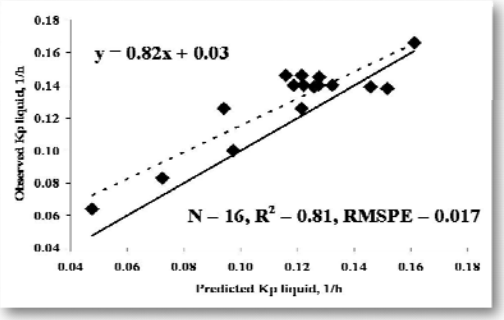
Quantification of digesta outflow

- Digesta outflow is a function of:
  - Frequency and duration of the ROO opening
  - Digesta flow per second of the ROO opening

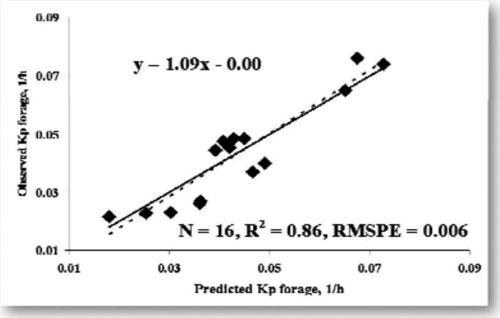
Liquid dynamics model



Prediction for Kp Liquid

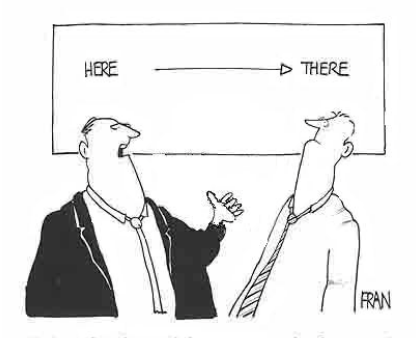


Prediction for Kp Forage



Summary

- Human mind is able to formulate concepts and hypothesis, but lack the ability to track quantitative relationship across time
- Mathematical modeling is a technique that allows us to systematically build representations of the real system using systems thinking
- They can be used on farms to integrate and apply accumulated scientific knowledge of animal requirements and rumen function



"It's a simple model... but it works for me..."