Feed efficiency in dairy cows

a data cruncher's perspective

Francisco Peñagaricano

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

What's the importance of feed efficiency?

- feed represents more than 50% of the total production costs
- benefits of improving feed efficiency:
  - increase farm profitability
  - reduce the environmental impact of dairy farming

The basics of feed efficiency

Energy flow in a cow

Gross Energy of Feed → **Net Energy of Feed** → **Energy captured as milk or body tissue**

energy lost as feces, gas, urine, and heat for digesting and metabolizing feed

energy lost as heat for maintenance

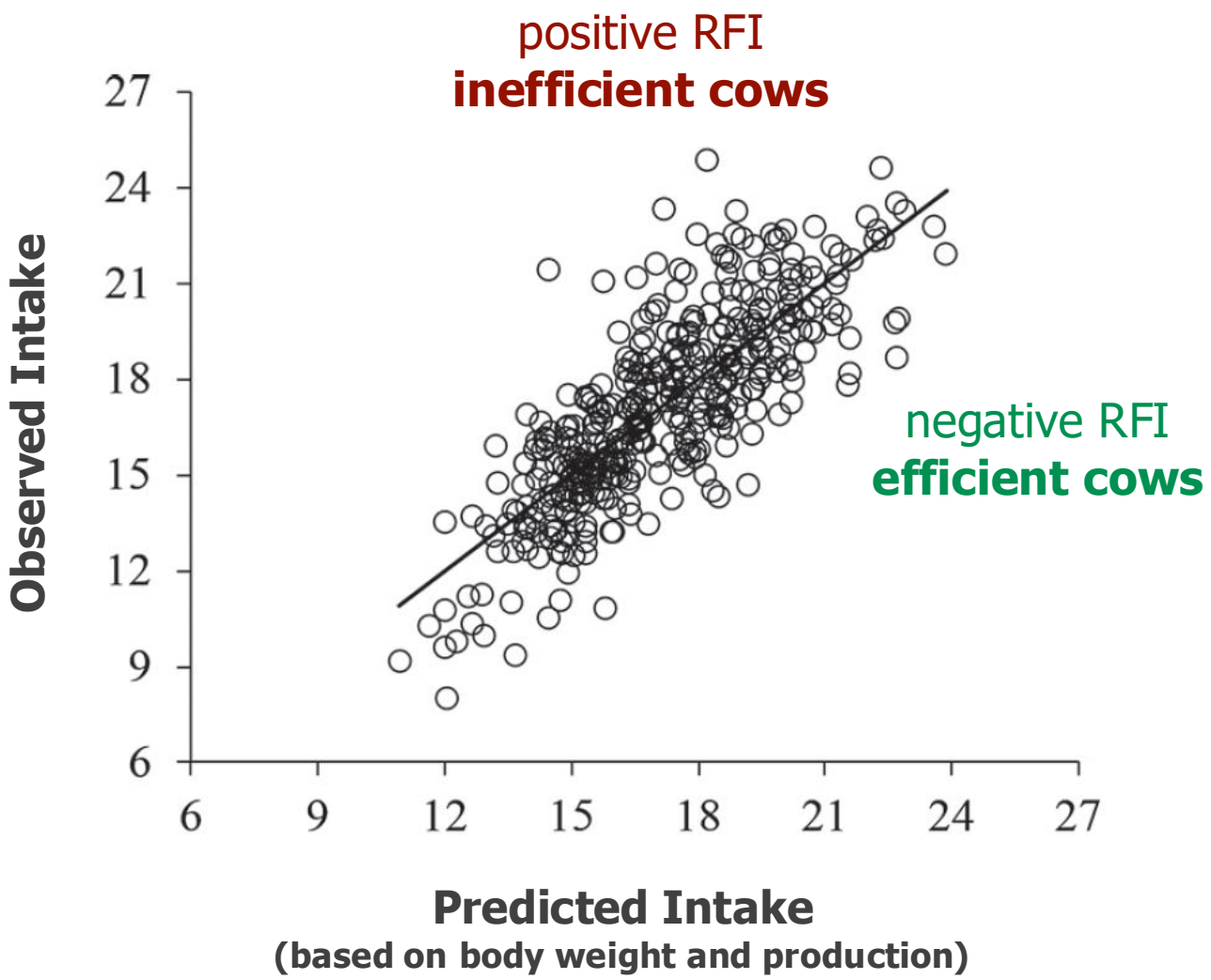
How can we improve gross feed efficiency?

1. increase the conversion of GE to NE
2. increase milk production relative to maintenance

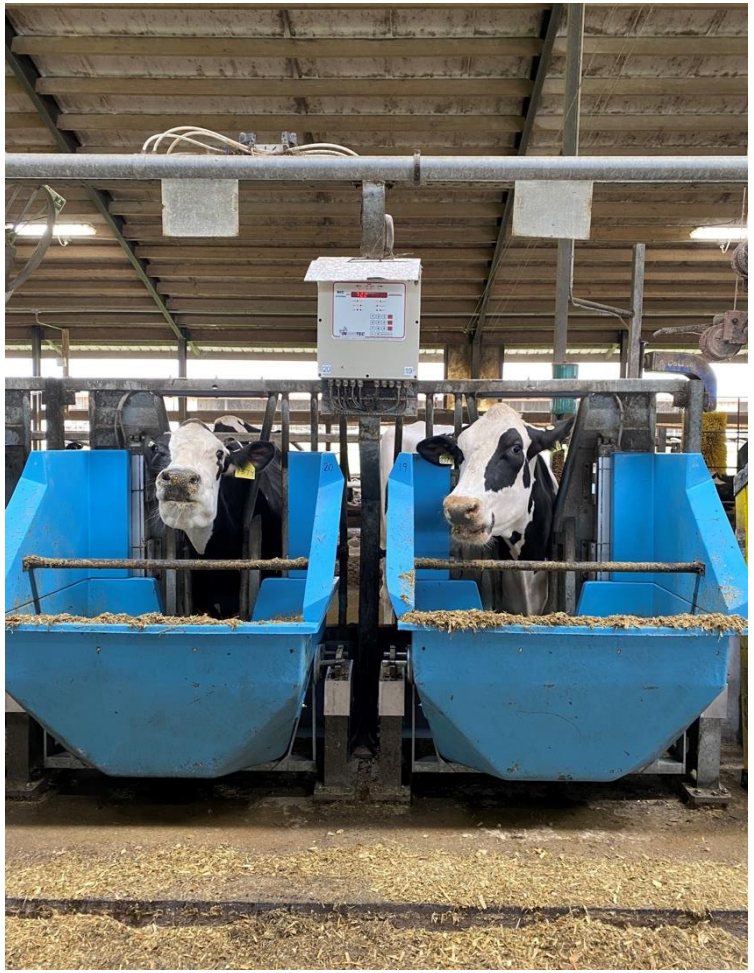
VandeHaar et al (2022) Journal of Dairy Science 99: 4941-4954

How do we measure feed efficiency?

Residual feed intake (RFI) = Observed intake – Predicted intake

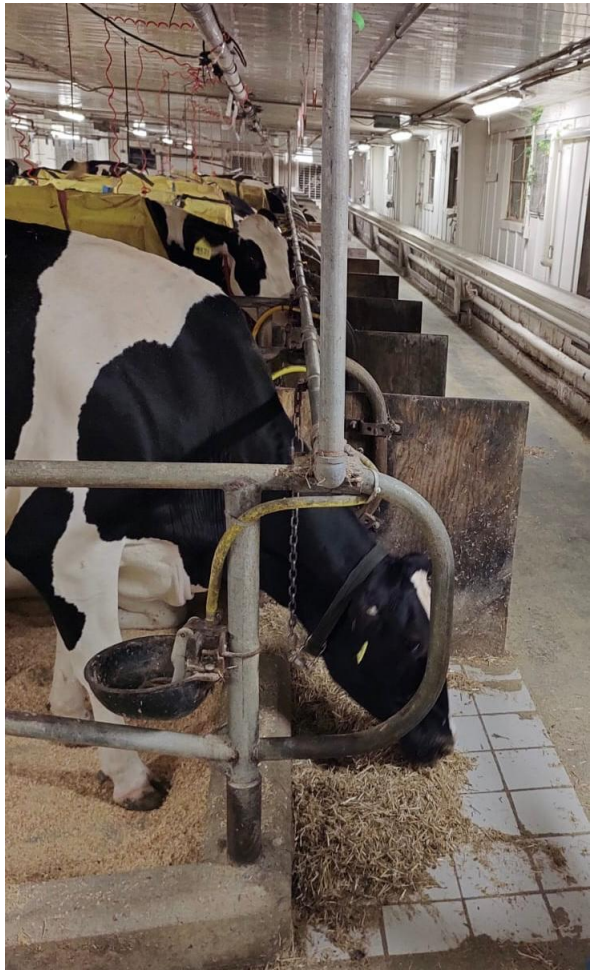


Individual feed intake recording



Insentec Gates

Calan Gates



Tie Stalls

Residual feed intake

Residual feed intake (RFI) = Observed intake – Predicted intake

DMI dry matter intake (based on feed intake)

MilkE milk energy (based on milk production and composition)

mBW metabolic body weight (based on body weight records)

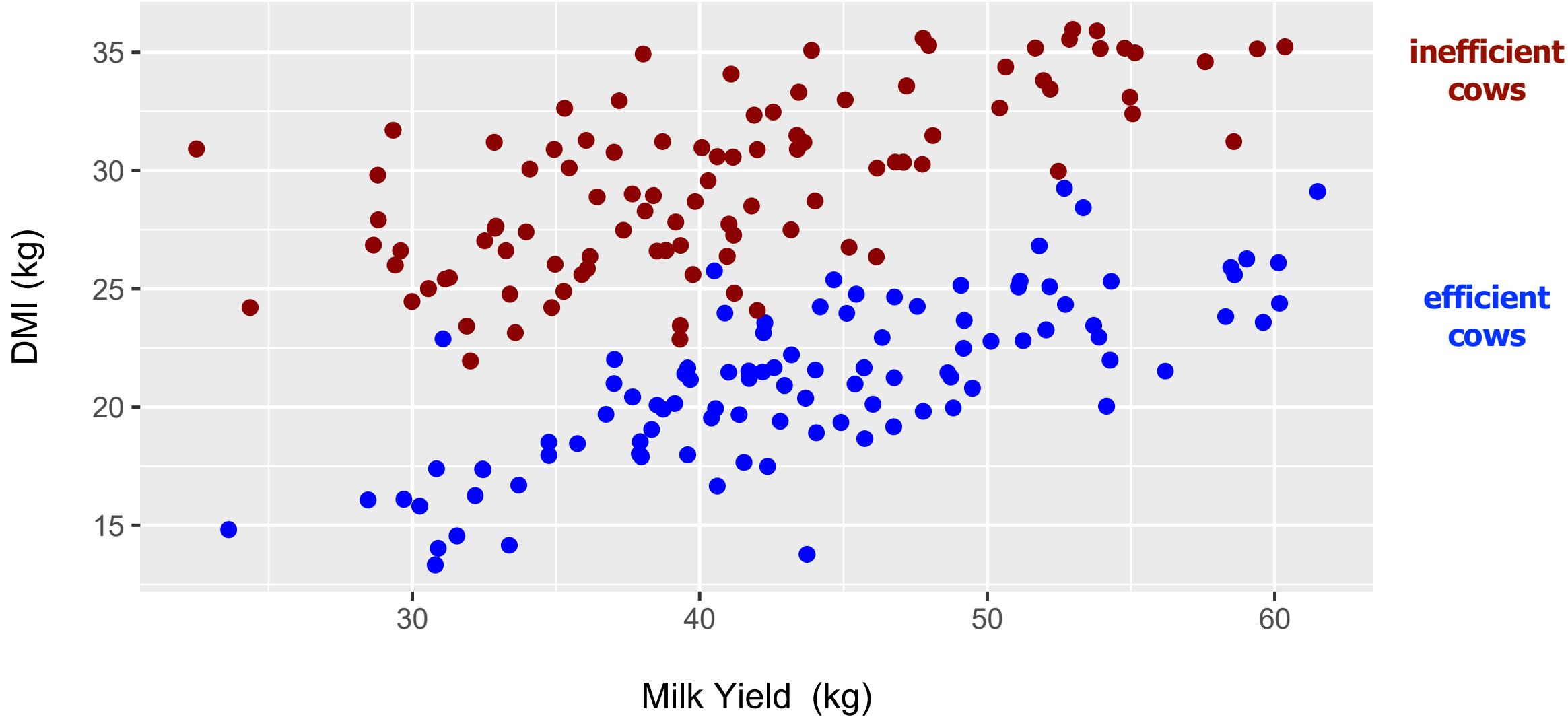
ΔBW change in body weight (based on body weight records)

$$\mathbf{DMI} = \mathbf{DIM} + \mathbf{Lact} + \boldsymbol{\beta}_1\mathbf{MilkE} + \boldsymbol{\beta}_2\mathbf{mBW} + \boldsymbol{\beta}_3\boldsymbol{\Delta}\mathbf{BW} + \mathbf{cohort} + \mathbf{week} + \mathbf{e}$$

$$\mathbf{e} = \mathbf{DMI} - \widehat{\mathbf{DMI}} = \mathbf{residual\ feed\ intake}$$

Cavani et al. (2023) JDS Communications 4: 201-204

Most/least efficient cows



Genetic variation of feed efficiency

Trait	σ^2_u	σ^2_{pe}	σ^2_b	σ^2_e	h^2	r^2
DMI (kg)	2.08 ± 0.41	3.24 ± 0.34	1.53 ± 0.39	3.32 ± 0.04	0.20 ± 0.04	0.52 ± 0.02
Milk energy (Mcal)	2.75 ± 0.88	9.82 ± 0.83	4.72 ± 1.14	5.97 ± 0.09	0.12 ± 0.04	0.54 ± 0.03
Metabolic BW ($kg^{0.75}$)	37.62 ± 4.71	23.43 ± 3.25	3.98 ± 1.42	6.11 ± 0.08	0.53 ± 0.05	0.86 ± 0.02
Change in BW (kg)	19.96 ± 2.57	7.39 ± 1.67	224.45 ± 42.79	4.49 ± 0.06	0.08 ± 0.08	0.11 ± 0.02
Residual feed intake (kg)	0.65 ± 0.15	1.40 ± 0.14	—	1.95 ± 0.03	0.16 ± 0.04	0.51 ± 0.01

[1] σ^2_u = additive genetic variance; σ^2_{pe} = permanent environmental variance; σ^2_b = block of experiment-treatment variance; σ^2_e = residual variance; h^2 = heritability; r^2 = repeatability.

Cavani et al. (2022) Journal of Dairy Science 105: 7564-7574

Heritability estimates

residual feed intake is more heritable than most fertility, health, and longevity traits!

PTA trait	PTA trait													
	Milk	Fat	Protein	PL	SCS	BWC	Udder	Feet/legs	DPR	CA$	HCR	CCR	LIV	HTH$
Milk	**0.20**[1]	0.43	0.83	0.10	0.02	−0.12	−0.10	−0.02	−0.23	0.19	−0.03	−0.16	0.03	0.03
Fat	0.69	**0.20**	0.59	0.15	−0.09	−0.05	−0.07	0.01	−0.15	0.13	0.03	−0.10	0.06	0.08
Protein	0.90	0.75	**0.20**	0.13	0.04	−0.09	−0.14	−0.01	−0.18	0.22	−0.07	−0.15	0.05	0.04
PL	0.15	0.17	0.16	**0.08**	−0.45	−0.10	0.18	0.14	0.64	0.40	0.32	0.62	0.70	0.56
SCS	−0.10	−0.10	−0.10	−0.40	**0.12**	−0.10	−0.23	−0.15	−0.27	−0.14	−0.12	−0.25	−0.25	−0.44
BWC	0.06	0.05	0.05	−0.20	−0.11	**0.40**	0.27	0.38	−0.052	−0.07	−0.01	−0.01	−0.14	−0.26
Udder	−0.02	−0.05	−0.06	0.15	−0.30	0.45	**0.27**	0.45	0.09	0.10	0.03	0.04	0.08	−0.01
Feet/legs	−0.14	−0.11	−0.18	0.08	−0.02	0.35	0.40	**0.15**	0.03	−0.01	−0.01	−0.04	0.06	0.02
DPR	−0.10	−0.10	−0.10	0.20	−0.05	0.00	0.00	0.00	**0.04**	0.41	0.87	0.35	0.43	0.42
CA$	0.02	0.02	0.02	0.20	−0.03	−0.10	0.00	−0.02	0.09	**0.07**	0.16	0.34	0.36	0.33
HCR	−0.05	−0.05	−0.05	0.10	−0.04	−0.02	−0.05	−0.05	0.10	0.16	**0.01**	0.54	0.22	0.18
CCR	−0.10	−0.10	−0.10	0.40	−0.20	−0.10	0.03	−0.04	0.70	0.20	0.45	**0.02**	0.43	0.36
LIV	0.11	0.13	0.12	0.70	−0.40	−0.20	0.10	0.05	0.40	0.35	0.20	0.15	**0.01**	0.55
HTH$	0.02	0.04	0.02	0.28	−0.22	−0.13	0.00	0.01	0.21	0.17	0.09	0.18	0.28	**0.01**

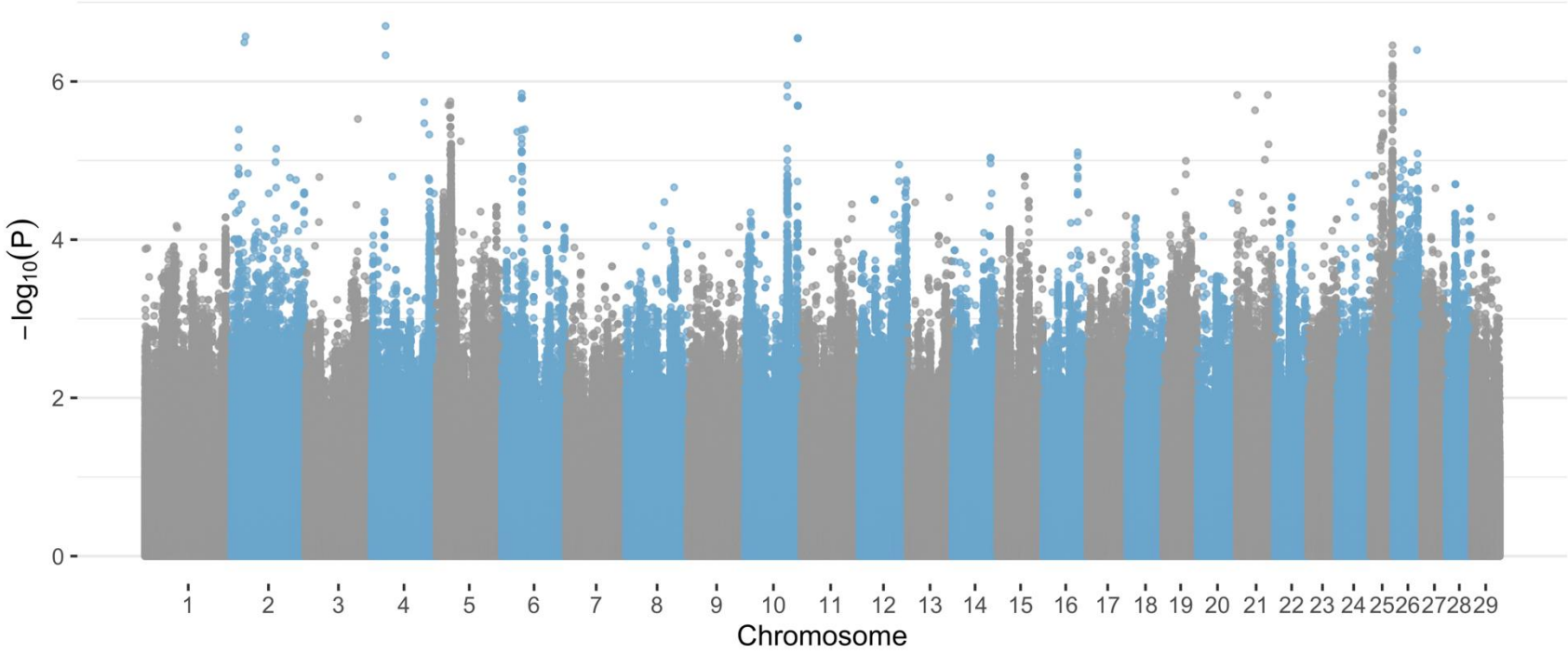
[1]Holstein heritabilities in **orange** on diagonal; heritabilities for other breeds are the same except for BWC (**0.35**), udder (**0.20**), and Jersey and Brown Swiss yield traits (**0.23**).

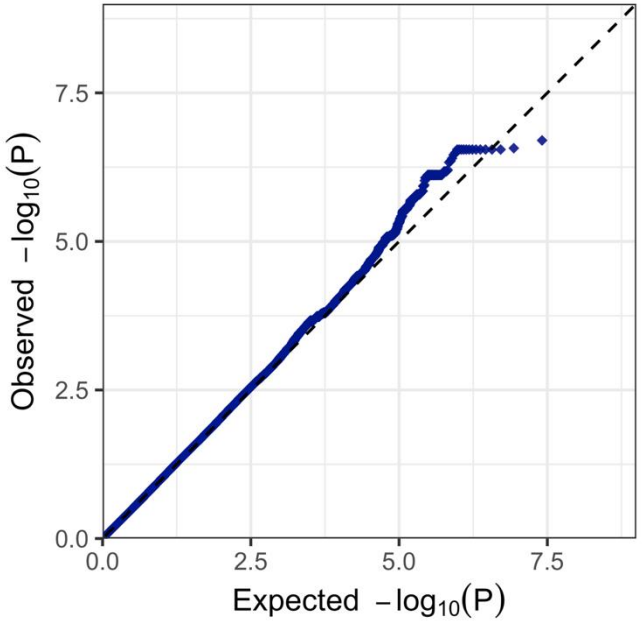
source: https://www.uscdcb.com

Genomic scan for residual feed intake

Data: 8k cows and 13 million genetic variants

residual feed intake is highly polygenic, many genes with small effects!

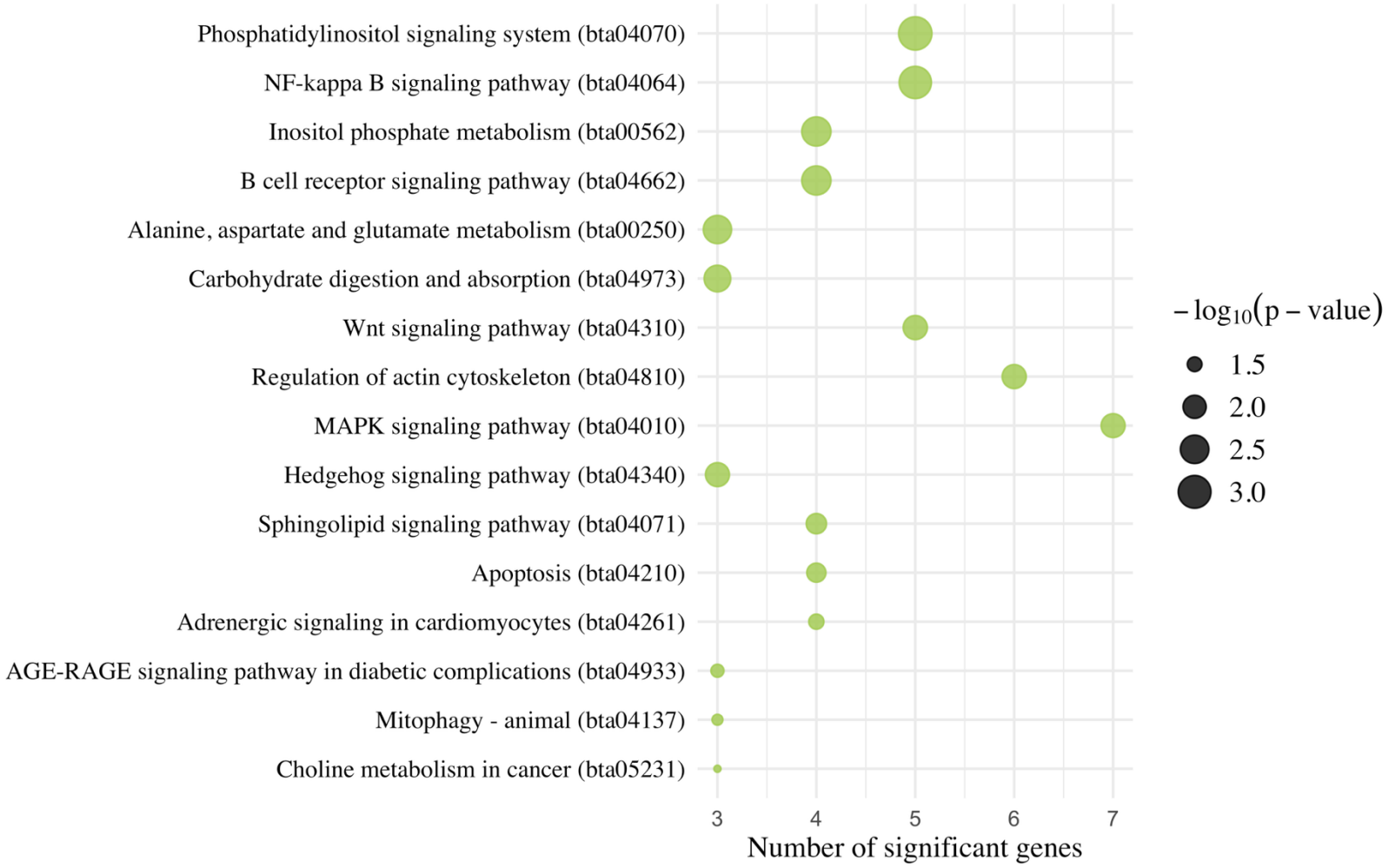




Nascimento et al. (2026) in preparation

Gene-set analysis for residual feed intake

rationale: go beyond single genes → evaluate sets of genes



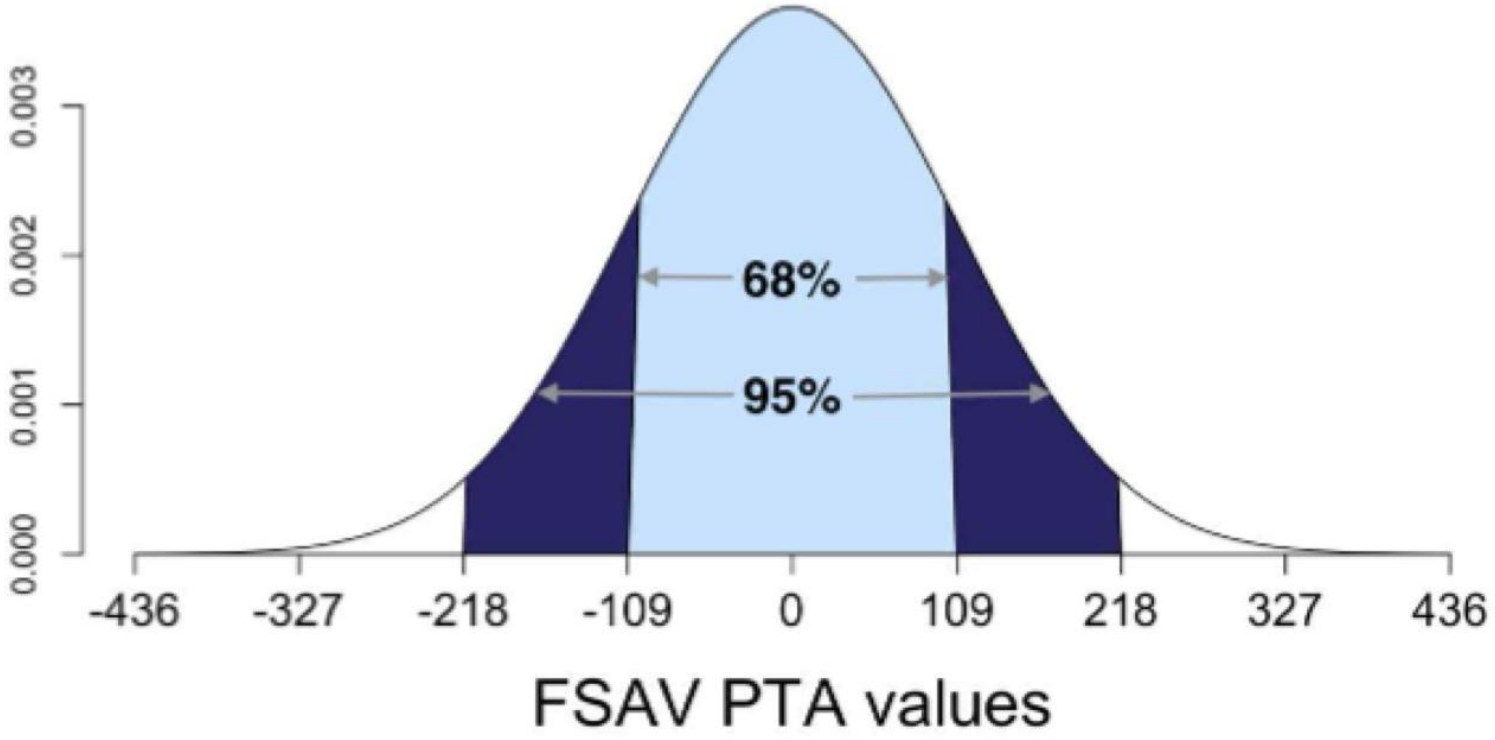
Nascimento et al. (2026) in preparation

Current traits under selection

Production	milk yield | protein yield & percentage | fat yield & percentage | milking speed
Fertility	daughter pregnancy rate | heifer/cow conception rate | age at first calving
Longevity	productive life | cow livability | heifer livability
Health	SCS | mastitis | ketosis | retained placenta | metritis | DA | milk fever
Calving ability	calving ease | stillbirth rate | gestation length
Conformation	body weight composite | feet and leg composite | udder composite | type
Feed efficiency	**residual feed intake | feed saved**

Trait definition: Feed Saved

Feed Saved combines Residual Feed Intake + Body Weight Composite

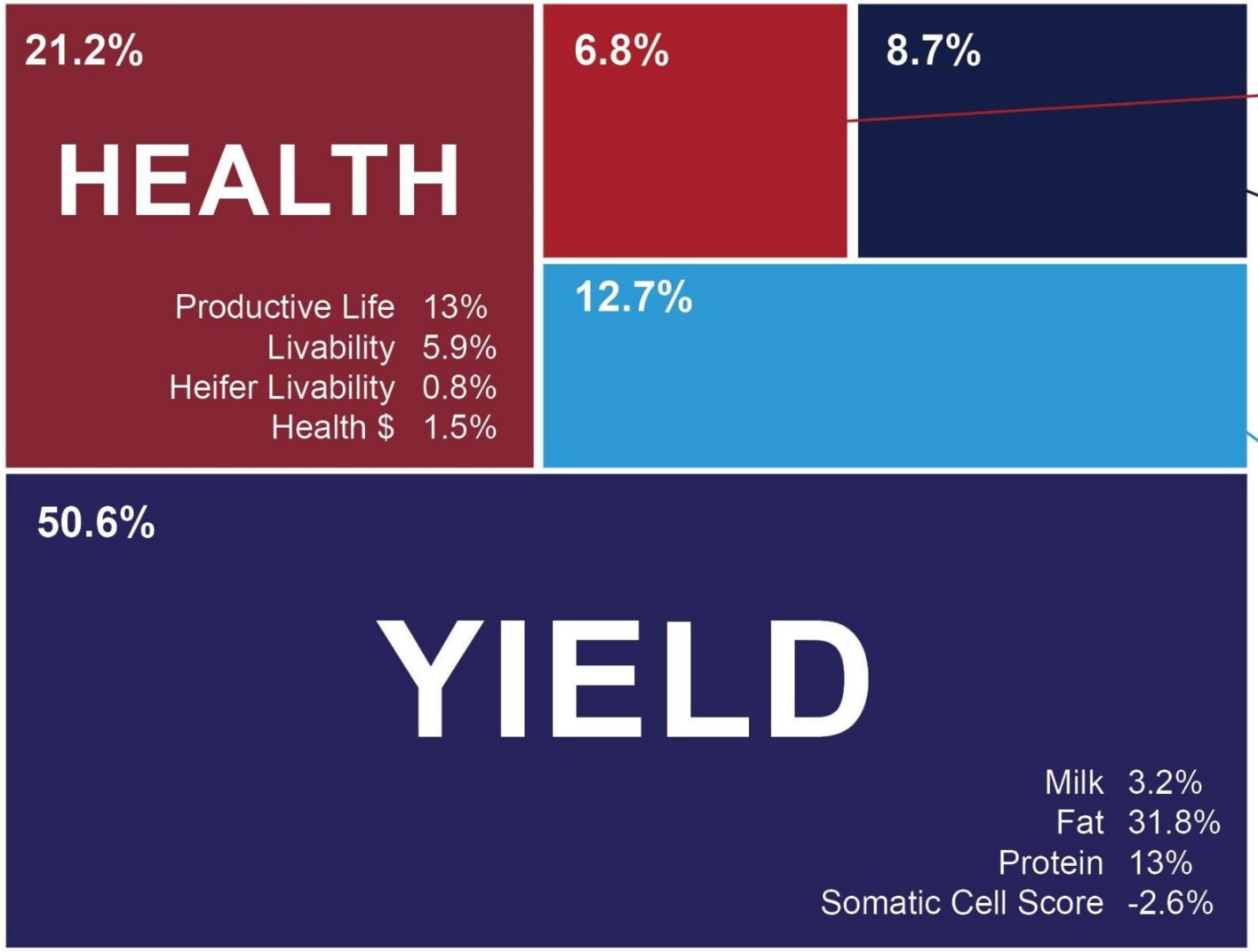


pounds of feed saved per lactation

(larger, positive values are more favorable)

Index: best selection tool!

Net Merit Index ($NM)



FEED EFFICIENCY

Residual Feed Intake -6.8%

FERTILITY & CALVING

Calving Ability $ 3.3%
Daughter Pregnancy Rate 2.1%
Cow Conception Rate 1.8%
Heifer Conception Rate 0.5%
Early First Calving 1%

CONFORMATION

Udder Composite $ 1.3%
Body Weight Composite $ -11%
Foot and Leg Composite $ 0.4%

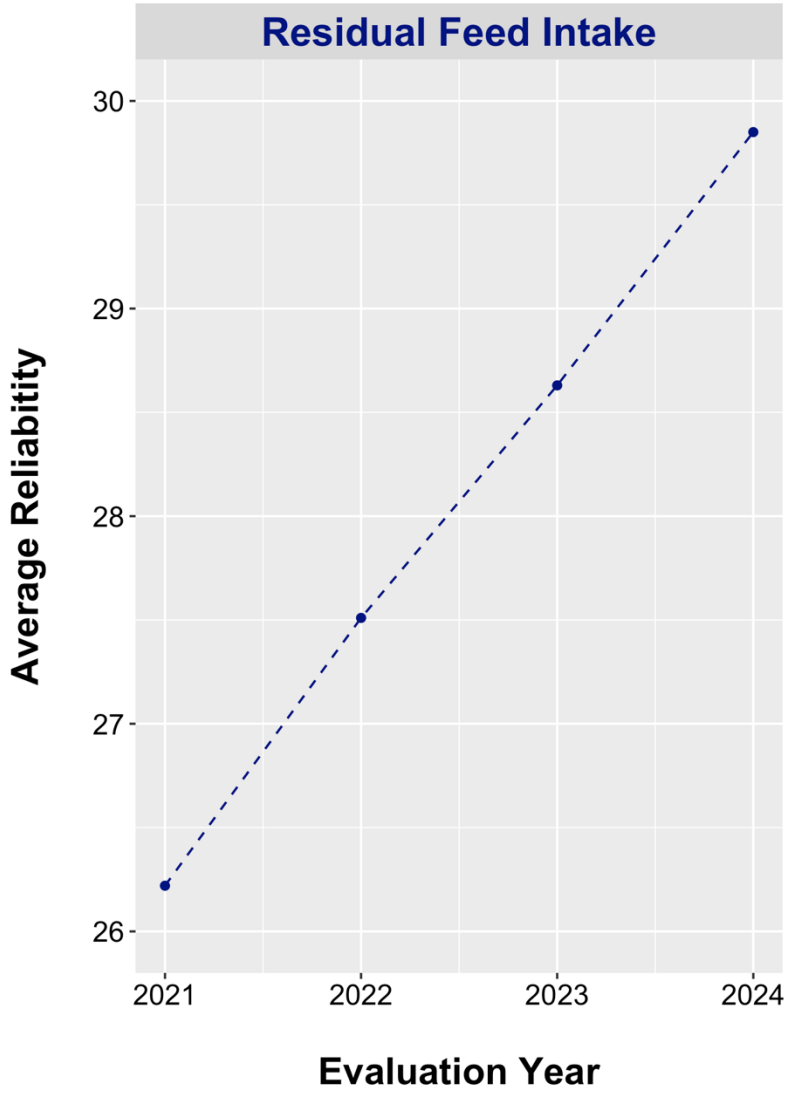
CDCB™ COUNCIL ON DAIRY CATTLE BREEDING

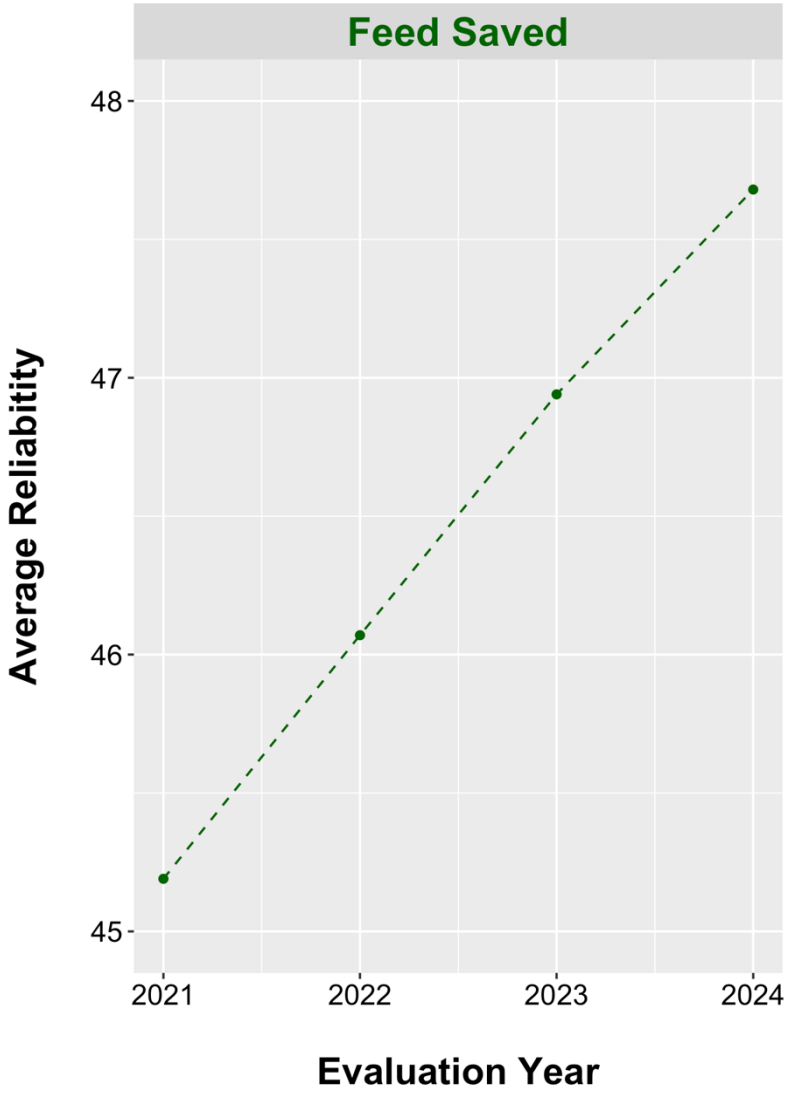
USDA

source: https://www.uscdcb.com

Change in reliabilities

Reliabilities are slowly but steadily improving





The million-dollar question

Why some cows are more efficient than others?

(some cows need less feed than others of similar body weight and milk production)

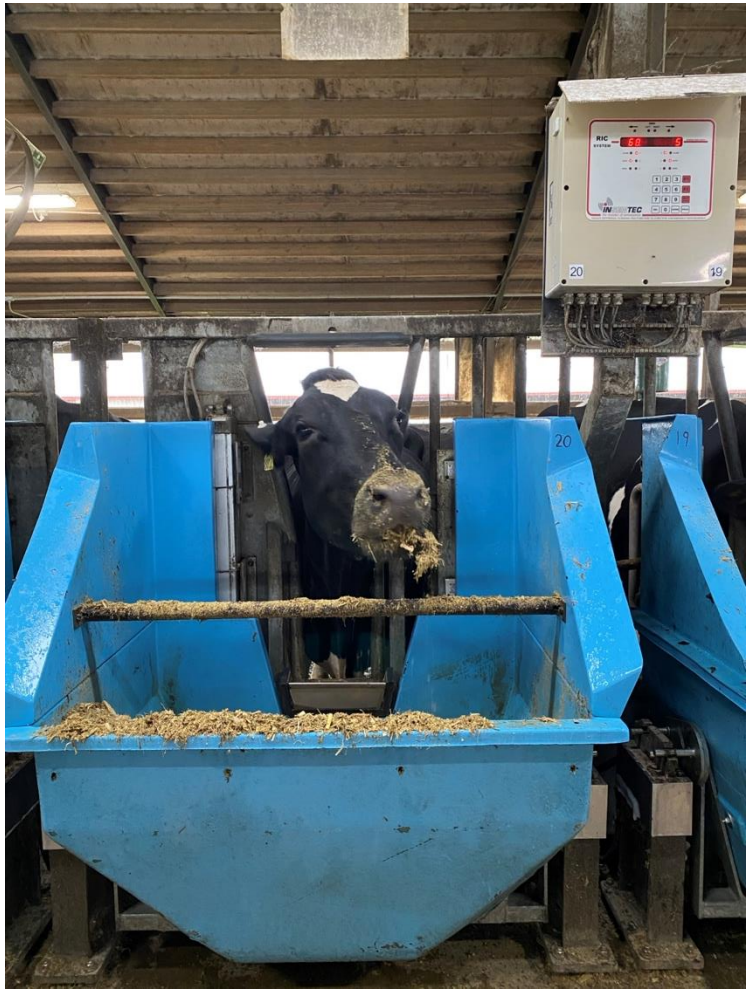
some processes that contribute to feed efficiency:

- **feeding behavior, feeding patterns**
- **rumination, physical activity, and lying behavior**
- **rumen microbiome composition**
- **thermoregulation**
- **metabolism, mitochondrial function**
- **diet digestibility**

Feeding behavior

- number of visits/meals per day
- duration of each visit/meal
- intake per visit/meal
- feeding rate per visit/meal

Insentec Gates



Feeding behavior

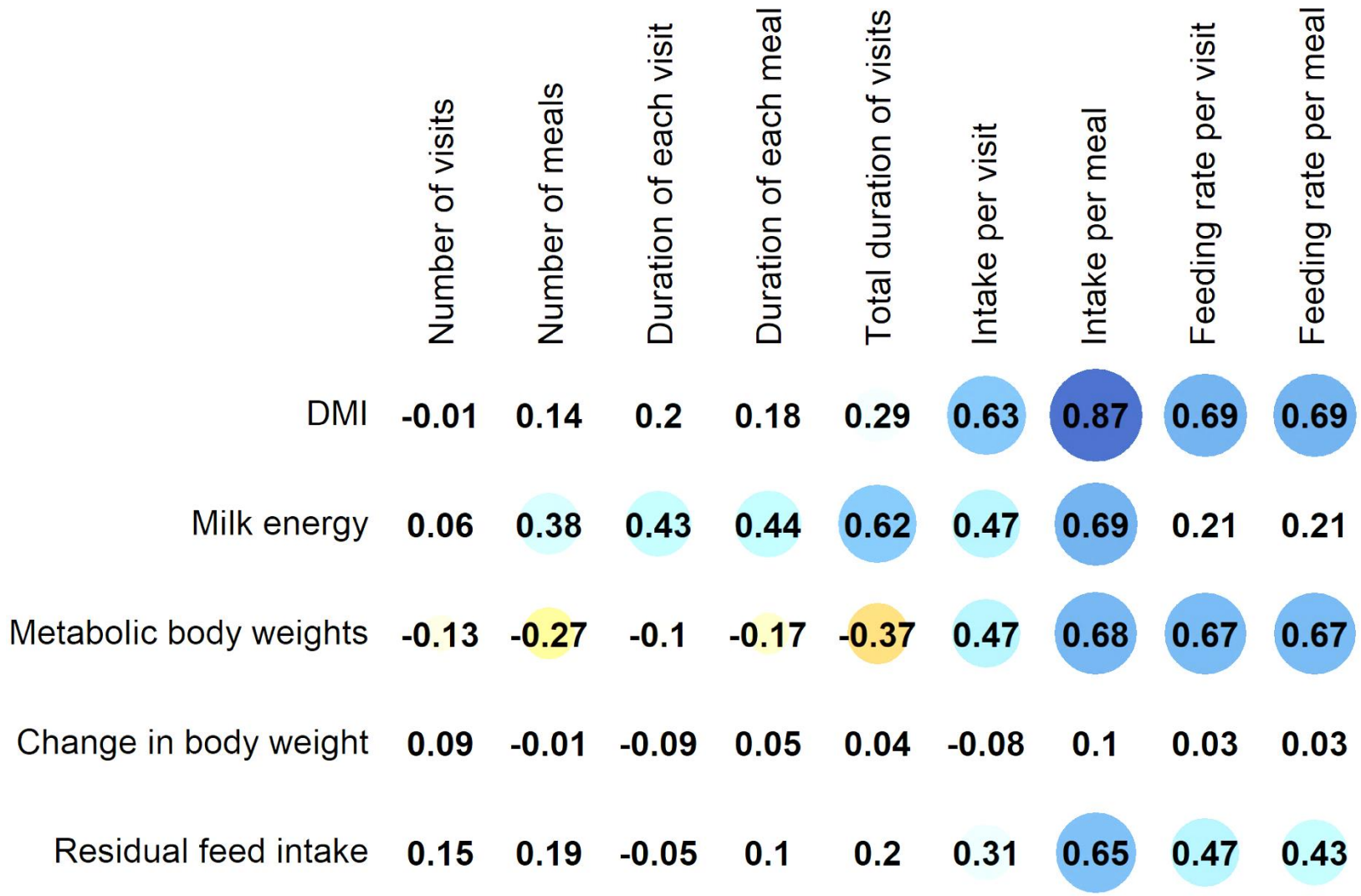
Feeding behavior traits are heritable and repeatable

Feeding behavior trait	h^2 (SE)	r (SE)
Number of feeder visits per day	0.16 ± 0.03	0.52 ± 0.02
Number of meals per day	0.09 ± 0.02	0.23 ± 0.01
Duration of each feeder visit (minutes)	0.16 ± 0.03	0.47 ± 0.02
Duration of each meal (minutes)	0.14 ± 0.02	0.31 ± 0.01
Total duration of feeder visits per day (minutes)	0.16 ± 0.03	0.38 ± 0.02
Intake per visit (kg of DM)	0.16 ± 0.03	0.49 ± 0.02
Intake per meal (kg of DM)	0.13 ± 0.02	0.28 ± 0.01
Feeding rate per visit (kg of DM per minute)	0.11 ± 0.02	0.32 ± 0.02
Feeding rate per meal (kg of DM per minute)	0.23 ± 0.03	0.49 ± 0.02
DMI (kg/d)	0.12 ± 0.02	0.31 ± 0.01

Cavani et al. (2022) Journal of Dairy Science 105: 7564-7574

Feeding behavior

Feeding behavior traits are correlated with feed efficiency traits



Cavani et al. (2022) Journal of Dairy Science 105: 7564-7574

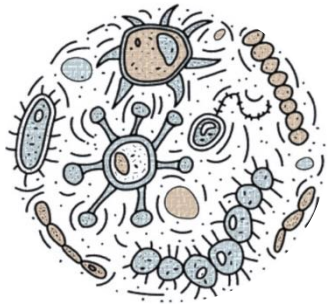
Behavioral traits

Genetic Correlations	**Rumination time** (min/d)	**Lying time** (min/d)	**Activity** (steps/d)
Dry matter intake (kg/day)	0.47 ± 0.17	-0.07 ± 0.10	0.18 ± 0.20
Milk energy (Mcal/day)	0.42 ± 0.21	0.06 ± 0.16	0.03 ± 0.19
BW change (kg/week)	-0.27 ± 0.73	-0.03 ± 0.43	0.04 ± 0.17
Metabolic BW ($kg^{0.75}$)	0.12 ± 0.13	0.14 ± 0.08	-0.02 ± 0.12
Residual feed intake (kg/day)	**0.40 ± 0.19**	**-0.27 ± 0.11**	**0.31 ± 0.22**

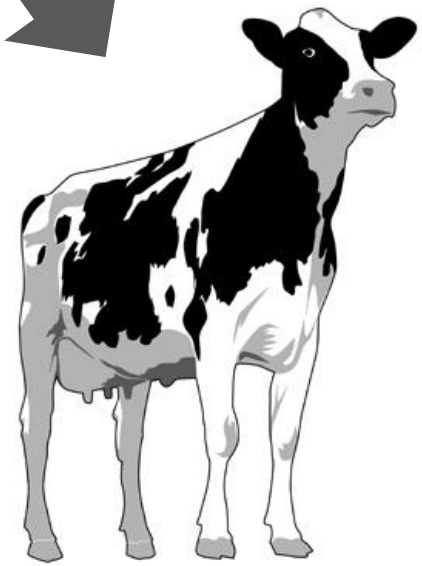
Nascimento et al. (2024) Journal of Dairy Science 107: 8141-8149

Microbiome and feed efficiency

Host Genome



Microbiome



Phenotype

Microbiome and feed efficiency

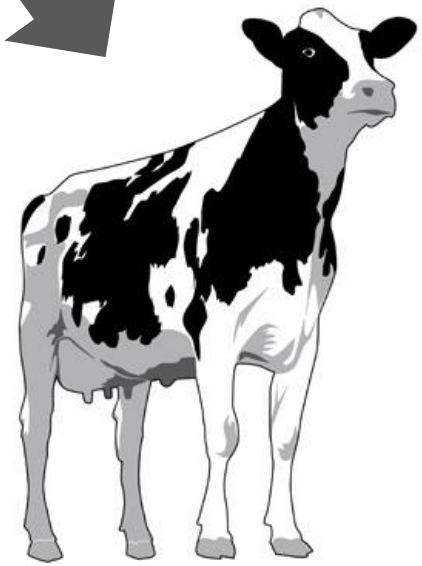
Cow Genome

79K SNP

448 lactating Holstein cows

Rumen Microbiome

16S rRNA gene V4 region

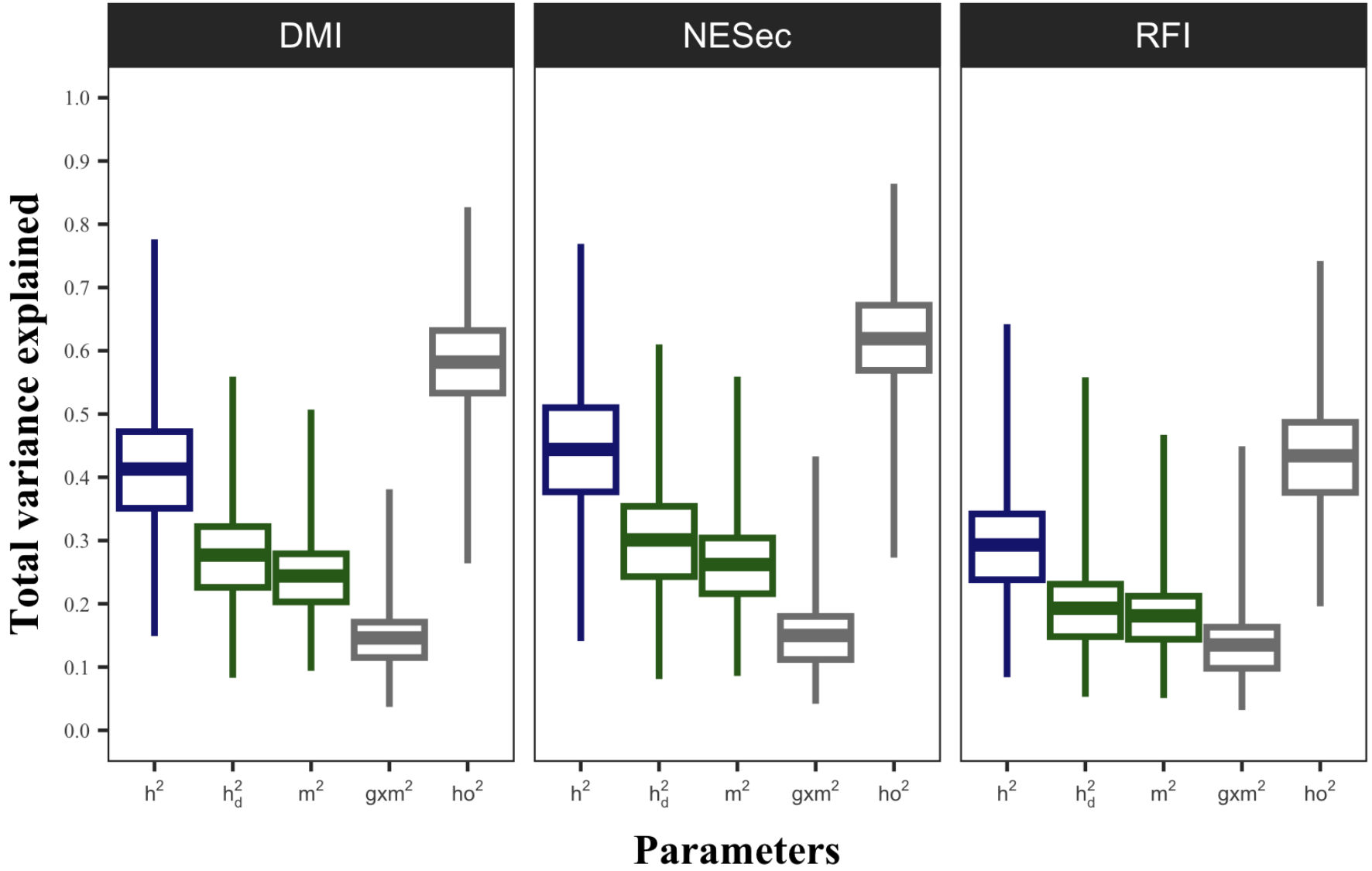


Phenotype

Residual feed intake
Dry matter intake
Milk energy

Microbiome and feed efficiency

Rumen microbiome mediates part of the host genetic effects



Martinez Boggio et al. (2024) Journal of Dairy Science 107: 3090-3103

Residual feed intake

- **feed efficiency impacts production costs and environmental sustainability**
- **residual feed intake:** the most popular index to measure feed efficiency
- **phenotyping RFI is expensive**, **labor-intensive**, and limited to research facilities
- **RFI does not fully reflect metabolic efficiency**
- **RFI does not fully account for energy partitioning**, maintenance vs production

How else can we quantify efficiency?

Heat Production

heat increment + maintenance

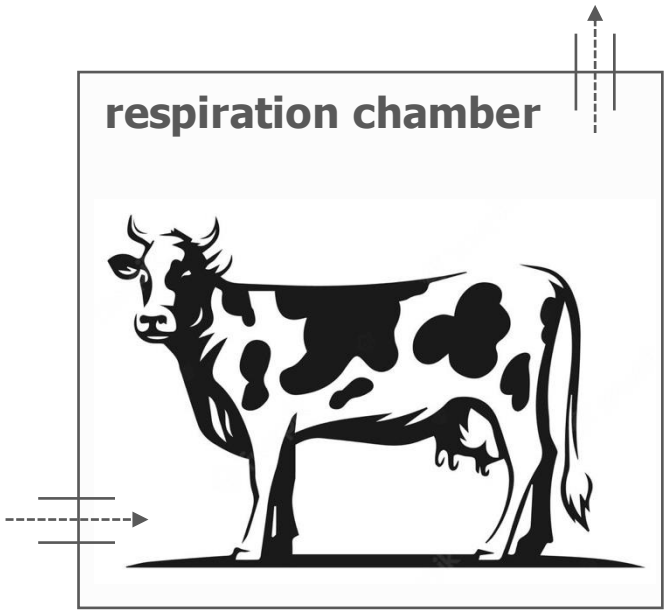
Gross energy → Digestible energy → Metabolizable energy → Net energy

- Gross energy → Digestible energy: **fecal energy 30%**
- Digestible energy → Metabolizable energy: **urine energy 5%**; **gas energy 5-10%**
- Metabolizable energy → Net energy: **heat increment 20%**

Net energy:

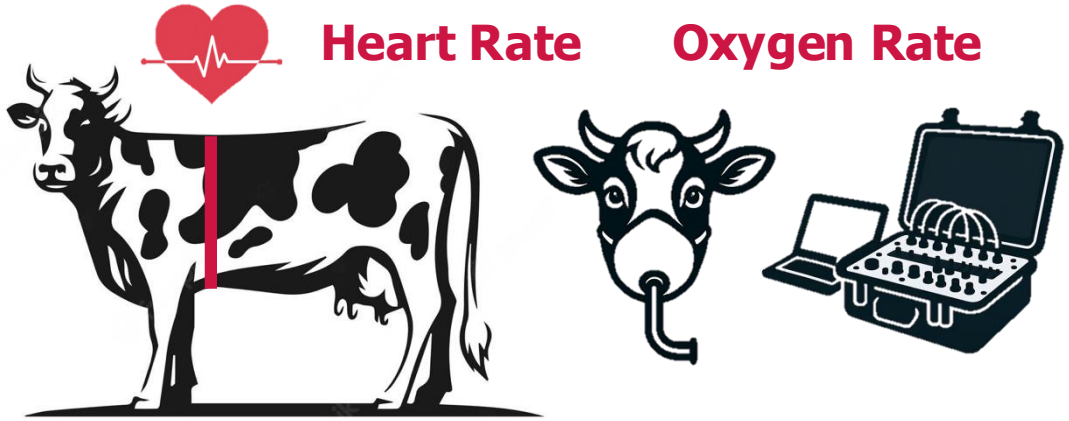
- Maintenance **20%**
- Production **20%**

How can we quantify heat production?



(Brouwer, 1965)

$$\mathbf{HP} = 16.18 \times \mathbf{O_2} + 5.02 \times \mathbf{CO_2} - 5.90 \times \mathbf{N} - 2.17 \times \mathbf{CH_4}$$

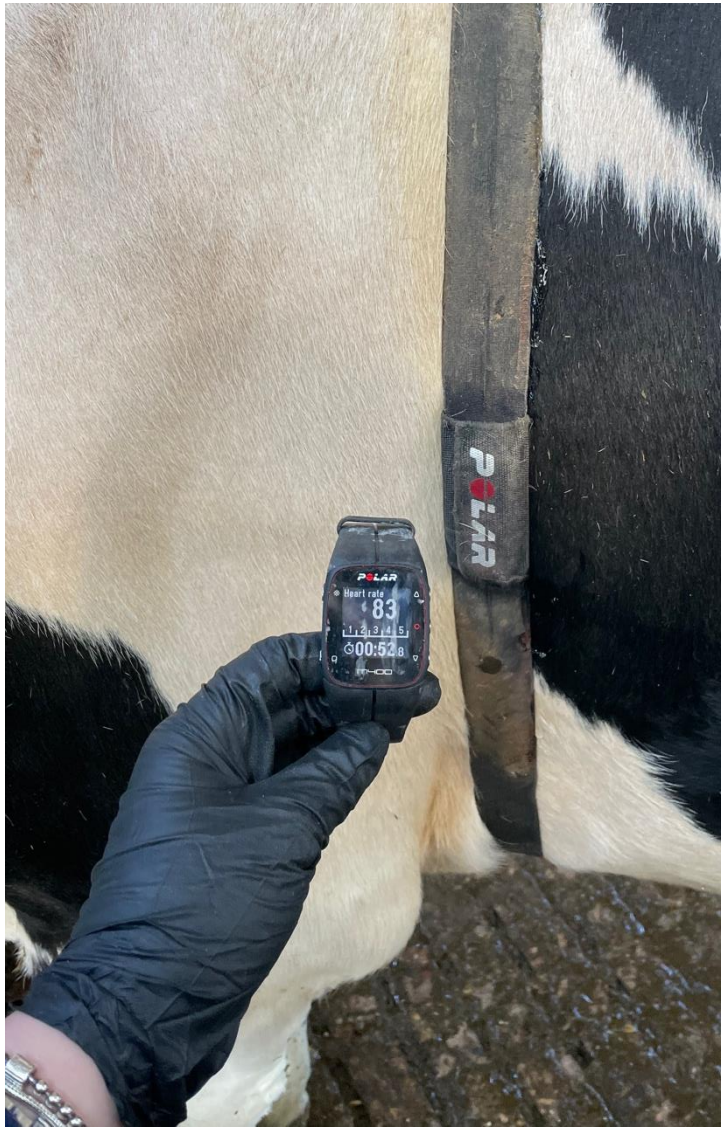


(Brosh, 2007)

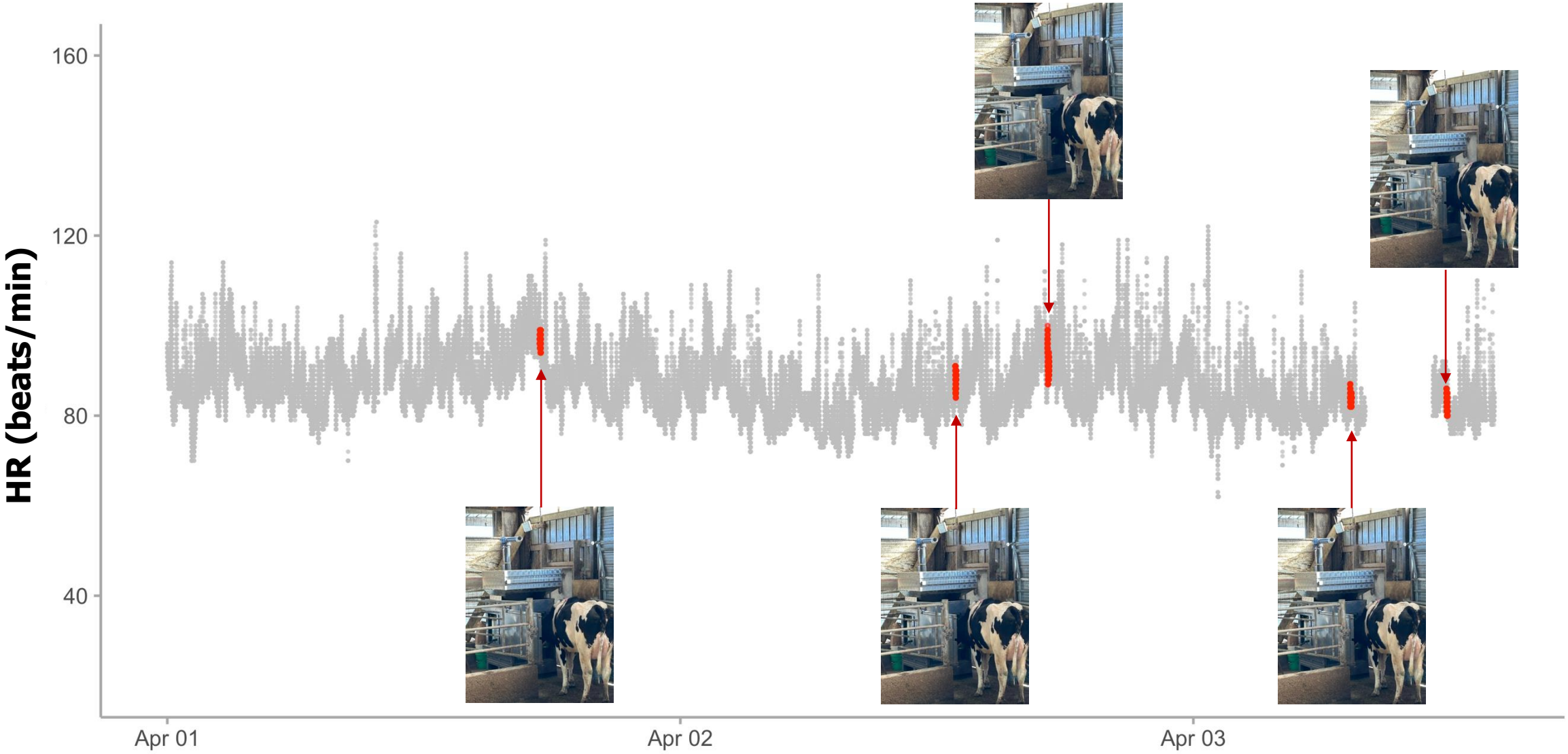
$$\mathbf{HP = HR} \times \mathbf{O_2\ pulse} \times \text{constant}$$

(heart beat/d) x (O_2 /heart beat) x 20.47

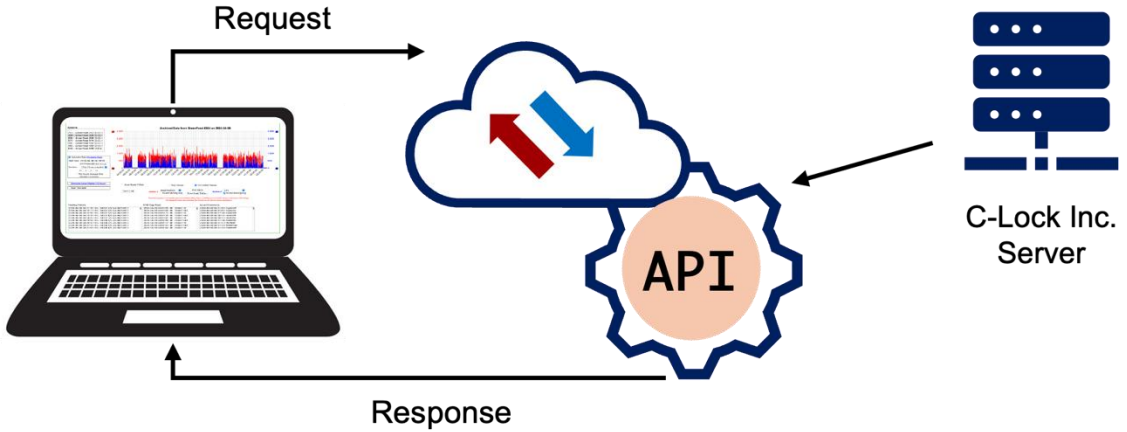
Validation: GF-Brouwer HR-O2pulse



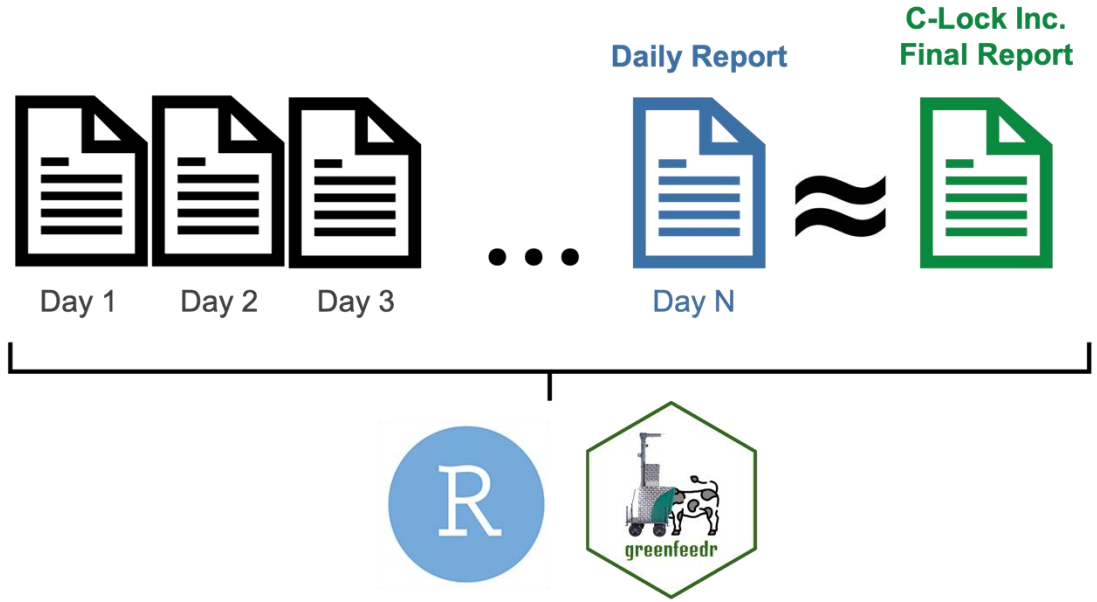
Validation: GF-Brouwer HR-O2pulse



greenfeedr R-package

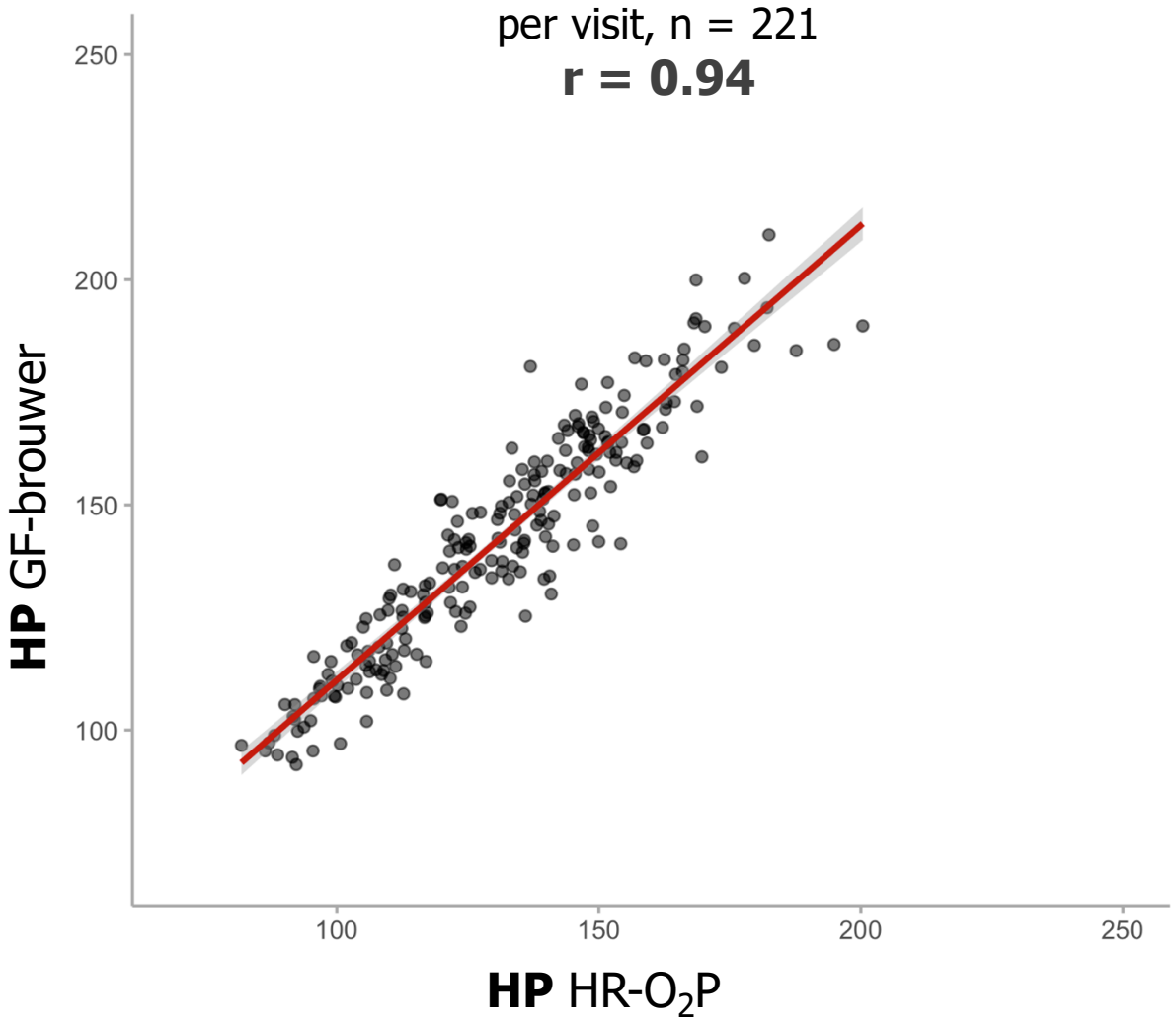


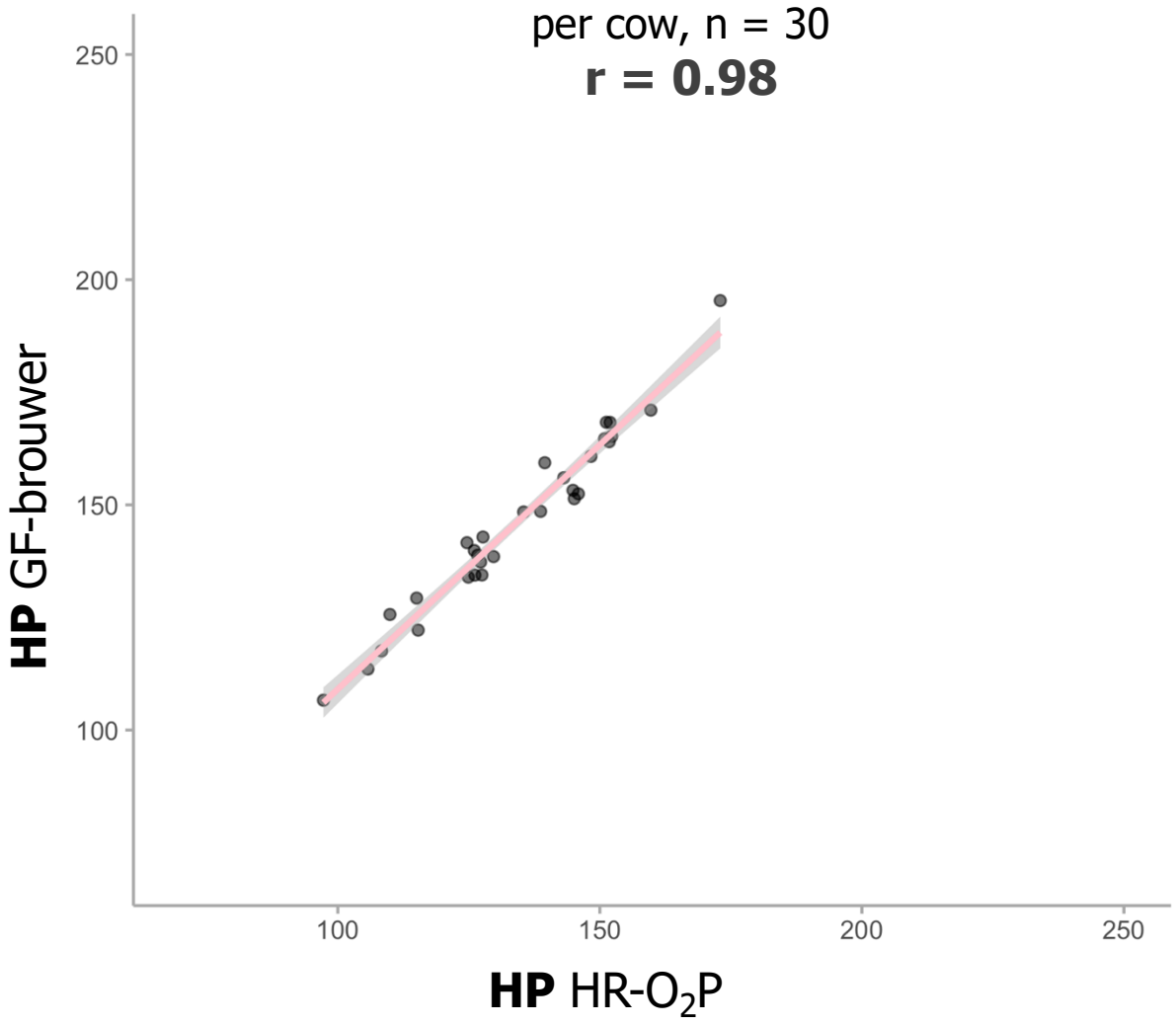
GreenFeed (C-Lock Inc.)



Martínez Boggio et al. (2025) JDS Communications 6: 227-230

Validation: GF-Brouwer HR-O2pulse





Marin et al. (2026) under review

How else can we quantify efficiency?

Residual Feed Intake vs Residual Heat Production

Residual Feed Intake

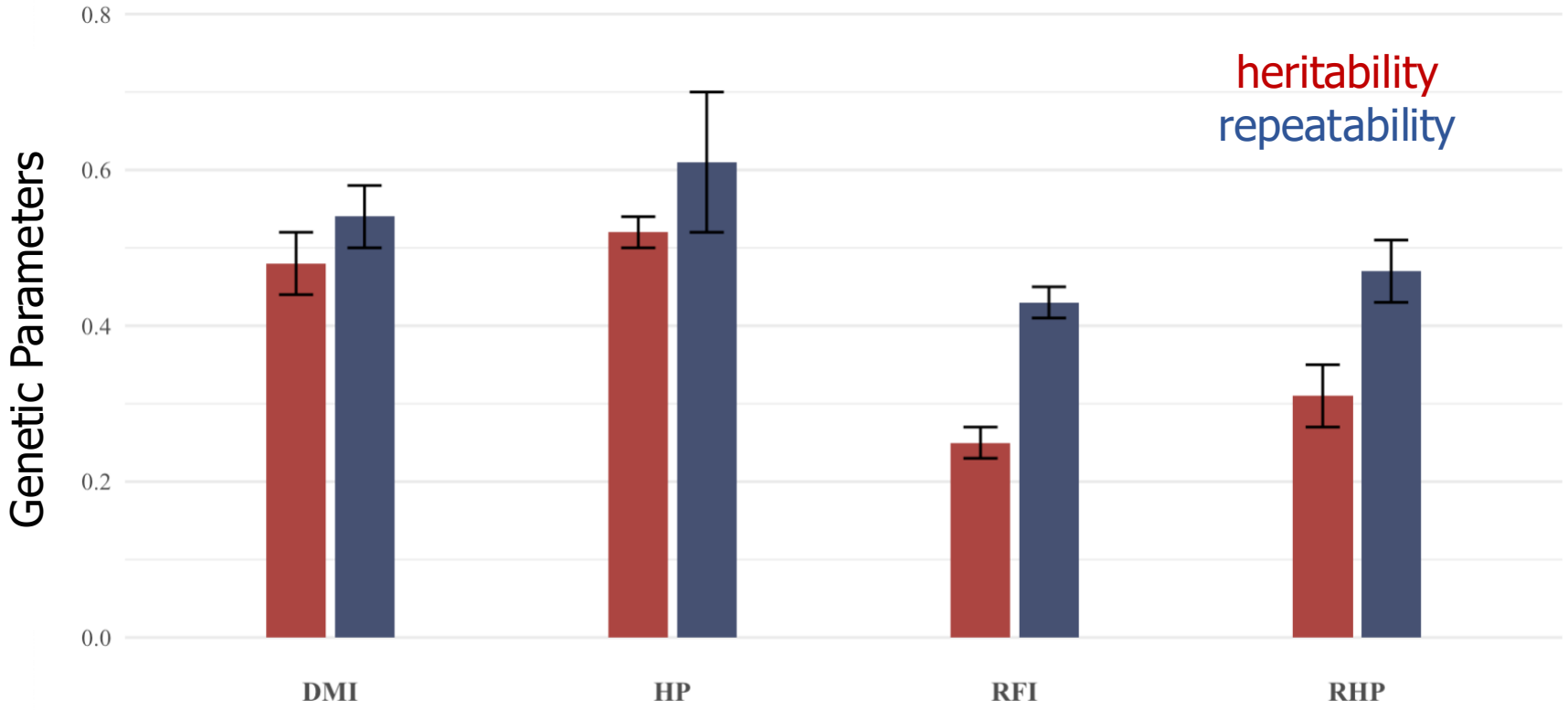
$$\mathbf{DMI} = \text{fixed effects} + \beta_1 \text{MilkE} + \beta_2 \text{mBW} + \beta_3 \Delta\text{BW} + \text{random effects} + \mathbf{e_{RFI}}$$

Residual Heat Production

$$\mathbf{HP} = \text{fixed effects} + \beta_1 \text{MilkE} + \beta_2 \text{mBW} + \beta_3 \Delta\text{BW} + \text{random effects} + \mathbf{e_{RHP}}$$

Efficiency: RFI vs RHP

Data: DMI & RFI 10k cows | HP & RHP 2200 cows



genetic correlations: $rg_{DMI,HP} = 0.78 \pm 0.09$ and $rg_{RFI,RHP} = 0.50 \pm 0.09$

Marin et al. (2026) under review

Take home messages

- **feed efficiency is an economically relevant trait**
- **residual feed intake is a heritable trait** ($h^2 \approx 16\%$)
- **genetic selection can effectively improve dairy cow feed efficiency**

- **residual feed intake is highly polygenic, many genes with small effects**
- **some mechanisms:** digestion and absorption, metabolism, immunity

- **feeding behavior traits are genetically correlated with feed efficiency traits**
- **behavioral traits are genetically correlated with feed efficiency traits**
- **rumen microbiome affects feed efficiency traits**

- **residual heat production: promising trait to measure efficiency**

Team


Barbara Nascimento


Afees Ajasa


Gabriel Zayas


Bruno D'Ambrosio


Derick Rosler


Emily Tabor

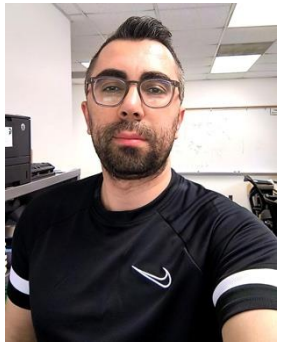

Andre Zambon


Agustín Chasco


Negin Sheybani


Fiona Guinan


Federica Marín


Ümit Bilginer

Acknowledgments

Thanks for your attention!

Department of
Animal & Dairy Sciences
UNIVERSITY OF WISCONSIN–MADISON

Dr. Francisco Peñagaricano

fpenagarican@wisc.edu

http://fpenagaricano-lab.org