Methane-Busting Diets: Feeding Cattle for a More Sustainable Future

Jan Dijkstra - Wageningen University & Research

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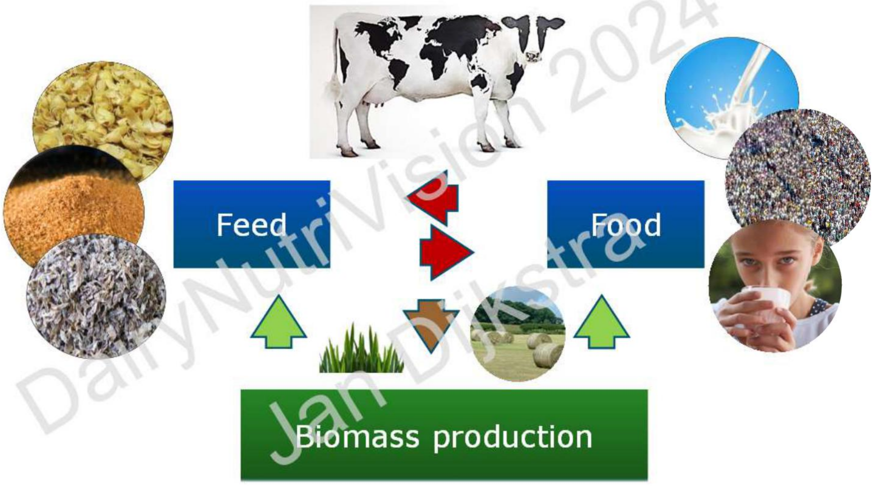
Ruminants in the circular bioeconomy



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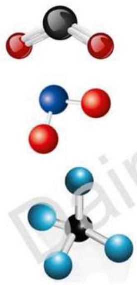
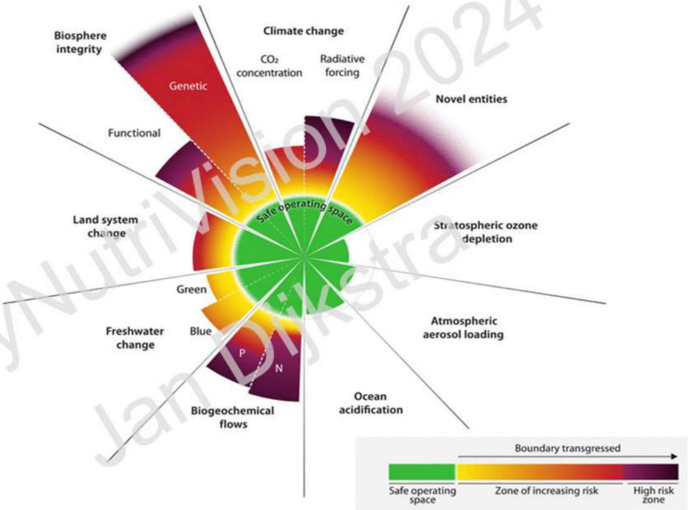
Earth beyond six of nine planetary boundaries

Greenhouse gases





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Richardson et al. (2023)

Presentation today

- Methane and rumen methanogenesis
- Methane mitigation strategies
  - general nutritional strategies
  - specific anti-methanogenic feed additives
- Quantitative approaches

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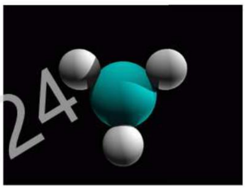
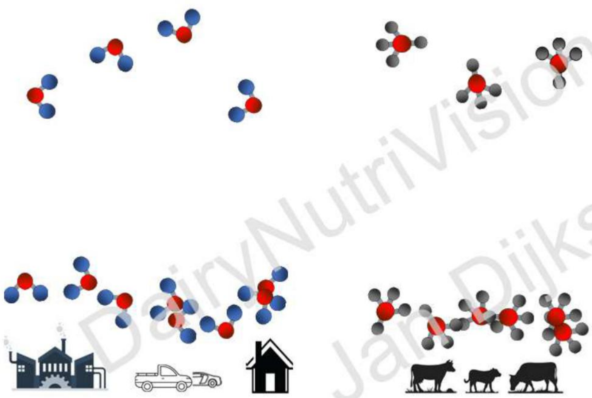
The challenge: methane

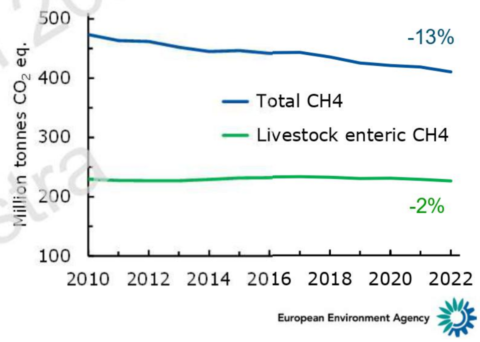


Global Warming Potential (GWP) of methane:
27 (100-yr time horizon)
81 (20-yr time horizon)
(*relative to CO_2*) IPCC (2021)

Methane: unusual GHG



no decline in enteric CH_4 EU



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Methane mitigation: good news and bad news
Target 2030
11-30% CH_4
<1.5 °C
Target 2050
24-47% CH_4
<1.5 °C
IPCC (2018)
Europe: 1.5 °C reduction target (methane) feasible adopting one (2030) or two (2050) strategies
Africa: adopting two best strategies still far from 1.5 °C reduction target (methane)
Arndt et al.
Proc Nat Acad Sci 2022
PNAS
RESEARCH ARTICLE
SUSTAINABILITY SCIENCE
OPEN ACCESS
Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050
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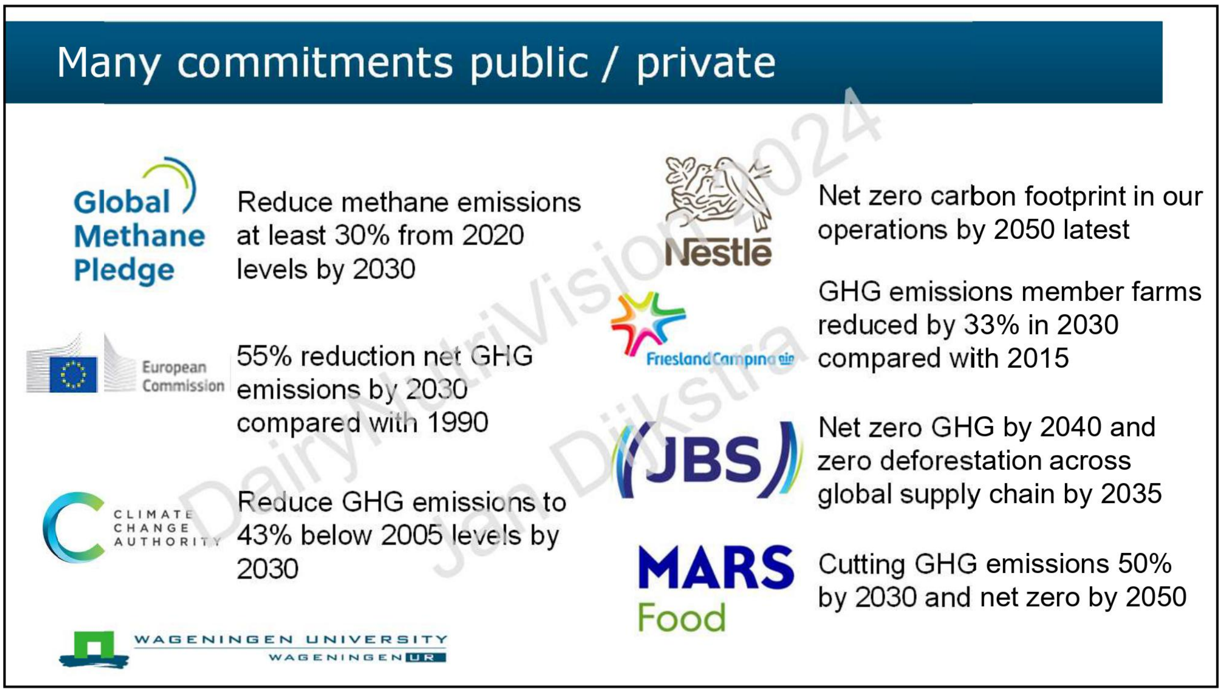
Many commitments public / private
Global Methane Pledge
Reduce methane emissions at least 30% from 2020 levels by 2030
European Commission
55% reduction net GHG emissions by 2030 compared with 1990
CLIMATE CHANGE AUTHORITY
Reduce GHG emissions to 43% below 2005 levels by 2030
Nestlé
Net zero carbon footprint in our operations by 2050 latest
FrieslandCampina
GHG emissions member farms reduced by 33% in 2030 compared with 2015
JBS
Net zero GHG by 2040 and zero deforestation across global supply chain by 2035
MARS Food
Cutting GHG emissions 50% by 2030 and net zero by 2050
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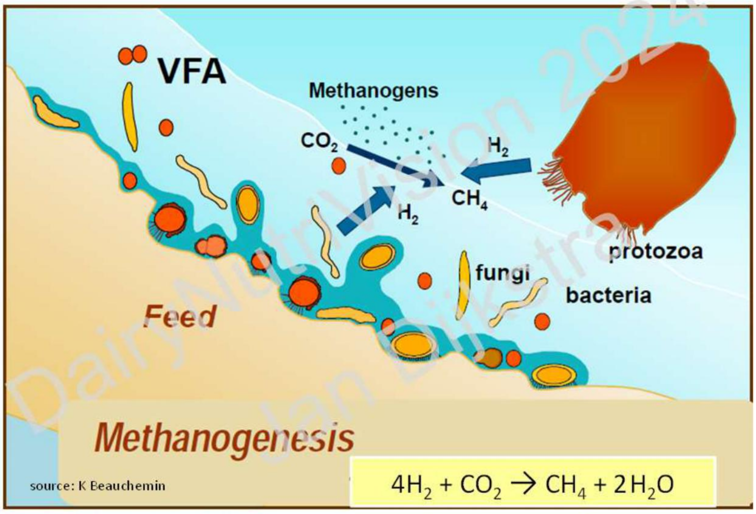
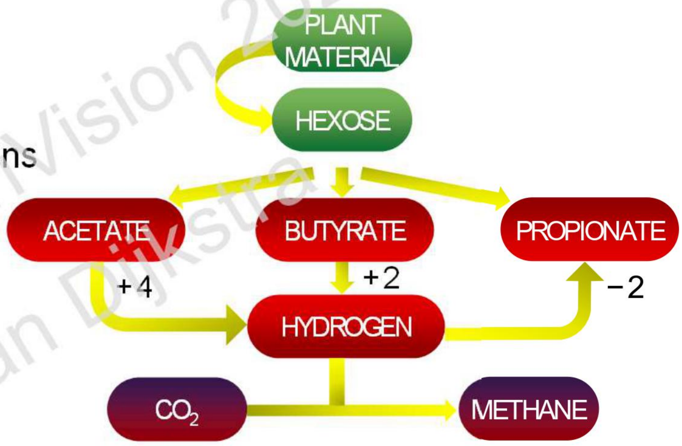
Production of methane



Anti-methanogenic targets

Targets:

- decrease H_2 production
- alternative H_2 sink
- directly inhibit methanogens



Presentation today

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Many methane mitigation strategies not effective

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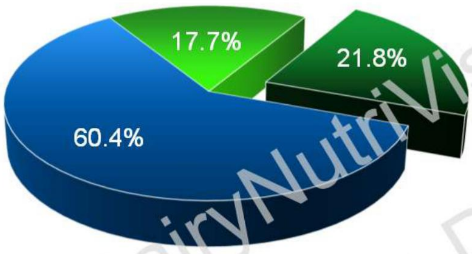
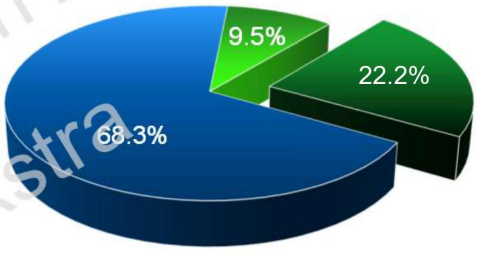
GLOBAL NETWORK PROJECT

Methane yield (g/kg feed DM)
(n = 96)



strategies (% of total)
No effect ■ Effect < 10% ■ Effect > 10%

Methane intensity (g/kg FPC milk)
(n = 63)



strategies (% of total)
No effect ■ Effect < 10% ■ Effect > 10%


PNAS
Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050

meta-analysis
Arndt et al. (2022)

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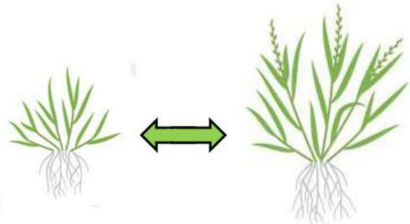
Decreasing grass maturity

- Shifts rumen fermentation and increases production (milk / growth)
- ↑ absolute methane emission (g/head/day): +7% (*1 to 17%*)
- ↓ methane yield (g/kg feed): −4% (*−1 to −8%*)
- ↓ methane intensity (g/kg product): −13% (*−7 to −18%*) (milk)
- Trade-offs:
  - increased nitrogen (N) excretion
  - more intense management



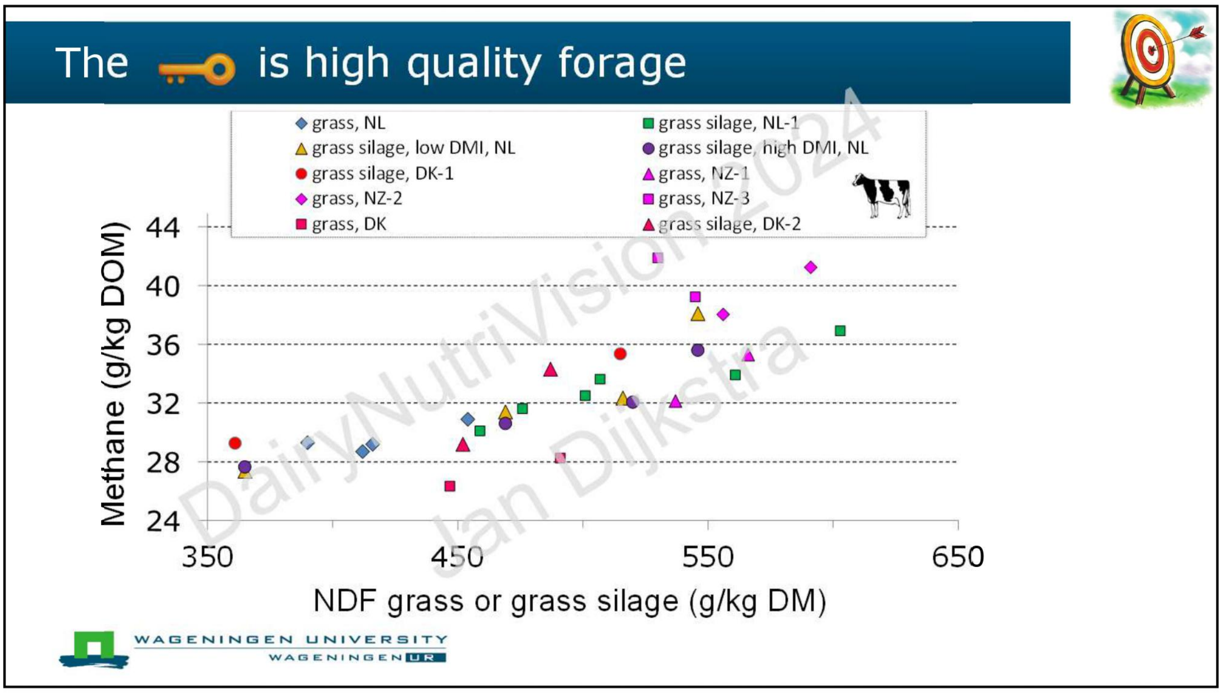
Arndt et al. (2022)

Grass silage: large effect of maturity

	Maturity				*P*-value
	leafy	boot	early hdng	late hdng	
NDF (g/kg DM)	365	469	518	546	-
NE_L (MJ/kg DM)	6.86	6.58	6.18	5.84	-
OM digestibility (%)	77.7	78.2	74.3	68.5	<0.01
FPCM (kg/d)	29.9	27.8	26.6	26.4	0.02
CH_4 (g/d)	308	353	357	345	<0.01
CH_4 (g/kg DM)	19.5	22.0	22.0	23.6	<0.01
CH_4 (g/kg digestible OM)	27.5	30.9	32.2	36.8	<0.01
CH_4 (g/kg FPCM)	10.7	12.8	13.5	13.8	<0.01

grass silage 70% of diet (DM basis); cows 96 DIM

Warner et al. (2017)


The [key] is high quality forage
grass, NL
grass silage, low DMI, NL
grass silage, DK-1
grass, NZ-2
grass, DK
grass silage, NL-1
grass silage, high DMI, NL
grass, NZ-1
grass, NZ-3
grass silage, DK-2
Methane (g/kg DOM)
24
28
32
36
40
44
350
450
550
650
NDF grass or grass silage (g/kg DM)
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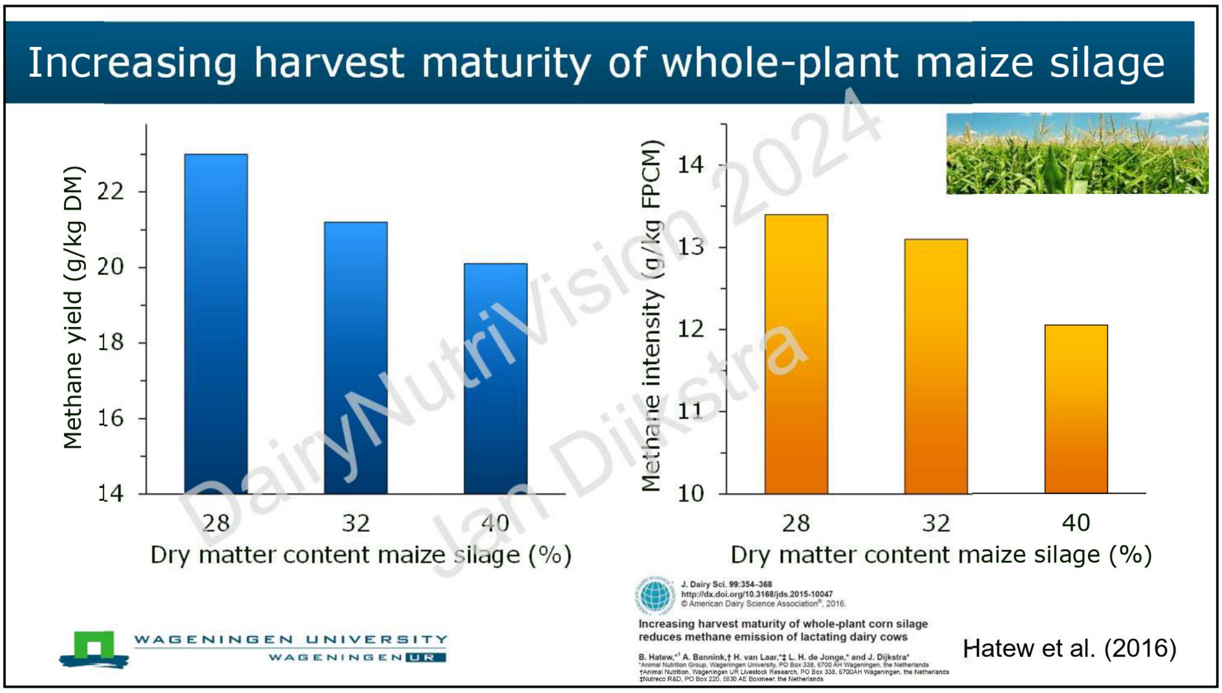
Increasing harvest maturity of whole-plant maize silage
Methane yield (g/kg DM)
14
16
18
20
22
28
32
40
Dry matter content maize silage (%)
Methane intensity (g/kg FPCM)
10
11
12
13
14
28
32
40
Dry matter content maize silage (%)
J. Dairy Sci. 99:354–368
http://dx.doi.org/10.3168/jds.2015-10047
© American Dairy Science Association®, 2016.
Increasing harvest maturity of whole-plant corn silage reduces methane emission of lactating dairy cows
Hatew et al. (2016)
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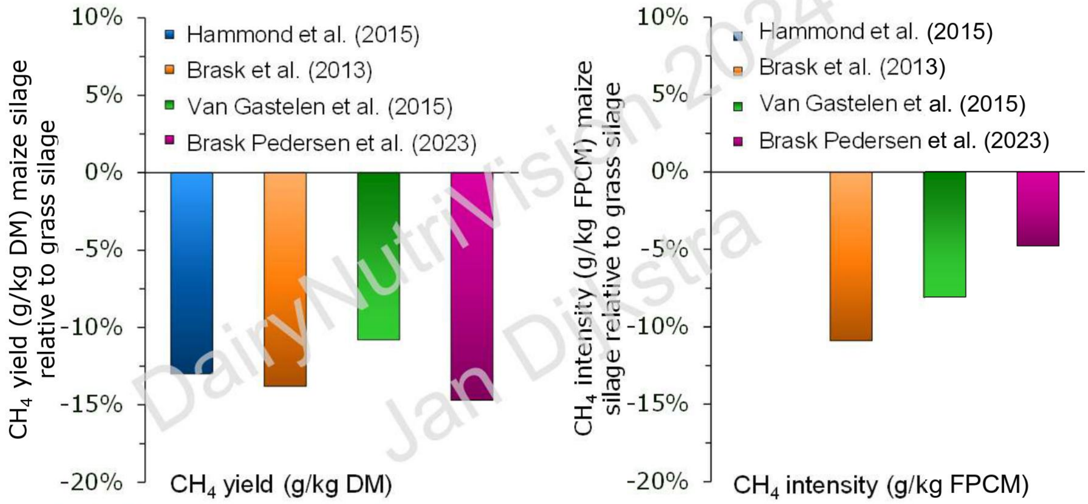
Replacing grass silage with maize silage decreases CH_4



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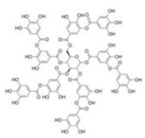
Inclusion of tanniferous forages

- Tannins are plant secondary compounds rich in phenols
  - inhibit rumen methanogens and protozoa; shift rumen fermentation
- ↓ absolute methane emission (g/head/day): −12% (*−6 to −17%*)
- ↓ methane yield (g/kg feed): −10% (*−6 to −14%*)
- ↓ methane intensity (g/kg product): −18% (*−8 to −26%*) (milk)



- Promising species include bushclover, birdsfoot trefoil, Leucaena
- Commercial tannin extracts available

- Trade-offs: decreased protein and fibre digestibility; shift urinary to faecal N; astringency with extracts

Arndt et al. (2022)

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Inclusion of oilseeds / oils and fats

- High energy; inhibit rumen methanogens; shift rumen fermentation
- ↓ absolute methane emission (g/head/day): −20% (*−15 to −24%*)
- ↓ methane yield (g/kg feed): −15% (*−11 to −18%*)
- ↓ methane intensity (g/kg product): −22% (*−8 to −35%*) (growth)
- ↓ methane intensity (g/kg product): −12% (*−6 to −18%*) (milk)

(values presented for oilseeds; values for oils and fats comparable)

Trade-offs:

- limited inclusion; too high levels negative impact rumen fermentation
- may decrease weight gain
- significant increase upstream GHG emissions

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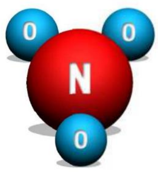
Arndt et al. (2022)

Nitrate *(SilvAir – Cargill)*



$$4H_2 + 2H^+ + NO_3^- \rightarrow NH_4^+ + 3H_2O$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Dose-dependent methane reduction

Example: 1% nitrate, 8% less methane; 2% nitrate, 16% less methane

Feng et al. (2020)

Trade-offs nitrate

- adds nitrogen to diet
- if unadapted: methemoglobinemia
- high levels: DMI ↓

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Essential oil blends

- Volatile aromatic compounds from herbs and spices
  - e.g. allicin from garlic; cinnamaldehyde from cinnamon
  - bind to protein; shift rumen fermentation
- Promising results in vitro
- Meta-analysis Agolin: methane yield reduction 13% (Belanche et al. 2020)
  - effect more pronounced in long term studies (2% in studies <4 wk)
  - majority studies in vitro or not published

	CON	AGOLIN	P-value
Carrasco et al. (2020)	24.1	24.5	NS
Bach et al. (2023)	20.1	17.6	<0.01
Silvestre et al. (2023)	14.1	14.2	NS

Essential oil blends

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  - e.g. allicin from garlic; cinnamaldehyde from cinnamon
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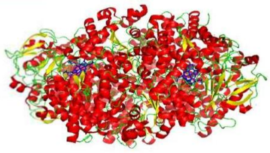
  - effect more pronounced in long term studies (2% in studies <4 wk)
  - majority studies in vitro or not published
- Trade-offs
  - may decrease growth rate but increase milk production

3-nitrooxypropanol (3NOP) (*Bovaer*)

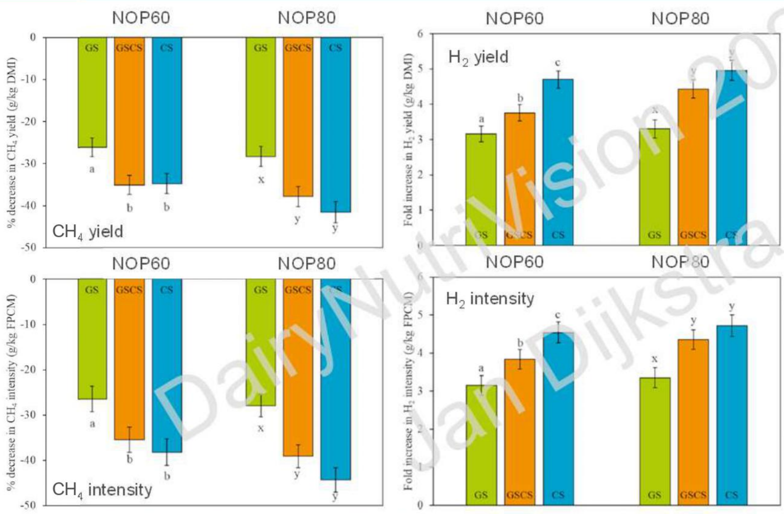
- Methyl-coenzyme M reductase (MCR) is defining reaction of methanogens
  - 3-nitrooxypropanol (3NOP) inhibits MCR activity



Methyl-coenzyme M   3-Nitrooxypropanol

- Major effects CH_4 emission in cattle
  - large variation in response to 3NOP: −84% to +7% compared with control

Impact dose 3-nitrooxypropanol and diet



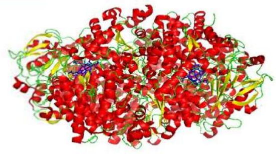
Dairy cattle 146 DIM
3NOP 60 or 80 mg/kg DM

- GS: 70% grass silage
- GSCS: 42% grass silage, 28% corn silage
- CS: 14% grass silage, 56% corn silage

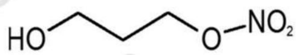
Van Gastelen et al. (2022)

3-nitrooxypropanol (3NOP) (*Bovaer*)

- Methyl-coenzyme M reductase (MCR) is defining reaction of methanogens
  - 3-nitrooxypropanol (3NOP) inhibits MCR activity



Methyl-coenzyme M



3-Nitrooxypropanol

- Major effects CH_4 emission in cattle
  - large variation in response to 3NOP: −84% to +7% compared with control
- Target dose 60 to 90 mg/kg DM (EFSA) ~ 20 to 40% less methane
- ↓ feed intake/performance at high inclusion levels

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Seaweed / seaweed extracts

- Several bioactive compounds
  - non-halogenated (phlorotannins, saponins, alkaloids, ...)
  - halogenated (bromoform, chloroform, iodoform, ...) Abbott et al. (2021)
- Promising methane mitigation results in vitro
- Cattle experiments: no methane decrease (e.g., Antaya et al. 2019; Muizelaar et al. 2023; Thorsteinsson et al. 2023)
- Health benefits: improved fertility, reduced incidence ketosis
- Presence inorganic elements / heavy metals
  - iodine, arsenic, cadmium, bromine

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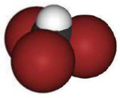
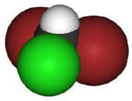
Halogenated compounds seaweeds

- Red seaweed (*Asparagopsis*) inhibits 2nd to last step methanogenesis
  - active compounds bromoform and dibromochloromethane





- Major effects methane emission in cattle
  - large variation in response to *Asparagopsis*: 0 to 99% compared with control
- Dose-dependent methane mitigating effect
- More methane inhibition, more performance impact

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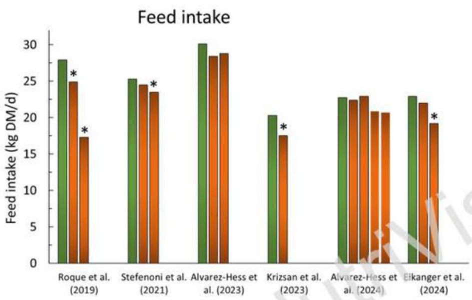
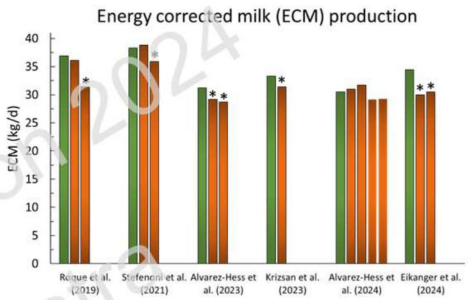
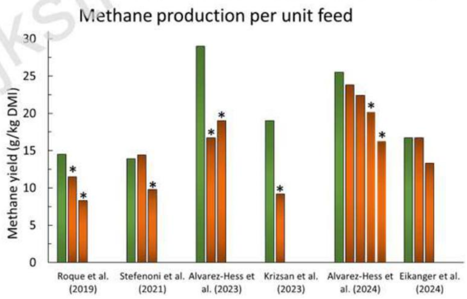
Halogenated compounds seaweeds: dairy





Control
Asparagopsis

* Significant difference with control ($P < 0.05$)



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Halogenated compounds seaweeds

- may ↓ performance dairy cattle / ↑ feed efficiency beef cattle
- bromoform possible human / animal carcinogen
- bromoform contributes to atmospheric ozone depletion
- rumen wall damage
  Li et al. 2018; Sena et al. 2024; Muizelaar et al. 2021
- undesired product changes (Stefenoni et al. 2021; Krizsan et al. 2023)
  - milk iodine content ↑ 5 to 15-fold
  - milk bromine content ↑ 8-fold

Current research development: pharmaceutical products

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  - milk t ↑
  - milk ent

Current re opm utical products

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Reflections on anti-methanogenic feed additives

- Several strategies great potential / readily applied
- Methane inhibitors usually do not improve animal performance
  - requires (government) policies / incentives
- Consumer acceptance of anti-methanogenic additives
  - even when approved by authorities (e.g. EFSA)
- Most promising additives not effective in grazing / mixed systems
  - research in progress on slow-release type additives
- Virtually no data on combinations of strategies

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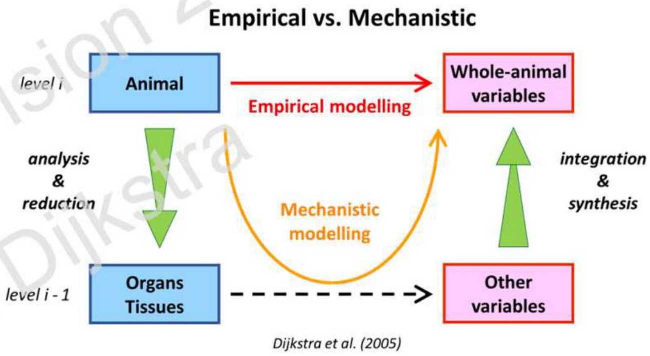
Not all models are cut from the same cloth

Empirical models

- data used directly to quantify relationships
- without preconceived biological theory

Mechanistic models

- seek to understand causation
- describe system in terms of components / processes one level lower



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Empirical models enteric methane

- > 50 prediction equations enteric CH_4 cattle
  - national inventories and whole farm/system analyses
  - includes IPCC Tier 2
- Global Network project
  - dairy cattle (Niu et al. 2018 – *Glob Change Biol* 24:3368)
  - beef cattle (Van Lingen et al. 2019 – *Agric Ecosyst Environm* 283:106575)
  - sheep (Belanche et al. 2023)

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Dairy cattle intercontinental database

- Individual cow observations (n = 2,566) Niu et al. (2018)
  - Australia, Europe, US
  - intake, diet composition, body weight, milk production/composition
  - excluded anti-methanogenic feed additives
- Linear mixed models
  - key variables with increasing complexity
  - intercontinental and regional models

$$\mathbf{y} = \beta_0 + \sum \beta_i \mathbf{x}_i + \gamma + \varepsilon$$

Response variable | Global intercept | Fixed effect parameters | Fixed effect variables | Random effect variance | Residual variance

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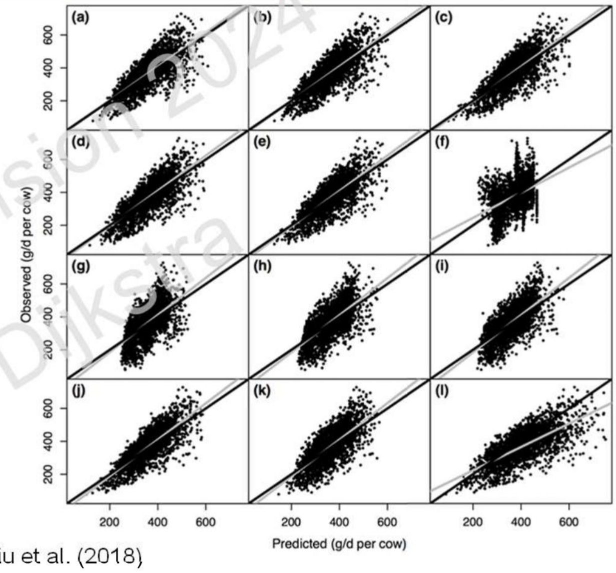
Dairy cattle intercontinental database

MAE (g/d) RSR

MAE: Mean Absolute Error

RSR: ratio of root mean square prediction error to SD of observations



Niu et al. (2018)

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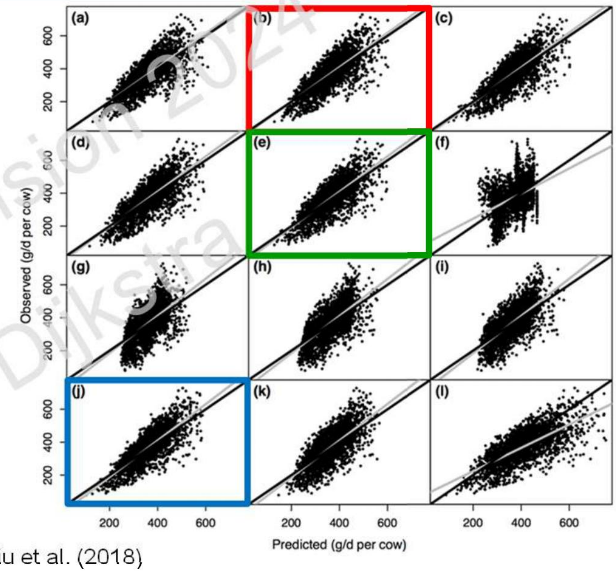
DMI central to predict CH_4 production (g/d)

	MAE (g/d)	RSR
DMI only (red box)	50.3	0.64
DMI + diet (↑*NDF*, ↓*EE*) (green box)	49.2	0.63
DMI + diet + animal (↑*NDF*, ↓*EE*, ↑*MF*, ↑*BW*) (blue box)	47.5	0.61



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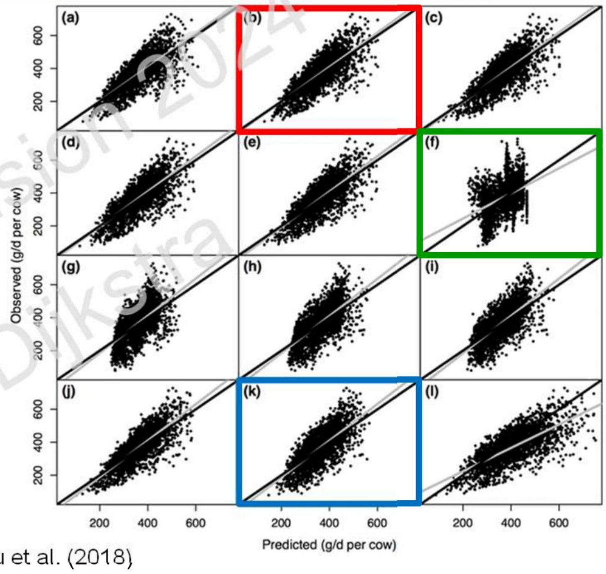
Niu et al. (2018)

DMI central to predict CH_4 production (g/d)

	MAE (g/d)	RSR
DMI only (red box)	50.3	0.64
Diet only (↑*NDF*, ↓*EE*) (green box)	73.2	0.92
Diet + animal only (↑*NDF*, ↓*EE*, ↑*ECM*, ↑*MF*, ↑*MP*, ↑*BW*) (blue box)	55.1	0.69



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Niu et al. (2018)

Separate regional CH_4 (g/d) models required

Models based on gross energy intake (GEI; MJ/d))

		RSR		
		Intercontinental	EUR	US
All	$128 + (0.0391 \times GEI) / 0.05565$	**0.65**	0.70	0.65
EUR	$111 + (0.0425 \times GEI) / 0.05565$	0.70	**0.70**	0.74
US	$131 + (0.0358 \times GEI) / 0.05565$	0.71	0.81	**0.65**

Niu et al. (2018)

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Methane as fraction of gross energy intake

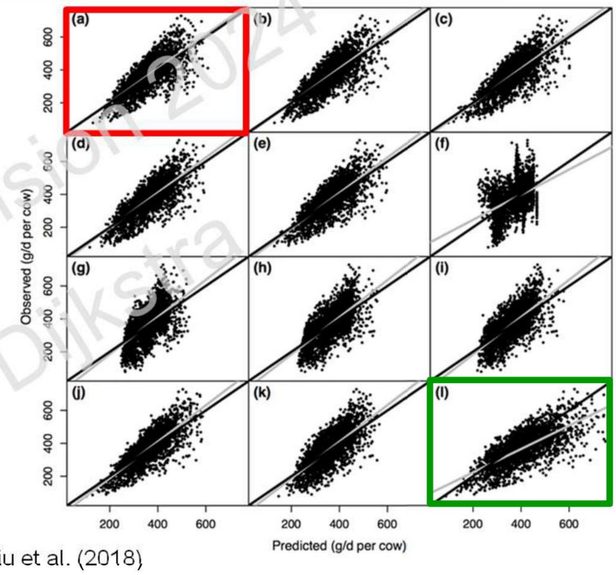
GEI to predict CH_4 production (g/d)

	MAE (g/d)	RSR
	50.9	0.65

IPCC 2006: Y_m = 6.5% of GEI

	64.3	0.84

IPCC 2019: Y_m 5.7% - 6.5% of GEI



Niu et al. (2018)

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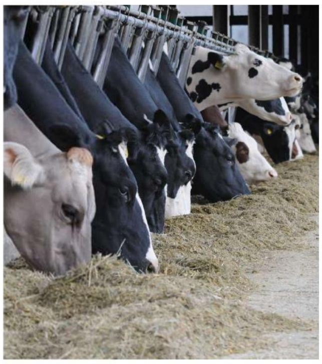
Feed intake not available on farm

- Equations to estimate feed intake required
- IPCC (2019) Tier 2 estimate based on feed digestibility, body weight, milk production and composition
- Applied to Wageningen respiration chamber dataset dairy cattle (n = 205)
  - Y_m 5.7 - 6.3% of GEI



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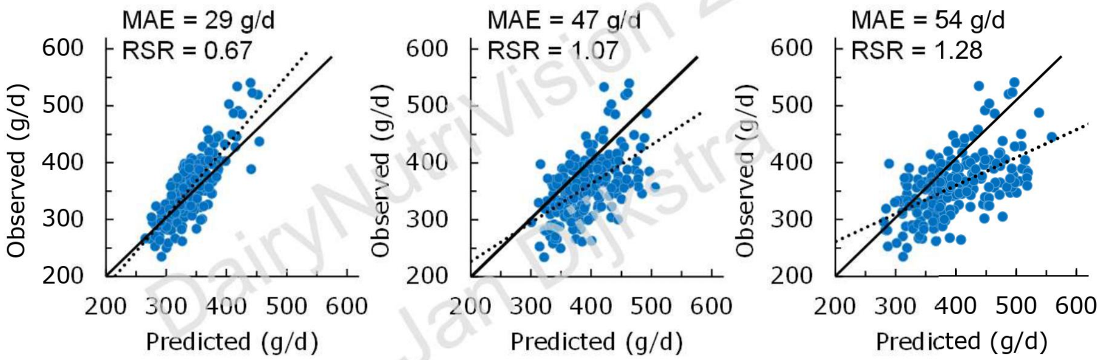
Observed and predicted methane production

Niu et al. (2018) EUR model observed DMI | Niu et al. (2018) EUR model IPCC (2019) predicted DMI | IPCC (2019) Y_m IPCC (2019) predicted DMI



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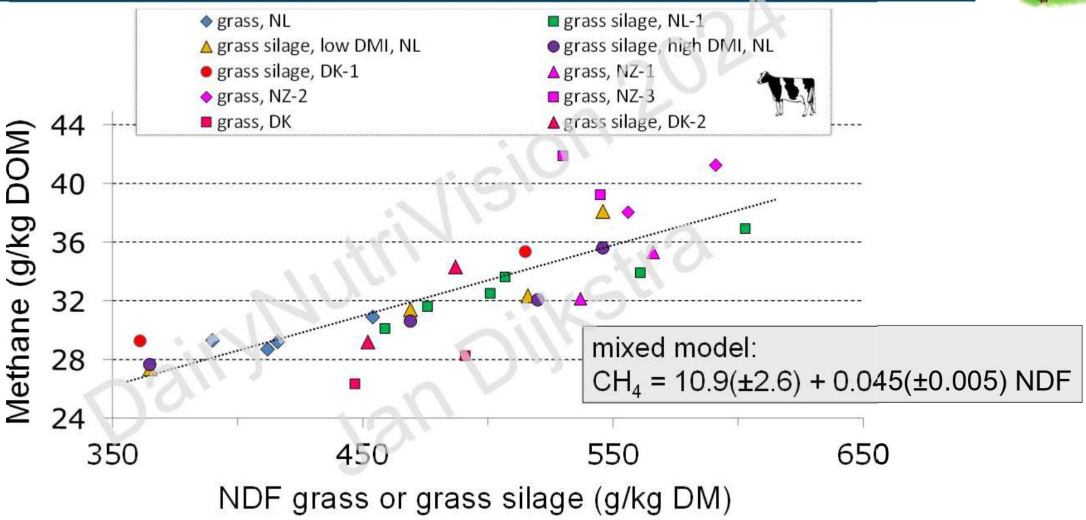
Prediction equations for individual feeds



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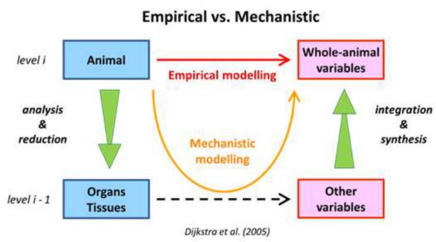
Midpoint recap: empirical models

- Feed intake central to predict CH_4 production
- Separate regional CH_4 models required
- Prediction equations for individual feed variation are helpful



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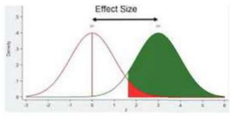
Meta-analyses

- Systematic method aggregating data from several studies
- Enhances statistical power
- Identifies patterns and trends
- Reduces bias and conflicts



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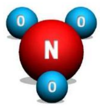
Meta-analysis CH_4 production: nitrate supplementation

	Mean	Effect	SE	P-value	*P*-value type of cattle
Random effect model	Mean difference (% of control)				
Overall effect size		−13.9	1.2	<0.01	

Heterogeneity > 90%



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Feng et al. (2020)

Meta-analysis CH_4 production: nitrate supplementation

	Mean	Effect	SE	*P*-value	*P*-value type of cattle
Random effect model		Mean difference (% of control)			
Overall effect size		−13.9	1.2	<0.01	
Mixed effect model					
dairy cattle	n.a.	−20.4	1.9	<0.01	0.02
beef cattle	n.a.	−10.1	1.5	<0.01	
		Change in mean difference*			
nitrate dose (g/kg DM)	16.7				
DM intake (kg/d)	11.1				

*centered on their means

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Feng et al. (2020)

Meta-analysis CH_4 production: nitrate supplementation

CH_4 reduction in % allows incorporation in GHG accounting tools

	Mean	Effect	SE	*P*-value	*P*-value type of cattle
Random effect model		Mean difference (% of control)			
Overall effect size		−13.9	1.2	<0.01	
			1.9	<0.01	0.02
beef cattle	n.a				
nitrate dose (g/kg DM)	16.7	−0.	0.14	<0.01	
DM intake (kg/d)	11.1	0.69	0.29	0.03	

NO_3 dose enhances mitigating effect by 9.1% for every 10 g NO_3/kg DM increase

DMI decreases mitigating effect by 0.69% for every 1 kg DM/d increase

*centered on their means

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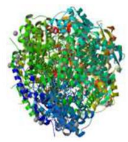
Feng et al. (2020)

Meta-analysis CH_4 production: 3-NOP supplementation

	Mean	Effect	SE	*P*-value
Mixed effect model	Mean difference (% of control)			
Overall effect size		−32.4	1.3	<0.01

Heterogeneity > 90%

3-Nitrooxypropanol



J. Dairy Sci. 106:927–936
https://doi.org/10.3168/jds.2022-22211

A meta-analysis of effects of 3-nitrooxypropanol on methane production, yield, and intensity in dairy cattle

Ermias Kebreab,[1]* André Bannink,[2] Eleanor May Pressman,[1] Nicola Walker,[3] Alexios Karagiannis,[3] Sanne van Gastelen,[2] and Jan Dijkstra[4]
[1]Department of Animal Science, University of California, Davis 95616
[2]Wageningen Livestock Research, Wageningen University & Research, PO Box 338, 6700 AH, Wageningen, the Netherlands
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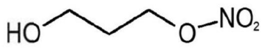
Kebreab et al. (2023)

Meta-analysis CH_4 production: 3-NOP supplementation

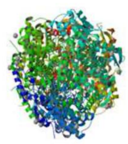
	Mean	Effect	SE	*P*-value
Mixed effect model	Mean difference (% of control)			
Overall effect size		−32.4	1.3	<0.01
	Change in mean difference*			
3-NOP (mg/kg DM)	71	−0.28	0.07	<0.01
NDF (g/kg DM)	329	0[illegible]92	0.034	0.02
Crude fat (g/kg DM)	4[illegible]	[illegible].31	0.13	0.04

*centered on their means

dose-dependent



3-Nitrooxypropanol



[illegible]06:927–936
[illegible]/10.3168/jds.2022-22211
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[illegible]of effects of 3-nitrooxypropanol on methane
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Kebreab et al. (2023)

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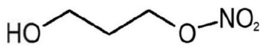
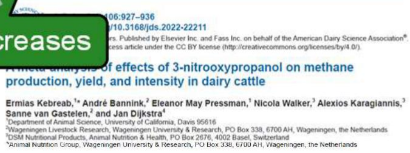
NDF (g/kg DM)	329	0.092	0.034	0.02
Crude fat (g/kg DM)	42	0.31	0.13	0.04

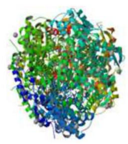


3-Nitrooxypropanol

*centered on their means

lower efficacy when fibre content increases





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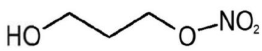
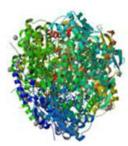


3-Nitrooxypropanol

*centered on their means

lower efficacy when fat content increases



Kebreab et al. (2023)

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Midpoint recap: empirical models

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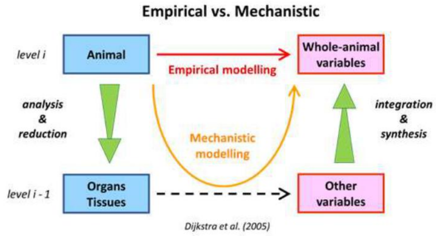
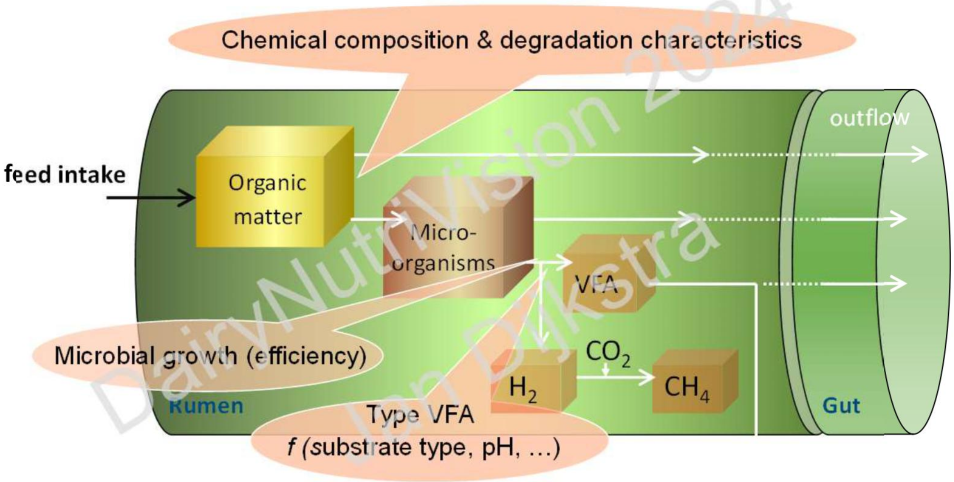
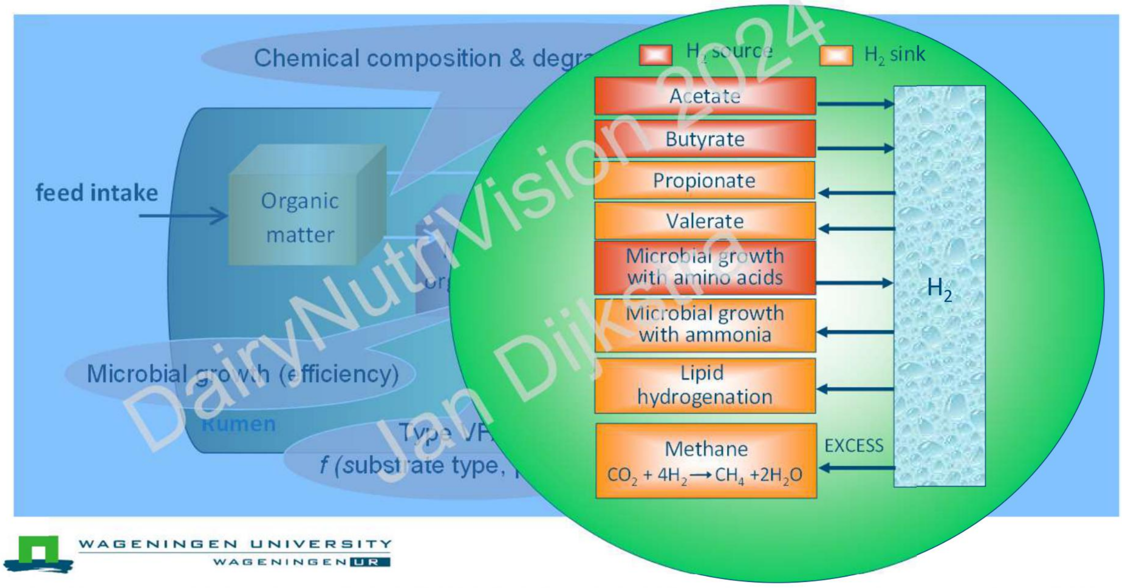
- Meta-analysis CH_4 reduction in % of control useful in accounting tools



Mechanistic models enteric methane

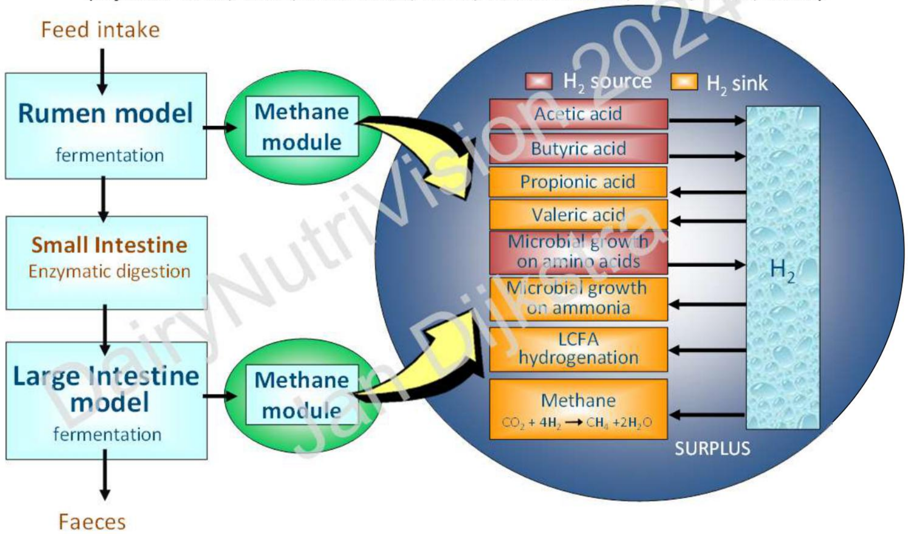


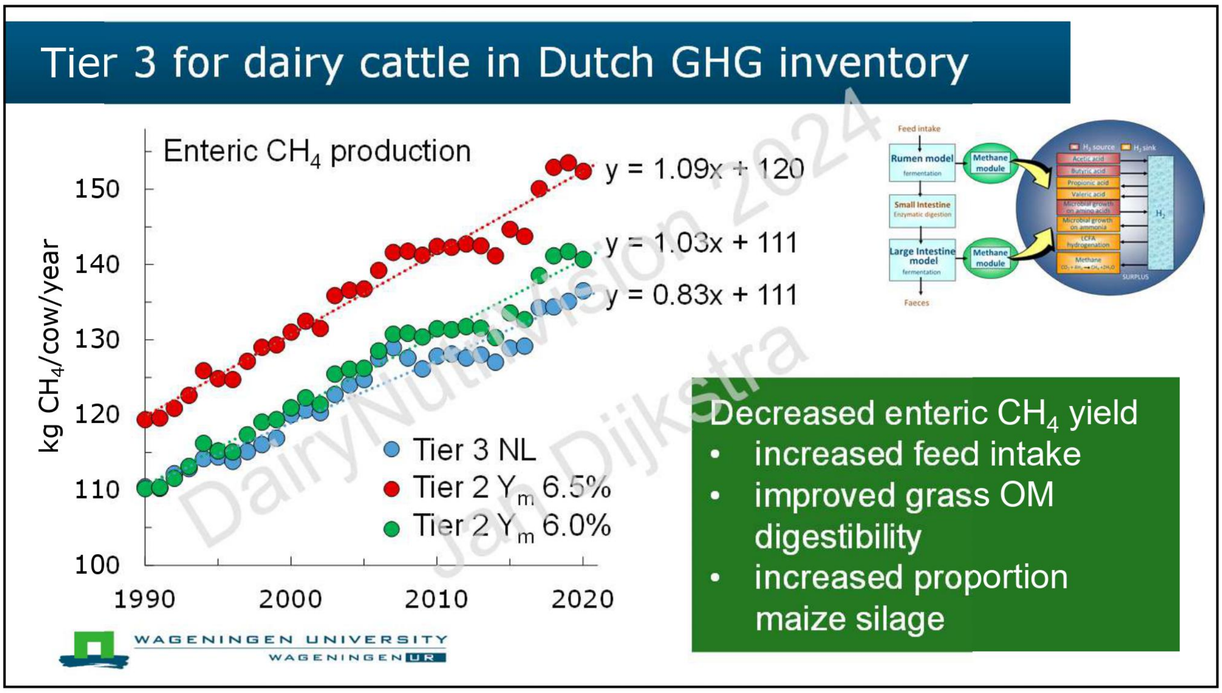
Mechanistic models enteric methane



Mechanistic model – Tier 3 for dairy cattle

(Dijkstra et al., 1992; Mills et al., 2001; Bannink et al., 2008; 2011, 2020)




Tier 3 for dairy cattle in Dutch GHG inventory
Enteric CH4 production
kg CH4/cow/year
150
140
130
120
110
100
1990
2000
2010
2020
y = 1.09x + 120
y = 1.03x + 111
y = 0.83x + 111
Tier 3 NL
Tier 2 Ym 6.5%
Tier 2 Ym 6.0%
Decreased enteric CH4 yield
• increased feed intake
• improved grass OM digestibility
• increased proportion maize silage
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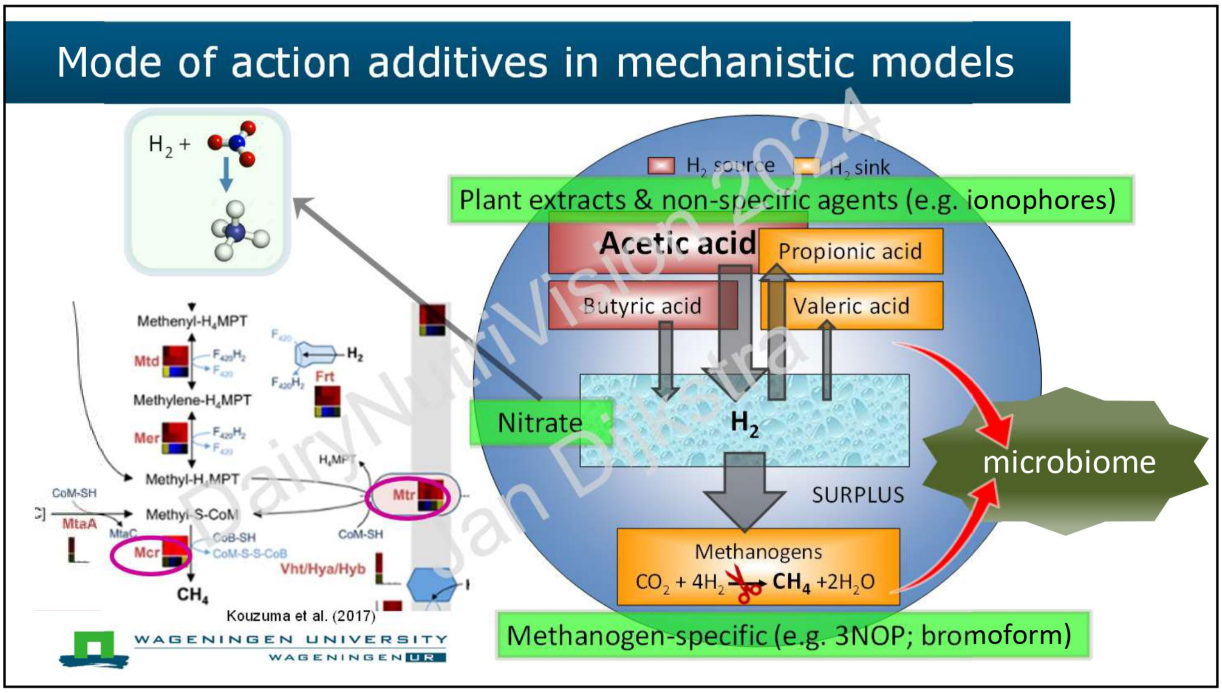
Mode of action additives in mechanistic models
H2 source
H2 sink
Plant extracts & non-specific agents (e.g. ionophores)
Acetic acid
Propionic acid
Butyric acid
Valeric acid
Nitrate
H2
SURPLUS
microbiome
Methanogens
CO2 + 4H2 → CH4 +2H2O
Methanogen-specific (e.g. 3NOP; bromoform)
Methenyl-H4MPT
Methylene-H4MPT
Methyl-H4MPT
Methyl-S-CoM
CH4
Mtd
Mer
Mtr
Mcr
Frt
Vht/Hya/Hyb
Kouzuma et al. (2017)
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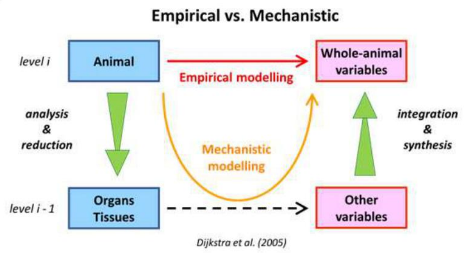
Summary: mechanistic models enteric methane

- Feed intake central to predict CH_4 production
- Integrate knowledge and help understand responses
- Evaluate consequences of policies aimed at reducing enteric CH_4 production



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Conclusions on methane emission

- No / limited effectiveness of many mitigation strategies
- Several strategies high potential / readily applied
  - forage type/quality; anti-methanogenic feed additives
- Implementation requires (government) policies / incentives
- Quantification of variation in efficacy is vital
  - based on solid scientific evidence

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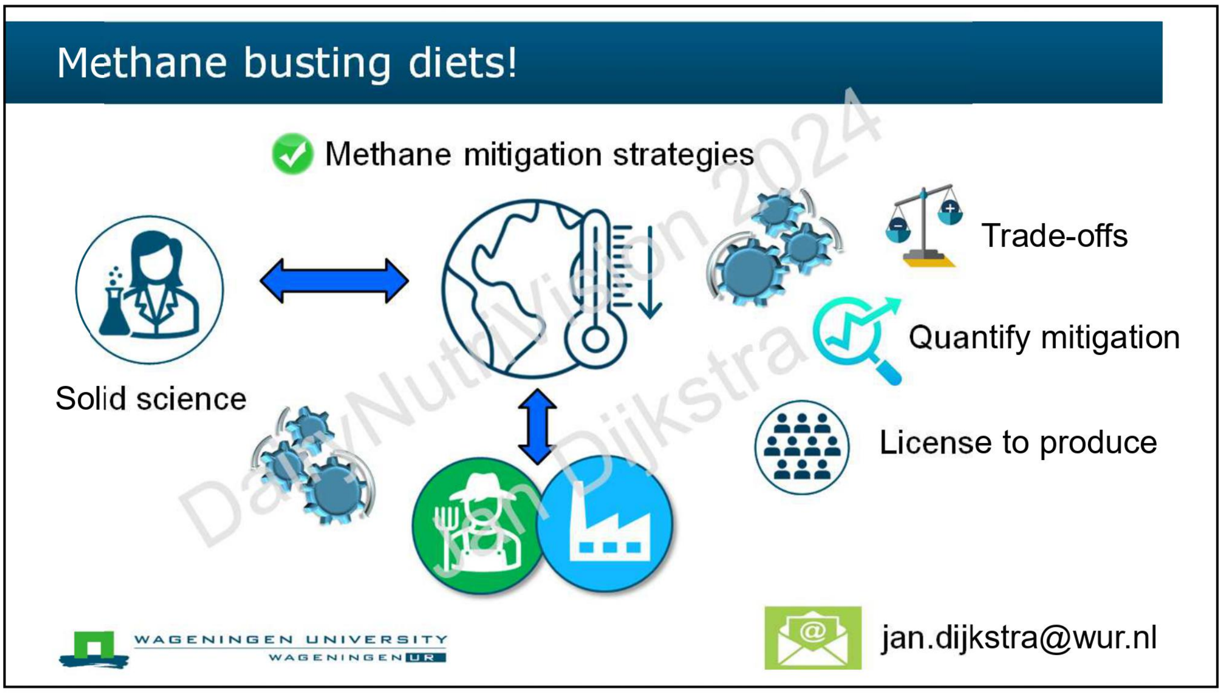
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Methane mitigation strategies
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