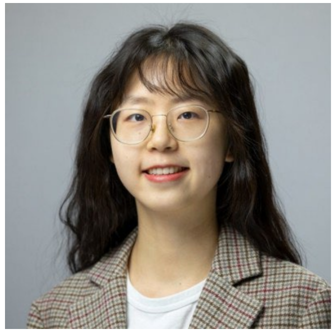
Enhancing Agricultural Sustainability



An Optimization Model for Crop Rotation and Diet Formulation in Dairy Farms under European Union Common Agricultural Policy (EU CAP)

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Crop Rotation

- Enhanced soil fertility
- Improved crop yield
- Pest and weed management
- Pollution reduction
- Biodiversity conservation

(Nadeem et al., 2019)

Home-grown Feeds

Table 5
Production practices on dairy farms, 2016

	Farm production practices			
	Hired share of labor	Purchased share of feed	Farms that purchase all feed	Farms that do not graze cows
	Percent of expenses		Percent of farms	
All farms	22.7	53.6	3.1	47.0
All cows	67.1	70.6	13.7	80.0

(USDA, 2020)

“At least 71% of the EU’s farmland is used to feed livestock, according to new research published by Greenpeace. Around 63% of arable land is dedicated to feeding farm animals.”

(ERPS, 2023)

A Unique Challenge for Dairy Farmers

What is the best way for dairy farmers to use their croplands to feed their cows while implementing crop rotation practices?

Crop Production

Single/double cropping
Crop rotation
Crop production cost & yield
Cash crop or save for animals

Feed Storage

Storage limitation

Diet Formulation

Nutrient adequate
Least cost
Enteric methane emissions

Converting Practical Challenge to Optimization Problem

What is the best way for dairy farmers to use their croplands and feed their cows under the crop rotation regulations?

- Fulfil crop rotation regulations
- Fulfil animal nutritional requirements

} Constraints

- Net revenue

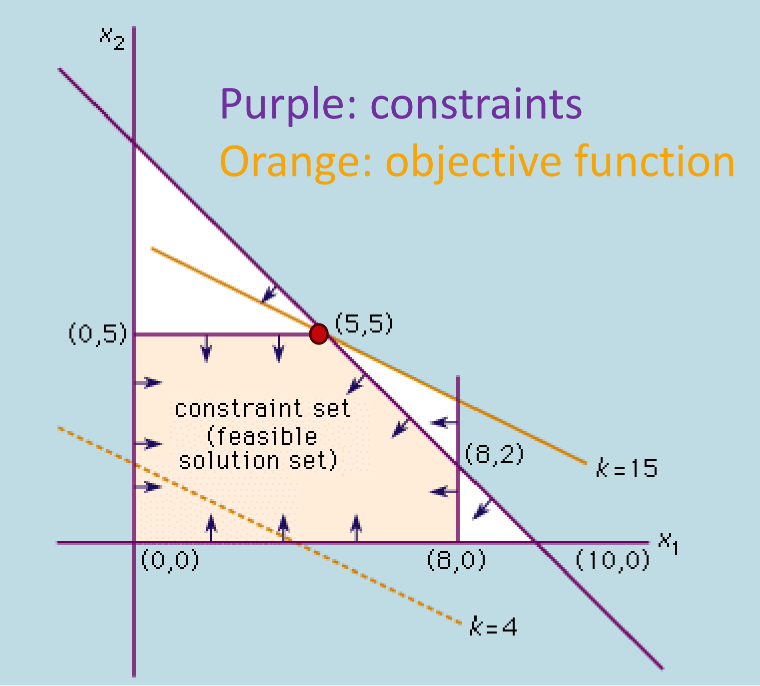
$$\uparrow\ Net\ revenue = milk\ income + cash\ crop\ income - crop\ production\ cost - market\ feed\ cost$$

- Enteric methane emissions

$$\downarrow\ Methane = 4.41 + 0.0224 * ME + 0.98 * NDF$$

(Ellis et al., 2007)

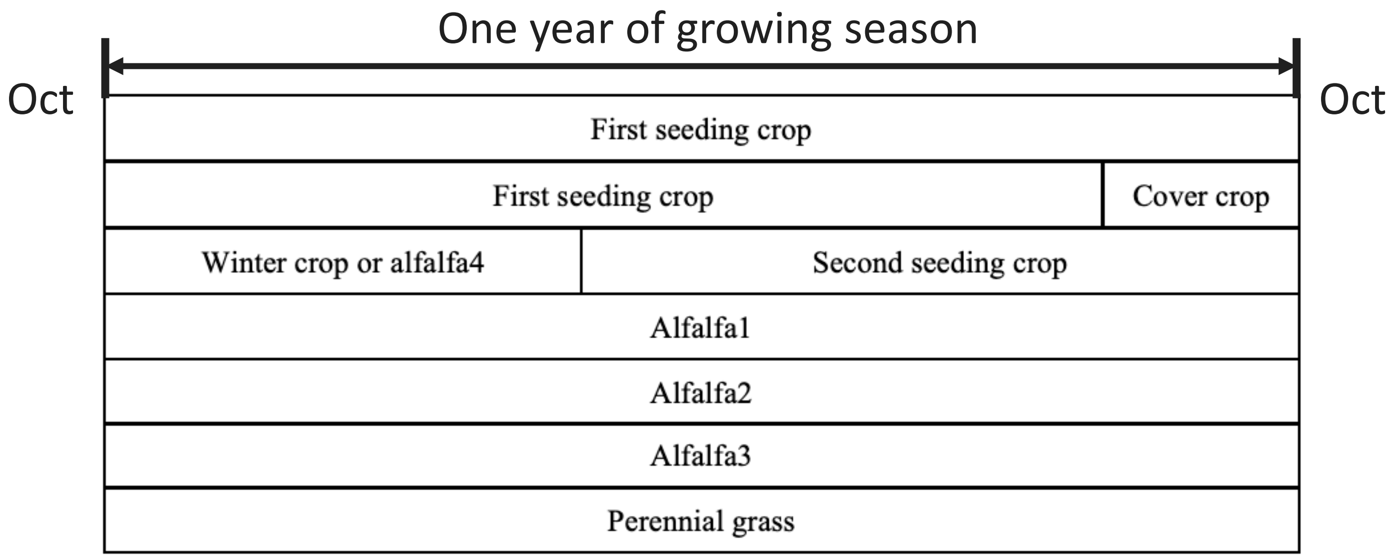
} Objective functions



GAMS

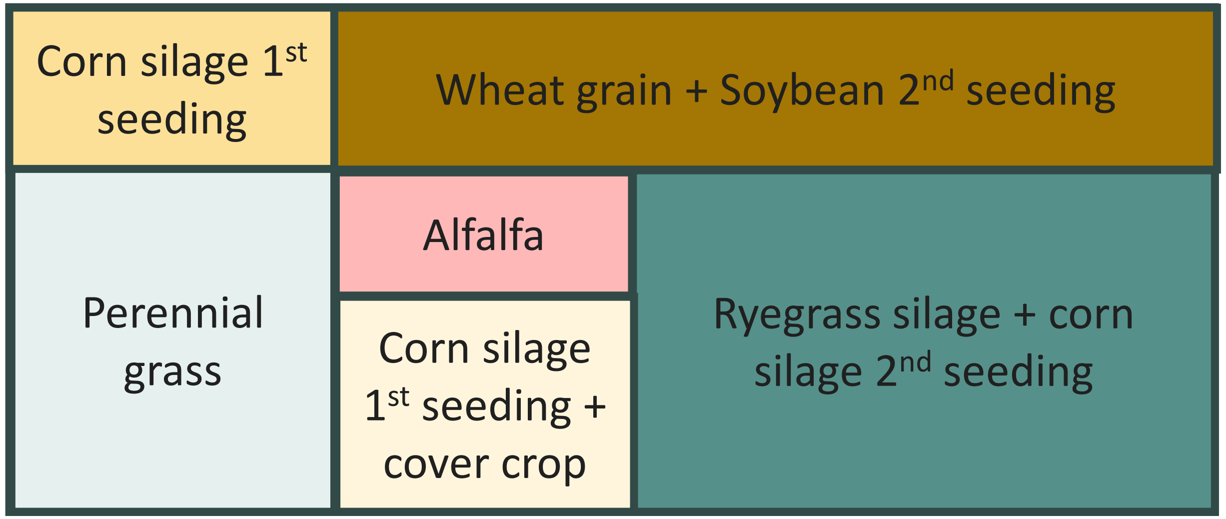
Crop Planning Part - Crops

- 33 crop types (9 winter crops, 12 first seeding crops, 6 second seeding crops, 5 perennial crops, and 1 cover crop)
  - 88 possible crop configurations within one year of growing season



Crop Planning Part - Fields

- Fields have various sizes
- All fields are assumed to be uniform
- Each field can accommodate at most one crop configuration each year



Crop Planning Part - Rotation

- Perennial grass grow rule
  - “Permanent” grassland
  - Which fields are grassland are given as an input
- Alfalfa grow rule & rotation rule
  - Alfalfa grow for 3.5 yr (alfalfa1 grows to alfalfa2, grows to alfalfa3, grows to alfalfa4)
  - After the termination of alfalfa, it cannot be grown again in the same field for at least 2 years
- General rotation rule
  - Crops with the same species cannot be continuously grown

Year1		Year2		
Corn silage 1^{st} seeding		Corn silage/snaplage/grain 1^{st} seeding		✗
Corn silage 1^{st} seeding	Cover crop	Corn silage/snaplage/grain 1^{st} seeding		✓
Ryegrass silage	Corn silage 2^{nd}	Corn silage/snaplage/grain 1^{st} seeding		✗
Ryegrass silage	Corn silage 2^{nd}	Ryegrass silage	Corn silage 2^{nd}	✓

Diet Formulation

- Animal diets (home-grown + purchased) need to meet the Dry Matter Intake (**DMI**) and nutritional requirements for 11 animal groups

$$DMI_a min \leq DMI_{t,a} \leq DMI_a max,$$

$$Nutrient_a min \leq Nutrient_{t,a} \leq Nutrient_a max,$$

where a: animal group,
t: year

$Nutrient$ is either Energy for Lactation (**NEL**), Crude Protein (**CP**), Neutral Detergent Fiber (**NDF**), **starch**, and **fat**

(NASEM,2021)

TABLE 21-1 Predicted Nutrient Concentrations (DM Basis) Needed to Meet the Nutrient Requirements for Holstein Cattle at Varying Stages of Lactation and Ages of Maturity

	Growing Calves and Heifers						Dry Cows		Lactating Cows by Parity (Body Weight) and Days in Milk[a]					
							Days Prepartum			First (570 kg)		Mature (700 kg)		
									Days-in-Milk	15	150	20	100	200
Age, days	30	100	225	350	475	600	60–21d1	<21d	Milk, kg	33	39	53	55	43
BW, kg	65	120	230	330	420	530	740	740	Fat %	3.9	3.6	3.7	3.5	3.8
Growth Rate, kg/d	0.7	0.7	0.9	0.8	0.7	0.9	0.0	0.0	Protein %	3.1	3.0	2.8	2.8	3.3
Dry matter intake, kg/d	1.4	3.9	6.6	8.5	9.8	11.0	13.9	13.0		20.8	23.9	25.8	29.4	27.4
ME, Mcal/kg	3.68	2.26	2.09	1.95	1.92	2.12	1.93	1.89		2.39	2.61	2.58	2.73	2.60
NE_L, Mcal/kg	—	—	—	—	—	—	1.28	1.28		1.51	1.72	1.61	1.80	1.73
Rumen-degraded protein, %	—	10.0	10.0	10.0	10.0	10.0	10.0	10.0		10.0	10.0	10.0	10.0	10.0
Rumen-undegraded protein, %	—	6.6	4.4	2.6	1.7	2.7	1.9	3.6		6.2	7.0	7.5	7.4	7.5
Crude protein, %	21.0	16.6	14.4	12.6	11.7	12.7	11.9	13.6		16.2	16.0	17.5	17.4	17.5
Metabolizable protein, %	16.5	9.5	8.1	6.8	6.1	14.0	5.2	6.2		9.9	9.8	10.8	10.7	10.8
Net protein, %	10.7	5.1	4.4	3.9	3.6	10.7	3.6	4.2		6.7	6.7	7.4	7.3	7.3
NDF, min %	—	25–33	25–33	25–33	25–33	25–33	25–33	25–33		25–33	25–33	25–33	25–33	25–33
Forage NDF, min %	—	19–25	19–25	19–25	19–25	19–25	19–25	19–25		19–25	19–25	19–25	19–25	19–25
Starch max, % (varies)	—	15–20	15–20	15–20	15–20	15–20	15–20	15–20		22–30	22–30	22–30	22–30	22–30

Three Policies to Mitigate Methane Emissions

- BASELINE

$$\begin{aligned} \mathit{Maximize\ Net\ revenue} &= \mathit{milk\ income} + \mathit{cash\ crop\ income} \\ &\quad - \mathit{crop\ production\ cost} - \mathit{market\ feed\ cost} \end{aligned}$$

- 1. **MULTI**: multi-objective

$$\mathit{Maximize}\ \alpha * \mathit{net\ revenue}' + (1-\alpha) * \mathit{methane}',$$

where α is weighting factor within the range [0, 1]

- 2. **TAX**: applying taxation on methane emissions

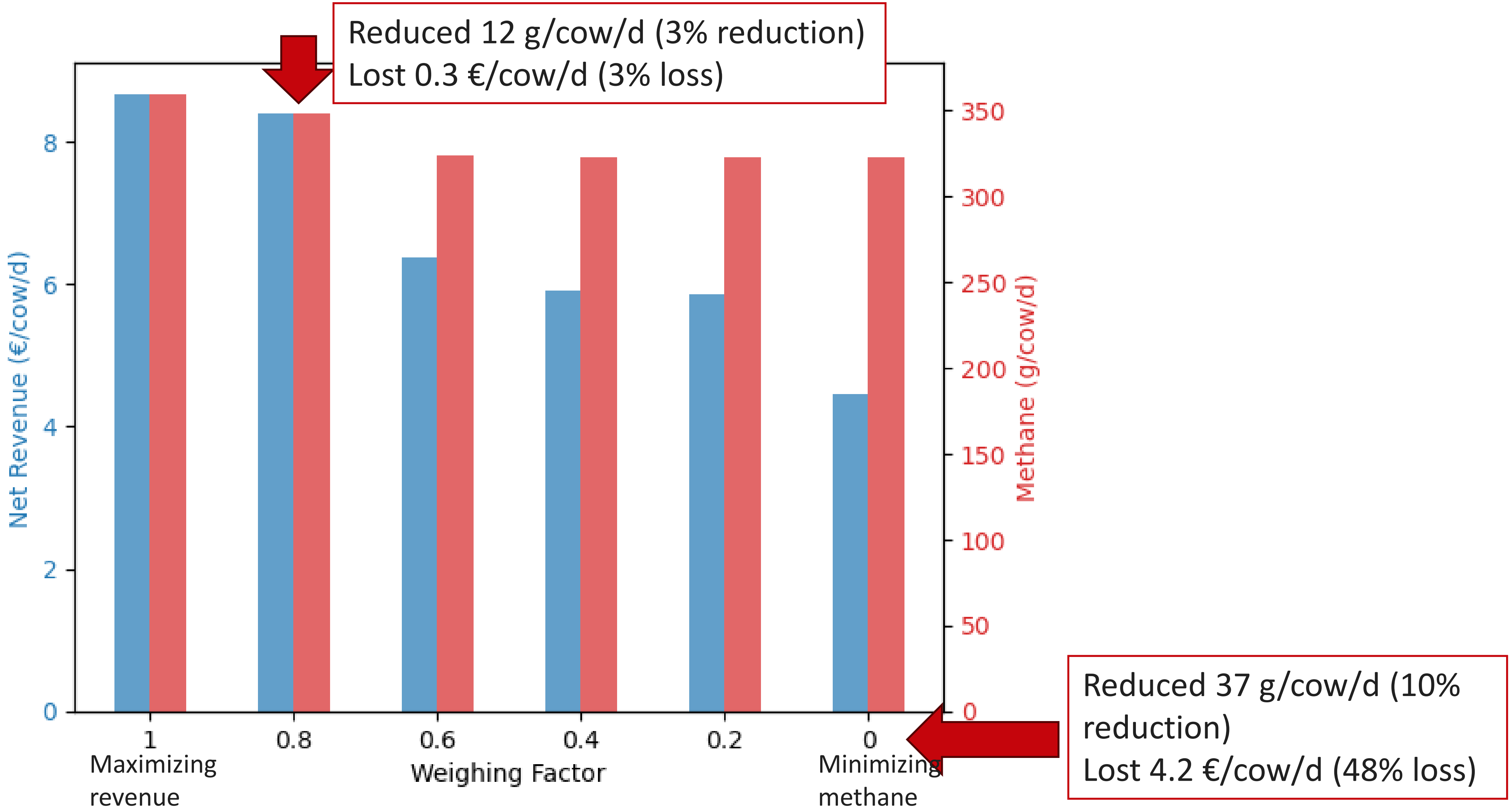
$$\begin{aligned} \mathit{Maximize\ Net\ revenue} &= \mathit{milk\ income} + \mathit{cash\ crop\ income} \\ &\quad - \mathit{crop\ production\ cost} - \mathit{market\ feed\ cost} - \mathit{tax\ cost} \end{aligned}$$

- 3. **RED**: explicit reduction percentage (1%, 2%, … max%)

Case Study Farm

- a North Italian dairy farm
- 300 ha. (45 fields)
- 1007 animals (478 lactating cows)
- Milk price: 38.4 €/100kg
- Crop rotation for 5 years

Results – MULTI (Revenue vs. Methane)

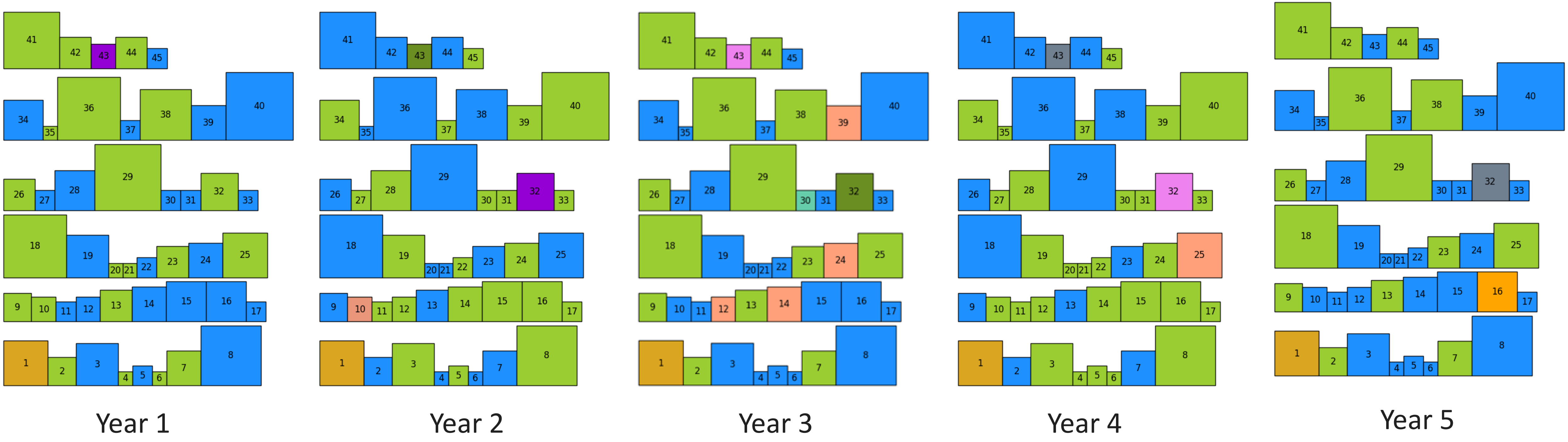


Results – MULTI (Crop Plan)

Weighting factor = 1 (only maximizing net revenue)

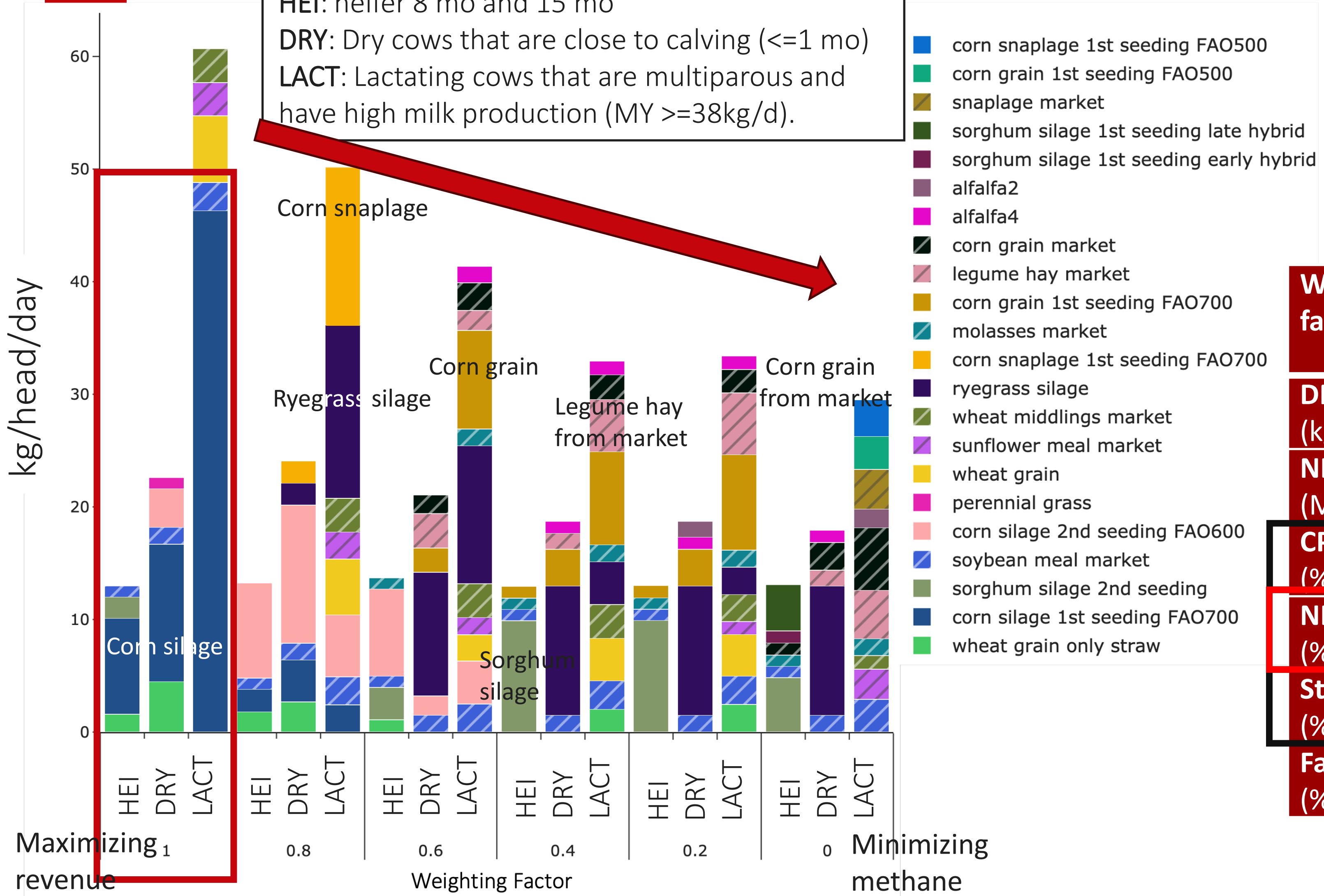
Crop configuration

- perennial grass
- corn silage 1st seeding FAO700
- wheat grain and straw + soybean grain 2nd seeding
- alfalfa1
- ryegrass silage + corn silage 2nd seeding FAO600
- alfalfa2
- wheat grain and straw + sorghum silage 2nd seeding
- wheat hay + soybean grain 2nd seeding
- alfalfa3
- alfalfa4 + corn silage 2nd seeding FAO600
- wheat hay + corn silage 2nd seeding FAO600



Results – MULTI (Animal Diets)

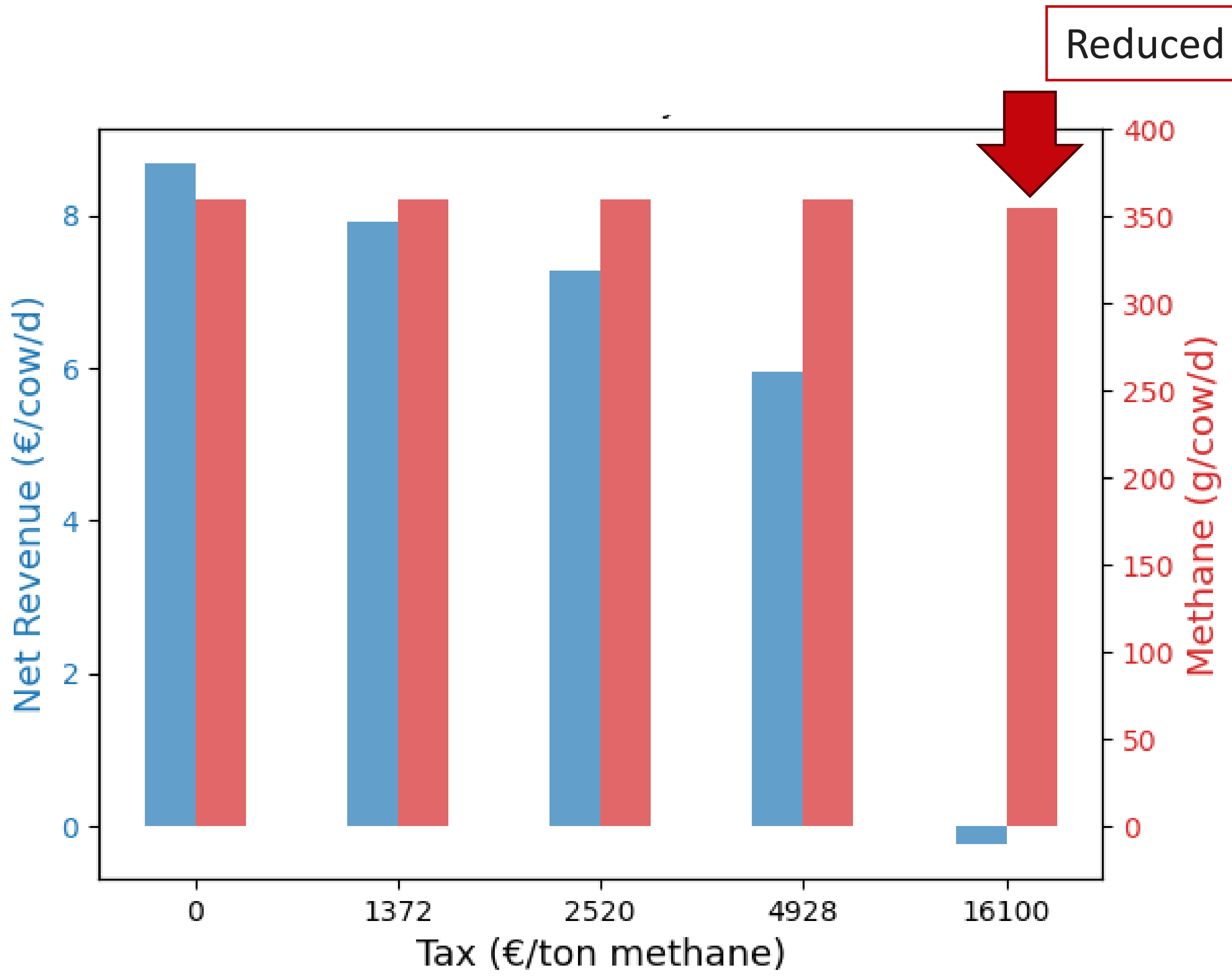
HEI: heifer 8 mo and 15 mo
DRY: Dry cows that are close to calving (<=1 mo)
LACT: Lactating cows that are multiparous and have high milk production (MY >=38kg/d).



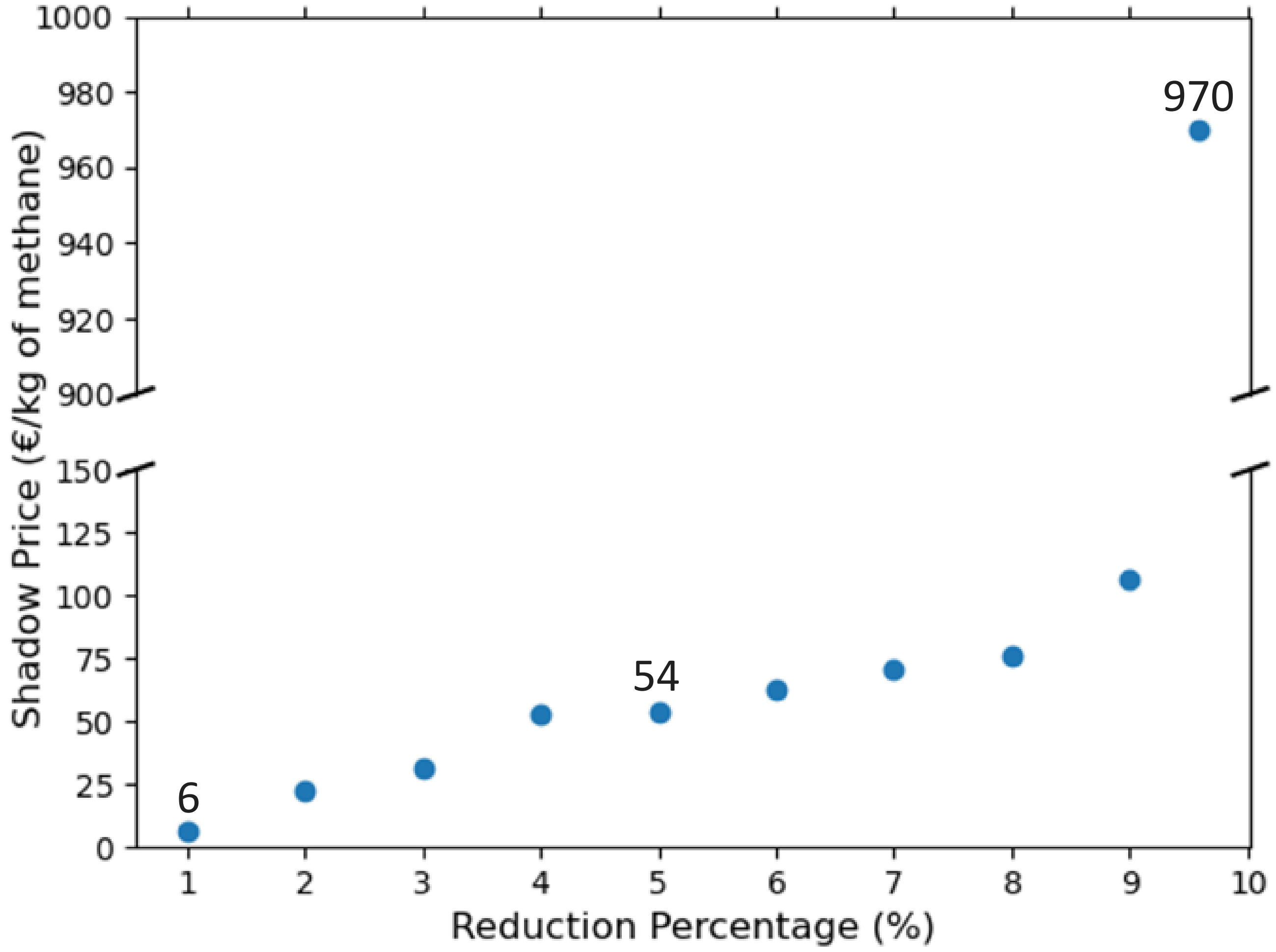
Nutritional profile

Weighting factor	1 (base line)	0.8	0.6	0.4	0.2	0
DMI (kg/d)	16.2	16.1	16.1	16.1	16.1	16.1
NEL (Mcal/kgDM)	1.5	1.6	1.6	1.6	1.6	1.6
CP (% DM)	14.5	14.8	15.7	15.9	15.9	16.2
NDF (% DM)	41.5	38.2	32.7	31.8	31.8	31.8
Starch (% DM)	21.1	24.0	22.9	23.7	23.7	23.3
Fat (% DM)	3.3	3.3	2.9	2.7	2.7	2.9

Results – TAX (Revenue vs. Methane)



Results – RED (Shadow Price)



Take-home Messages

- TAX policy is not very effective.
  - Only an extremely high tax rate leads to a methane reduction exceeding 1%
- MULTI and RED policies are effective in inducing methane emission reductions.
  - Trade-off between economic returns and methane emissions
  - Relationship is non-linear
- Methane mitigation prompts dietary changes.
  - Farm-grown corn silage decreases
  - More nutrient-dense diets (higher DM%, CP%, and Starch% and a decreased NDF%)

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Thank you!

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