

LCA of cropping and farming systems: from emission modelling to whole system assessment

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8 September 2026

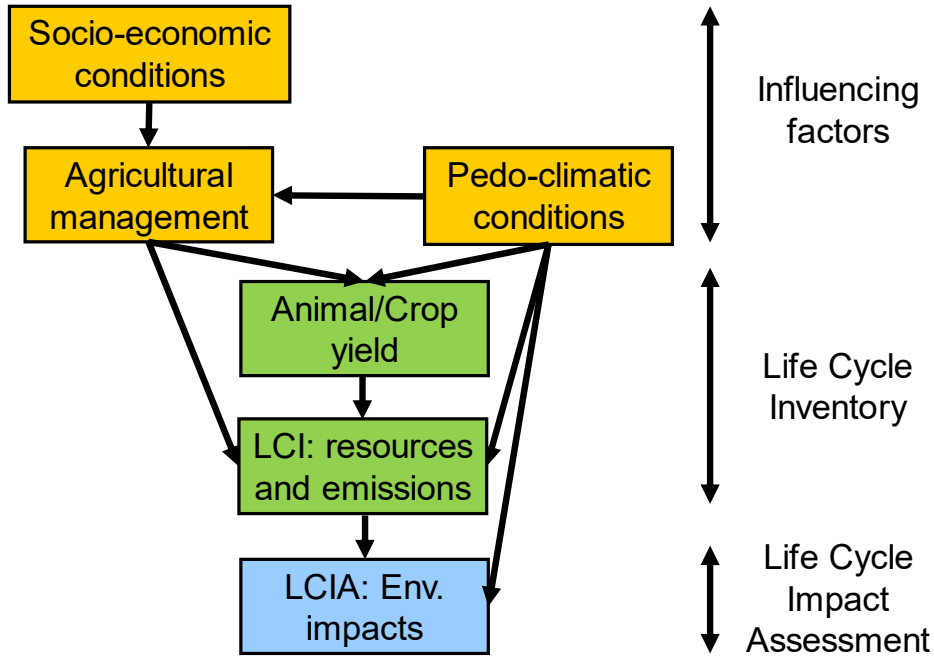
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Today's Menu

- Challenges for the LCA in the agri-food sector
- Variability of environmental impacts of food
- System boundaries – functional unit – allocation
- Swiss Agricultural Life Cycle Assessment (SALCA)
- Productivity – intensity – efficiency
- LCA of cropping systems
- Mitigation options for environmental impacts
- Ecosystem service assessment
- Some take-aways

LCA of the agri-food sector is challenging

- Open systems
  - Emissions difficult to control
  - Boundary between technosphere (economic system) and the ecosphere (natural system) not clear (e.g. soil)
  - Management depends on the context
- Dependent on natural resources
  - Emissions and impacts depend on management and site conditions
  - Need parameterised models for estimation of emissions
- Large number of farms, mostly comparatively small (~600 mio. farms worldwide)
- High spatial and temporal variability of resource use, emissions and impacts
  - need efficient tools
- Different methodologies make comparisons tedious
  - functional units, system boundaries, allocation methods, emission modelling, LCI databases, LCIA methods
- Various perspectives may lead to conflicting conclusions



Roesch et al. (2024)
https://doi.org/10.34776/as184e

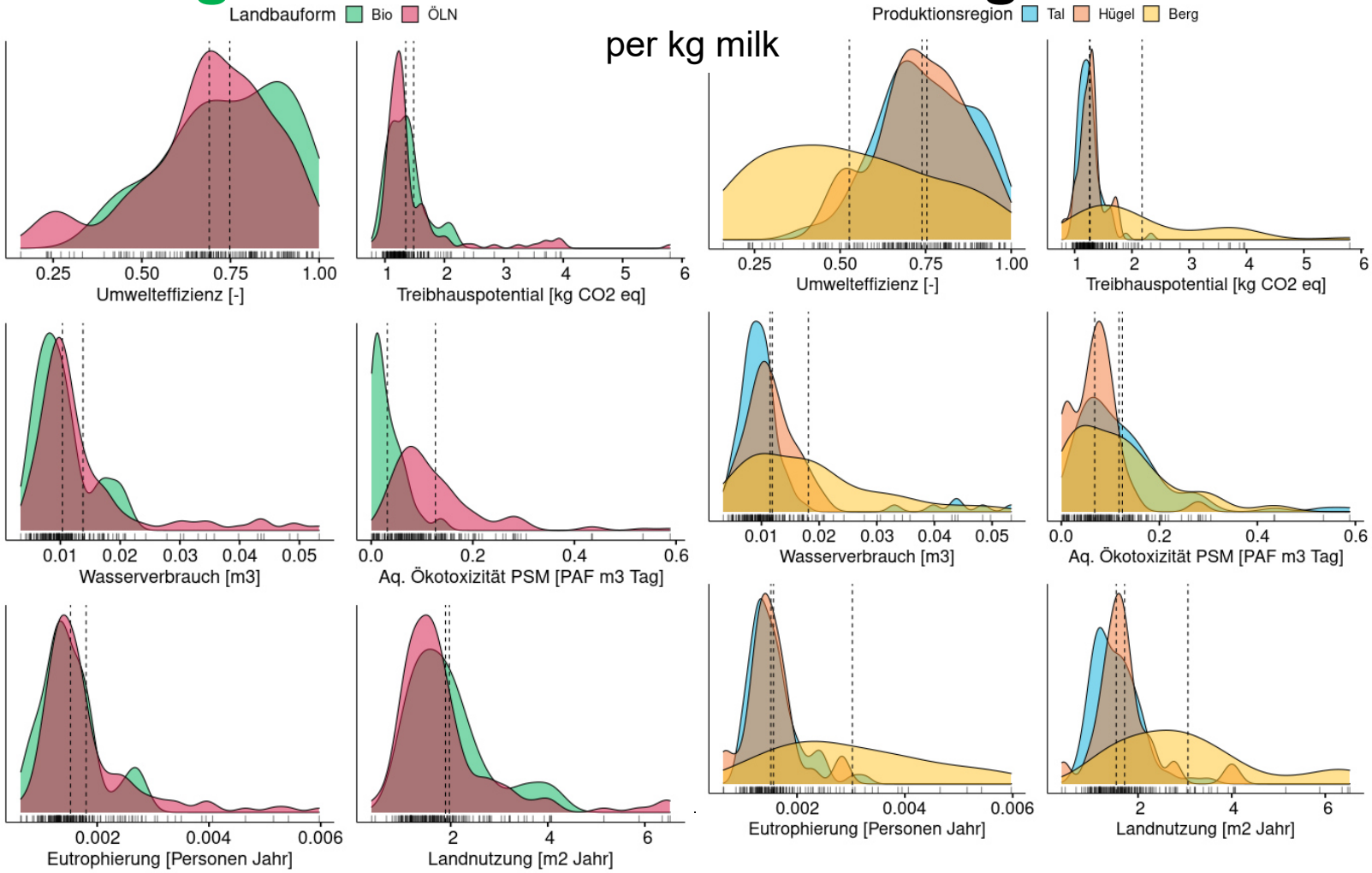
Variability of environmental impacts of dairy farms

Variability

Organic/conv.

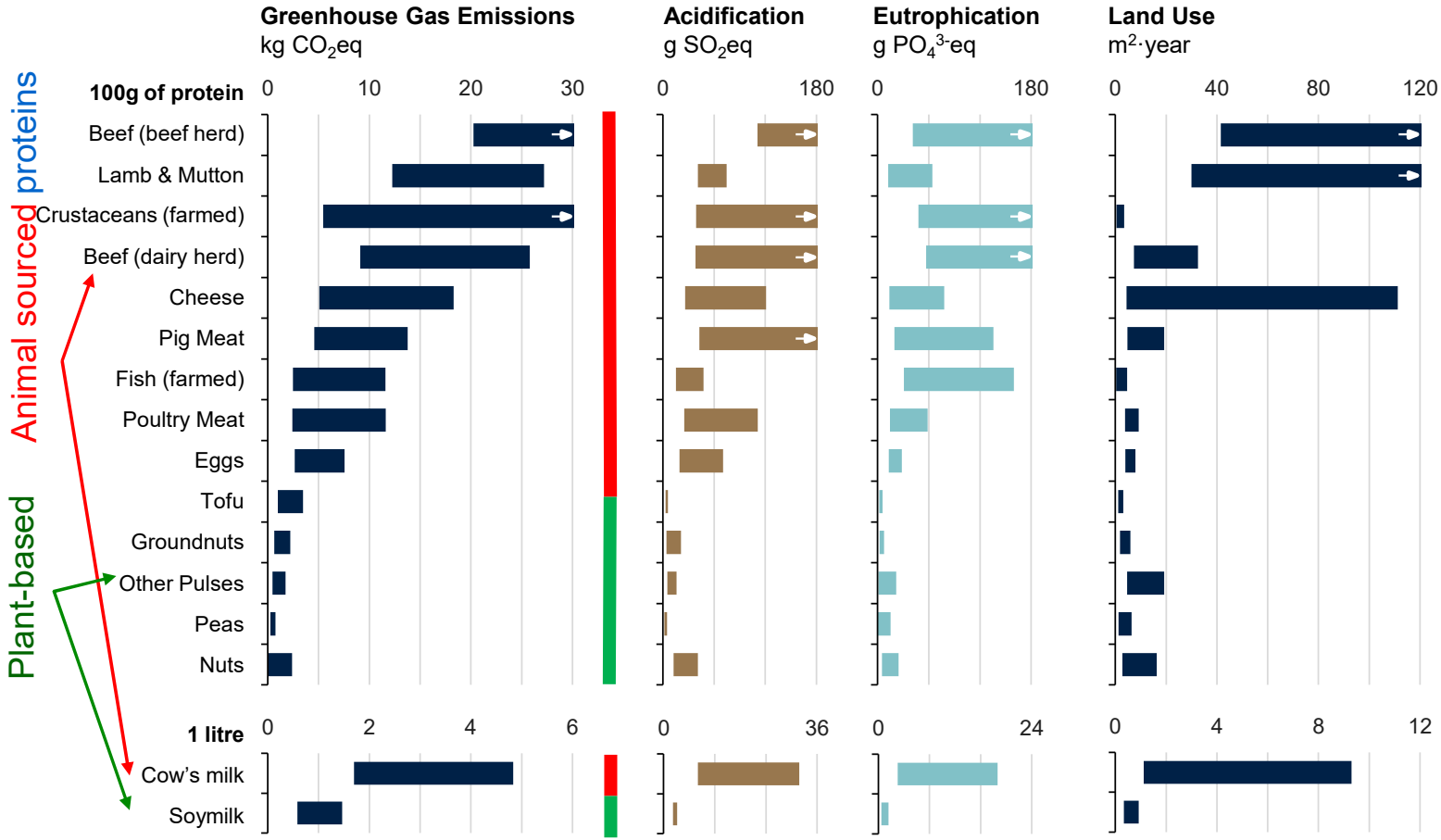
Region

per kg milk



Quelle: Pedolin, D. *et al*. (2021). Agronomy **11**(9): 1862. doi:10.3390/agronomy11091862

- **The variability between supply chains is huge**
- **Plant-based protein-rich foods have much lower impacts than animal-sourced foods**



J. Poore, and T. Nemecek, Science 2018;360:987-992

The variability of environmental impacts is high

	Land Use	GWP	Acidification	Eutrophication	Freshwater withdrawals	Stress-Weighted Water Use
Ratio 90th to 10th perc.	6.0	4.3	4.0	11	840	5500
Ratio 95th to 5th perc.	12.9	7.8	5.5	15	280	8200

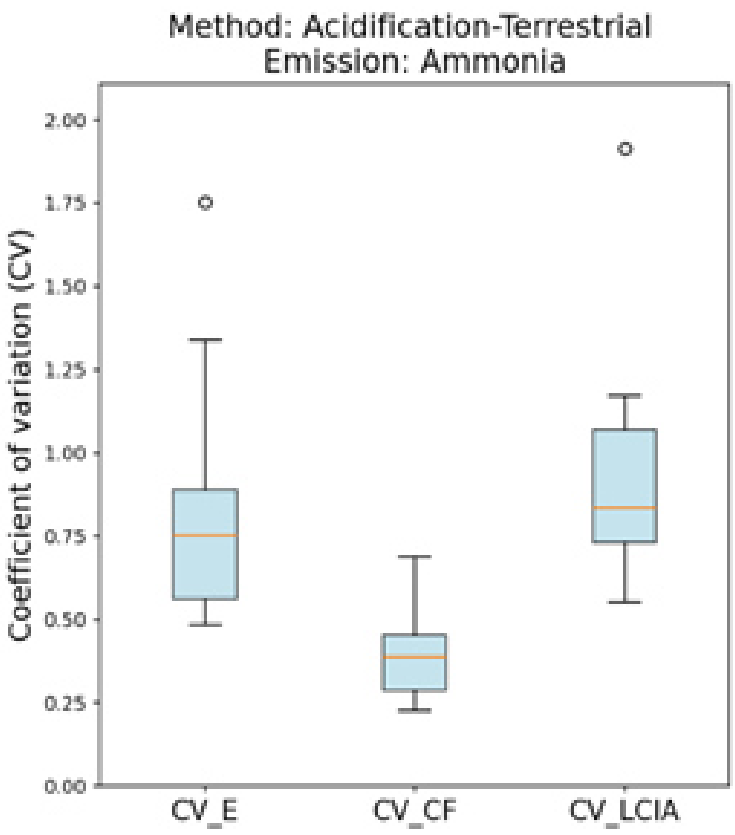
Example: The best 10% are at least 4.3x better than the worst 10% for GWP (Global Warming Potential)

Source: Poore & Nemecek (2018), Science 360 (6392), 987-992.

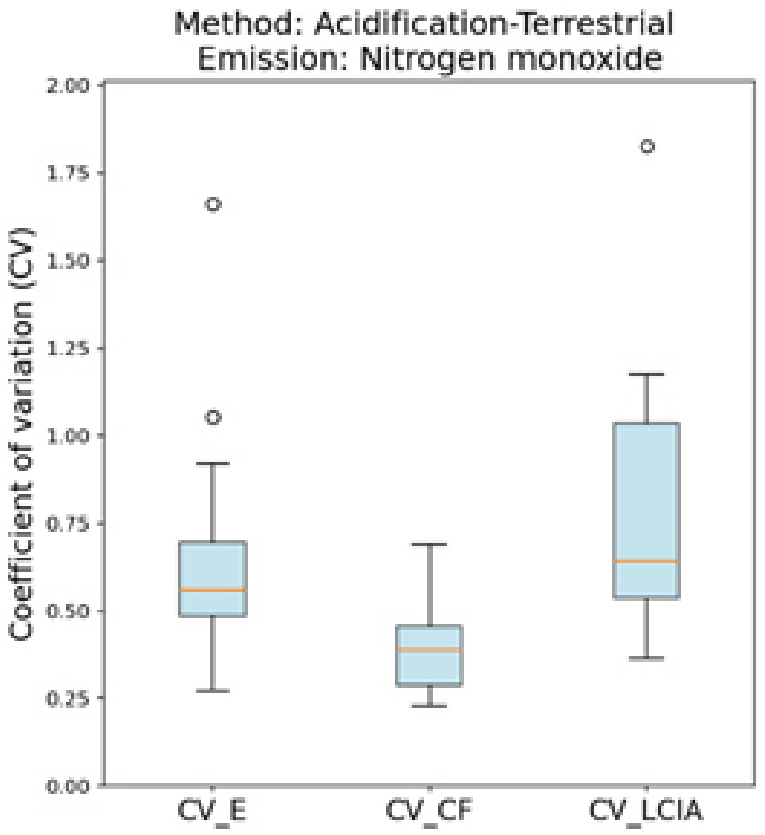
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Regional variability of inventory higher than of impact assessment

a)



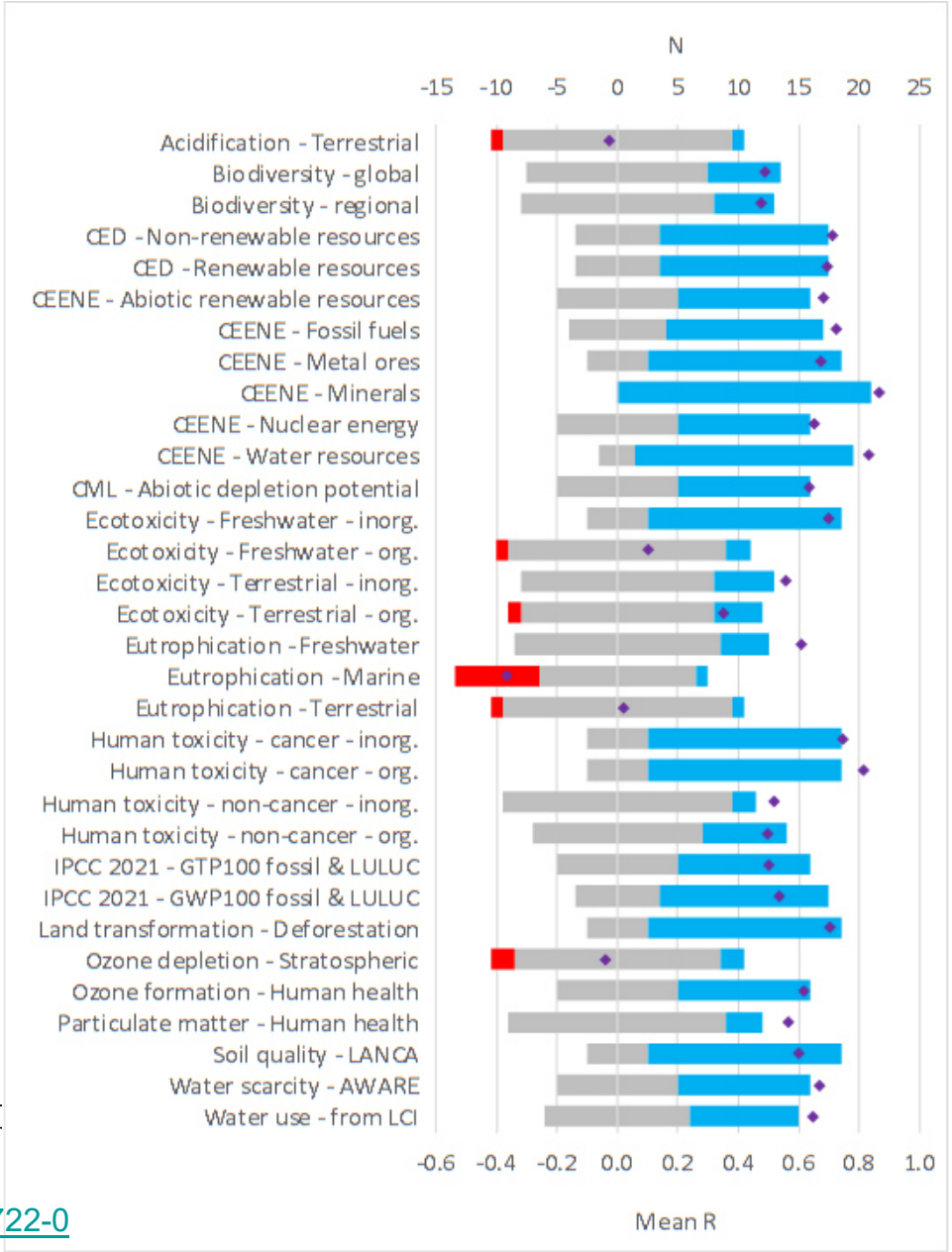
b)



Roesch et al. (2026) https://doi.org/10.1007/s11367-026-02722-0

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Correlations between agricultural land occupation and environmental impacts
→ Higher yields lead to lower impacts

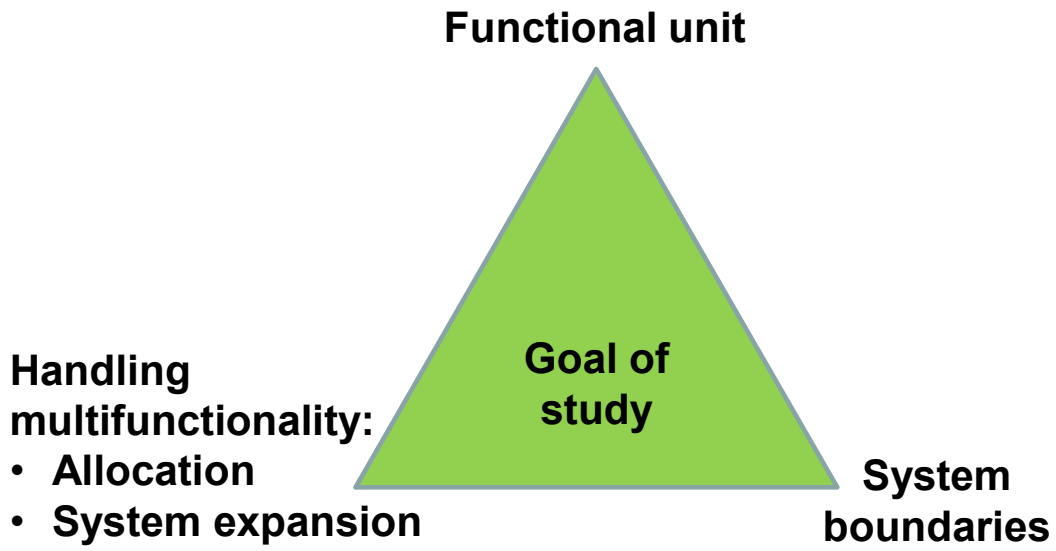


Variability

Roesch et al. (2026) https://doi.org/10.1007/s11367-026-02722-0

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Trilogy of functional unit, system boundaries and multifunctionality



1. Define goal
2. Define functional unit
3. Define multifunctionality handling and system boundaries accordingly

If one element changes, the others must be adapted.

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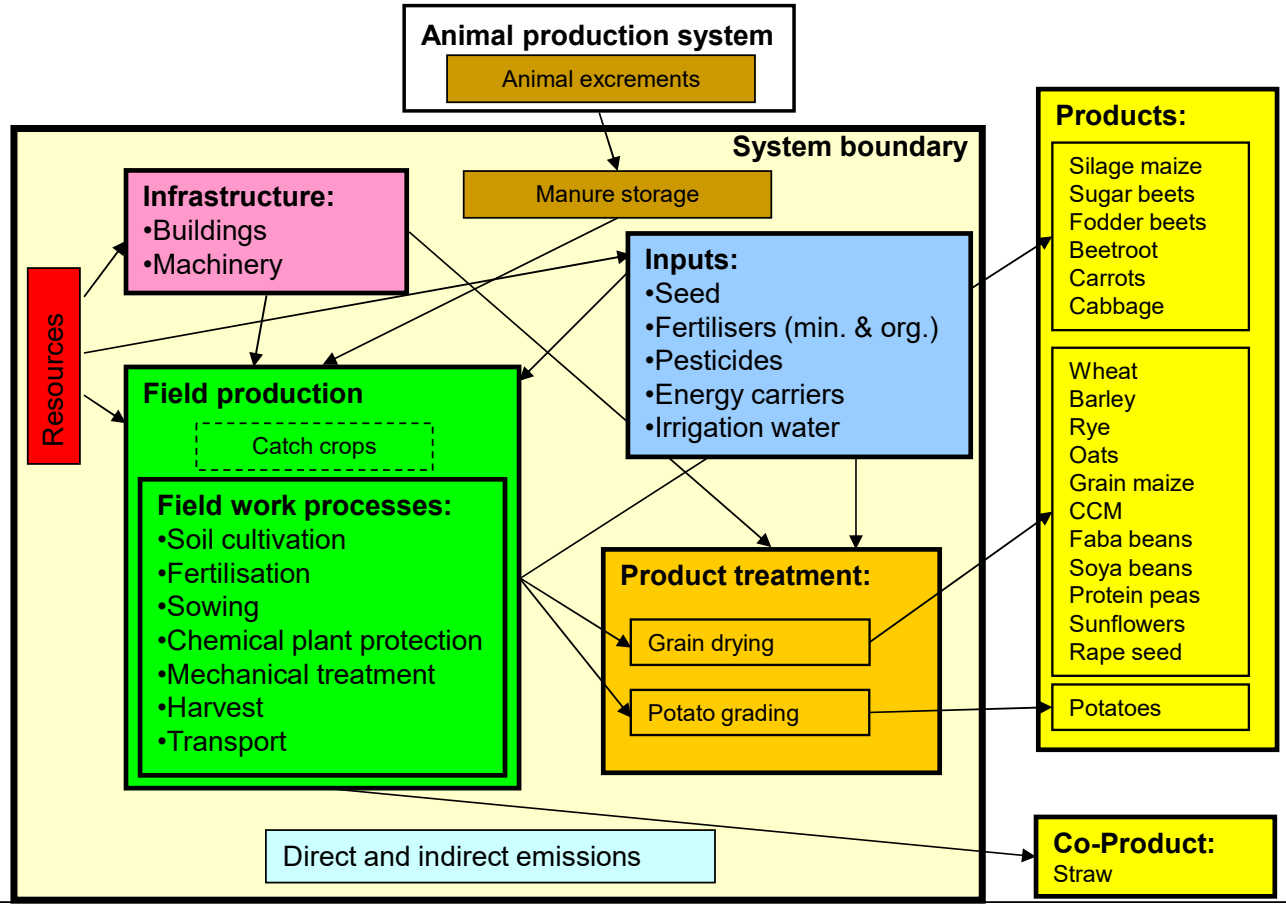
System boundaries: Choose the right level of assessment

Production perspective
- Crop product (wheat, potatoes, ..)
- Cropping system (crop rotation)
- Animal product (milk, beef, eggs, …)
- Farms
- Food item → eco-labelling

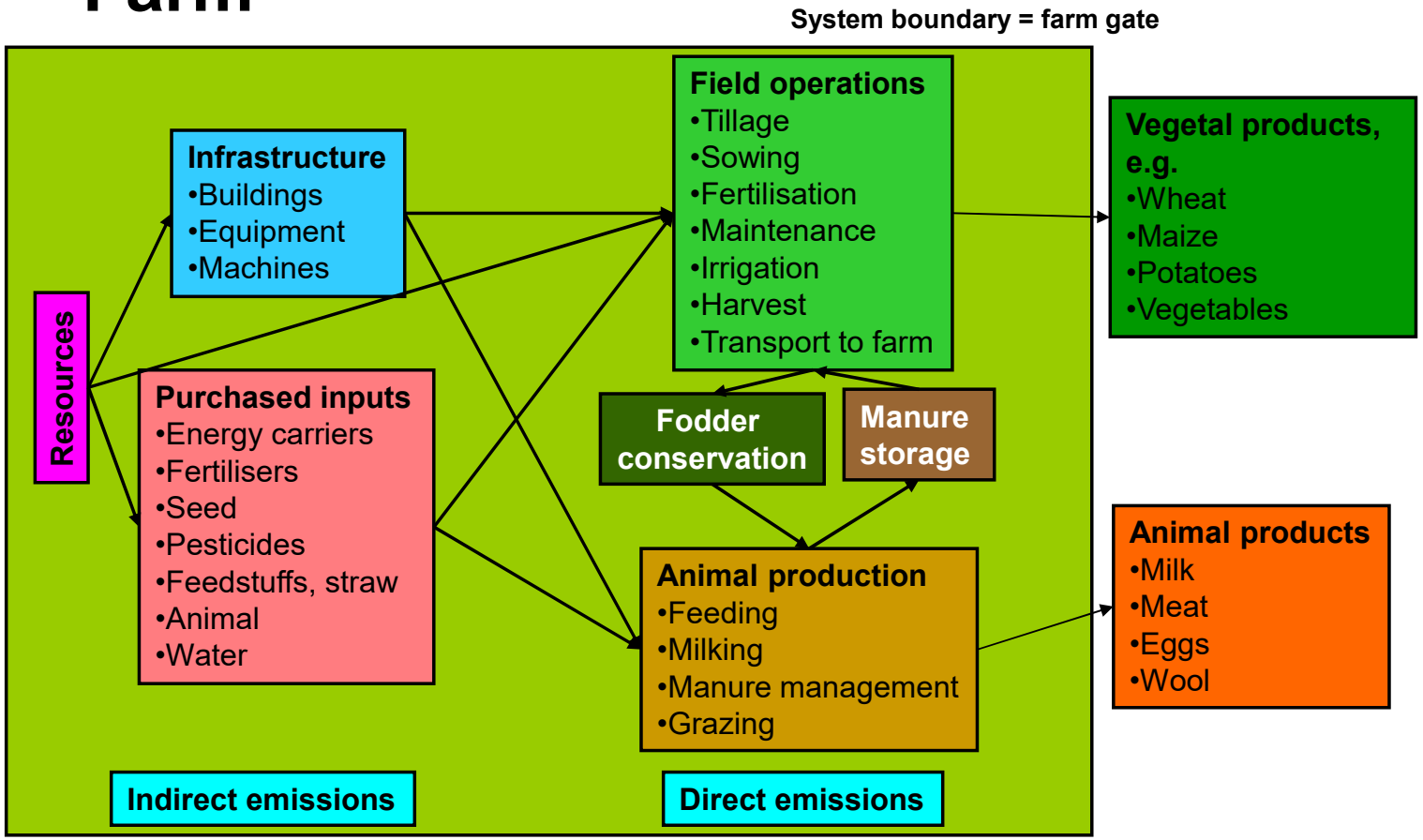
Consumption perspective
- Meal
- Diet

Production and consumption perspective
- Region
- Country
- Global system
- Food system

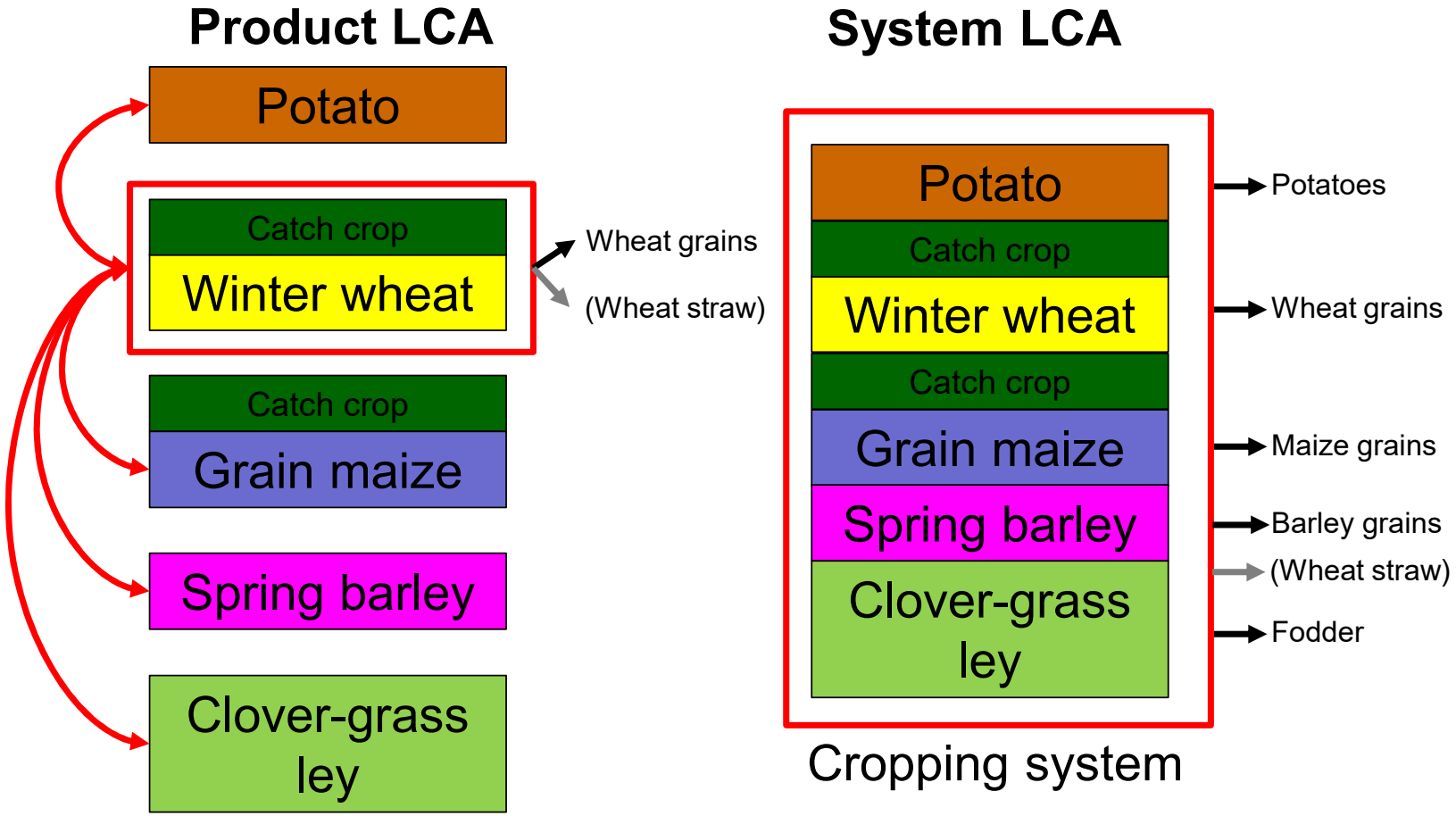
Defining system boundaries: Example of crop production



Defining system boundaries: Farm



LCA of product vs. LCA of system



Life cycle assessment (LCA) and the multifunctionality of agriculture

Functions and functional units

1. **Productive function**: physical unit (kg, MJ, …) → goal: optimise eco-efficiency
   → nutritional LCA
2. **Financial function**: monetary unit
   → goal: optimise eco-efficiency
   (minimal impact per CHF, €, $, …)
3. **Land management function**: ha*year
   → goal: minimize land use intensity
   → should not be used alone

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Swiss Agricultural Life Cycle Assessment (SALCA)

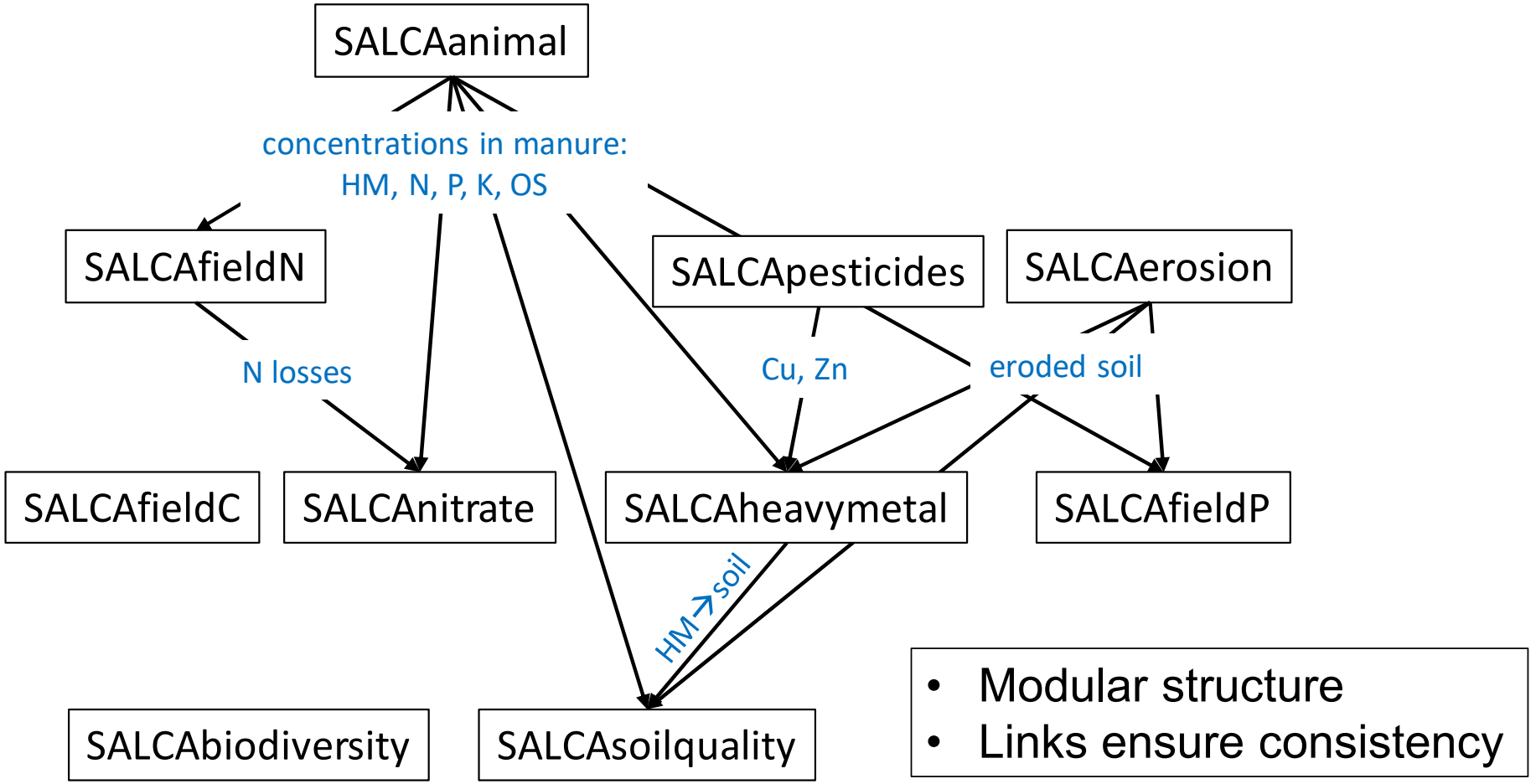
SALCA supports the 4 phases of an LCA:

1. **Goal and scope**
   a) Rules for the definition of system boundaries, functional unit and allocation for agricultural products, farms and the agrifood sector
2. **Life cycle inventory (LCI)**
   a) Models to calculate direct field and farm emissions relevant for agriculture, such as N and P emissions, methane, carbon dioxide, heavy metals, pesticides and soil erosion
   b) A database with LCI for inputs and processes for agrifood systems
   c) A software environment to collect input data, check their plausibility, and calculate agricultural LCAs in a robust and efficient manner
3. **Life cycle impact assessment (LCIA)**
   a) Midpoint impact assessment methods specific to agricultural applications due to direct land use (biodiversity and soil quality)
   b) Selection of impact assessment methods specific to agricultural systems
4. **Interpretation**
   a) A concept for analysing and interpreting LCA results
   b) A concept to communicate the results, conclusions and recommendations

Nemecek T., Roesch A., Bystricky M., Jeanneret P., Lansche L., Stüssi M., Gaillard G., 2023. Swiss Agricultural Life Cycle Assessment: A method to assess the emissions and environmental impacts of agricultural systems and products. Int. J LCA 29, 433–455. https://doi.org/10.1007/s11367-023-02255-w

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SALCA models and data flow



Nemecek et al. (2024) https://doi.org/10.1007/s11367-023-02255-w

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SALCAfieldN and SALCAfieldC

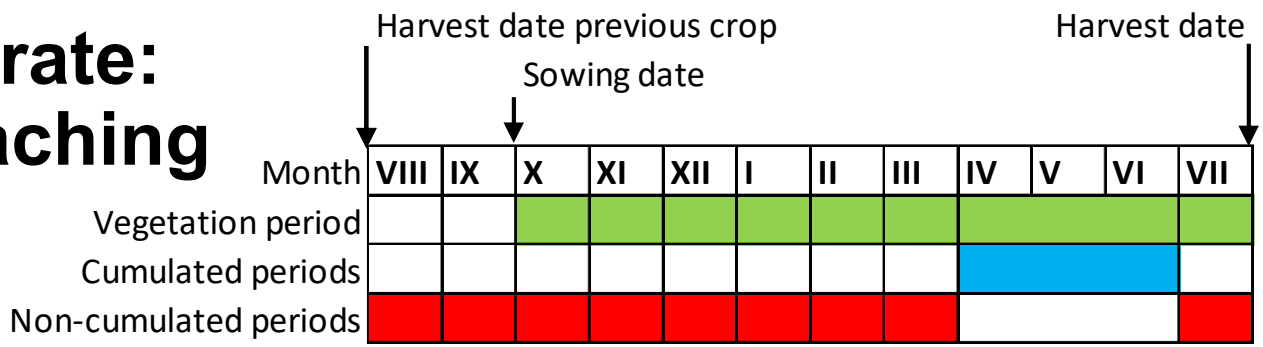
SALCAfieldN: gaseous N emissions

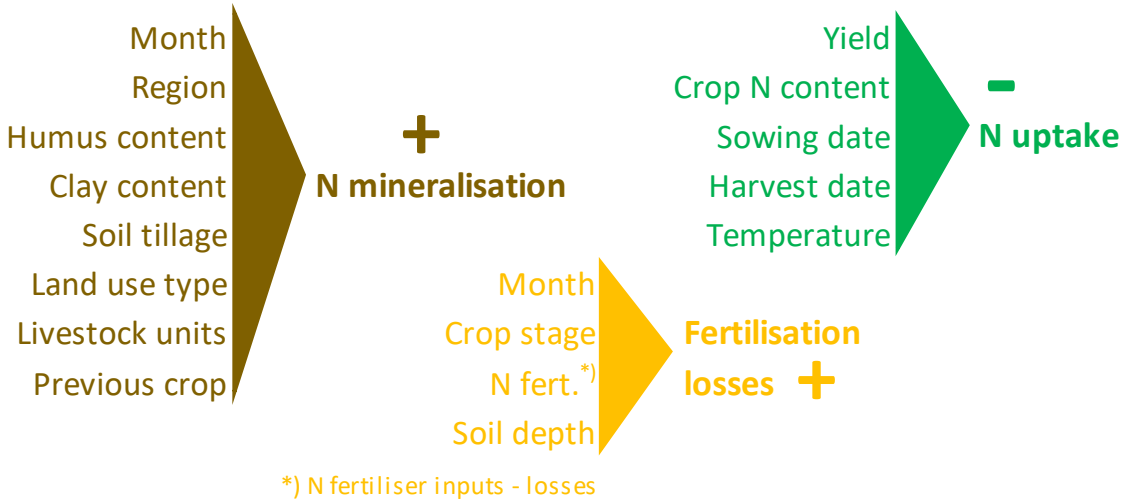
- NH_3: Agrammon and EEA/EMEP models
- N_2O: IPCC 2019 with specific scaling factors for N fertilisation, climate and soil characteristics
- NO_x: EEA/EMEP model

SALCAfieldC: CO_2 emissions and C sequestration

- Fossil CO_2: from lime and urea (CO_2 from fossil fuels covered by database entries)
- CO_2 emissions and C sequestration from land use and land use change:
  - Organic soils
  - Grassland types of different intensities
  - Cropland management and conversion between cropland and grassland

SALCAnitrate: Nitrate leaching



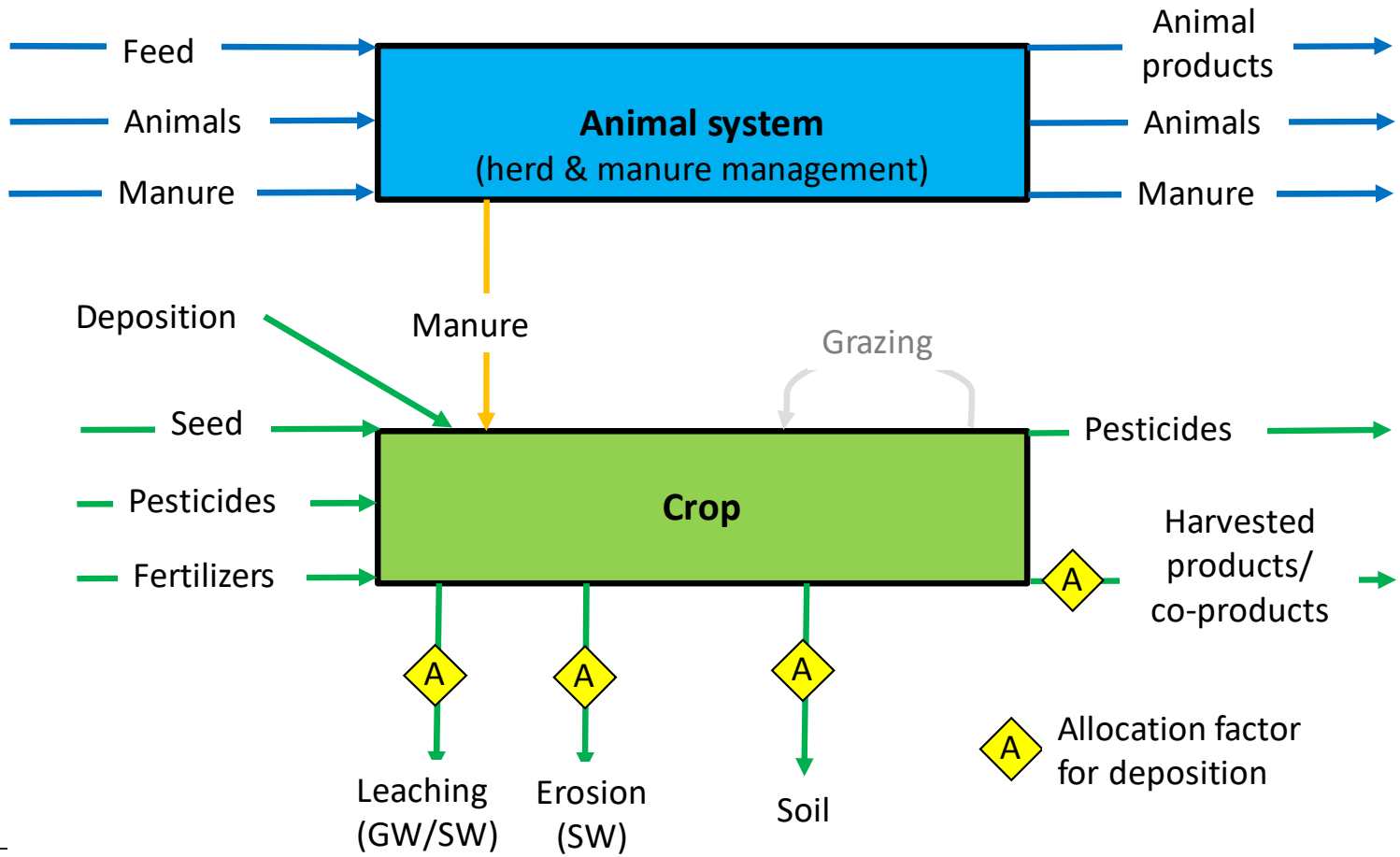


N mineralisation
\+ Fertilisation losses
\- N uptake
= Leaching

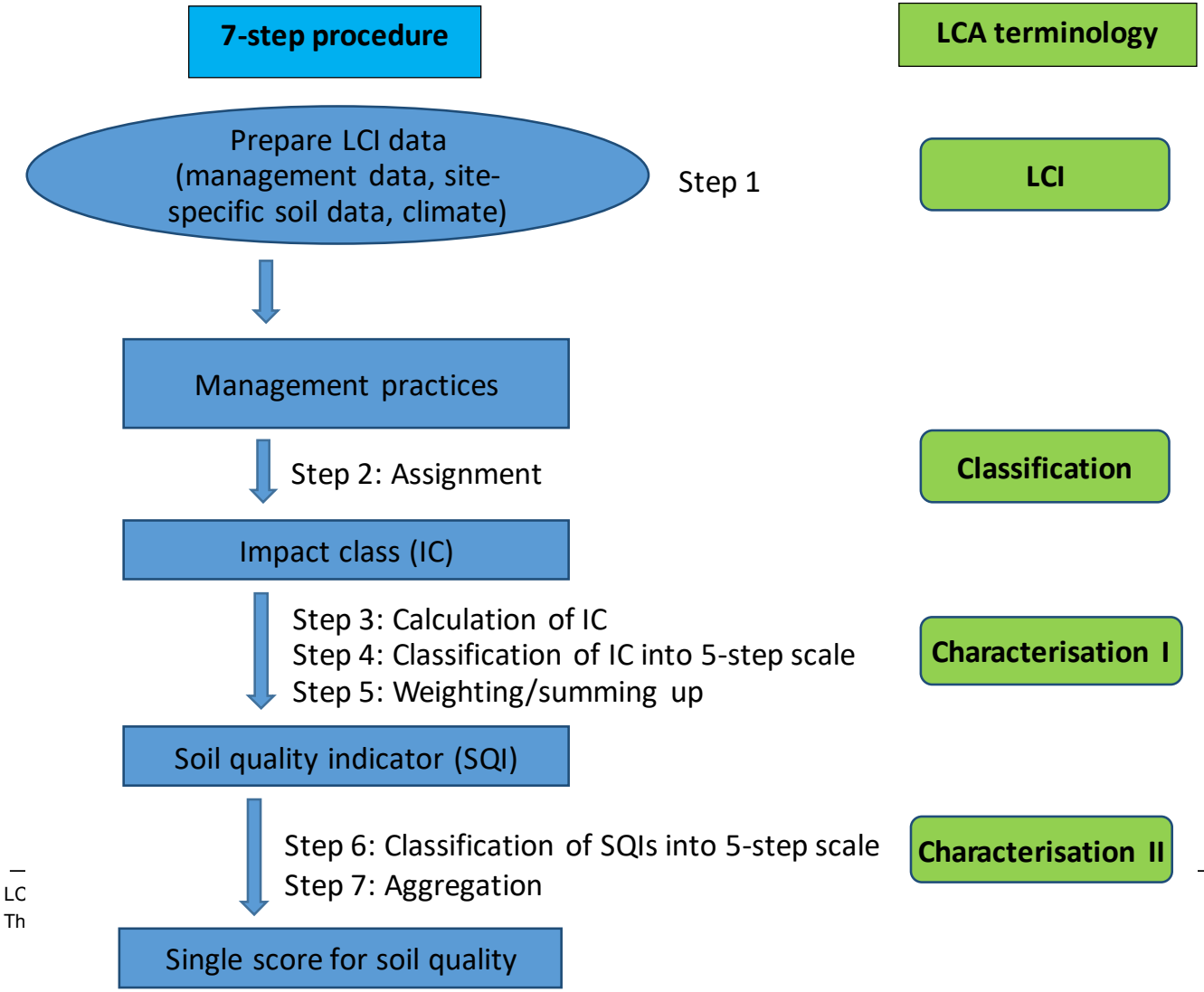
Winter precipitation
Drainage

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SALCAheavymetals: heavy metal emissions



SALCAsoilquality: impacts on soil quality



Soil quality indicators	
P: Potential plant rooting depth	Physical
P: Macropore volume	Physical
P: Aggregate stability	Physical
C: Organic carbon	Chemical
C: Heavy metals	Chemical
C: Organic pollutants	Chemical
B: Earthworm biomass	Biological
B: Microbial biomass	Biological
B: Microbial activity	Biological

SALCAsoilquality: impacts on soil quality

- Spatial system boundary = farm;
- Temporal system boundary = crop rotation period (6-8 years)
- Management data of all plots of a farm in a single year are considered as representative for a whole crop rotation
- Only influences of agricultural management practices are included, not immissions
- The development trend of soil properties is assessed, not absolute values

Soil properties
Physical
Chemical
Biological

Criteria
According to ISO 14040 and ISO 14042
Depending on the needs of Life Cycle Assessment

9 Direct Indicators = measurable soil properties		
	Physical	**Rooting depth of soil**
		Macropore volume
		Aggregate stability
	Chemical	**Soil organic matter**
		Inorganic pollutants
		Organic pollutants
	Biological	**Earthworm biomass**
		Microbial biomass
		Microbial activity

Source: Oberholzer et al. (2006)

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SALCAsoilquality: impacts on soil quality

Example: slurry application

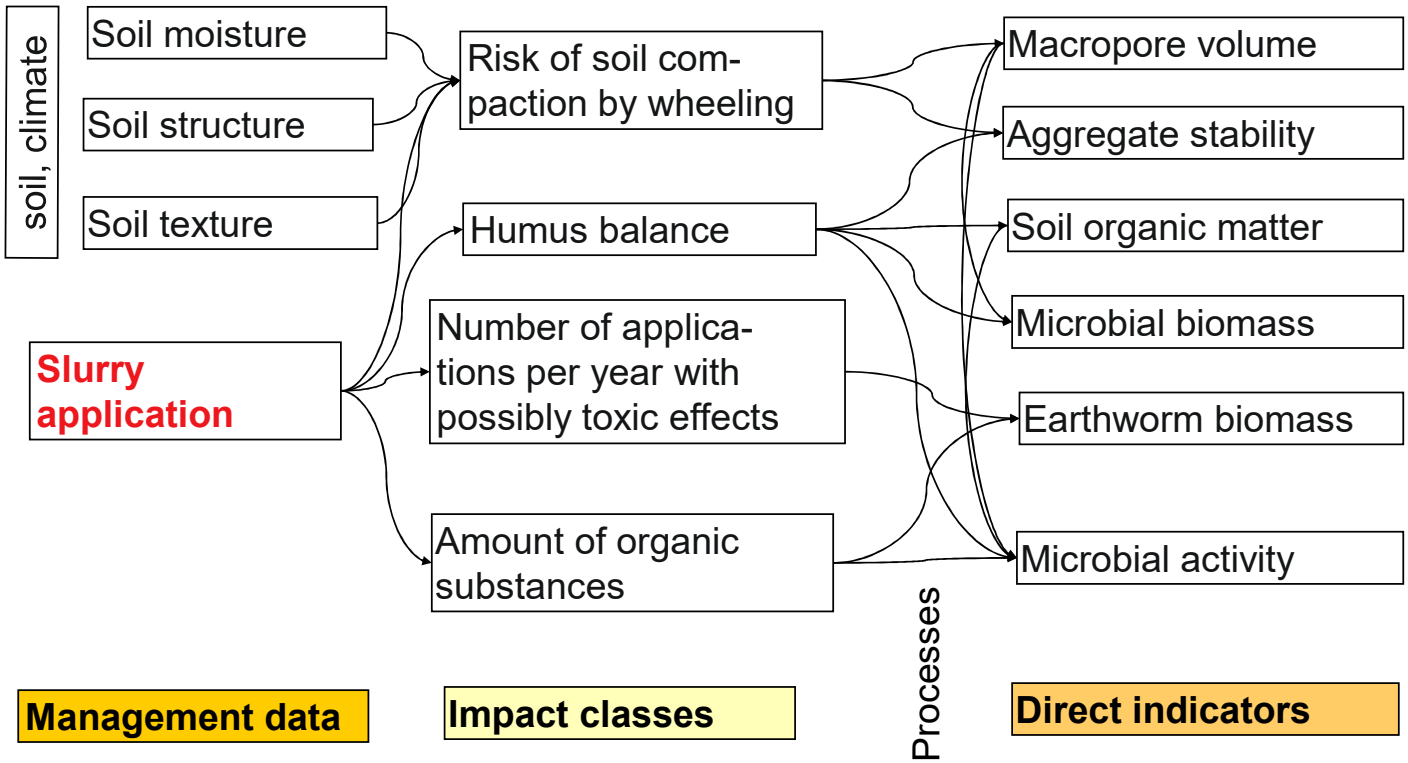
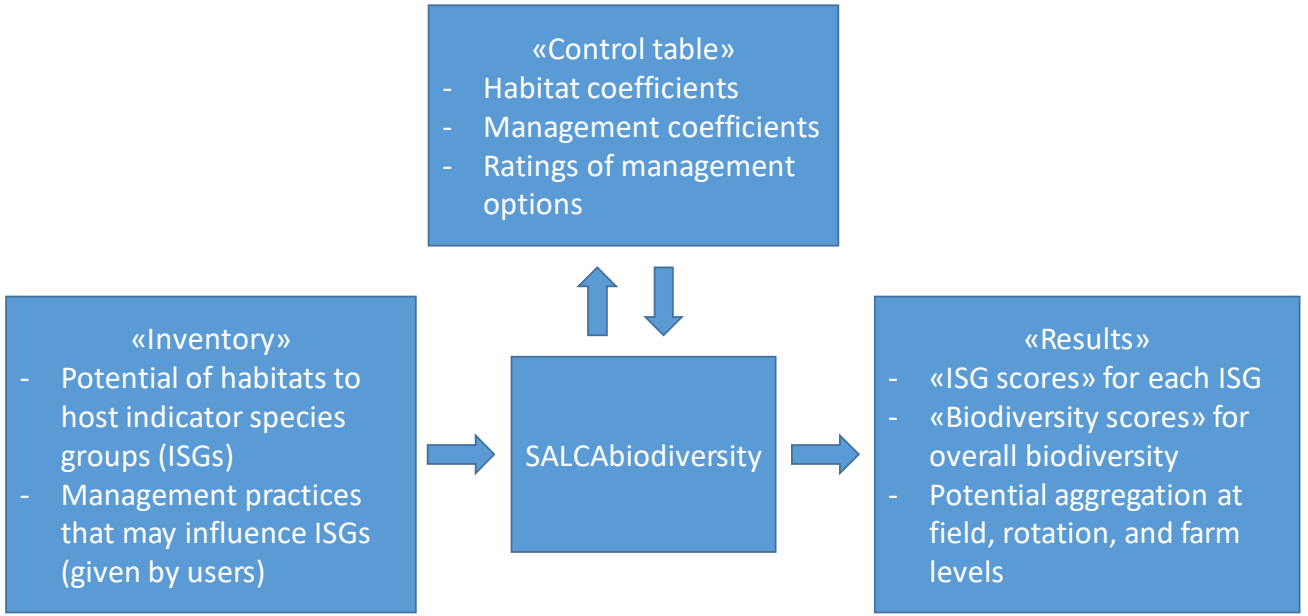


Figure 1: Example of impact assessment of a slurry application

SALCAbiodiversity: impacts of agricultural management on species richness

Indicator species groups:

- grassland and crop flora
- birds
- small mammals
- amphibians
- snails
- spiders
- carabid beetles
- butterflies
- wild bees
- grasshoppers

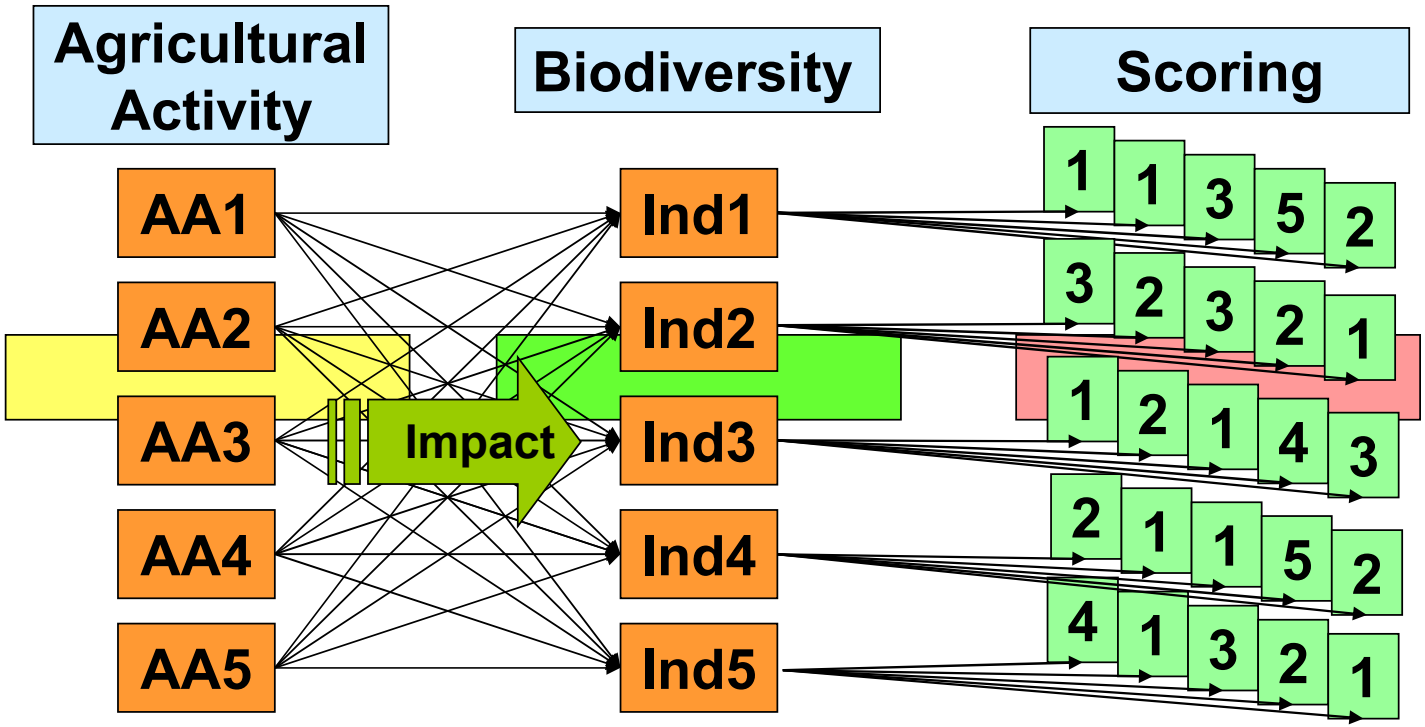


Indicators:

- overall species diversity within the 11 groups
- ecologically demanding species for amphibians, snails, spiders, carabid beetles, butterflies and grasshoppers
- Total biodiversity score

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SALCAbiodiversity



Source: Jeanneret *et al*. 2006

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Organisation of the SALCA model

Levels of organisation:

1. Farm
2. Animal group
3. Field
4. Crop

One farming year:

- One calendar year for the farm, animal production and permanent crops
- Harvest of the previous main crop to harvest of the main crop in the reference year

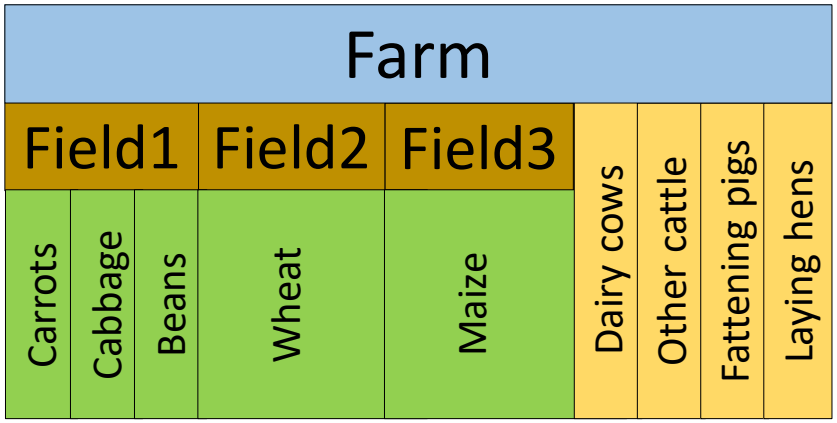


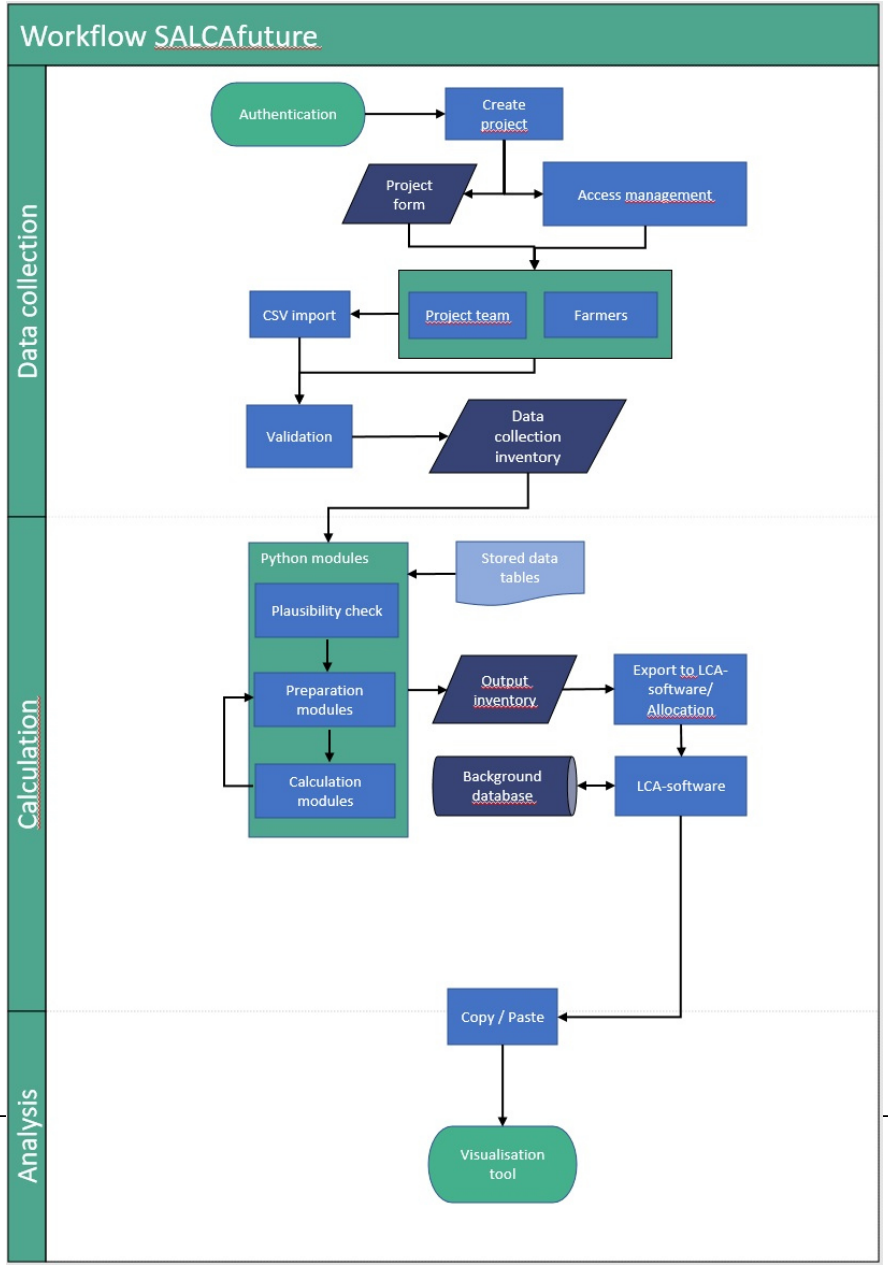
Table 1 Calculation levels for the different models

	Crop	Field	Animal group	Farm
SALCAfieldN		x		
SALCAfieldP	x			
SALCAfieldC		x		
SALCAnitrate		x		
SALCAerosion		x		
SALCAanimal			x	x
SALCAheavymetal	x		x	x
SALCApesticides	x			
SALCAsoilquality	x			x
SALCAbiodiversity	x	x		x

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SALCA: workflow

Python code open access:
https://github.com/agroscope-ch/salca
Published 4 June 2026



Productivity, intensity and efficiency

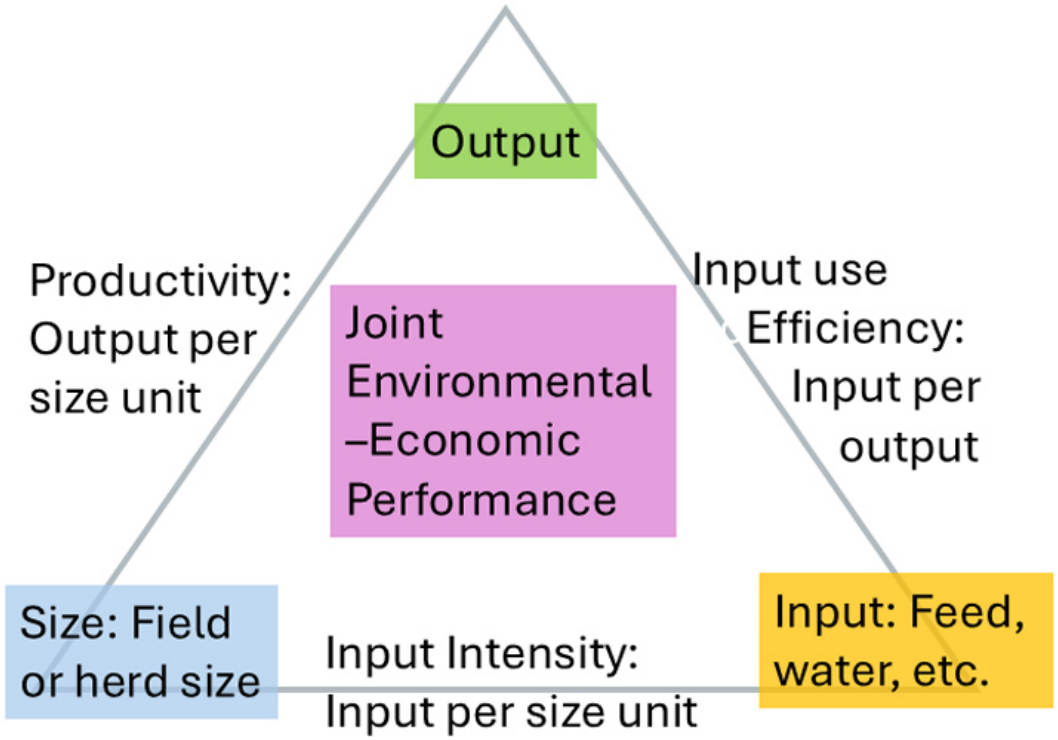


Figure 19: Schematic depiction of the relationship between input use efficiency, input intensity and productivity.

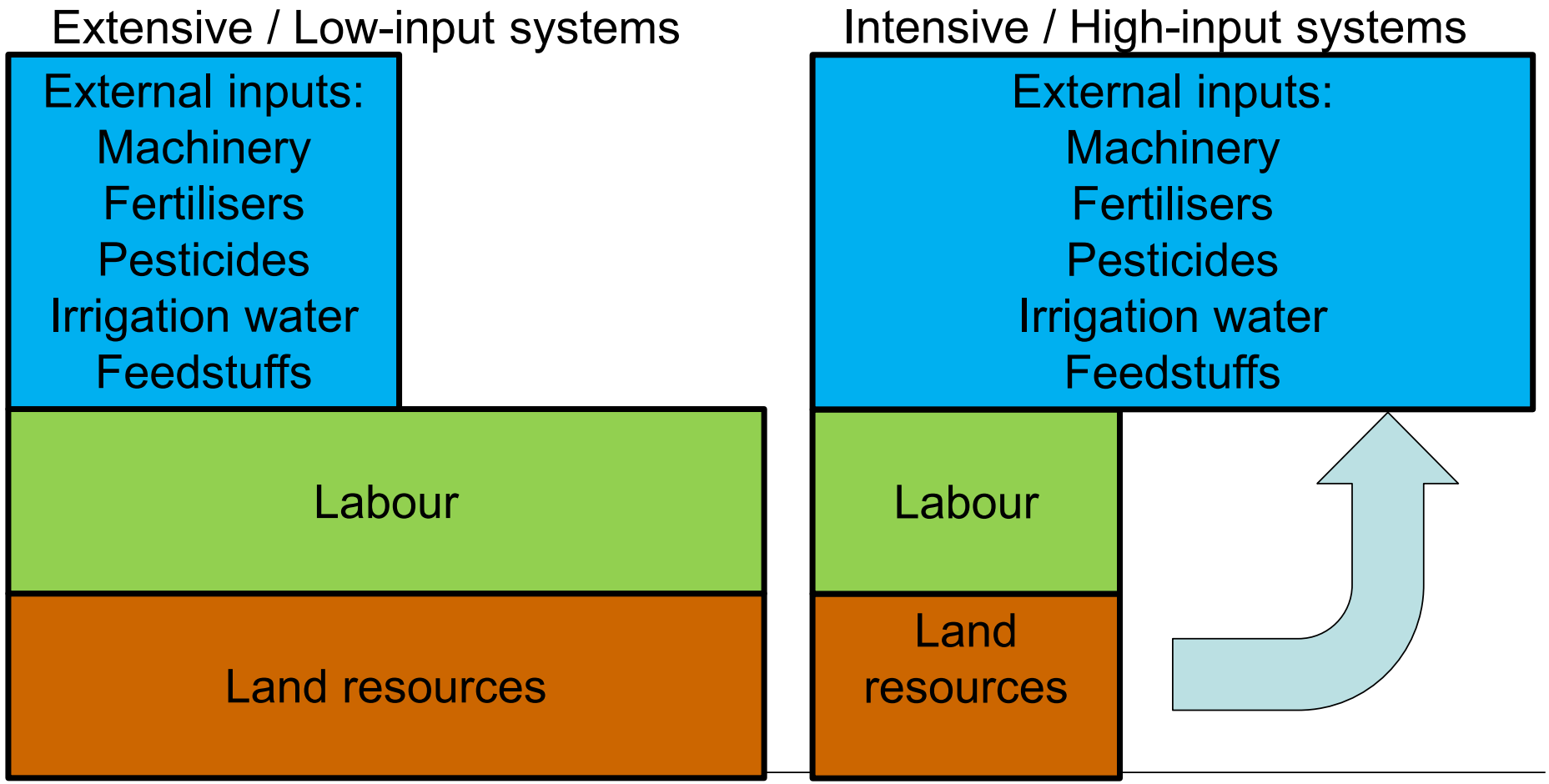
Pedolin *et al*. (under review) Clean. Circ. Bioeconomy

Paradoxes around eco-labelling of food

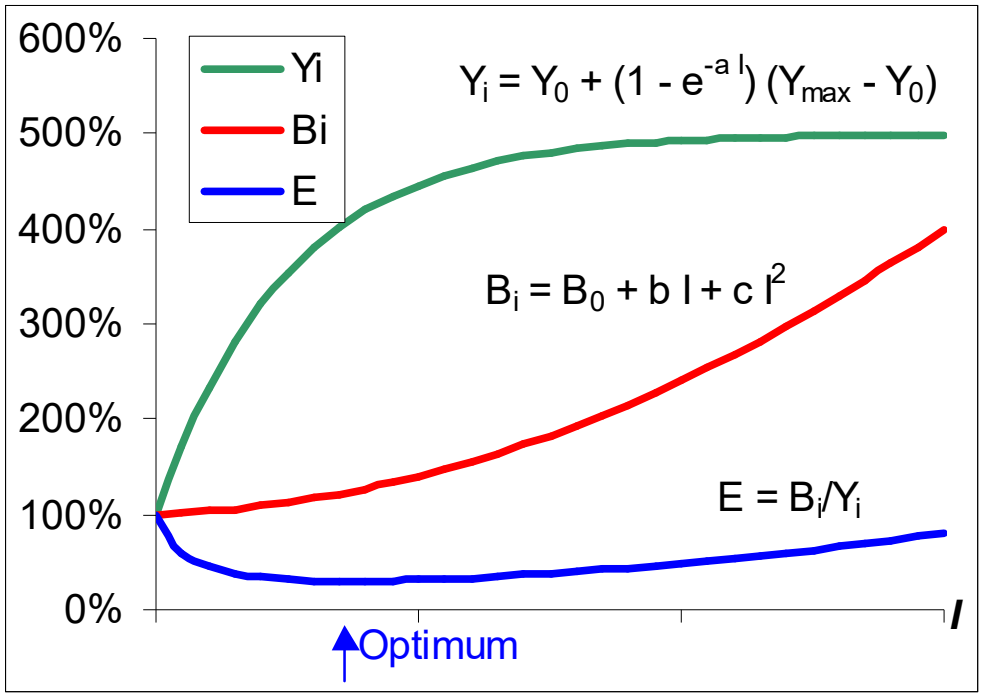
Public perception	Evidence from LCA
Organic products are much more environmentally friendly than conventional ones	Organic farming has lower impacts per area Organic products have lower, similar or higher impacts per kg Systematic advantage for toxicity related impacts (lower and more restrictive pesticide use)
Extensive animal production is more environmentally friendly	Extensive animal production has typically higher impacts per kg in many impact categories (lower per area)
Local/regional food has lower environmental impacts	Local/regional food has not generally lower impacts, transports/food miles play no dominant role Seasonal and regional production generally favourable for fruit and vegetables (but depending on production system)

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Shift of production factors from extensive to intensive systems



Eco-efficiency analysis: Where is the optimal intensity?



I = input or intensity

Yi = yield function

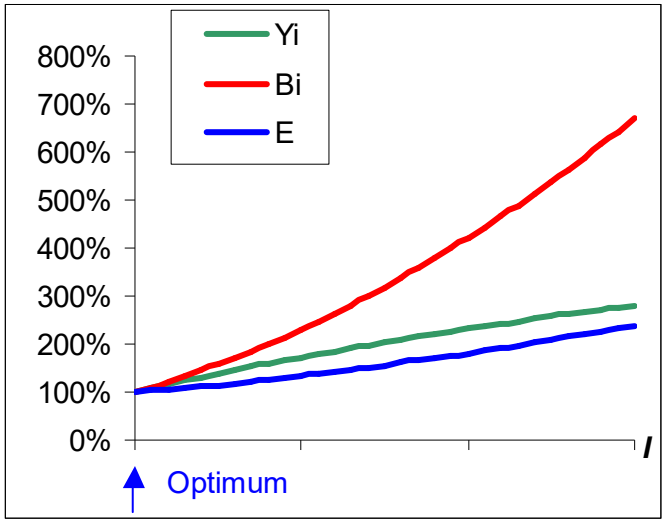
Bi = environmental impact function

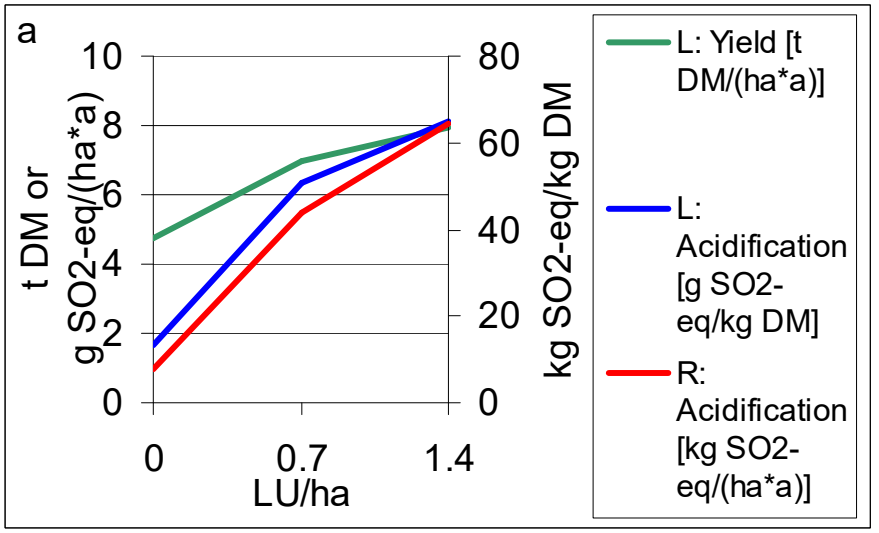
E = eco-efficiency function (low values are favourable)

Nemecek *et al*. (2005) FAL Schriftenreihe 58.

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Case A:
steadily increasing eco-efficiency function





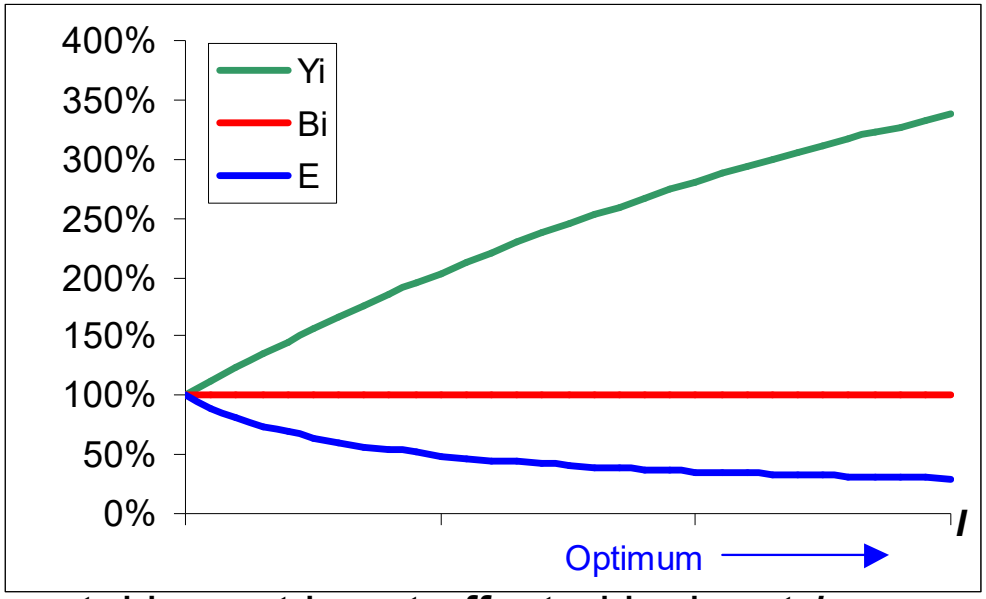
Environmental impact increases faster than yield

→Optimum at lowest intenstity

→Input should be avoided from environmental point of view

Nemecek *et al*. (2005) FAL Schriftenreihe 58.

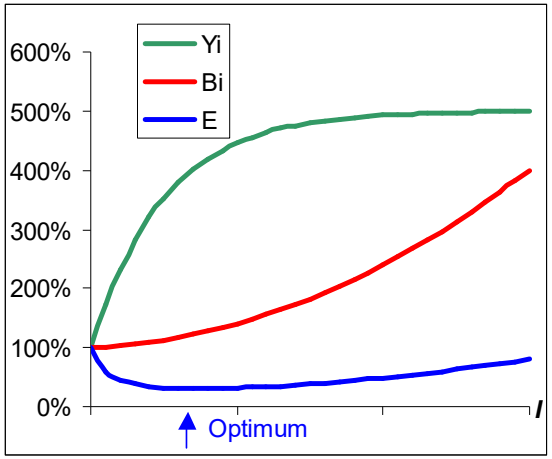
Case B:
steadily decreasing eco-efficiency function

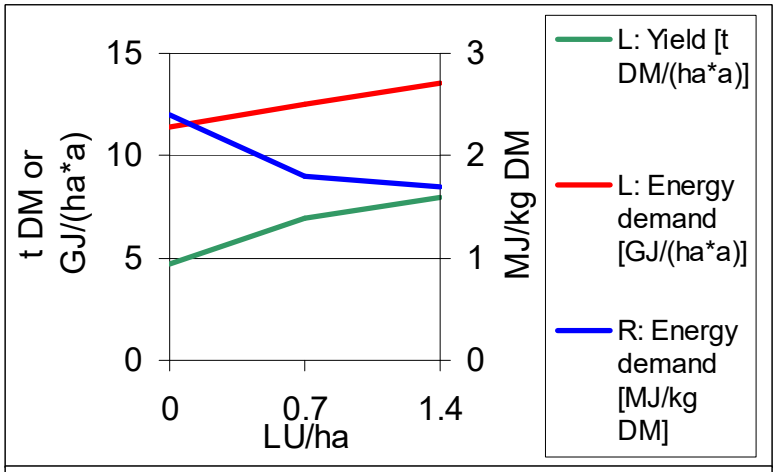


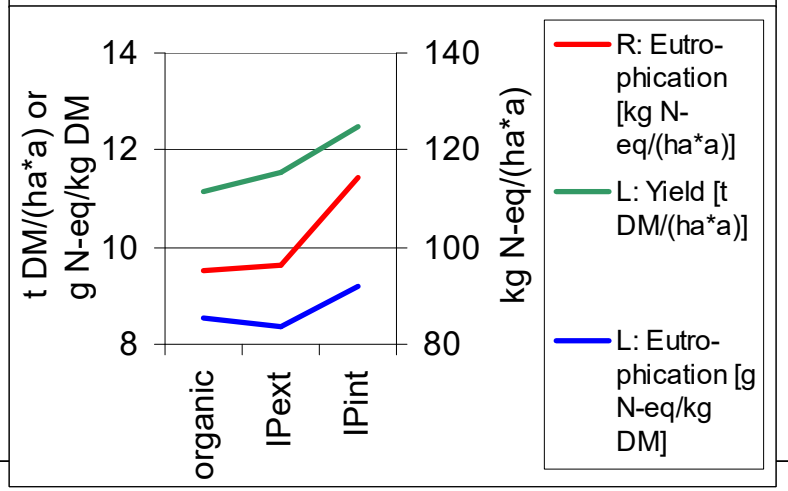
Environmental impact is not affected by input *I*
→*I* can be increased as long as there is a yield effect
→Optimum at high intensity level
This case is quite rare

Nemecek *et al*. (2005) FAL Schriftenreihe 58.

Case C:
convex eco-efficiency function



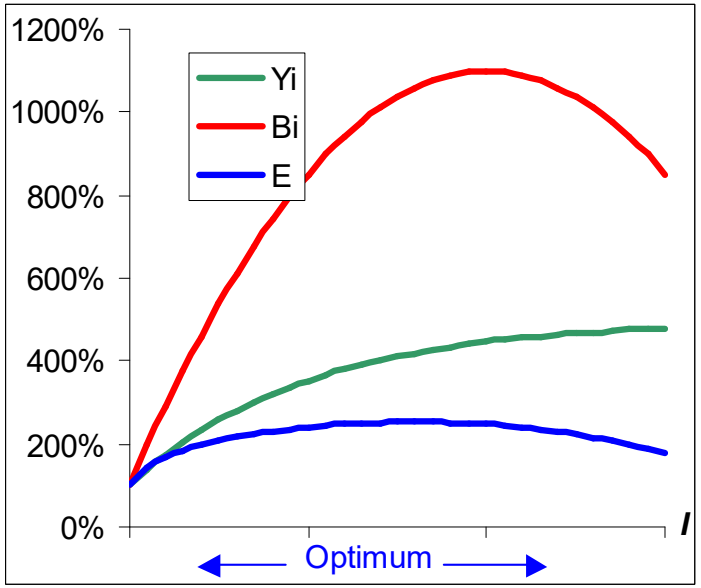


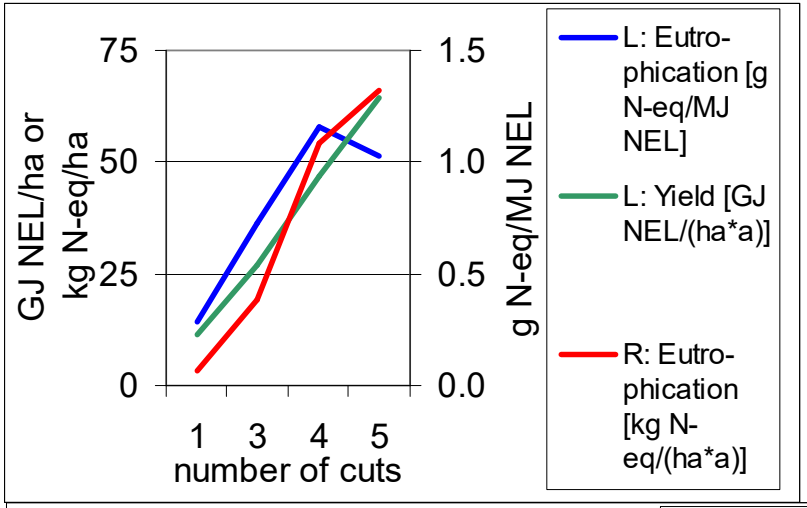


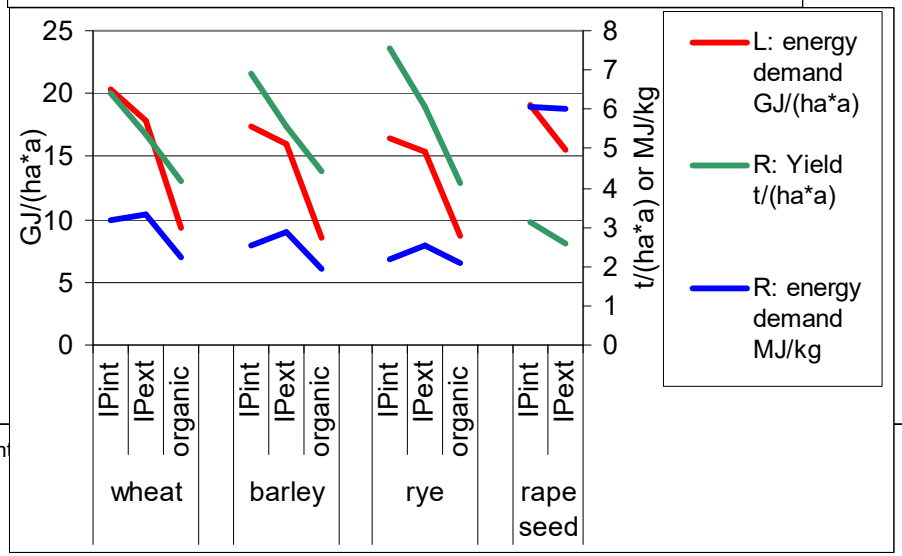
- Optimal eco-efficiency at medium intensity
- Intensity should be increased or decreased depending on situation
- Small deviations from optimum are not relevant

Nemecek *et al*. (2005) FAL Schriftenreihe 58.

Case D:
concave eco-efficiency function







Medium intensity gives worst eco-efficiency

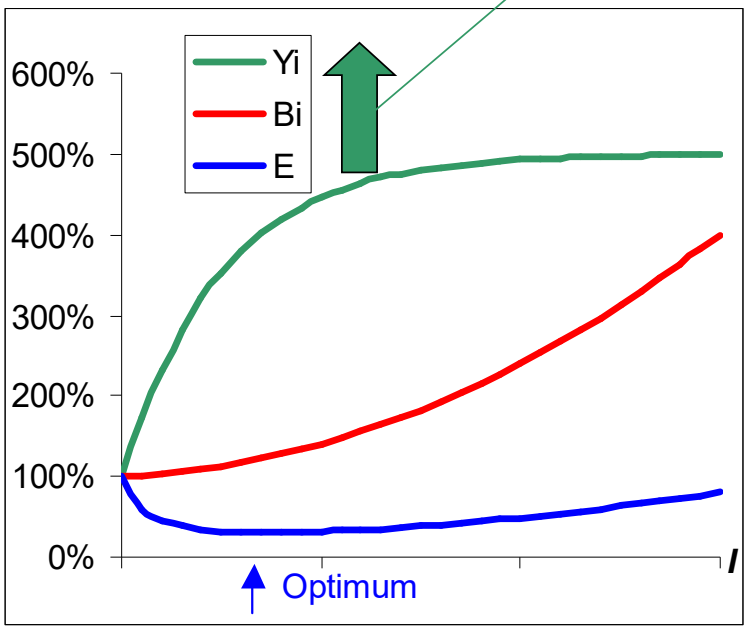
→Intensity should be either decreased or increased

Nemecek *et al*. (2005)
FAL Schriftenreihe 58.

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Consequences for eco-efficiency

organic farming / low-input systems
→ optimisation **output**-oriented



intensify

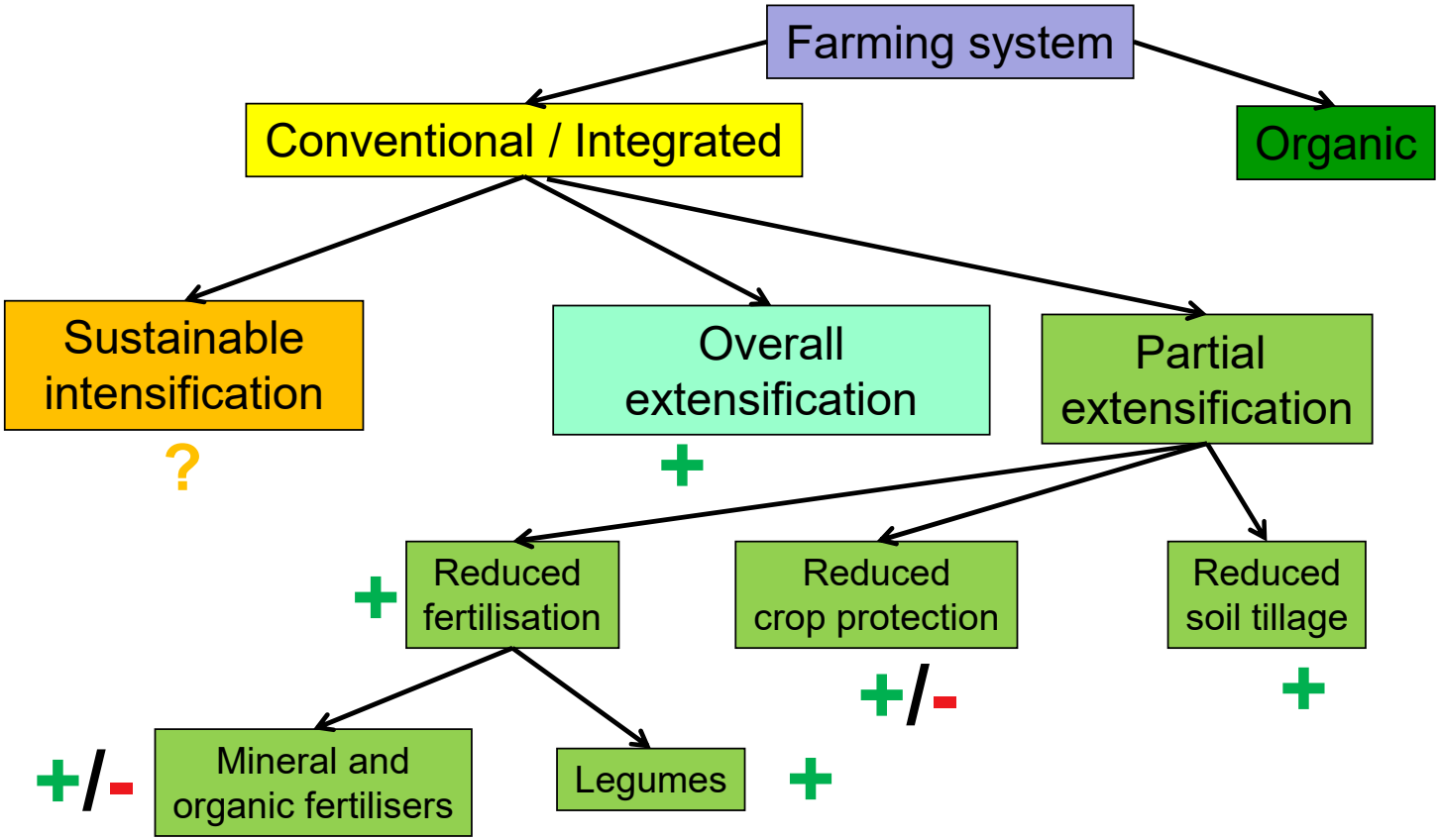
extensify

conventional / high-input systems
→ optimisation **input**-oriented

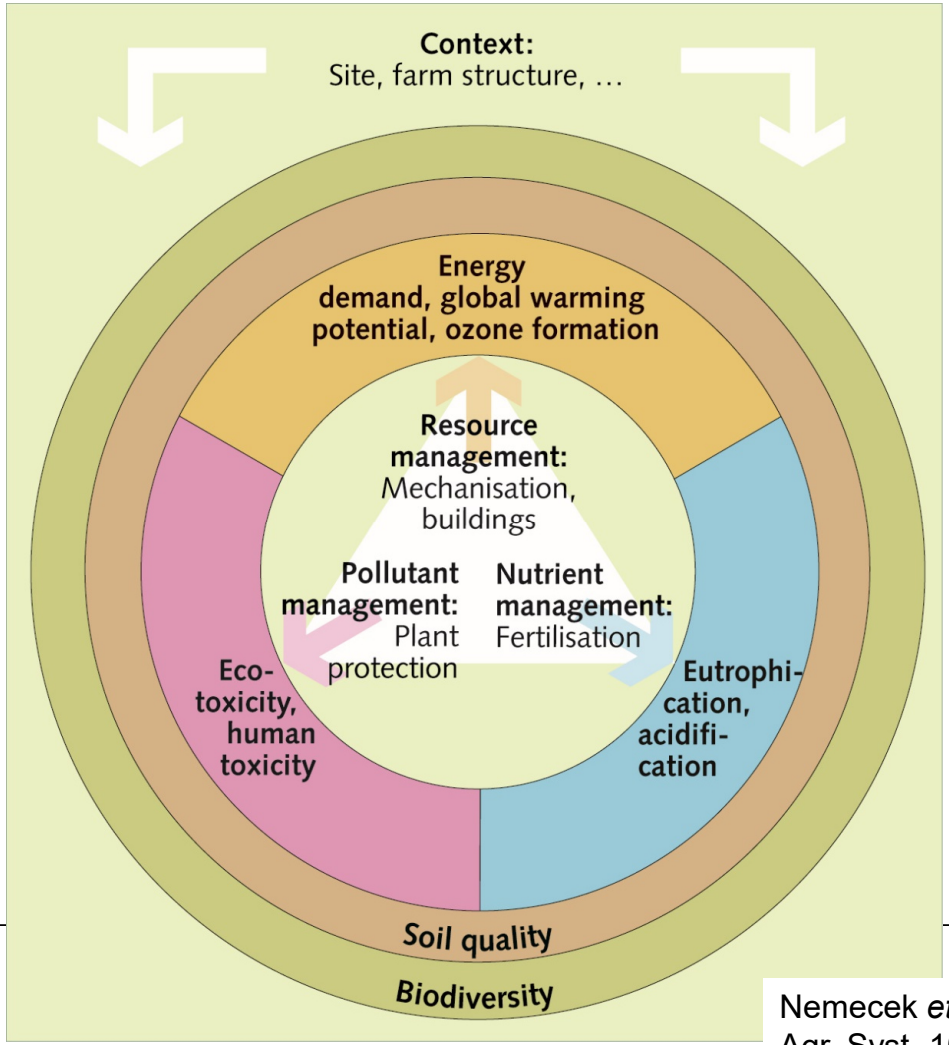
Nemecek *et al*. (2005) FAL Schriftenreihe 58.

Productivity-Intensity-Efficiency

Approaches to optimisation and sustainable intensification of cropping systems

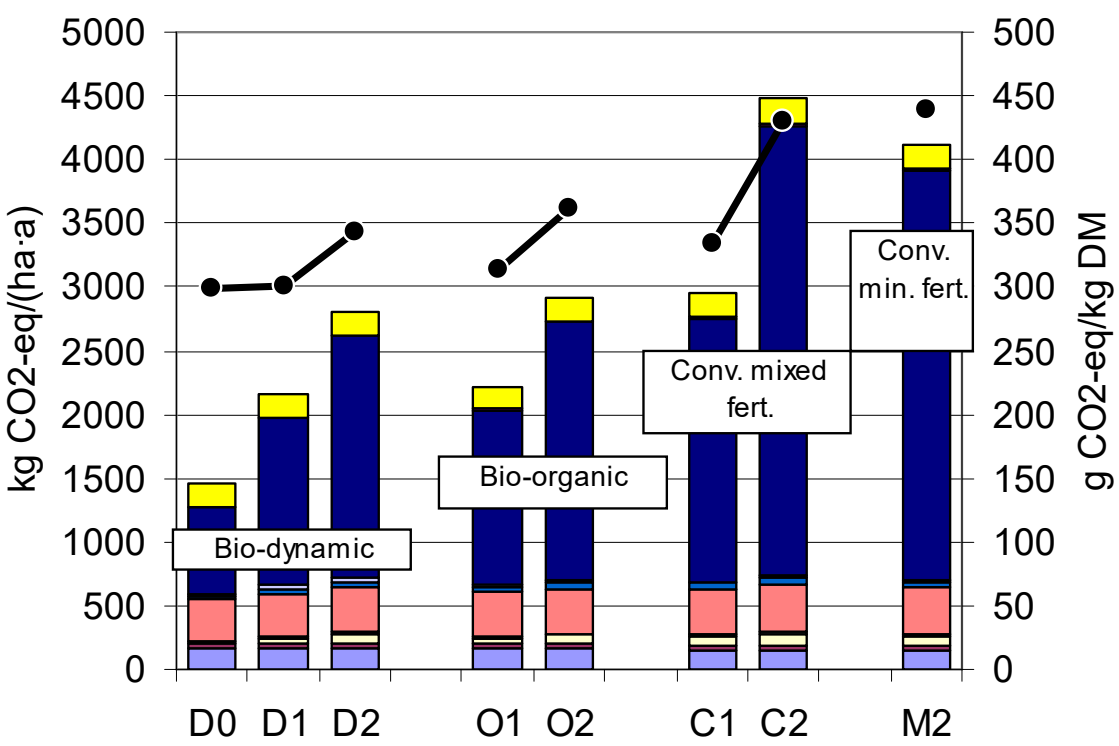


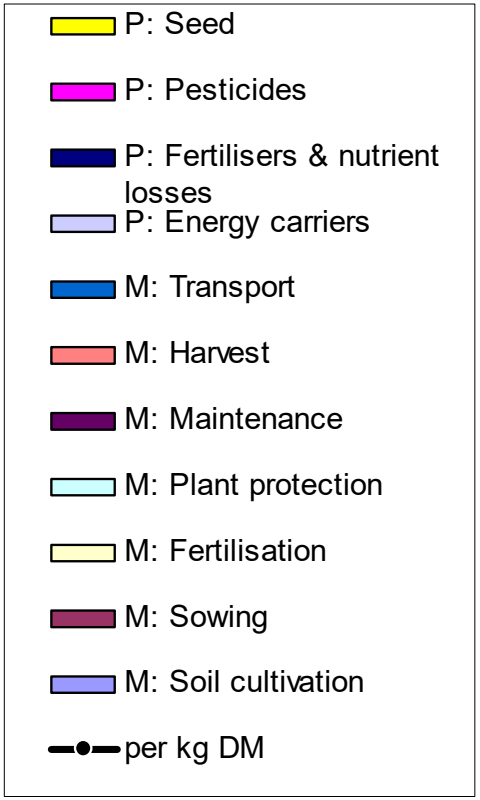
Management of farming systems: 3 axes of improvement



Nemecek *et al*. (2011a&b)
Agr. Syst. 104: 217-232 & 233-245

LCA of DOC trial
Climate change

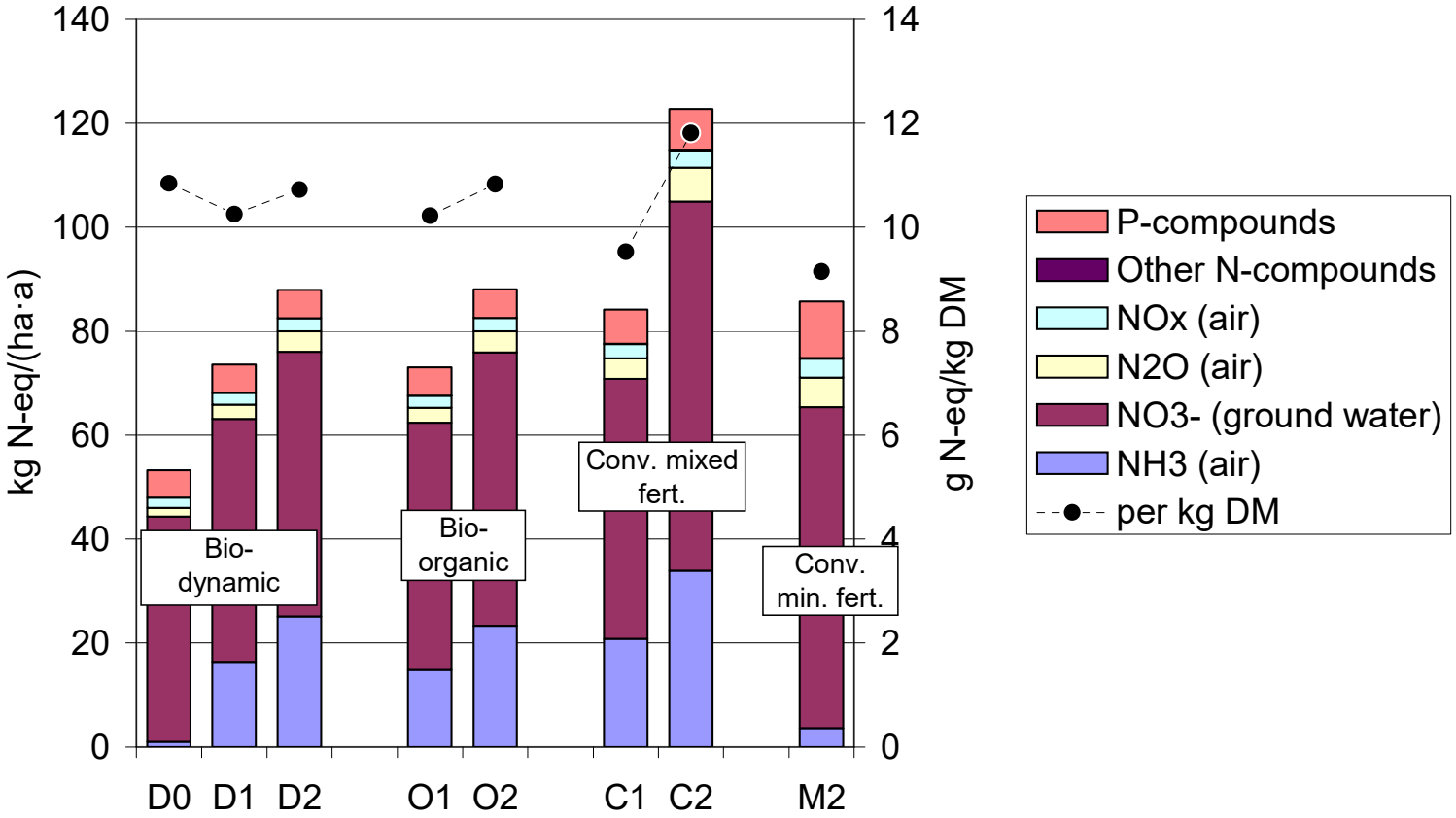




D = Bio-dynamic
O = Organic
C = Conventional (mixed min./org. fertilisation)
M = Conventional (mineral fertilisation)
2 = normal fertilisation level
1 = 50% fertilisation level
0 = no fertilisation

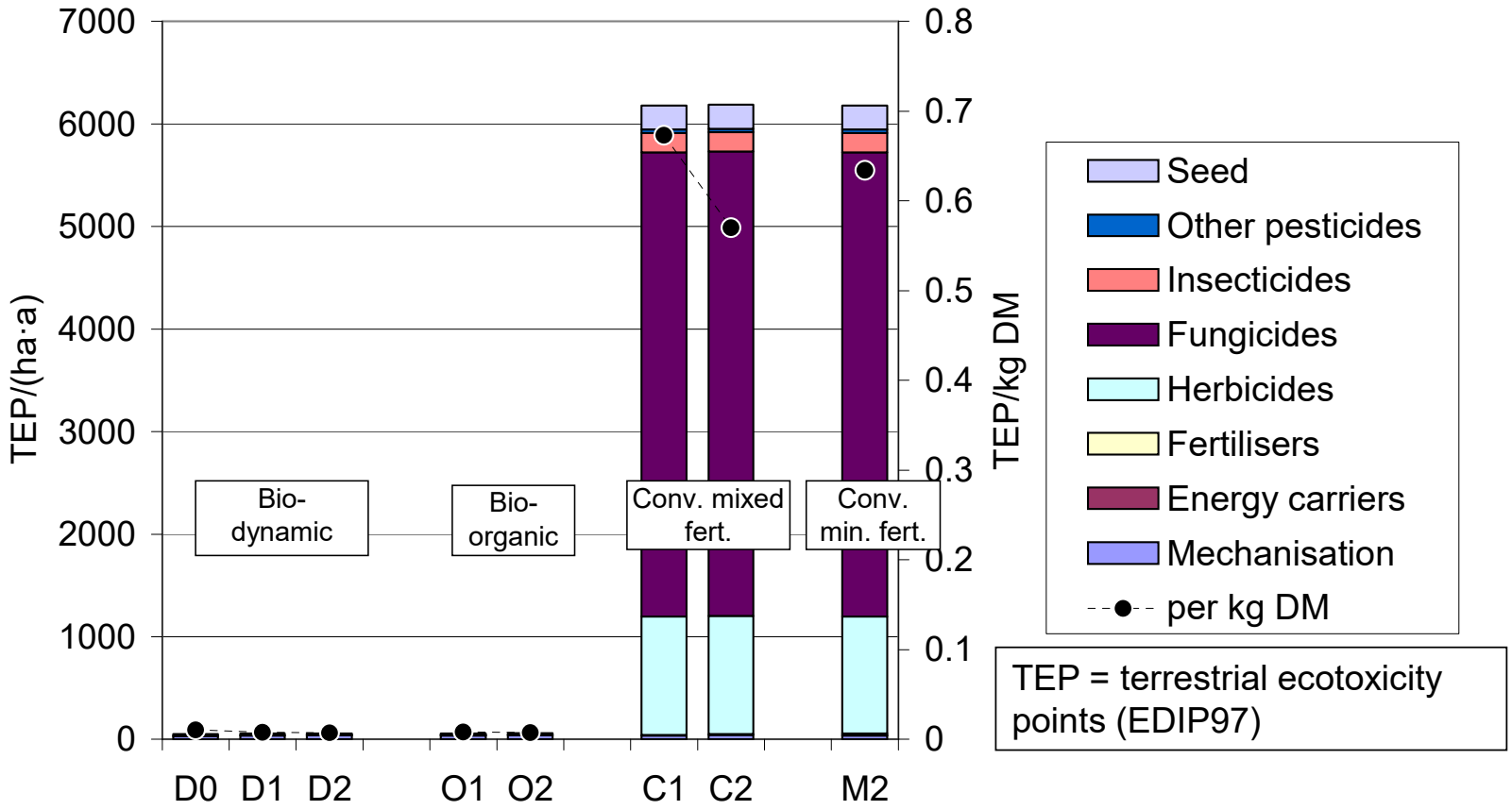
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LCA of DOC trial
Eutrophication potential



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LCA of DOC trial
Terrestrial ecotoxicity potential



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LCA of DOC trial
SALCA biodiversity assessment

Biodiversity points	D0	D1	D2	O1	O2	C1	C2	M2
Total species richness								
Total aggregated	**8.7**	**8.1**	**8.0**	**8.0**	**8.0**	**7.7**	**7.6**	**7.6**
Flora arable land	14.8	13.9	13.9	13.8	13.8	12.8	12.6	12.5
Flora grassland	4.9	4.3	4.1	4.2	4.2	4.1	3.9	3.9
Birds	10.3	8.7	8.6	8.5	8.5	8.0	8.0	7.9
Small mammals	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Amphibians	2.5	2.1	2.1	2.1	2.1	2.0	2.0	2.0
Molluscs	2.5	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Spiders	13.9	13.2	13.2	13.0	13.0	12.2	12.0	12.1
Carabids	14.7	14.0	14.0	14.0	14.0	13.7	13.5	13.6
Butterflies	9.8	8.8	8.6	8.8	8.6	8.5	8.4	8.5
Wild bees	4.9	4.8	4.8	4.8	4.8	4.8	4.8	4.9
Grasshoppers	11.0	9.8	9.5	9.9	9.6	9.4	9.3	9.3
Species with high ecological requirements								
Amphibians	1.7	1.4	1.3	1.3	1.3	1.3	1.2	1.3
Spiders	13.4	12.7	12.6	12.5	12.4	11.6	11.5	11.6
Carabids	14.7	14.0	14.0	14.0	14.0	13.7	13.6	13.7
Butterflies	9.8	8.8	8.5	8.8	8.5	8.4	8.4	8.5
Grasshoppers	10.9	9.6	9.3	9.6	9.4	9.2	9.1	9.2
Higher values mean higher species richness								
favourable								
very favourable								

compared to reference C2

D = Bio-dynamic
O = Organic
C = Conventional (mixed min./org. fertilisation)
M = Conventional (mineral fertilisation)
2 = normal fertilisation level
1 = 50% fertilisation level
0 = no fertilisation
Grey = reference

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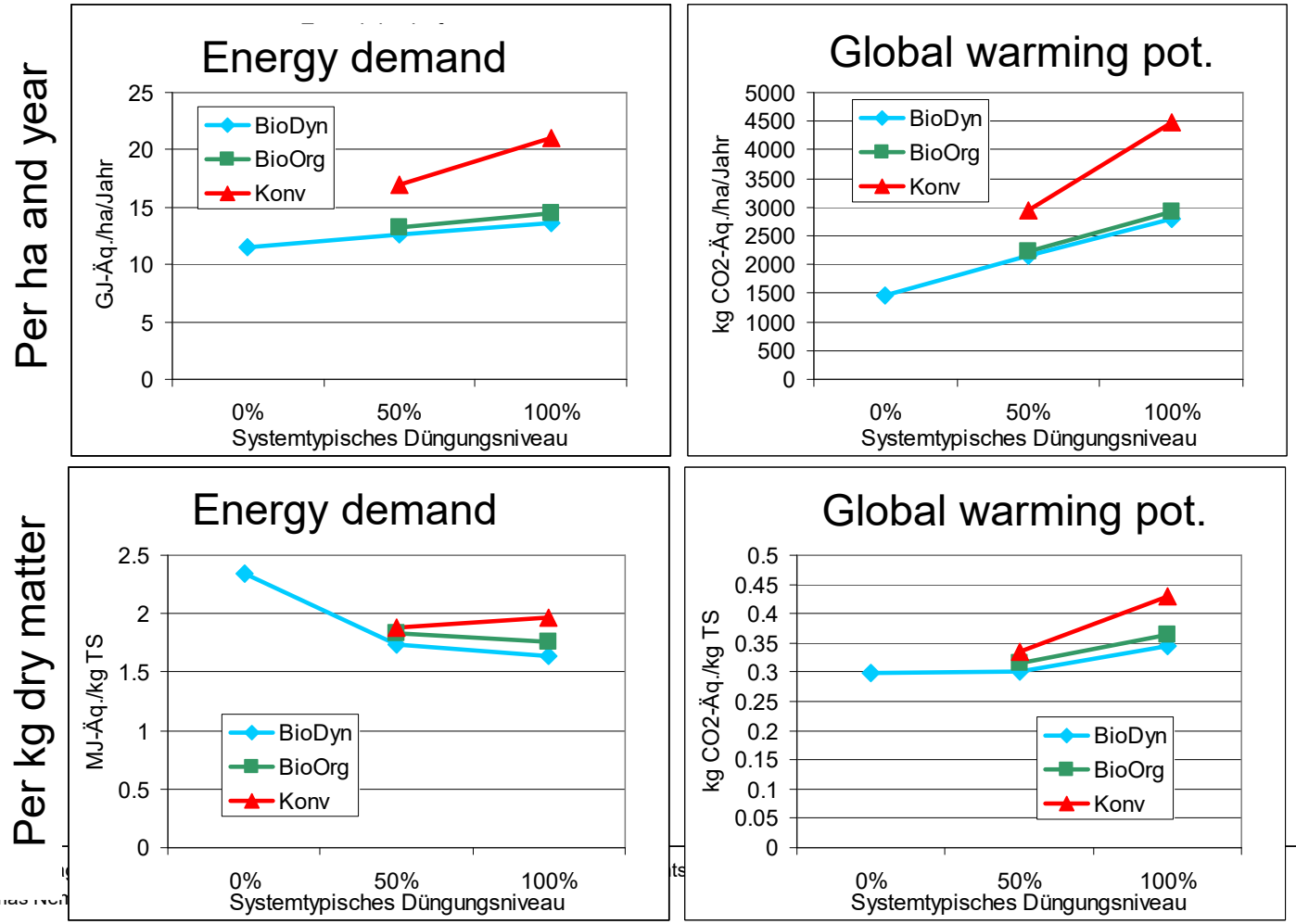
LCA of DOC trial: SALCA soil quality assessment (potential impacts)

		D0	D1	D2	O1	O2	C1	C2	M2
Phy-sical	Rooting depth of soil	0	0	0	0	0	0	0	0
	Macropore volume	0	0	0	0	0	0	0	0
	Aggregate stability	-	0	+	0	+	0	+	-
Chemi-cal	Corg content	--	0	+	0	+	0	+	--
	Heavy metal content	0	0	0	0	0	0	0	0
	Organic pollutants	0	0	0	0	0	0	0	0
Biolo-gical	Eathworm biomass	0	0	0	0	0	0	0	0
	Microbial biomass	-	0	+	0	+	0	+	-
	Microbial activity	-	0	+	0	+	0	+	-

very unfavourable	--
unfavourable	-
neutral	0
favourable	+
very favourable	++

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LCA of DOC trial: Reduced fertilisation



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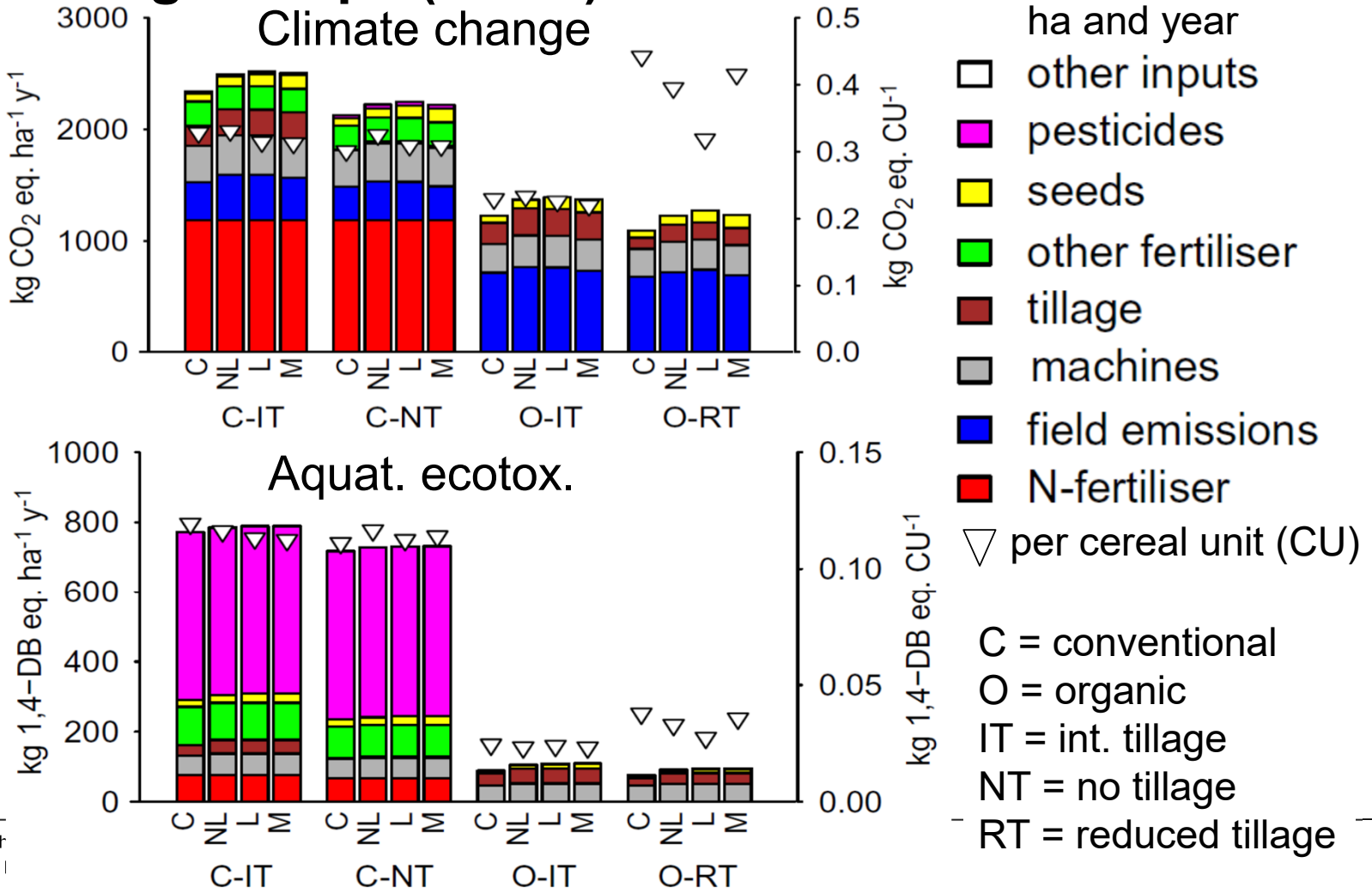
LCA of Oberacker trial: Plough vs. no-till

	Impact	Unit	Per ha and year			Per t DM yield		
			Ploughing (P)	No-till (N)	N in % P	Ploughing (P)	No-till (N)	N in % P
Ressource management	Energy demand	MJ-eq	16050	14746	92%	1655	1459	88%
	Global warming pot.	kg CO2-eq	0.59	0.48	82%	0.061	0.048	78%
	Ozone formation	kg C2H4-eq	2141	2070	97%	220.7	204.7	93%
Nutrient management	Eutrophication	kg N-eq	48.4	45.2	93%	4.99	4.47	90%
	Acidification	kg SO2-eq	14.1	13.2	93%	1.46	1.31	90%
Pollutant management	Aquatic ecotoxicity	points	1006119	840749	84%	103714	83163	80%
	Terrestrial ecotoxicity	points	827257	1938304	234%	85276	191728	225%
	Human toxicity	points	716	517	72%	73.8	51.2	69%

Soil quality	Indicator	P	N
Physical	Rooting depth of soil	0	0
	Macropore volume	+	++
	Aggregate stability	+	+
Chemical	Corg content	0	0
	Heavy metal content	0	0
	Organic pollutants	0	0
Biological	Eathworm biomass	+	++
	Microbial biomass	0	0
	Microbial activity	0	0

Nemecek *et al*. (2011a&b) Agr. Syst. 104: 217-232 & 233-245

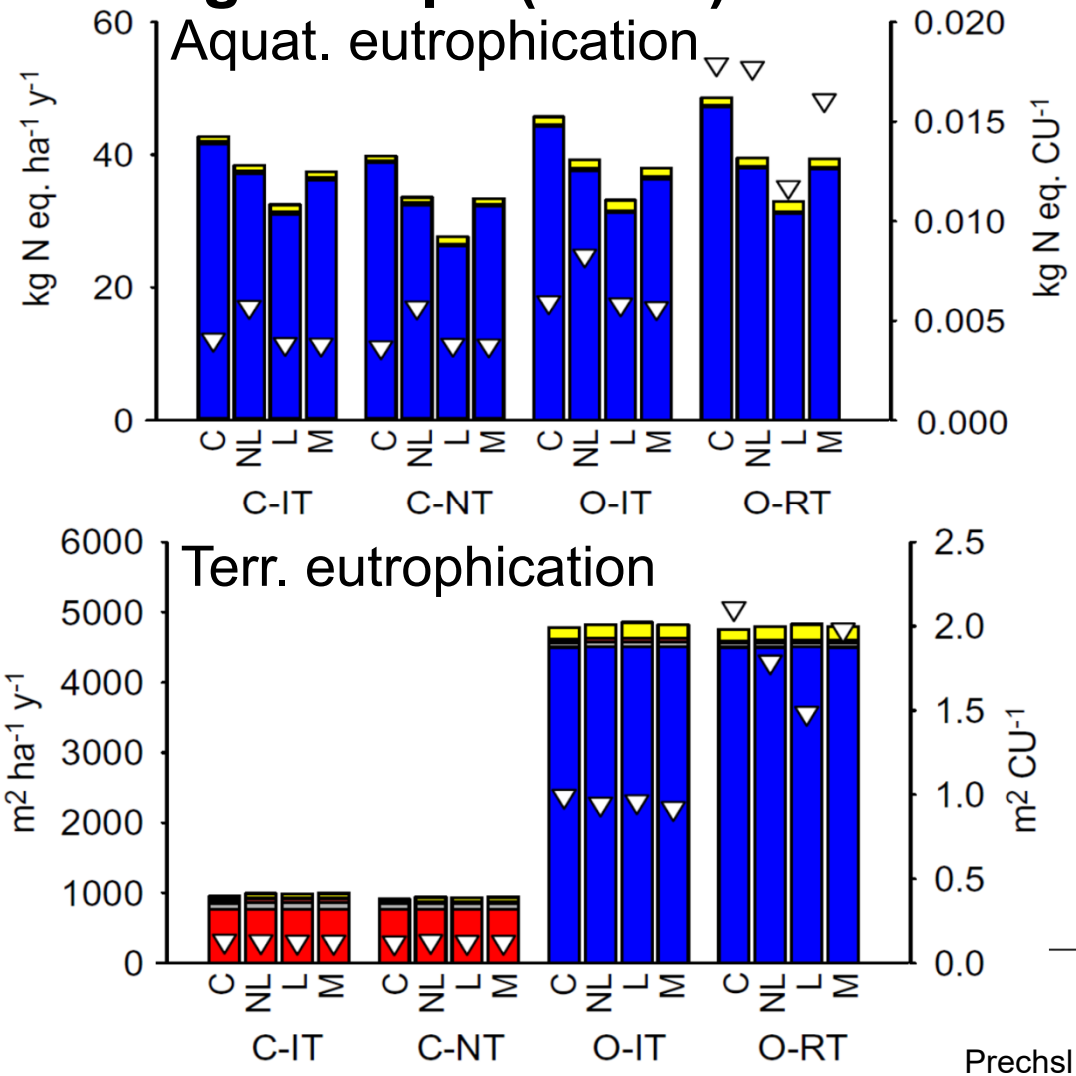
Farming System and Tillage Experiment Agroscope (FAST)



Prechsl *et al*. (2017) Agr. Syst., 157: 39-50.

Agroscope

Farming System and Tillage Experiment Agroscope (FAST)



Columns: per ha and year

- other inputs
- pesticides
- seeds
- other fertiliser
- tillage
- machines
- field emissions
- N-fertiliser

▽ per cereal unit (CU)

C = conventional
O = organic
IT = int. tillage
NT = no tillage
RT = reduced tillage

Prechsl *et al*. (2017) Agr. Syst., 157: 39-50.

Major mitigation opportunities in food production

- Crop production:
  - The right crop at the right place:
    - Avoid crops on peat soils and deforested areas
    - Avoid areas with endangered species
    - Avoid growing crops with high water demand in arid areas
  - Avoid too low yields
  - Avoid unnecessary fertilisation, plant protection, and irrigation (as much as needed, not less, not more)
- Animal production:
  - Choose the adequate production system (e.g. beef from dairy systems)
  - Develop animal-friendly and low-emission husbandry systems
  - Increase feed conversion efficiency
  - Produce and use feedstuffs with low environmental impacts
  - Increase the use of animal by-products for human consumption ("nose-to-tail" strategies)

Some limitations of LCA of agricultural systems possible solutions

- Not able to cover all environmental impacts
  → Needs comprehensive methods
- Not able to discriminate between systems
  → Needs specific methods (for the foreground system)
- Product LCA is unable to reflect the whole system
  → Extend the system boundaries → Use system LCA
- Ecosystem services not covered
  → Combine with ecosystem service assessment

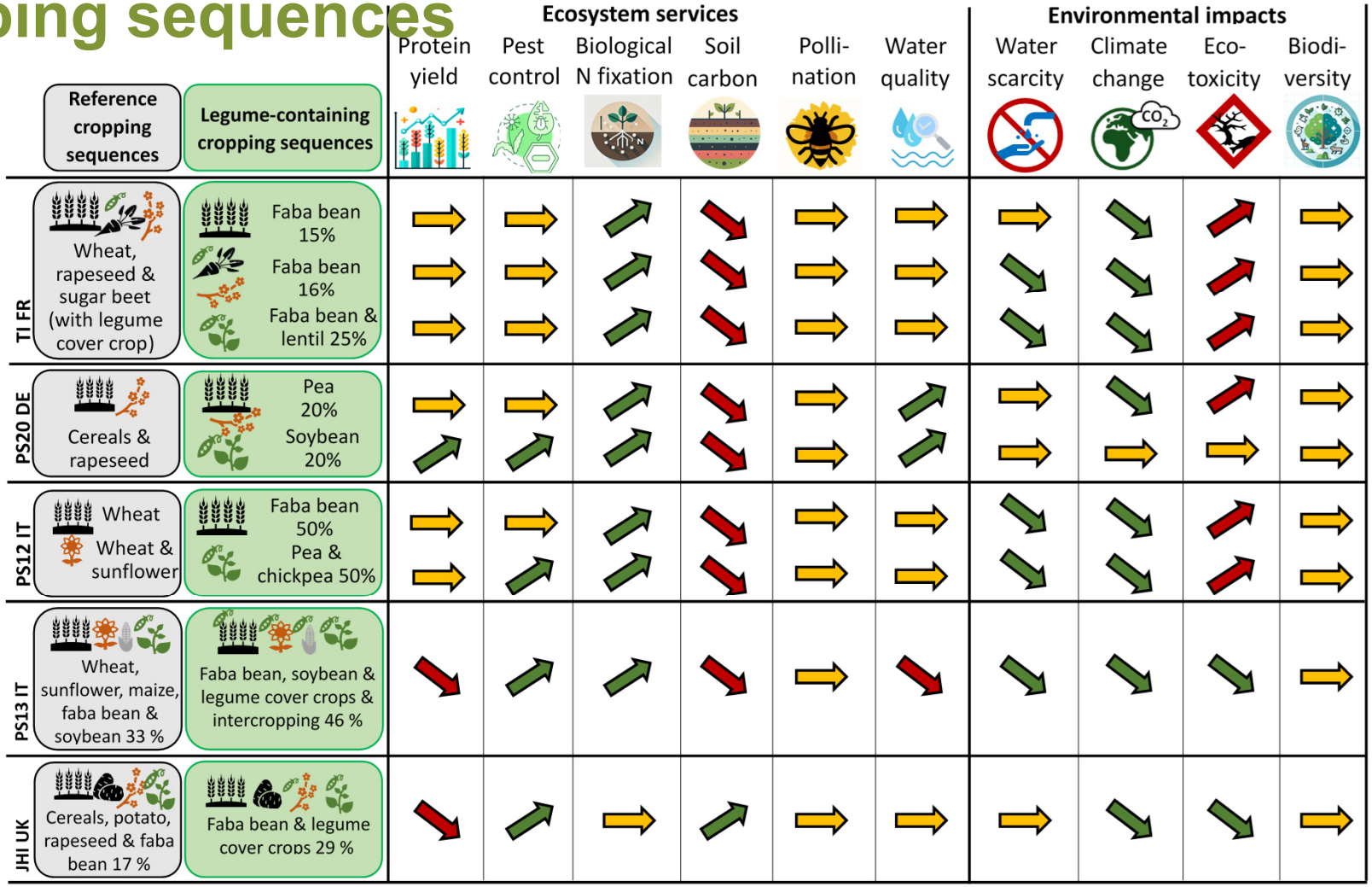
Agroscope

Combining LCA with ecosystem service assessment

	Class	Method to be used
Provisioning	1.1.1.1 Cultivated terrestrial plants grown for nutritional purposes	Yield measurement: kg DM yield, kg protein yield
	1.1.1.2 Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)	Not relevant for the current pilot studies
	1.1.1.3 Cultivated plants (including fungi, algae) grown as a source of energy	Not relevant for the current pilot studies
Regulation & Maintenance	2.2.1.1 Control of water erosion rates	Erosion (C-factor) based on RUSLE (Lago-Olveira et al. 2023)
	2.2.2.1 Regulation runoff and base flows	LANCA Infiltration reduction potential, $m^3/(m^2*a)$ (Bos et al. 2016)
	2.3.2.1 Pollination	Land use impact on pollinator abundance (Alejandre et al. 2023)
	2.3.2.4 Maintaining or regulating refuge habitats	SALCA-BD: habitat value (Jeanneret et al. 2014)
	2.3.2.5 Maintaining or regulating feeding grounds	SALCA-BD: habitat value (Jeanneret et al. 2014)
	2.3.3.1 Pest control (including invasive species)	SALCA-BD: Spiders, Carabids (Jeanneret et al. 2014)
	2.3.4.2 Decomposition and fixing processes and their effect on soil quality	BNF equation (Korsaeth & Eltun 2000), DNDC (UniPG)
	2.3.4.3 Maintenance of soil structure by biological agents and ecological processes	SALCA-SQ macropore volume (Oberholzer et al. 2012)
	2.3.5.1 Regulation of the chemical condition of freshwaters by living processes	P and N leaching assessed using SALCAnitrate and SALCAfieldP models
	2.3.6.1 Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental scale	Soil humus balance according to SALCA-SQ soil carbon content calculation (Oberholzer et al. 2012)

Joensuu *et al*. (unpublished)

Effect on key ES and EI indicators of adding legumes to the cropping sequences



Ecosystem services

= Difference compared to the reference more than -10%

= Difference compared to the reference more than +10%

Environmental Impacts

= Difference compared to the reference more than +10%

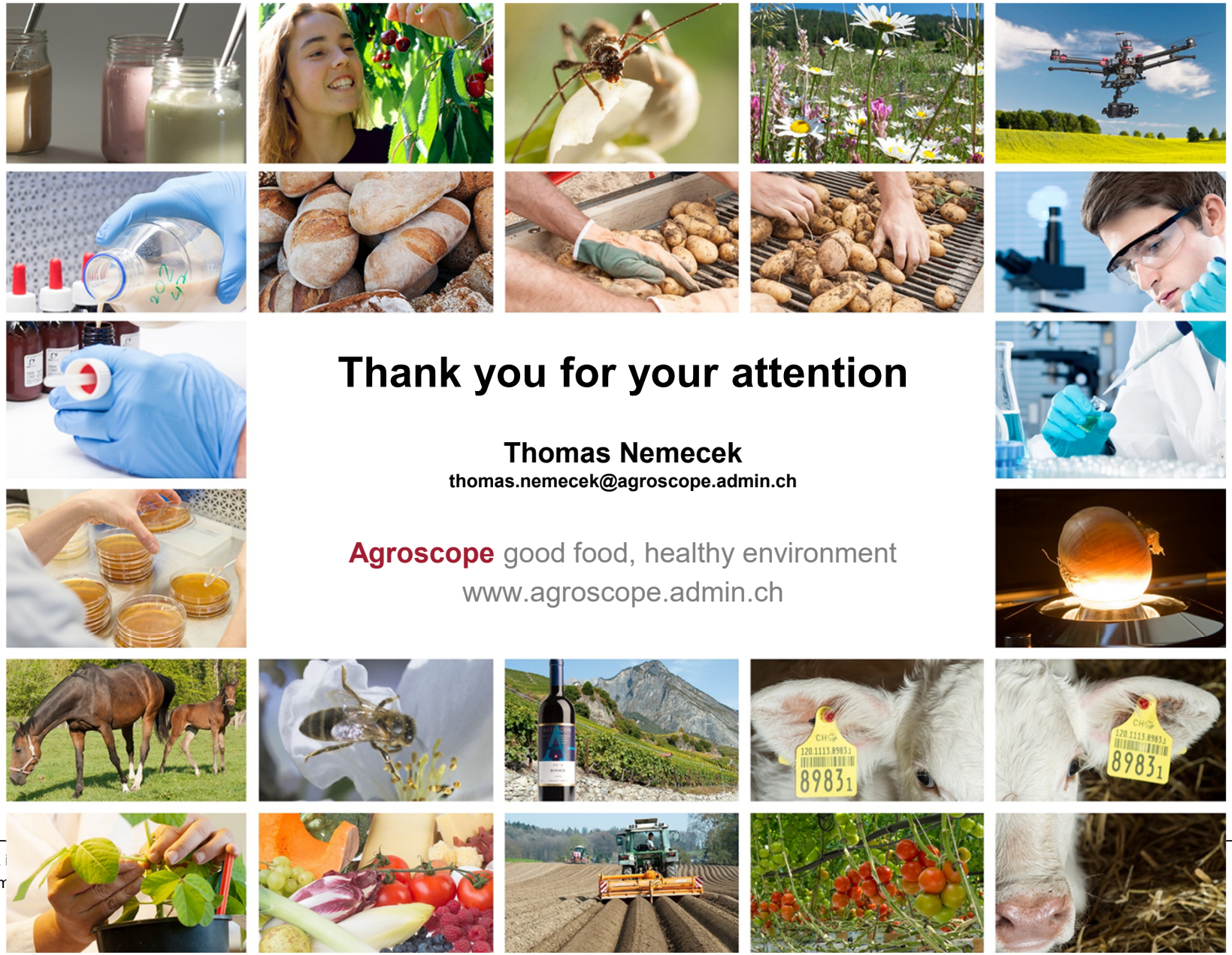
= Difference compared to the reference more than -10%

Joensuu *et al.* (unpublished)

Some take-aways

- Variability of environmental impacts is high
- Organic production has lower impacts per area, but this advantage is partly undermined by lower yields
- Comparison of farming systems are best done at system level (cropping system, farm, food system)
- Referring environmental impacts to the product is a shift in paradigm (choice of functional unit)
- Is LCA suited for the assessment of non-conventional and agro-ecological systems? Yes, but it needs
  - A comprehensive assessment
  - Specific methods
  - Extension with ecosystem services assessment

Agroscope



Thank you for your attention

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