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Model based approaches for the investigation of technical sustainability of agricultural production systems

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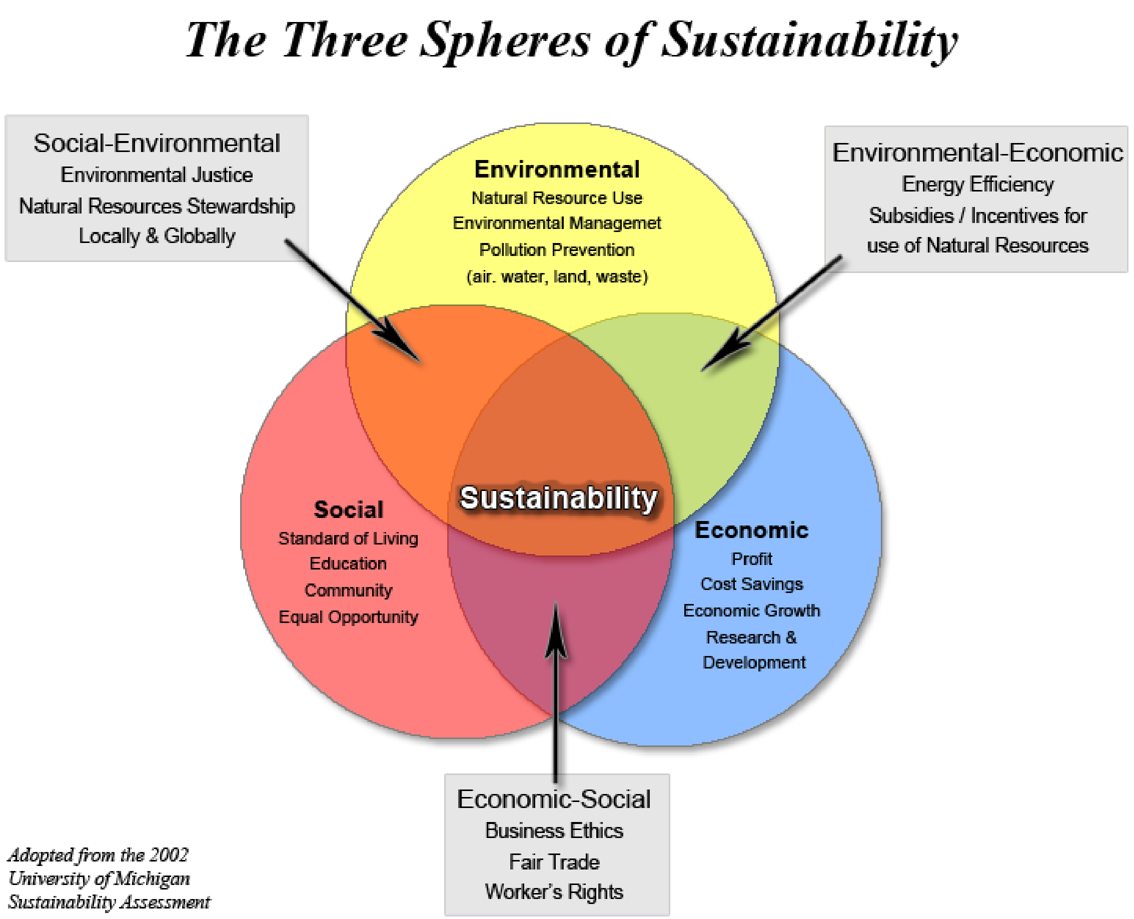
Sustainability

World Commission of Environment and Development (UN-WCED, 1987), Brundtland Commission

‘Meeting the needs of the present without compromising the ability of future generations to meet their own needs’

- Very philosophical definition
- How to implement in practice?

Sustainability



Technical sustainability

The ability of a Biological Production System (BPS) to make an efficient use of the available bio-physical resources with the main goal to maximize its economical output and minimize its environmental impact, given a set of uncontrolled biophysical constraints

Technical sustainability is related to overall resource-use efficiency

Efficiency can be described by output-input relations

Do more with less

A holistic or systems approach is necessary

Systems approach to Biological Production Systems (BPS)

A BPS is defined as a complex interplay of in- and outputs, managed by man and influenced by environmental-, political-, economical-, institutional- and social factors with as general objective to produce biomass and/or preserve the environment

- Production of 7f: food, feed, fiber, fuel, fertilizer, fine chemicals, flower
- Agro-ecological point of view: sustainable natural resource management

Technical sustainability focuses on the interplay of bio-physical factors

Systems approach to BPS

Bio-physical operational framework for BPS research

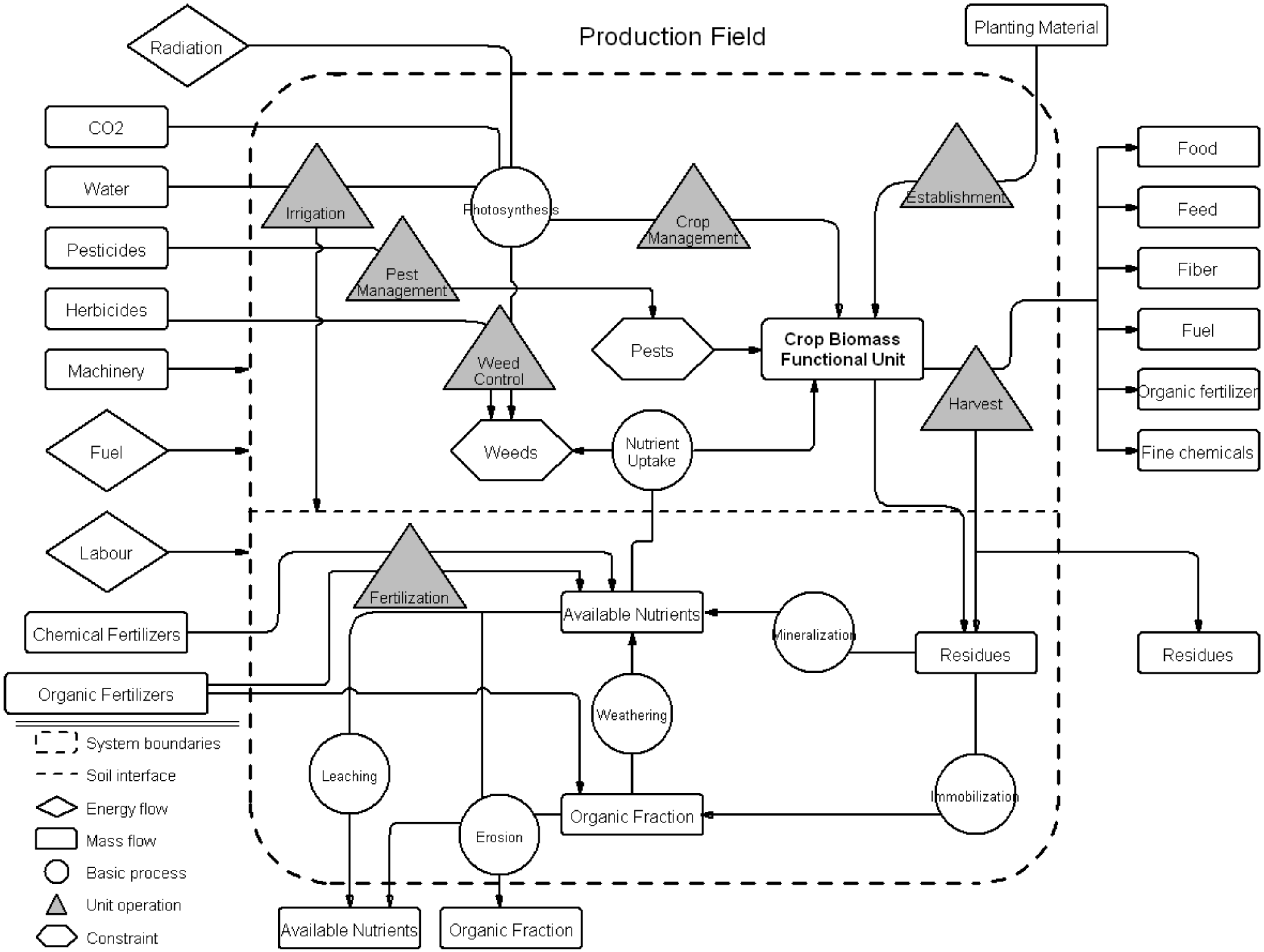
1. Functional unit: *kg produce or ha, farm*
2. Basic processes: *photosynthesis, respiration, nutrient and water uptake, transpiration, sink-source relations, …*
3. Constraints: *climate, soil, water, land, genetics, …*
4. Unit operations: fertilization, irrigation, pest management, postharvest operations, …

Unit operations are the building blocks of the BPS

Unit operations integrate basic processes and constraints

Unit operations can be described by the mass, energy and information flows they create

Systems approach to BPS



General objective

Development of generic methodologies for quantitative and holistic evaluation of technical sustainability of farming systems at field, farm and regional level

Research methodologies for technical sustainability (TS)

- Define an operational framework for farming systems research on the field and farm level, considering processes, constraints and unit operations as well as their interactions
- Conceptual analysis model ⇔ NO book of recipes
- Set mission of FSR
- Development of formal predictive models
- Develop optimal data acquisition methods
- Setup of optimal data base structure
- Characterize the error propagation of the methods by performing different types of uncertainty analysis

Data acquisition

- Inventory by sampling and experiment
  - Input-output accountancy (IOA)
- Inquiries by structured interviews
- Participatory research
- Verification of the information
- Corroboration of the information

Structured interviews

Universidad de Bogotá Jorge Tadeo Lozano
Centro de Bio-Sistemas
Multidisciplinary assessment of efficiency and sustainability of smallholder-based tomato production systems in Colombia, with a roadmap for change
II-2010
Productores de Tomate - Campo Abierto

Metadatos

Fecha de la encuesta | Número de la encuesta

Lugar de realización de la encuesta		
Latitud	Longitud	Altitud

Tiempo empleado para aplicar la encuesta	
Inicio	Final

Nombre del encuestador

Departamento | Municipio | Vereda

☐ Coordinador ☐ Est. PhD ☐ Est. BSc. ☐ Ingeniero ☐ Otro

1. El propósito es recopilar información básica del encuestado, incluyendo su nivel de educación

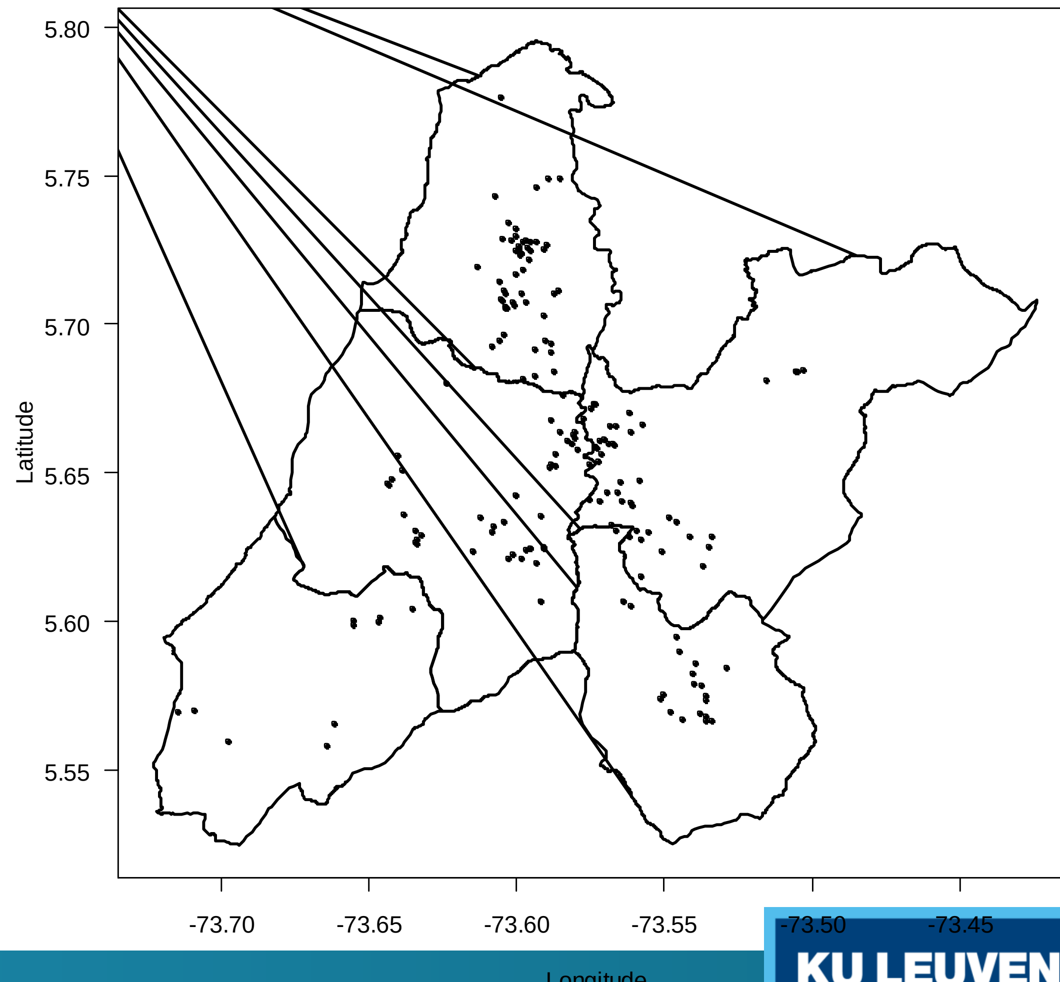
1.1 Nombre del encuestado | 1.2 Sexo ☐ Femenino ☐ Masculino

1.3 ¿Qué función desarrolla dentro de la unidad productiva? ☐ Propietario ☐ Administrador | Edad | 1.4 Teléfono

1.5 Área de la finca ☐ Ha ☐ Fa | 1.6 ¿Quién toma las decisiones técnicas en la finca en los siguientes aspectos? Técnico | Financiero

1.5 Nivel de educación de la familia del propietario de la unidad de producción de Tomate

Miembro d... | ... | Nivel | Actividad | En términos porcentuales cuál es el aporte ...



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Participatory research

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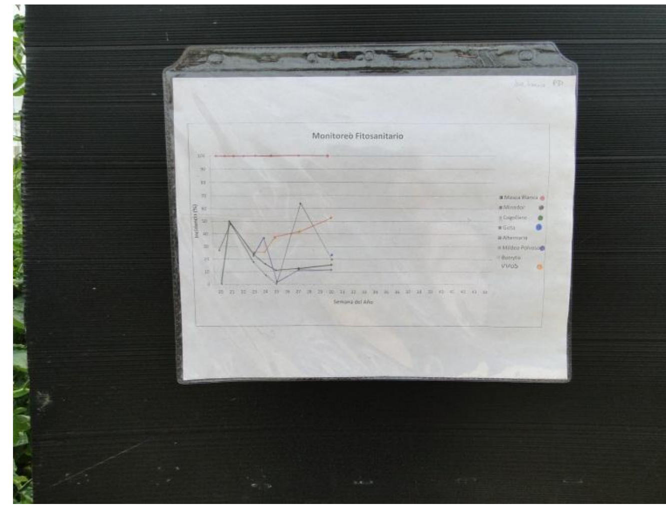
Detailed follow-ups



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Input output accountancy

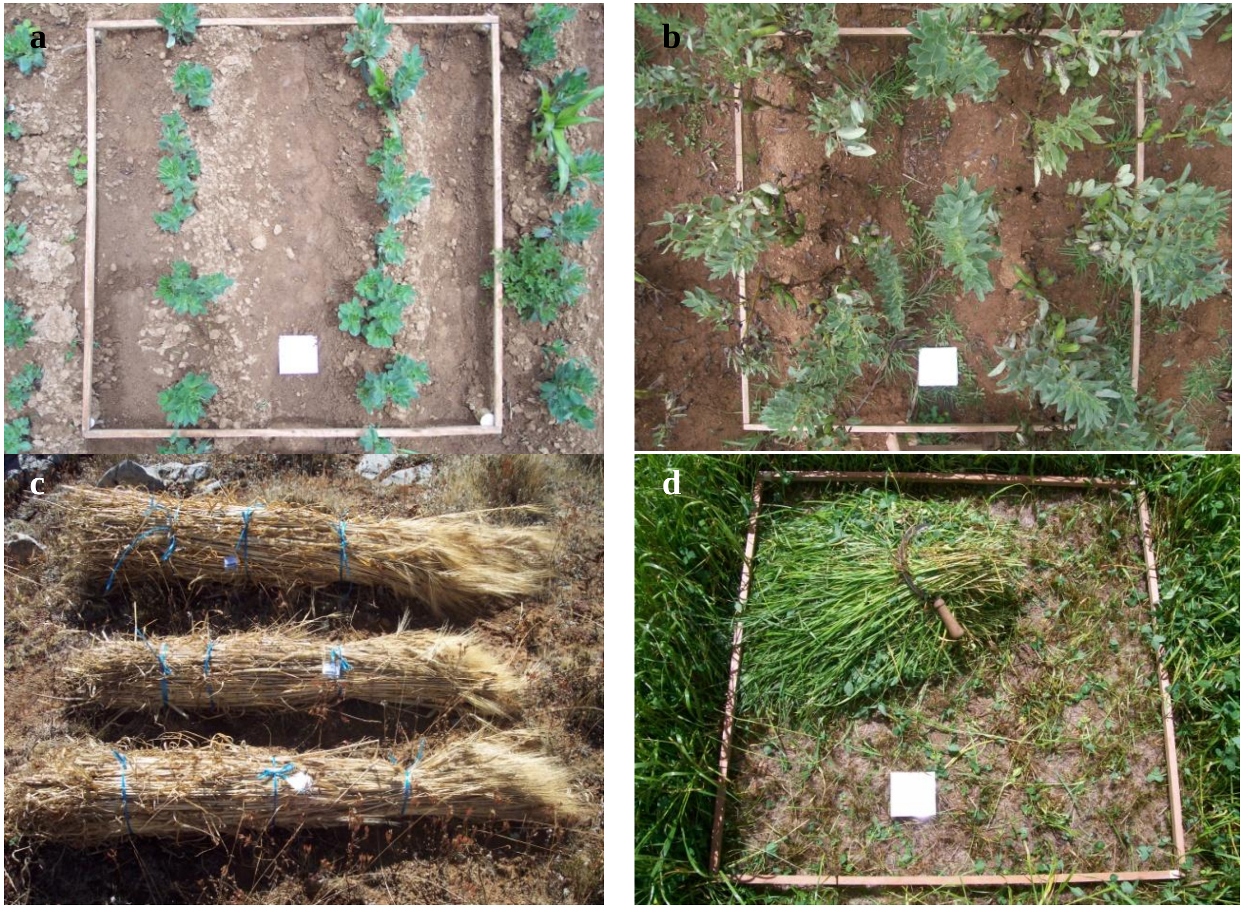
- Bio-physical input-output accountancy
  - ‘Measure’ all unit operations for the functional unit of the system on quantitative scales
    - Field level ⇔ crop production
    - Farm level ⇔ animal production
  - LCA-oriented approach, combined with structured interviews and participatory workshops
    - Quantitative description of representative farming systems
  - Integrate to farm, community and regional level

Data acquisition methodology

- Bio-physical input-output accountancy (IOA)
  - The unit-operations on pilot-plots are evaluated continuously through the crop season (planting to harvest).
    - Biophysical units: mass, energy
  - Biomass distribution over the growing season is measured through vegetation analysis on subplots (evaluation points).
    - Biomass of weeds (evaluated at weeding and before the harvest).
    - Commercial product, e.g. potato or barley grain.
    - Residual biomass that stays on the field, e.g. faba bean leaves.
    - Residual biomass removed for fodder, e.g. corn stalks.
    - Total harvested product per plot is registered and used to double-check the obtained yields from the evaluation points


Pilot plot 15

Evaluation points



Evaluation points

Image processing on evaluation points

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Research methodologies for TS

- Static, time invariant methods
  - Mass balances
  - Exploratory multivariate data analysis
  - Energy balances
  - Life Cycle Assessment (LCA)
- Dynamic methods
  - Nonlinear mixed models
  - Crop models
  - Systems models
    - Crop growth and development models, linked to soil nutrient and water transport models and crop management to investigate the technical sustainability of fertilization strategies
  - Modelbased LCA

Research methodologies for TS

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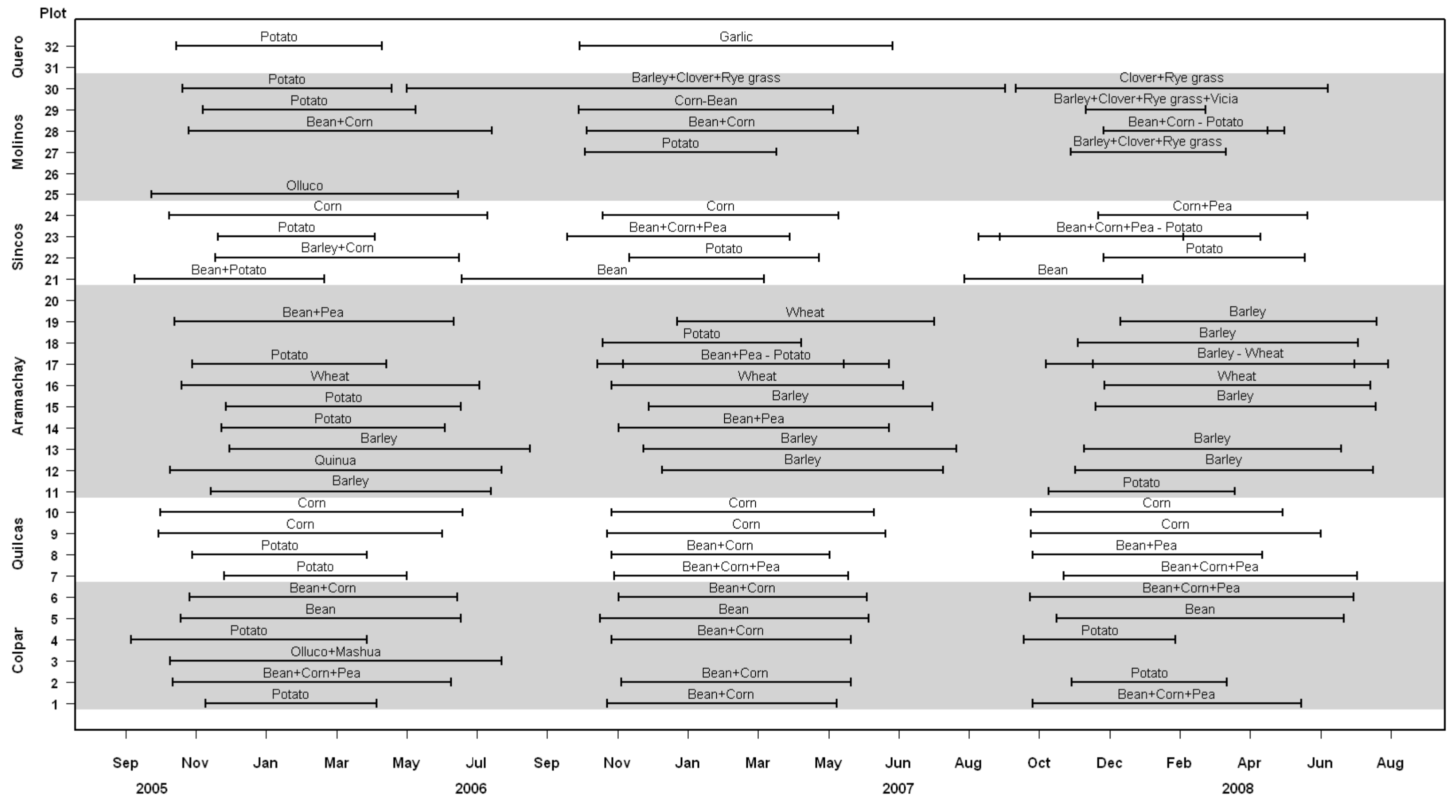
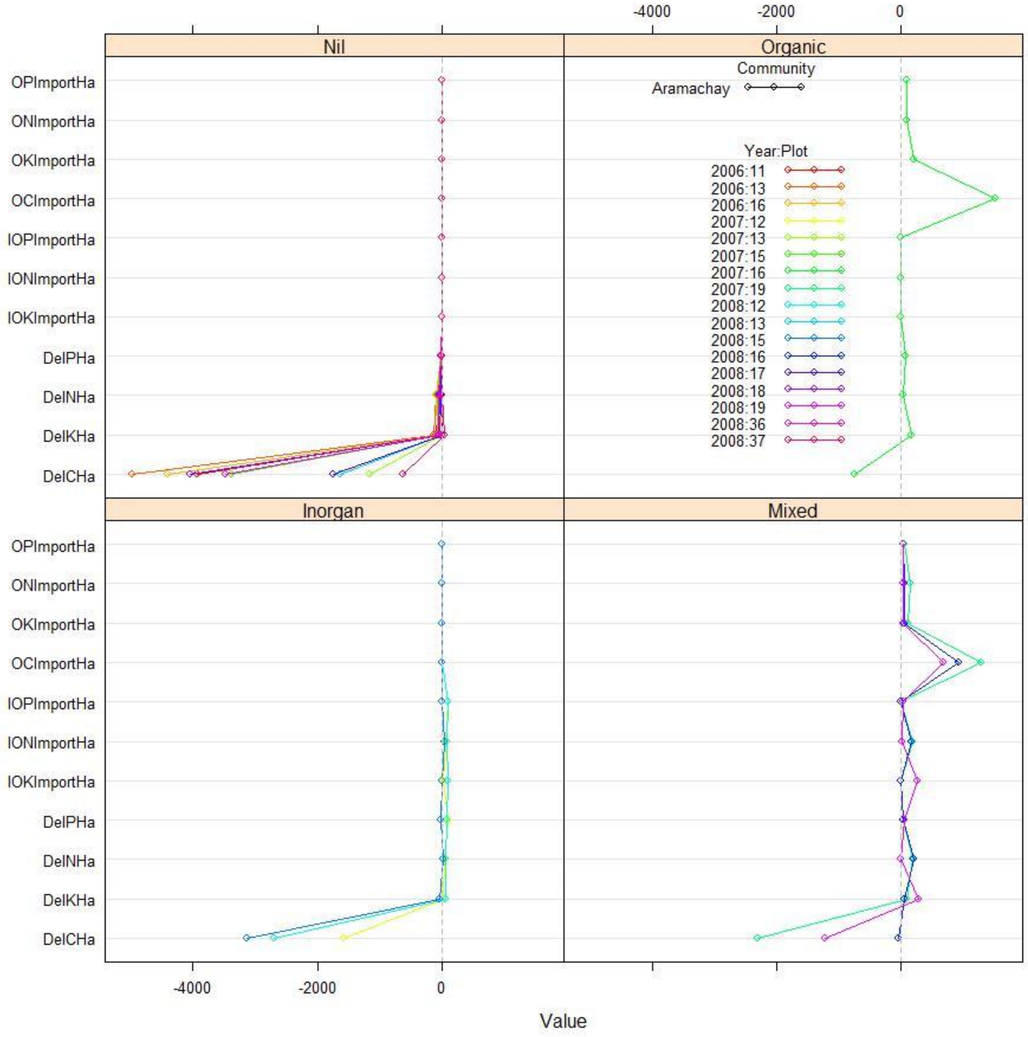
Mantaro valley, Peru



- 77 cropping cycles recorded, 2004 to 2008
- Most planted crop was potato, barley, corn, beans, associations
- 35% of the cycles included crop associations

Mass balances

- Barley production in Aramachay, Mantaro Valley, Peru



Four fertilization types (pannels)
- Nil: no fertilization
- Organic
- Inorganic
- Mixed

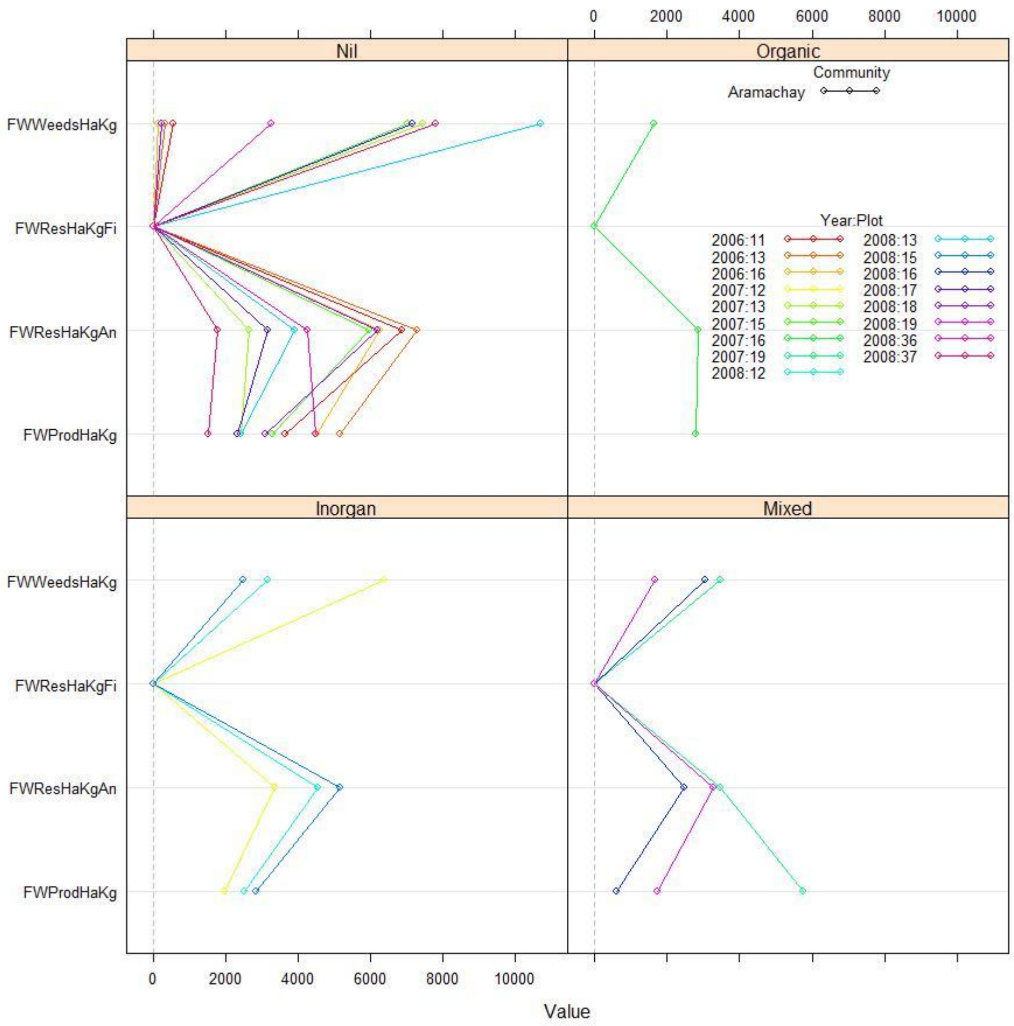
O.ImportHa: P, N, K and C-input by organic matter (kg ha-1)

IO.ImportHa: P, N, K-input by inorganic fertilizer (kg ha-1)

Del.Ha: Total import minus total export of P, N and K (kg ha-1)

Mass balances

- Barley production in Aramachay, Mantaro Valley,Peru



Four fertilization types (pannels)

Nil: no fertilization

Organic

Inorganic

Mixed

FWWeedsHaKg: weeds biomass production, remaining on the field (kg ha-1)

FWResHaKgFi: residual biomass production, remaining on the field (kg ha-1)

FWResHaKgAn: residual biomass, exported as animal fodder (kg ha-1)

FWProdHaKg: grain production (kg ha-1)

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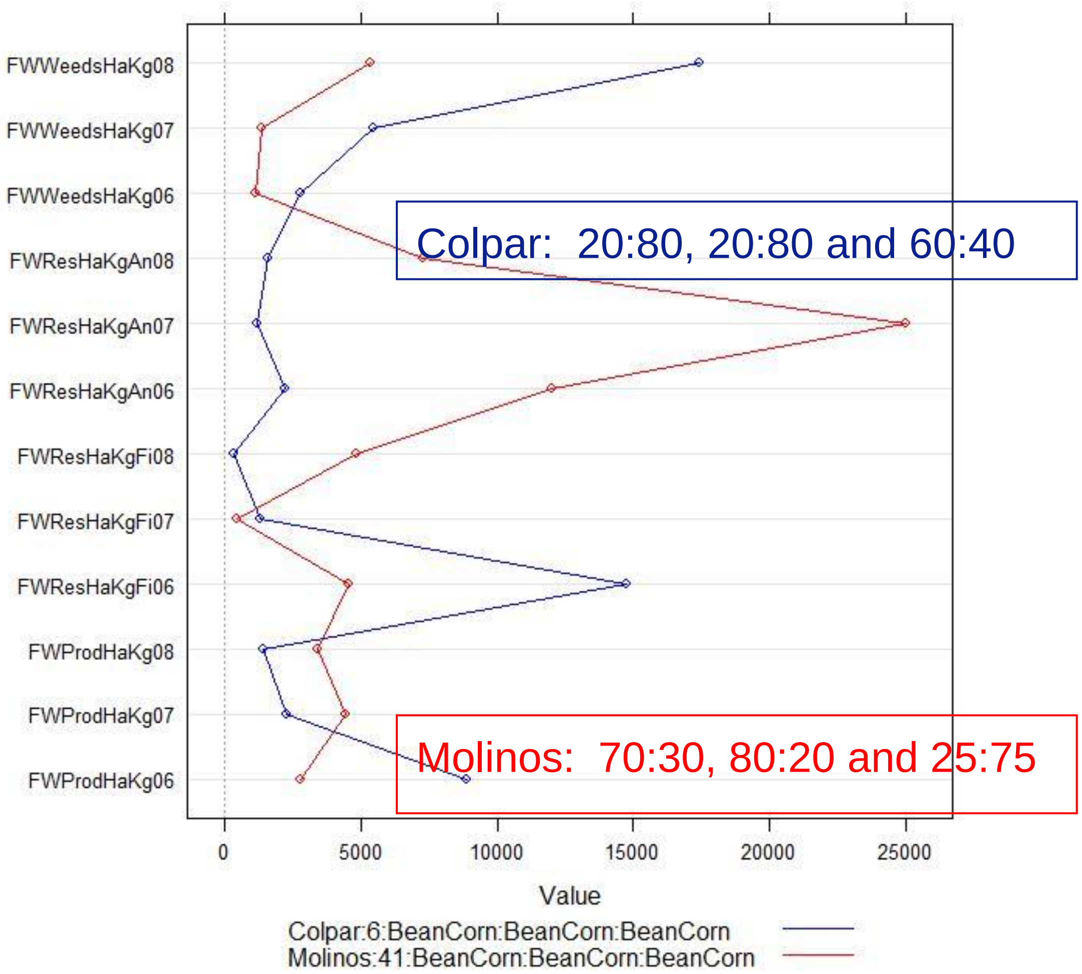
Mass balances

- Corn-bean association rotations in the Mantaro Valley, Peru



Evolution of yields, residues, straw and weeds in the continuous association of corn+faba bean in Colpar and Molinos.

FWWeedsHaKg: weeds biomass production, remaining on the field (kg ha-1)

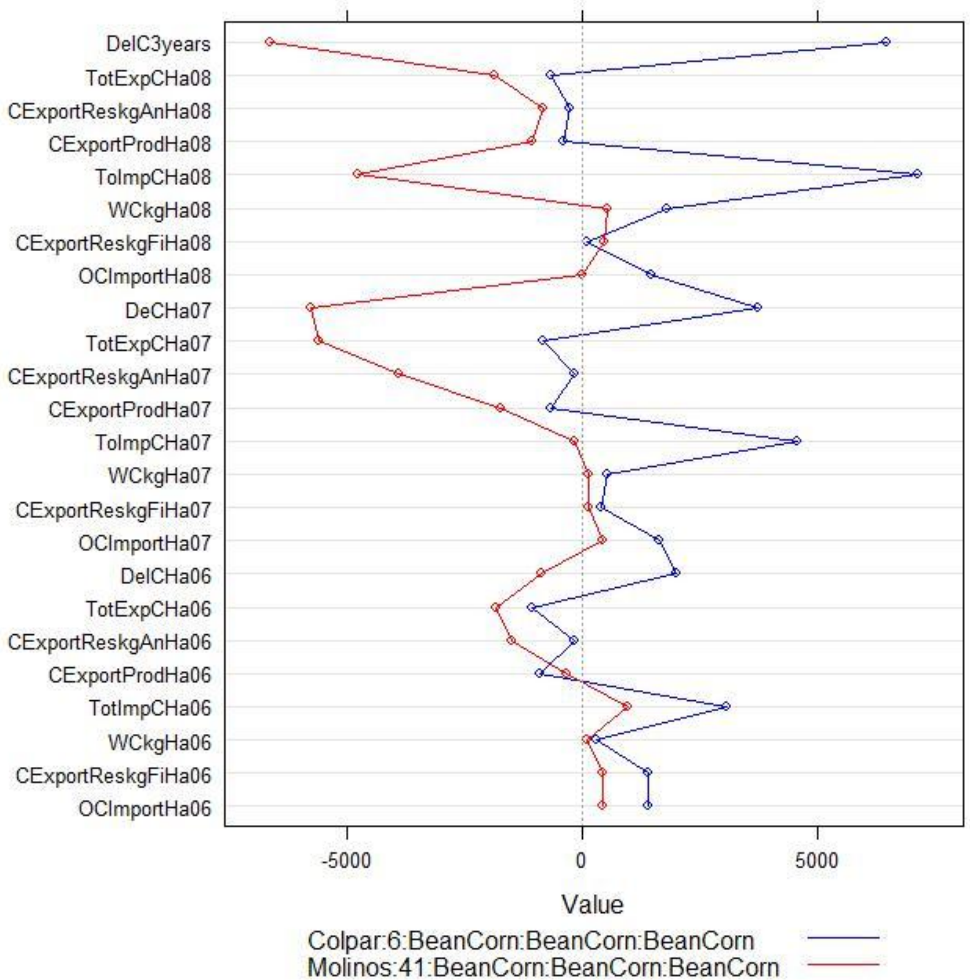
FWResHaKgFi: residual biomass production, remaining on the field (kg ha-1)

FWResHaKgAn: residual biomass, exported as animal fodder (kg ha-1)

FWProdHaKg: harvest production (kg ha-1)

Mass balances

- Corn-bean association rotations in the Mantaro Valley, Peru



C-balance (kg ha-1)

C-Imports in Manure, Weeds, Residual biomass

C-Exports in feed and food

DelC: C-Inputs – C-Exports

Colpar: 20:80, 20:80 and 60:40

Molinos: 70:30, 80:20 and 25:75

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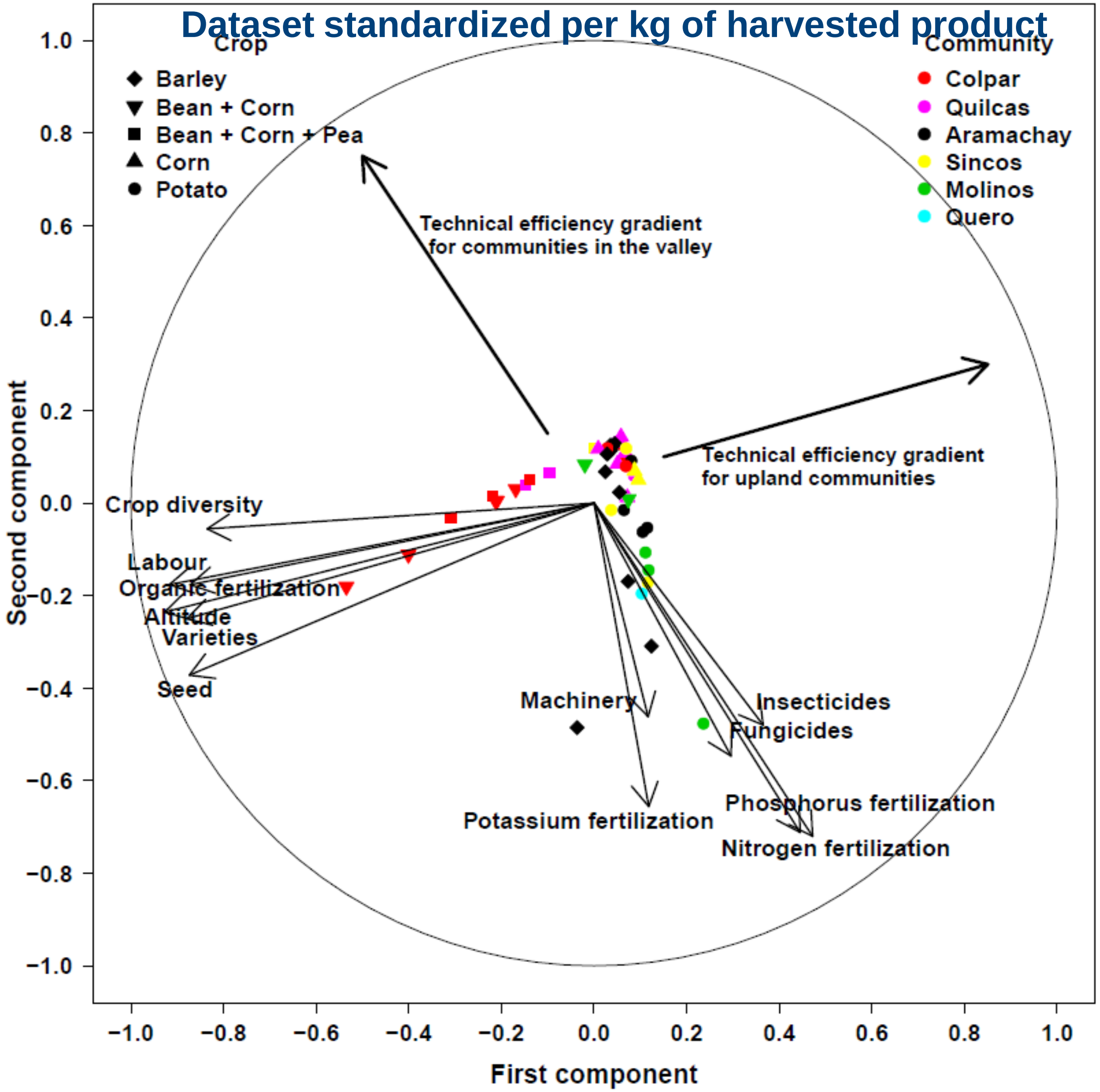
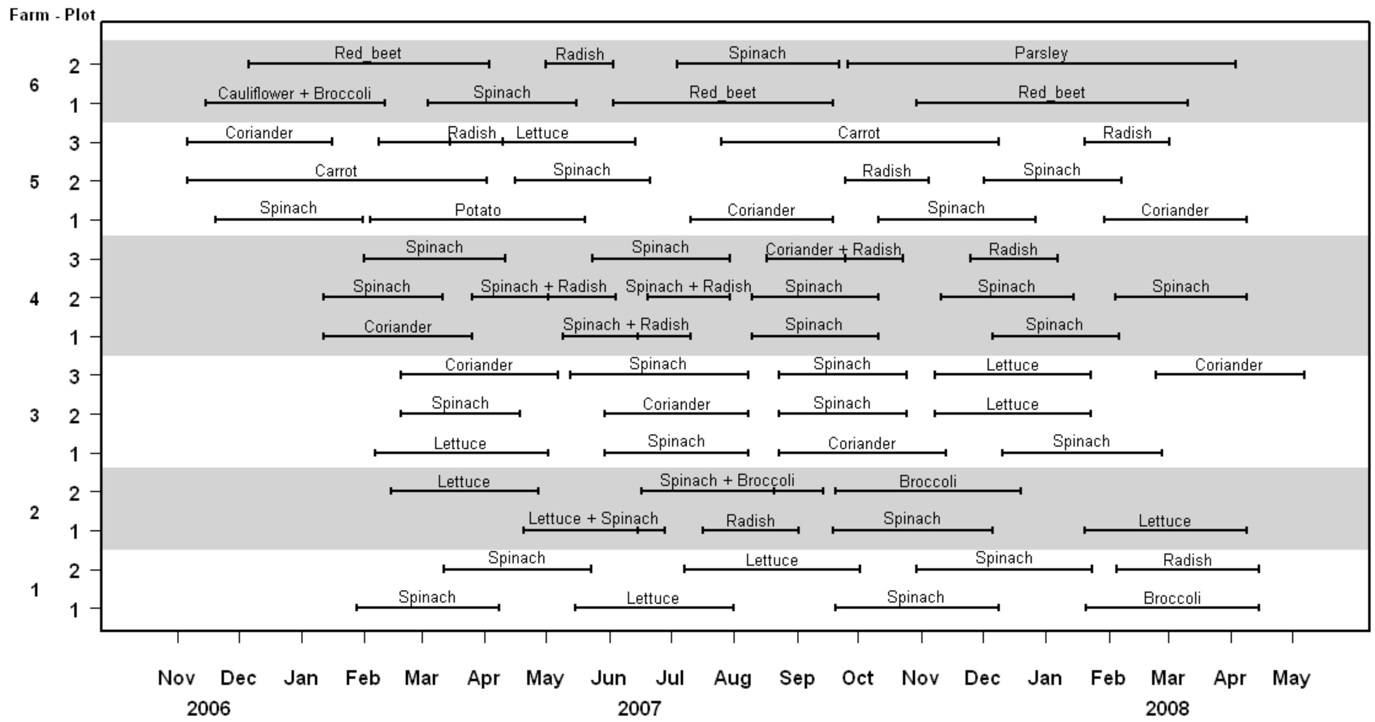
Statistical approaches
Exploratory multivariate analysis PCA Biplots



Peri-urban horticulture, Colombia



- Most planted crops were spinach (45%), radish (17%), lettuce (14%) and coriander (14%)
- Experimental area between 208 and 12560 m^2

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Energy balances (IOA)

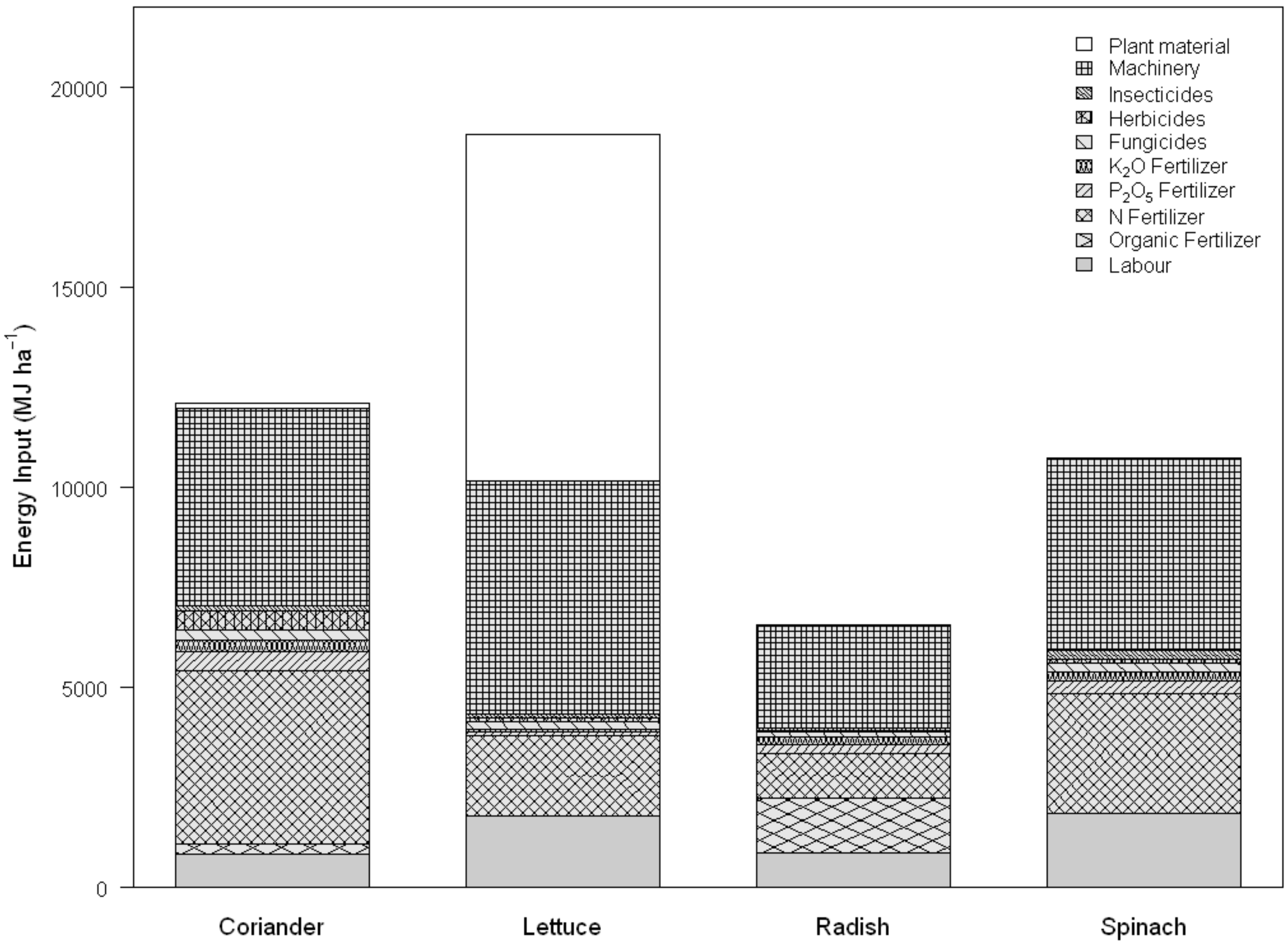
	Unit	Coriander	Lettuce	Radish	Spinach
Input sources					
Labour	h ha^{-1}				
Sowing/planting		9.7±69.4	27.4±3.8	8.0±35.0	10.4±34.1
Irrigation		28.7±21.5	39.9±39.4	15.9±12.6	29.2±20.3
Fertilization		34.4±26.5	98.09±17.7	13.3±24.4	31.7±25.3
Spraying		45.9±35.6	45.6±29.1	14.9±16.6	43.9±18.9
Weeding		207.7	397.9±238.4	238.8±51.9	449.3±268.7
Harvesting		336.9±359.9	309.7±213.1	286.1±338.9	496.9±268.4
Fertilizers	kg ha^{-1}				
N		71.3±74.2	33.3±61.0	18.6±30.8	48.9±55.5
P_2O_5		44.3±43.7	8.5±14.7	30.9±30.8	32.9±48.9
K_2O		40.9±45.1	8.5±14.7	30.9±42.4	32.9±49.8
Organic		820.7±1675.4	20.3±47.4	4582.3±11467.4	7.5±17.3
Plant material					
Seeds	kg ha^{-1}	37.2±14.6	–	5.2±6.3	8.7±3.2
Plantlets	units ha^{-1}	–	43335.1±17986.1	–	–
Pesticides (Active ingredient)	kg ha^{-1}				
Fungicides		1.8±0.9	1.2±1.2	1.2±1.9	1.9±1.4
Insecticides		0.8±0.7	0.6±0.3	0.2±0.1	0.8±0.7
Herbicides		1.3±0.8	0.8±0.6	0.4±0.1	0.8±0.6
Machinery					
Diesel	l ha^{-1}	102.2±89.5	118.0±65.2	52.7±44.3	97.4±75.6
Tractor	h ha^{-1}	5.6±5.6	9.4±10.8	4.6±5.9	6.9±7.9
Irrigation pump	h ha^{-1}	22.4±22.5	34.9±38.4	9.5±12.9	24.1±21.6
Output					
Economic yield	t ha^{-1}	7.6 ± 7.0	21.3 ± 6.5	4.1 ± 6.9	13.4 ± 4.4
Green residues	t ha^{-1}	0.5 ± 0.8	20.0 ± 7.8	6.2 ± 5.5	5.7 ± 3.4
Others					
Cycles recorded	*n*	9	8	9	26
Cycle length	days	70 ± 13	85 ± 14	50 ± 14	71 ± 8
Planting density at harvest	plants m^{-2}	129.5 ± 60.6	5.1 ± 1.4	39.4 ± 29.8	27.6 ± 11.9

Energy balances

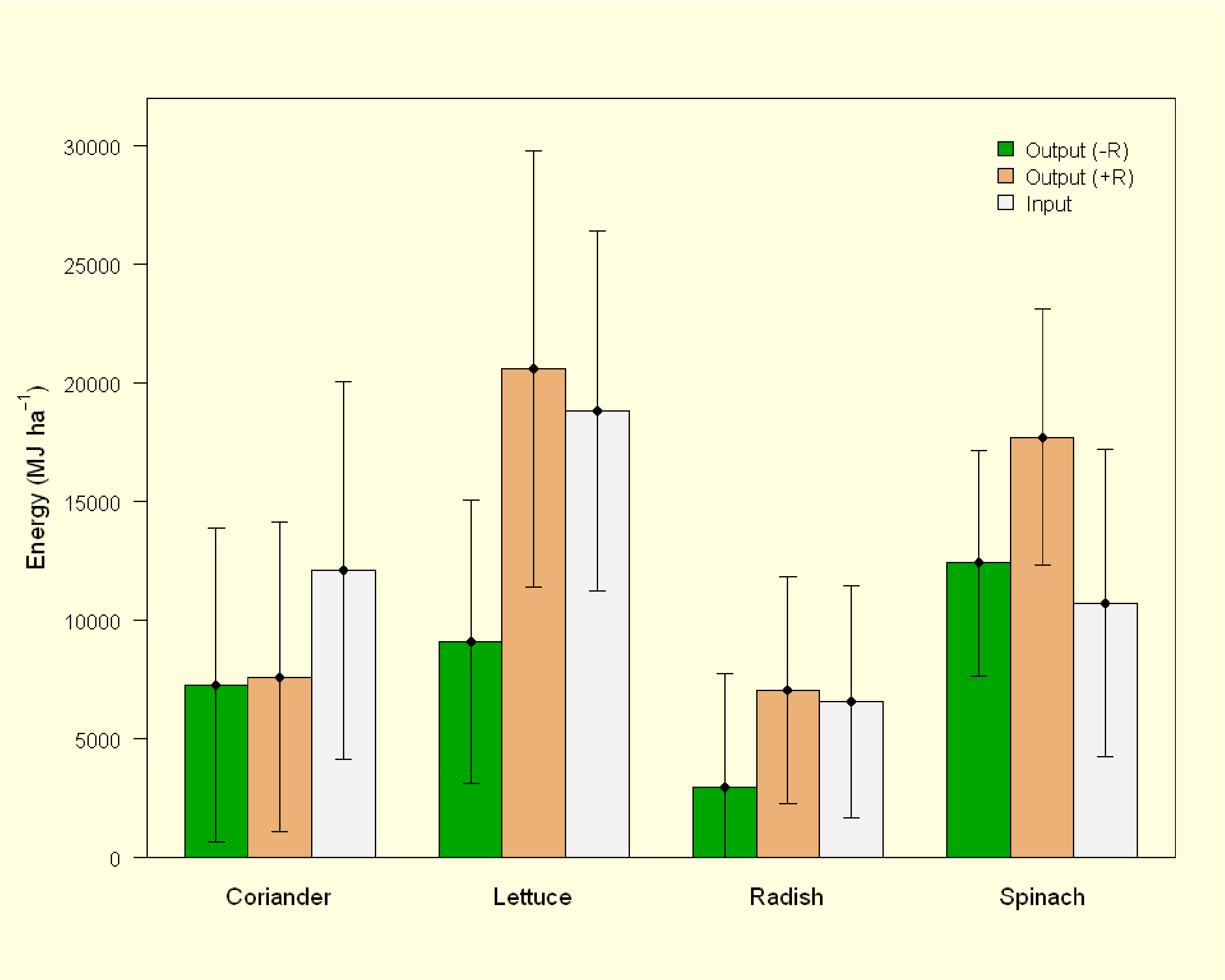
Energy source	Unit	Energy equivalent (MJ unit^{-1})	Reference
Human labour	h	1.96	Singh *et al.* (2002)
Diesel oil	l	45.4	Fluck (1992)
Fertilizers	kg		
N		60.6	Singh (2002)
P_2O_5		11.1	Singh (2002)
K_2O		6.7	Singh (2002)
Organic	kg	0.3	Singh (2002)
Plant material			
Seeds	kg	1.0	Singh (2002)
Transport	kg	3.0	Calculated
Plantlets	unit	0.2	Calculated
Output	kg		
Coriander		0.95	USDA-ARS (2008)
Lettuce		0.58	USDA-ARS (2008)
Radish		0.66	USDA-ARS (2008)
Spinach		0.97	USDA-ARS (2008)

Energy equivalents of different inputs and outputs

Energy balances



Energy balances



Energy balances

$$\text{Energy use efficiency} = \frac{\text{Energy output (MJ ha}^{-1}\text{)}}{\text{Energy input (MJ ha}^{-1}\text{)}}$$

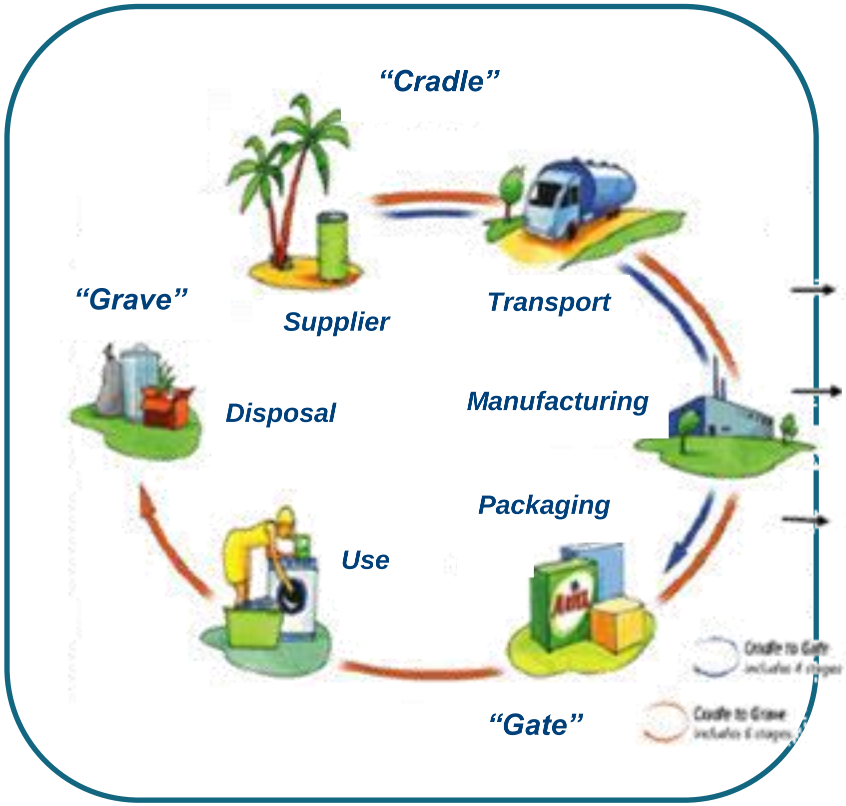
$$\text{Net energy} = \text{Energy output (MJ ha}^{-1}\text{)} - \text{Energy input (MJ ha}^{-1}\text{)}$$

Crop	**Energy use efficiency**		**Net energy (MJ ha^{-1})**	
	With residues	Without residues	With residues	Without residues
Coriander	0.62	0.59	-4508.3	-4852.5
Lettuce	1.09	0.48	1786.1	-9726.2
Radish	1.08	0.46	513.8	-3573.1
Spinach	1.65	1.16	6999.7	1687.5

Life Cycle Assessment

IOA over the full life cycle

Environmental impact studies



Use of resources

Emissions into air

Emissions into water

Environmental indicators

Energy consumption

Water consumption

Solid waste

Global warming

Ozone depletion

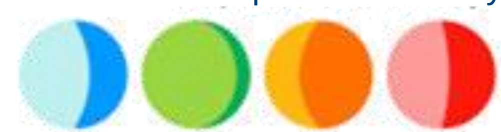
Human toxicity

Summer smog

Acidification

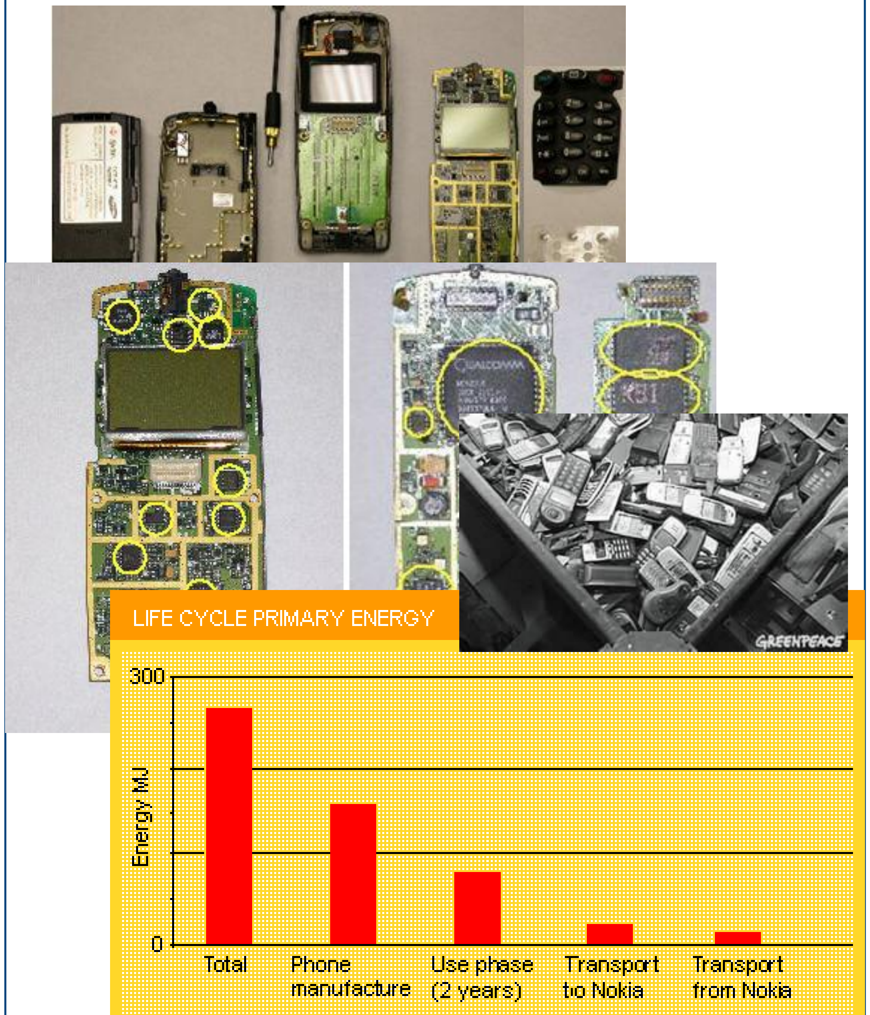
Eutrophication

Aquatic ecotoxicity



Life cycle assessment

- Cellular phone



- Crop production

Life cycle assessment

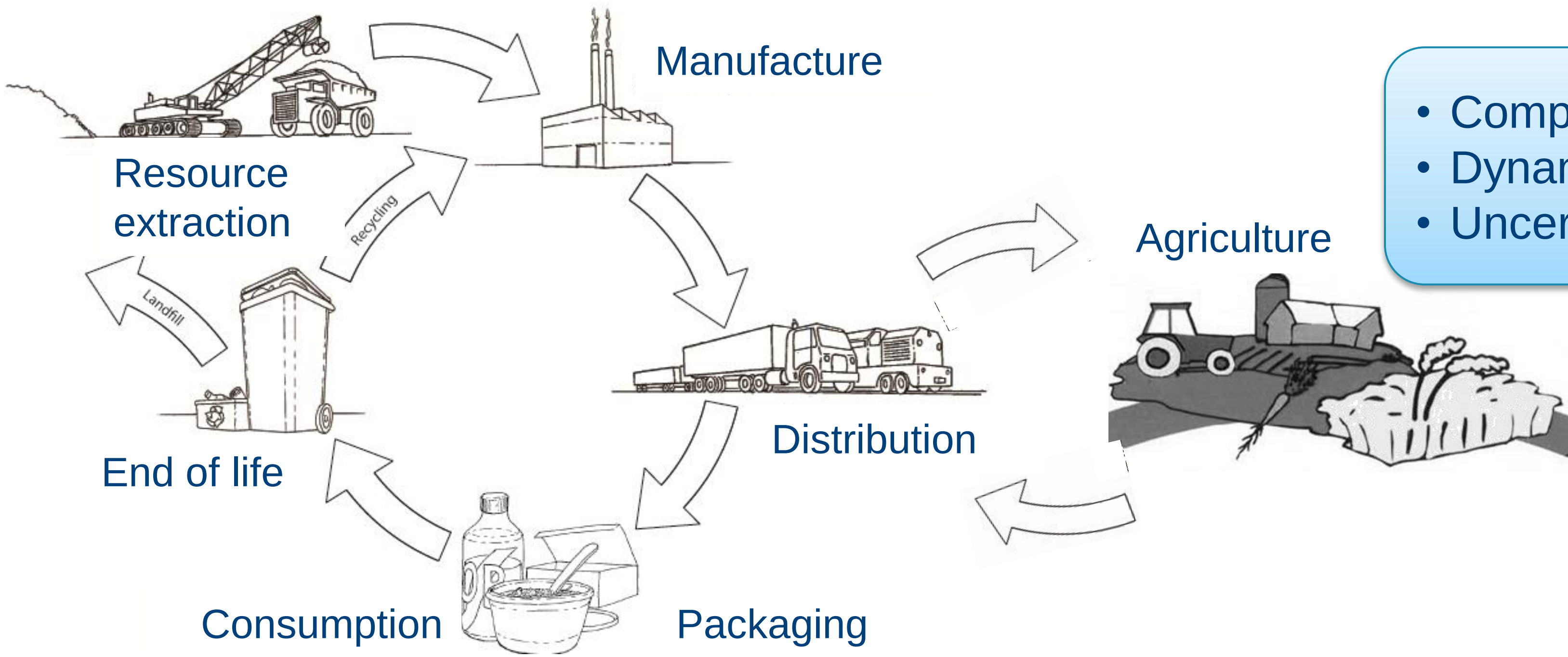
- Cellular phone
  - Production of the phone
    - Materials and energy
  - Use of the phone
    - Electricity
    - Grid of antennas
    - Electronics
  - Recycling of the phone

  - Full process well understood
  - Straightforward IOA ⇔ LCA
  - Limited variability
  - No spatial or temporal effects

- Fertilization in crop production
  - Production of fertilizer
    - NH_4NO_3
    - Well understood process
    - Straightforward IOA ⇔ LCA
  - Application of fertilizer
    - Tractor, fertigation, manually
    - Understand all the underlying biological, physiological processes
      - N-uptake, Nitrification, Denitrification, Leaching, Immobilization, Mineralization
    - Interactions between climate-soil-crop-cultural techniques
  - Large variability
  - Spatial or temporal effects

Life Cycle Assessment

Industrial products >< Agricultural products



- Complex
- Dynamic
- Uncertain

☺

- Production of fertilizer
- Emissions of fuel incineration
- …
- Eg. Ecoinvent DB

☹

- Application of fertilizer
- Nitrogen processes in crop and soil
- Leaching of nitrogen compounds
- Emissions of nitrogen compunds
- …

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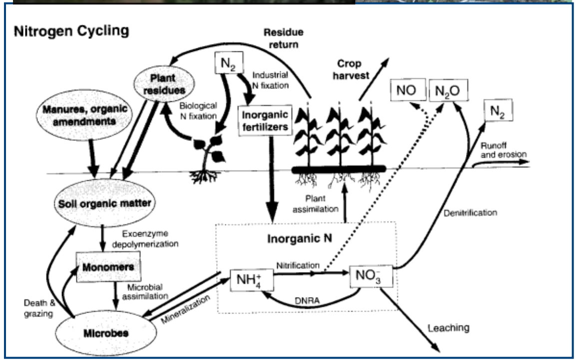
Life cycle assessment of fertilization

- Cauliflower field in Belgium
  - NH_4NO_3
  - Broadcast or fertigation
  - Low and high dosis

○ Industrial production of NH_4NO_3

○ Application of NH_4NO_3

○ Nitrogen cycle processes?



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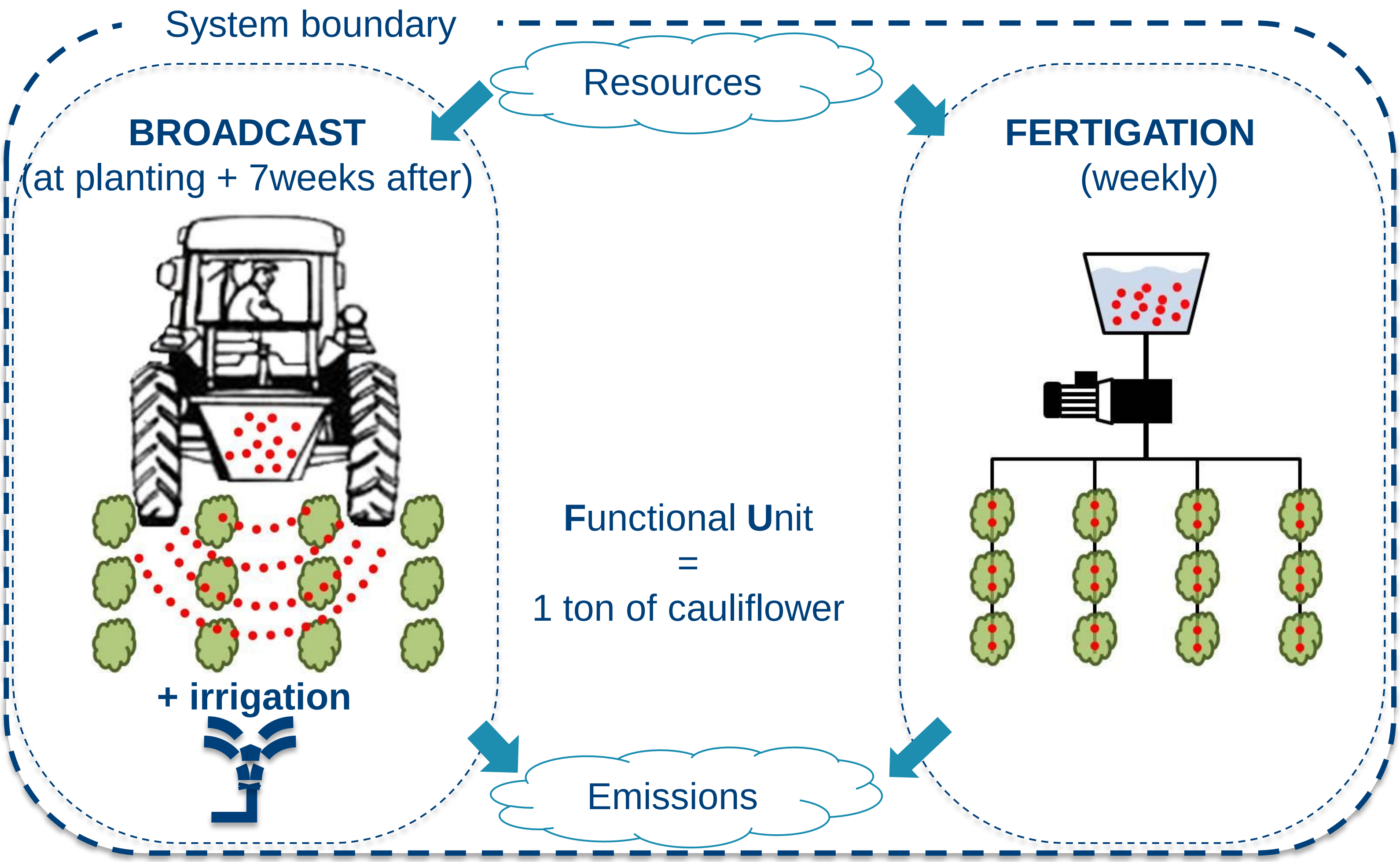
Technical sustainability of horticulture

- LCA
  - ➔Quantification of environmental impact of biological production system
  - ➔Focus on system component when comparing

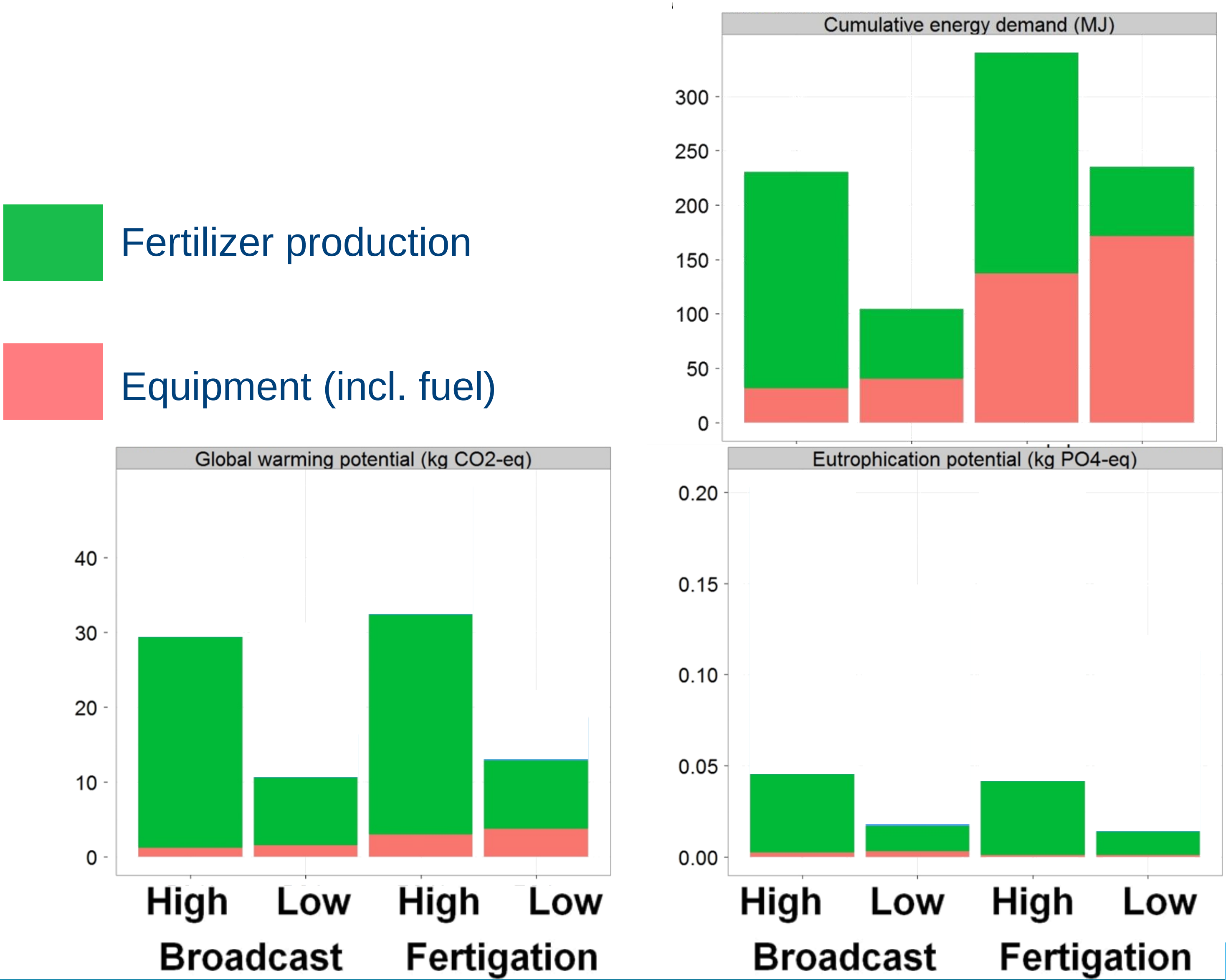


Inventory ➔ impact assessment

- $\sum(LCI * CFi) = impact$
  - CFs Transformation coefficients from IOA to environmetal impact category
  - LCI: Life Cycle Inventory with IOA

- Example Global warming potemntial
  - All mass, energy, processes transformed to equivalent CO_2 emission
  - Total CO_2 emission transformed to gloabal Warming Potential (expressed in CO_2 eq)

‘Basic’ LCA (NH_4NO_3 industrial production)



Emissions due to fertilizer application (empirical relations)

- Ammonia (Sutton *et al.* 2002):

  NH_3-N = $EF_{i,r}$* N-fertilizer input

  ~ type *i* fertilizer & ~ climatological region *r* (~ mean spring T°)

  = 1-2% ((C)AN) → 15-20% (urea)

- Nitrous oxide (IPCC (Intergovernmental Panel Climate Change) , 2006):

  N_2O-N = 1% * N-fertilizer input

  + 1% * N-cropresidu (above and below ground)

  + 1% * N-mineralized (ΔC_{min}*(N/C), no immobilization)

  + 1% * (NH_3-N+ NO_x-N) (atmospheric deposition ~ 10-20% of all N-sources)

  + 0.75% * NO_3^- N (leaching/runoff ~ 30% of all N-sources)

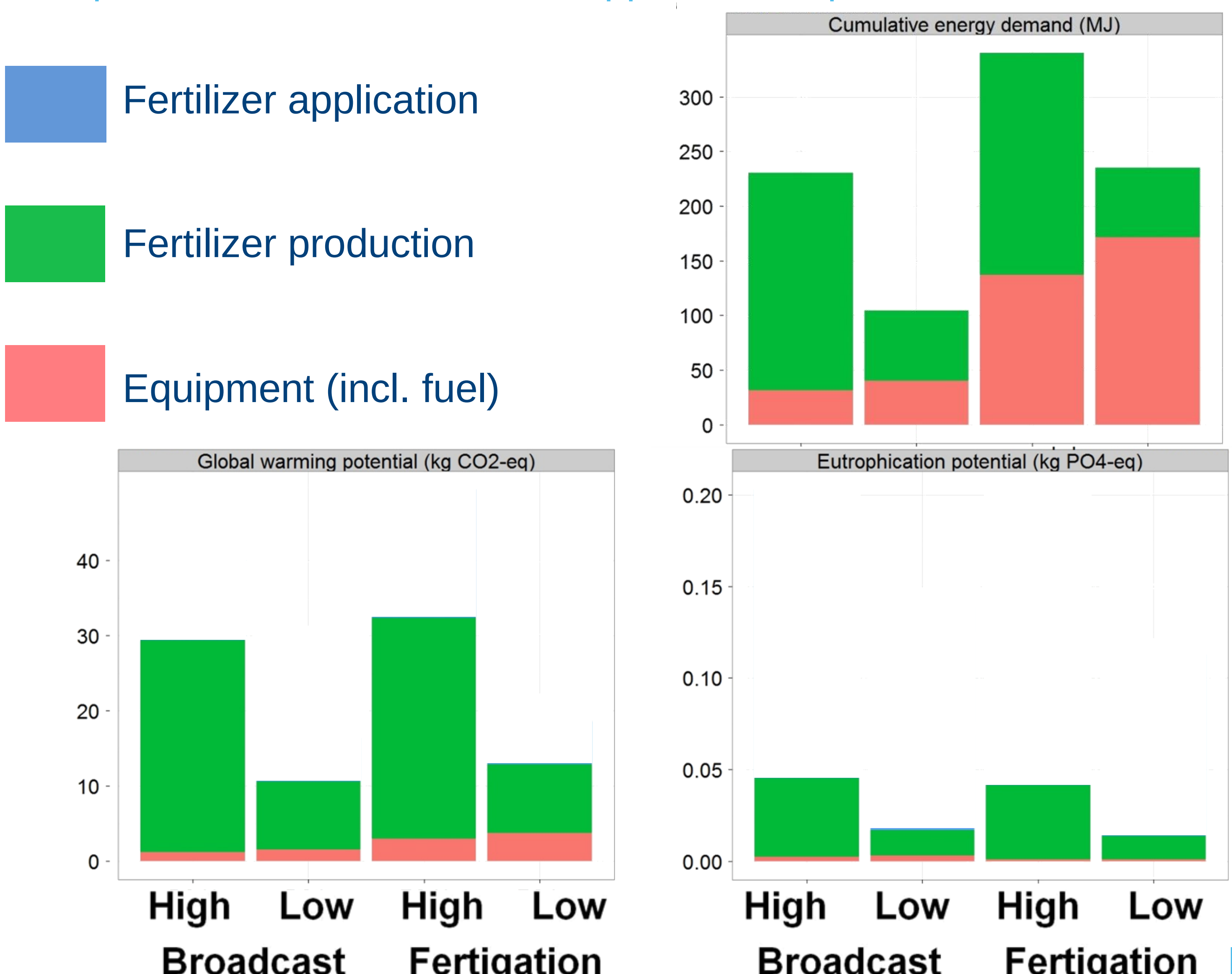
- Nitric oxide

  NO_x-N = 0.7% * N-fertilizer input (Bouwman *et al.* 2002)

  NO_x-N = 21% * NO_2-N (ecoinvent-report, pers. Comm. Grub '96)

Full LCA (Production + application of NH_4NO_3)

Empirical relations for fertilizer application impact



Emissions due to fertilizer applications

Empirical relations ⇔ Mechanistic models

↕

We could improve the LCA by using system dynamic models, simulating all these N-processes in the soil

Research methodologies for TS

- Static, time invariant methods
  - Mass balances
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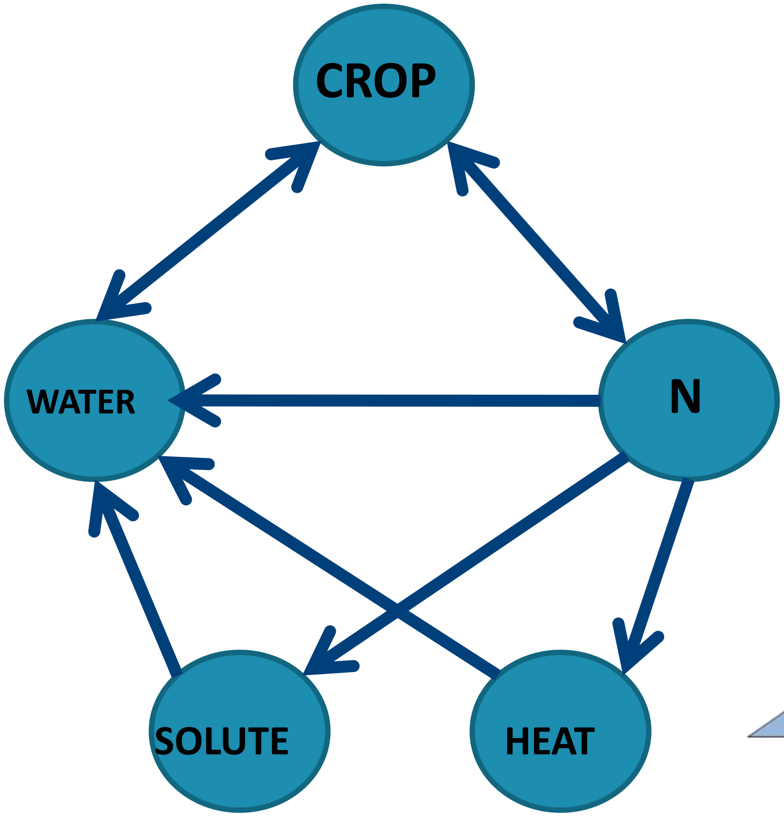
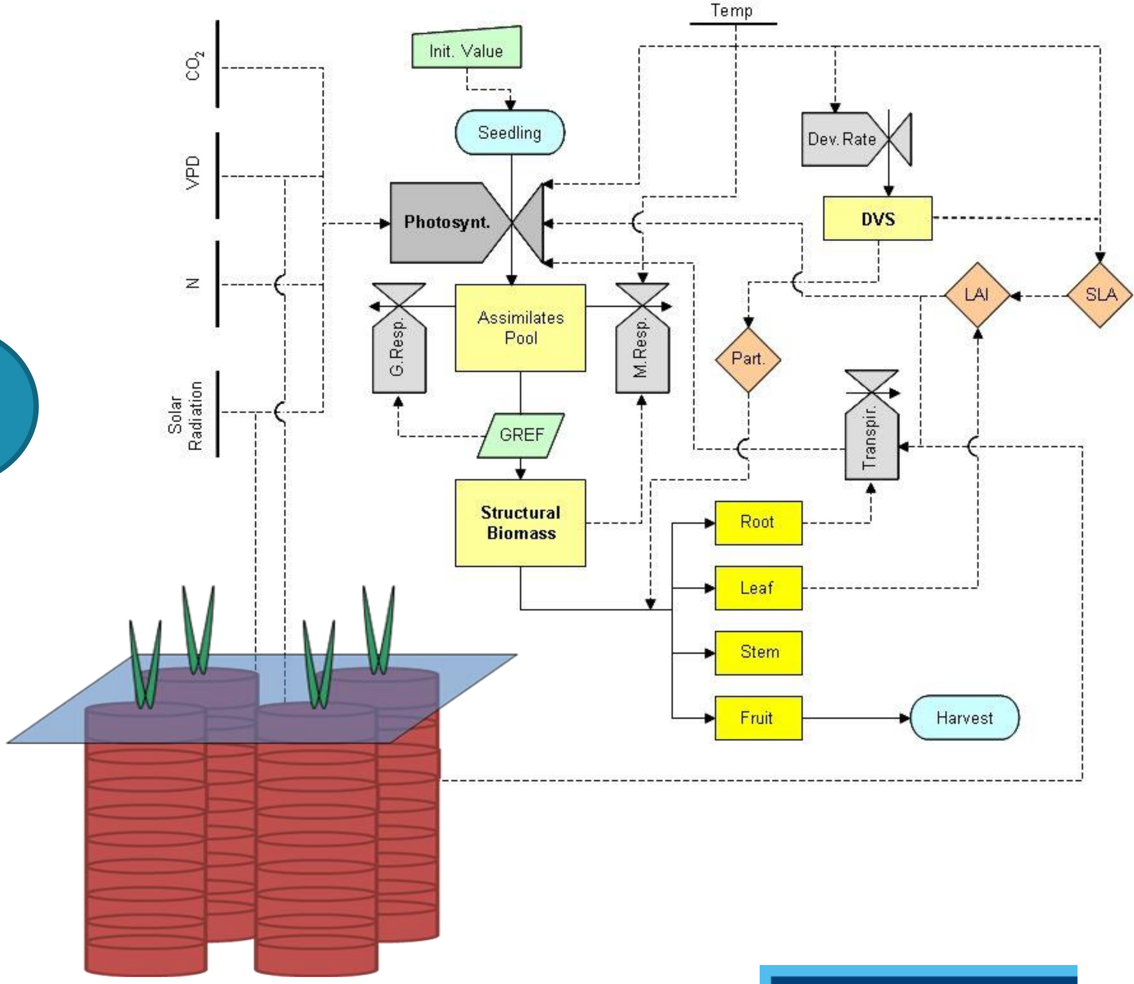
  - Life Cycle Assessment (LCA)
- Dynamic methods
  - Systems models
    - Crop growth and development models, linked to soil nutrient and water transport models and crop management to investigate the technical sustainability of fertilization strategies
  - Modelbased LCA
  - Nonlinear mixed models

Crop-soil-climate model

Soil transport model, WAVE



Generic crop model



Emissions due to fertilizer application

- Nitrate leaching (NO_3^-)

~ N-balance:

+ N-input	- N-uptake
+ N-mineralization	- N-immobilization
+ N-fixation/deposition	- N-volatilisation
$\sum$	

~ Experimental data

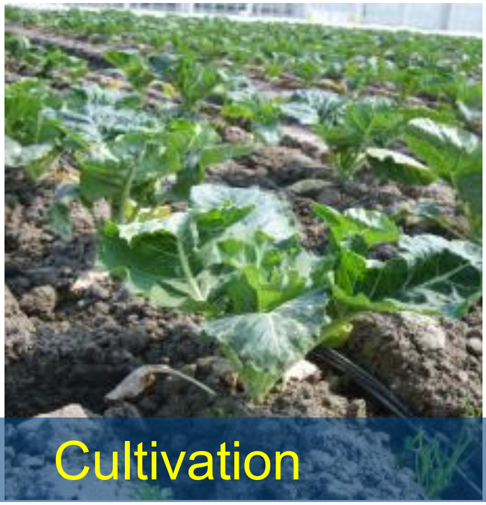
~ Model calibration

~ N-process simulation

Experimental setup

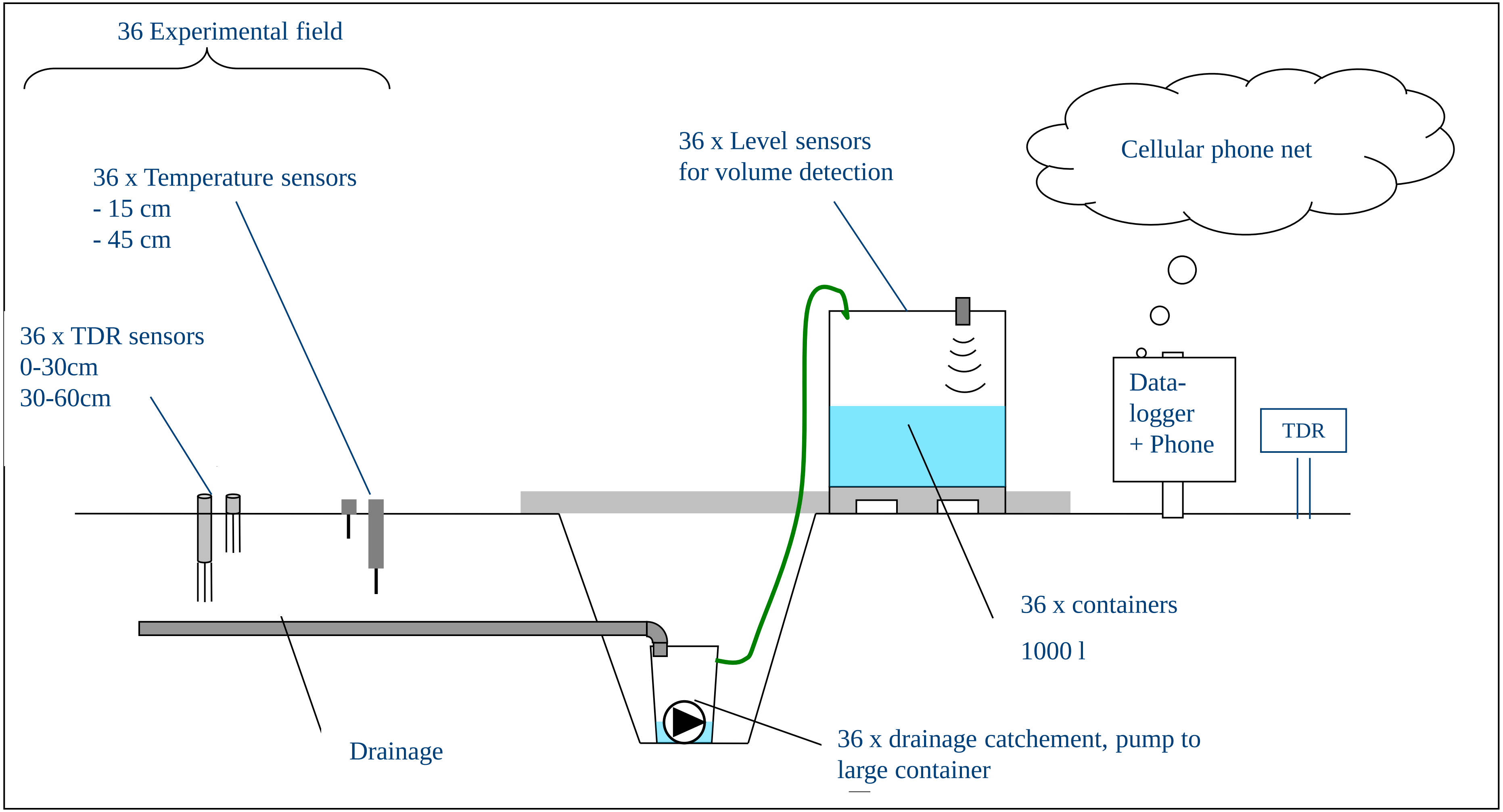

Cauliflower March- June 2010


'Foiled' plots


Cultivation


Measuring nitrate leaching

Experimental setup



Modelling climate-soil-crop

- Empirical ➔ mechanistic
  - Default IPCC ignores soil characteristics, climate conditions and agricultural practices other than N input rate

- Modelling subprocesses
  - Crop growth + soil dynamics + water transport

    ~ climate

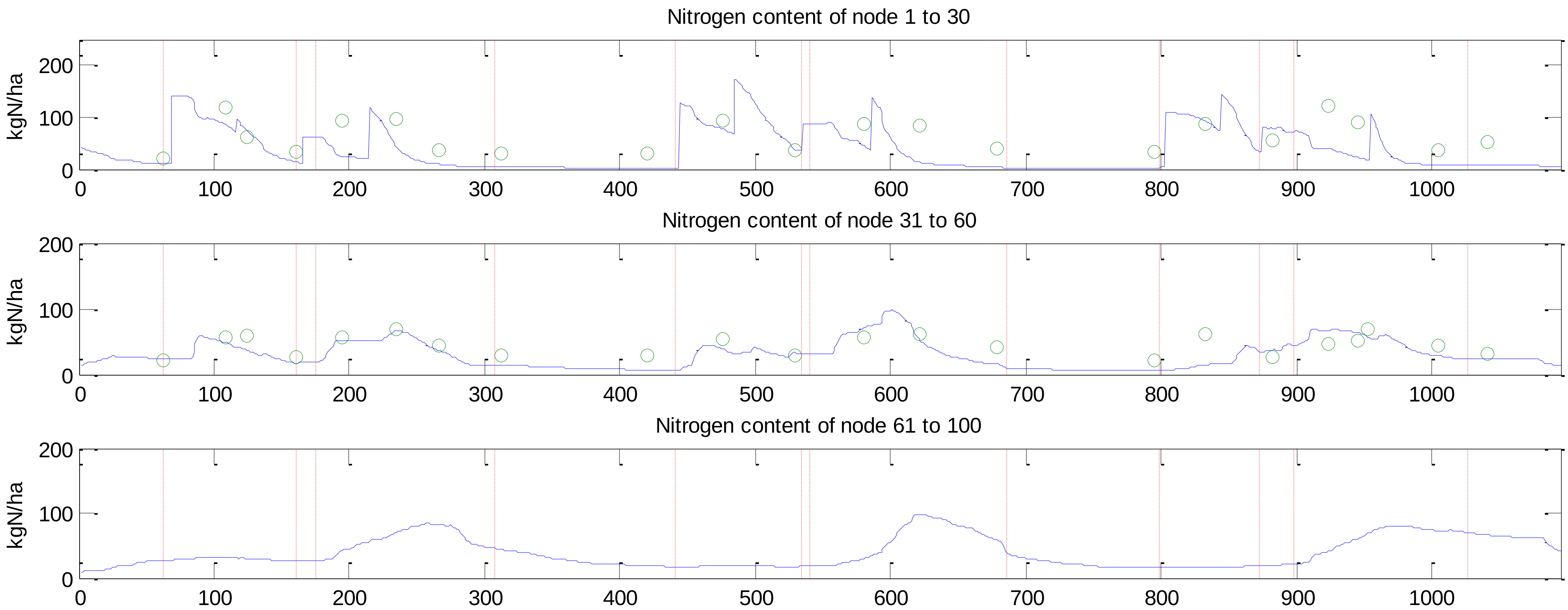
- Impact of rotation cauliflower AND leek within a year
  - Eg. Nitrate leaching difficult to attribute to a single crop

Rotation Cauliflower-Leek-winter

Fallow		Cauliflower				Leek					
J	F	M	A	M	J	J	A	S	O	N	D
		NH_4NO_3	NH_4NO_3			Residue, NH_4NO_3					

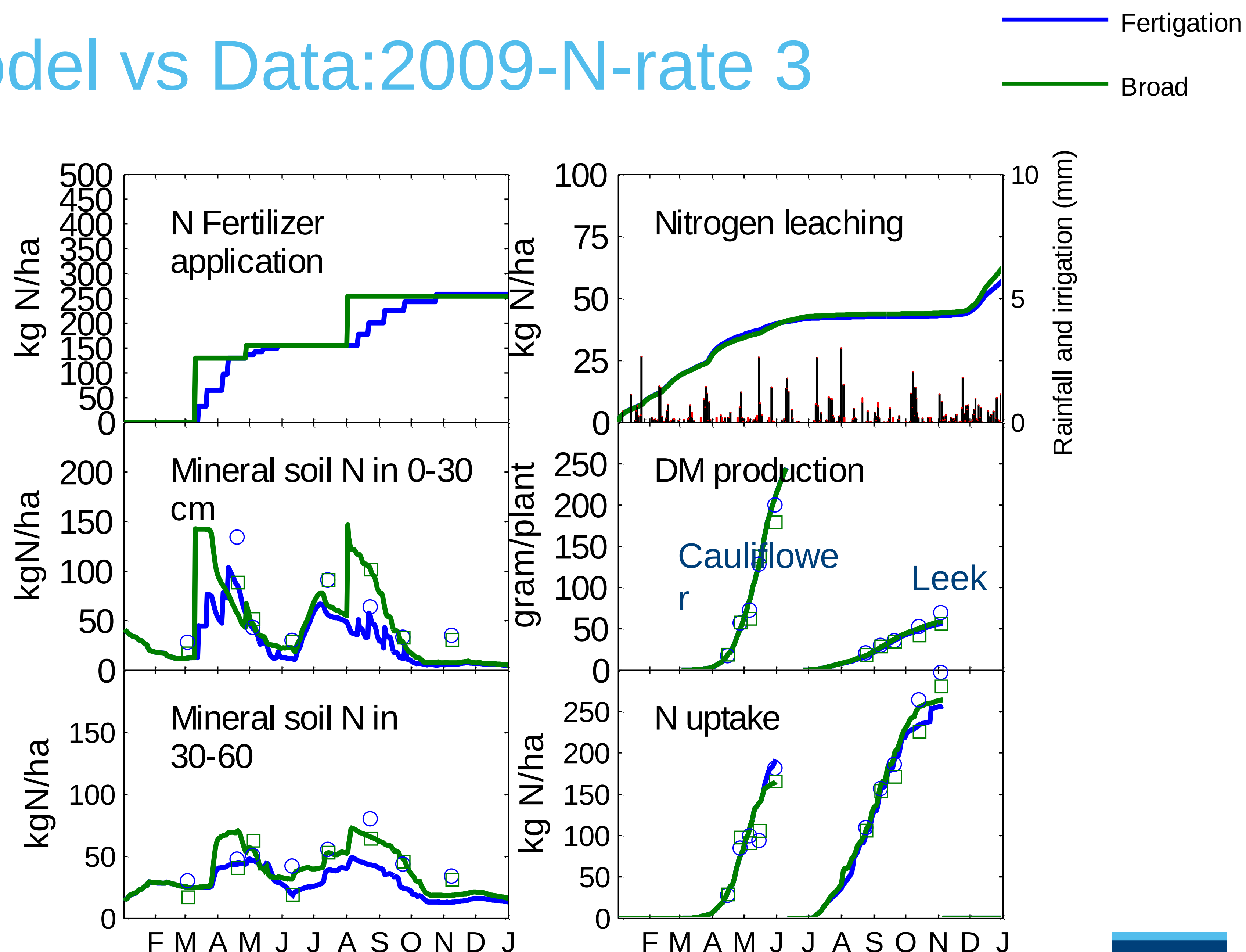
N-rate is 3

Nitrogen content in different soil layeres



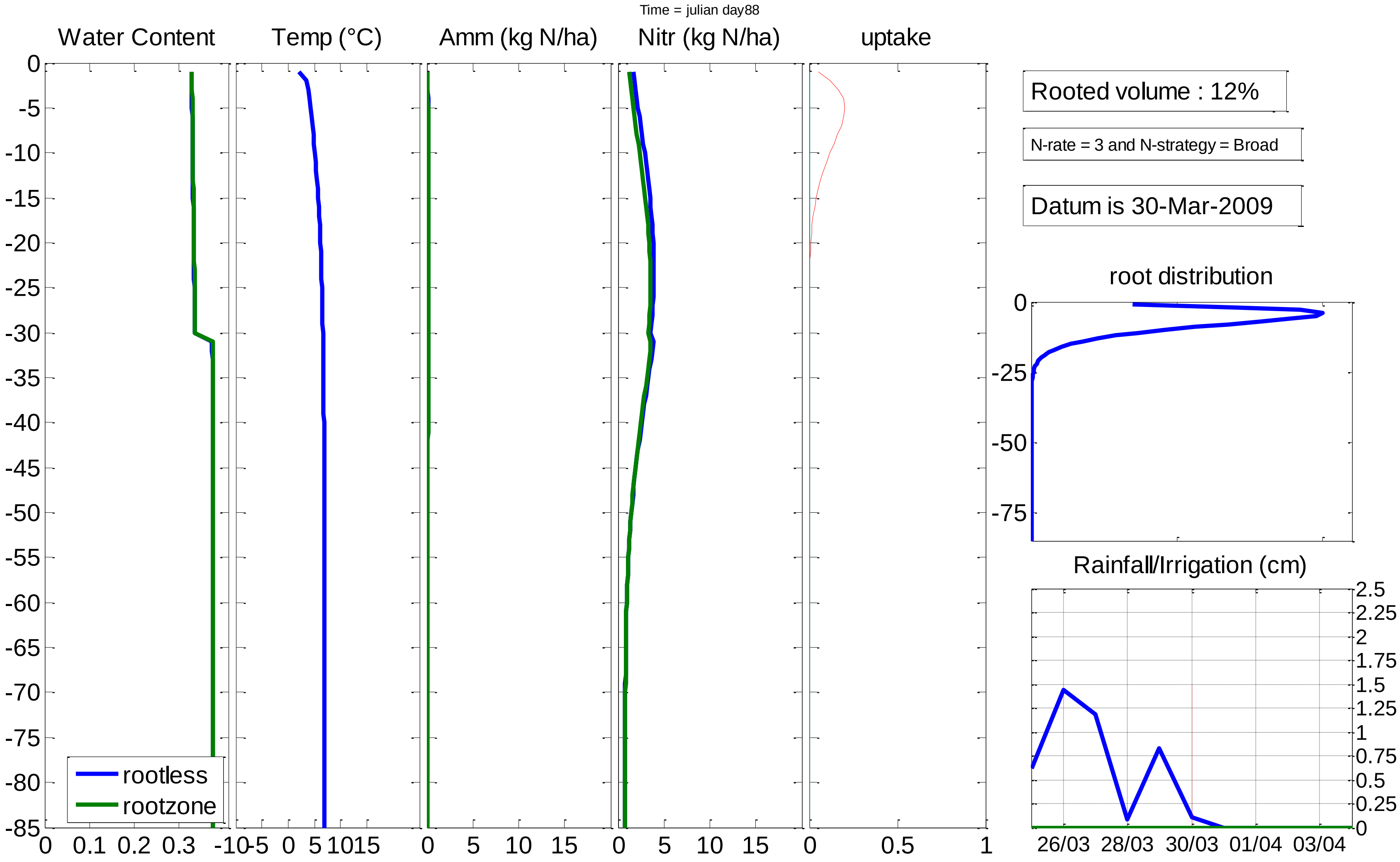
Days after 1st of January 2009

Model vs Data:2009-N-rate 3



Crop – soil – climate model

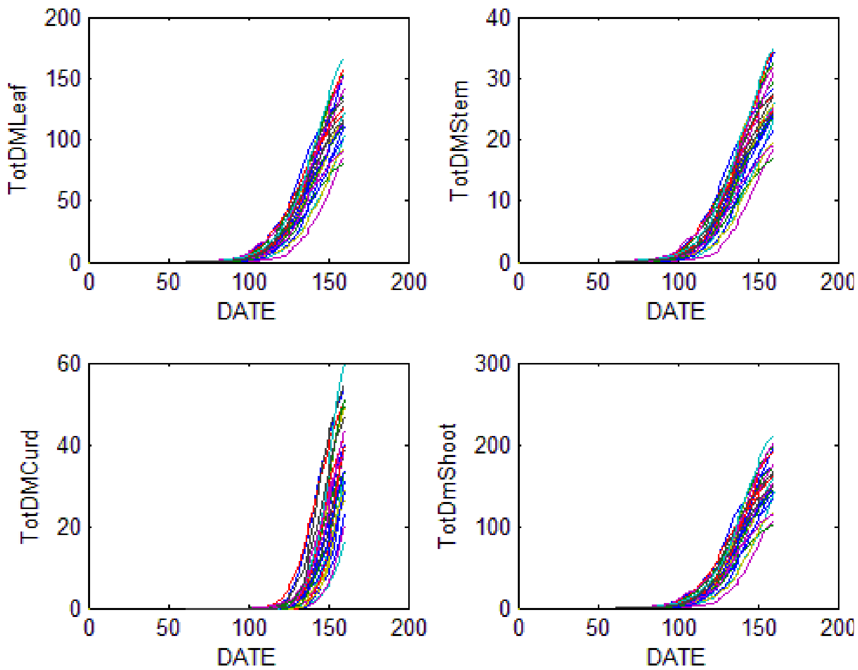
Animation



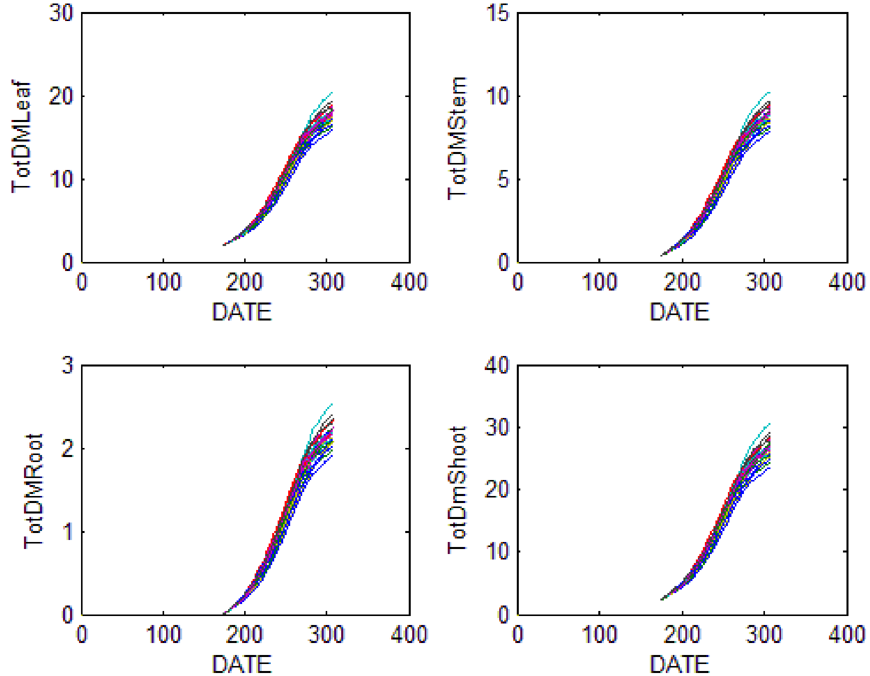
Climate of the last 43 years

Simulated production

Cauliflower

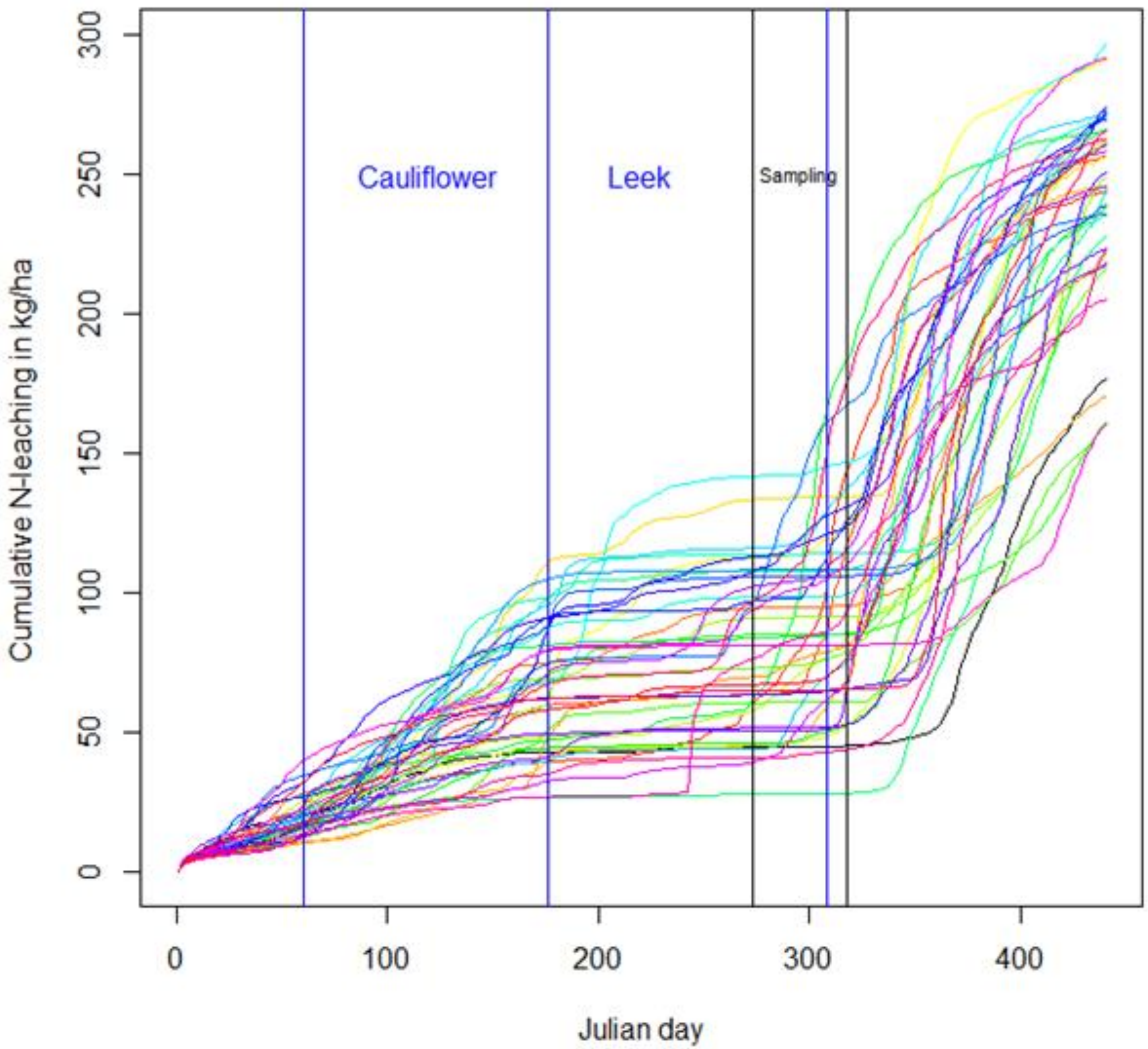


Leek



Climate uncertainty over the last 43 years

Simulate cumulative N-leaching under doses 3, broadcast application



42.8 % exceed the 90 kg/ha leaching on 1 Nov

52.3 % exceed the 90 kg/ha leaching on 15 Nov

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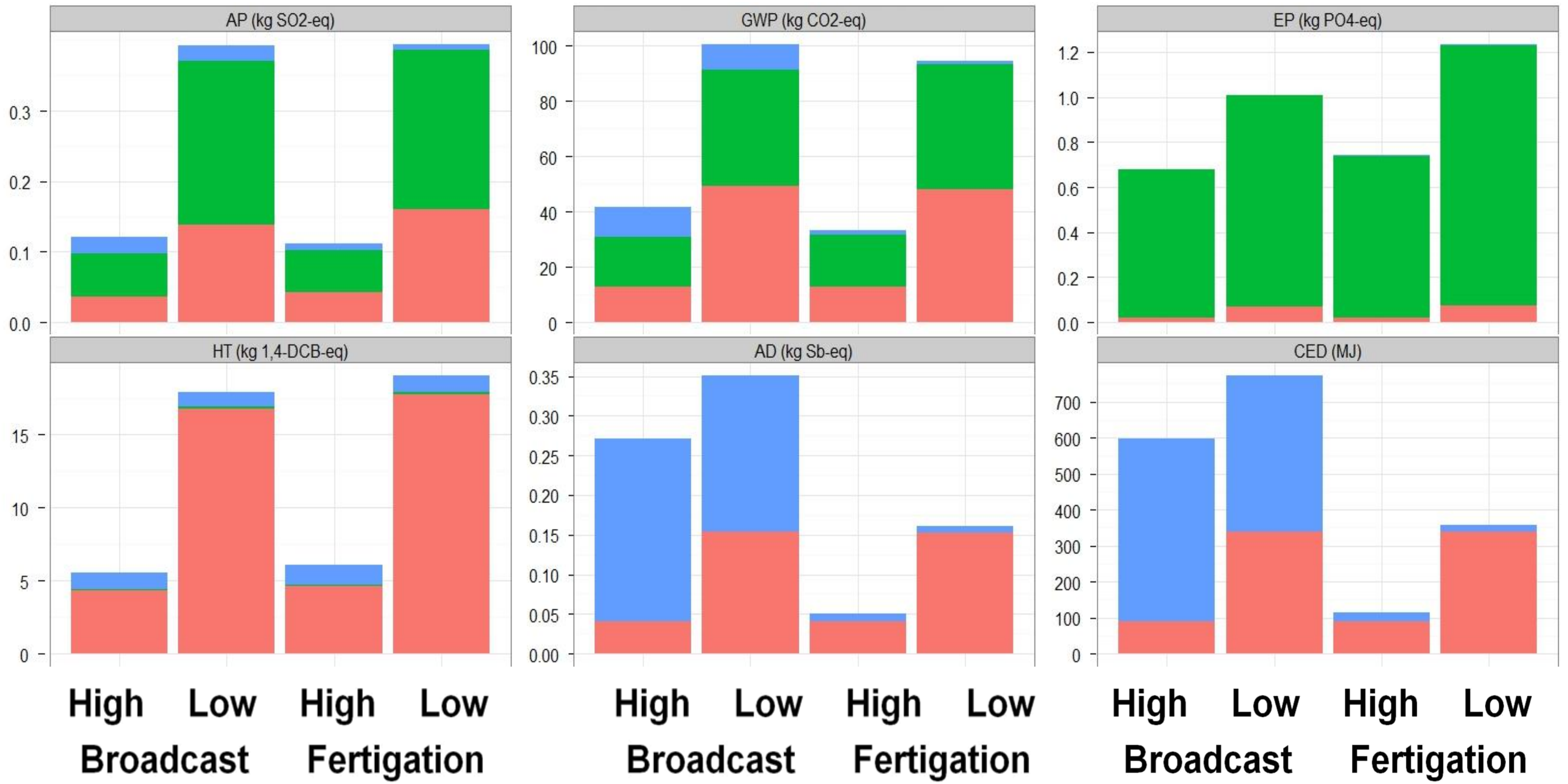
Model based LCA

- Examples
  - Rotation cauliflower – leek
    - Nitrate leaching difficult to attribute to a single crop
    - Influence climate – soil conditions
    - Sequential effects due to crop residu mineralisation

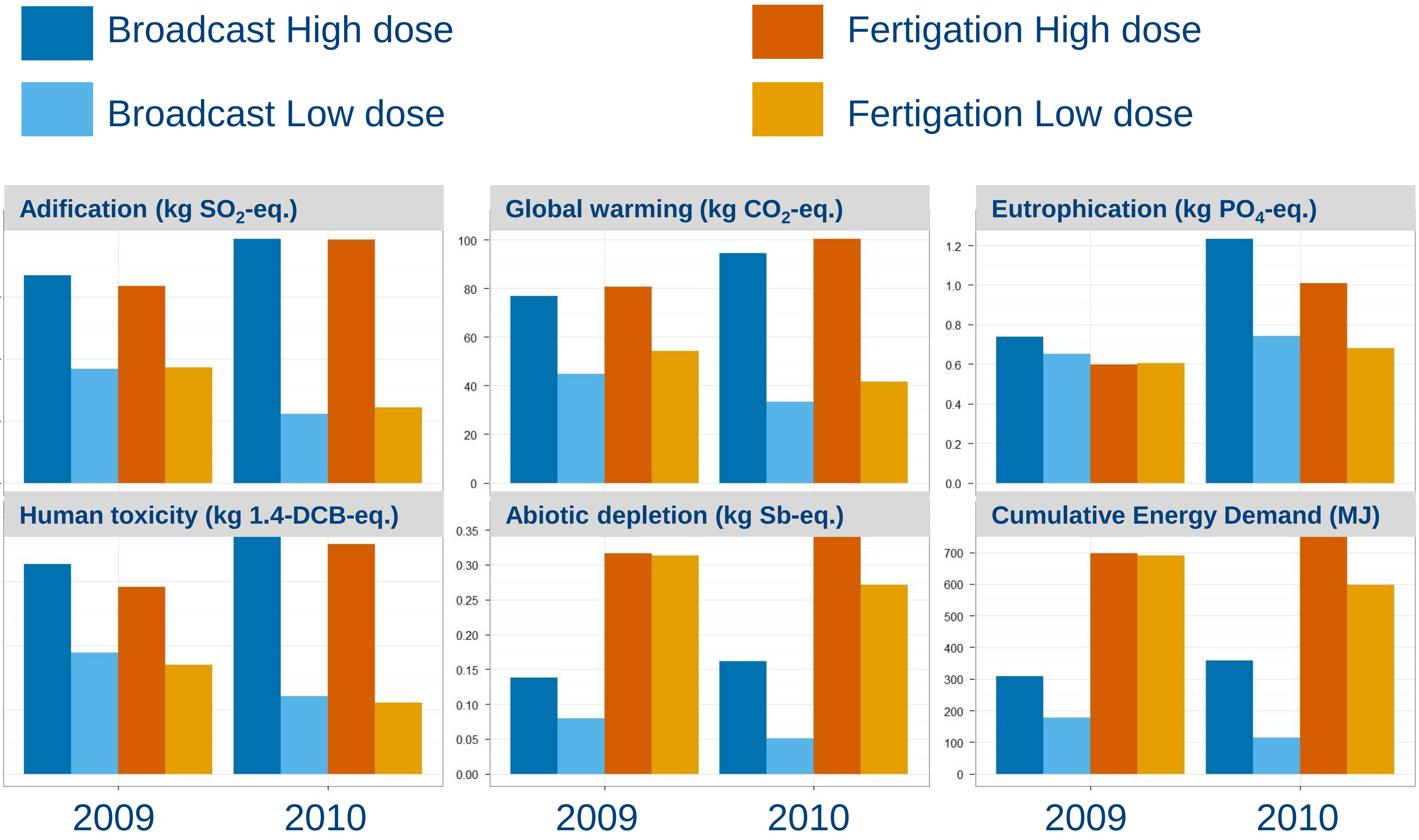
  - Incorporate simulated N-process results into the LCA framework
    - Cauliflower-Leek rotation
    - Multiple years ➔ climate variability

Model based LCA (cauliflower – leek 2010)

Equipment (incl. fuel) | Fertilizer production | Fertilizer application



Model based LCA (cauliflower – leek 09 - 10)



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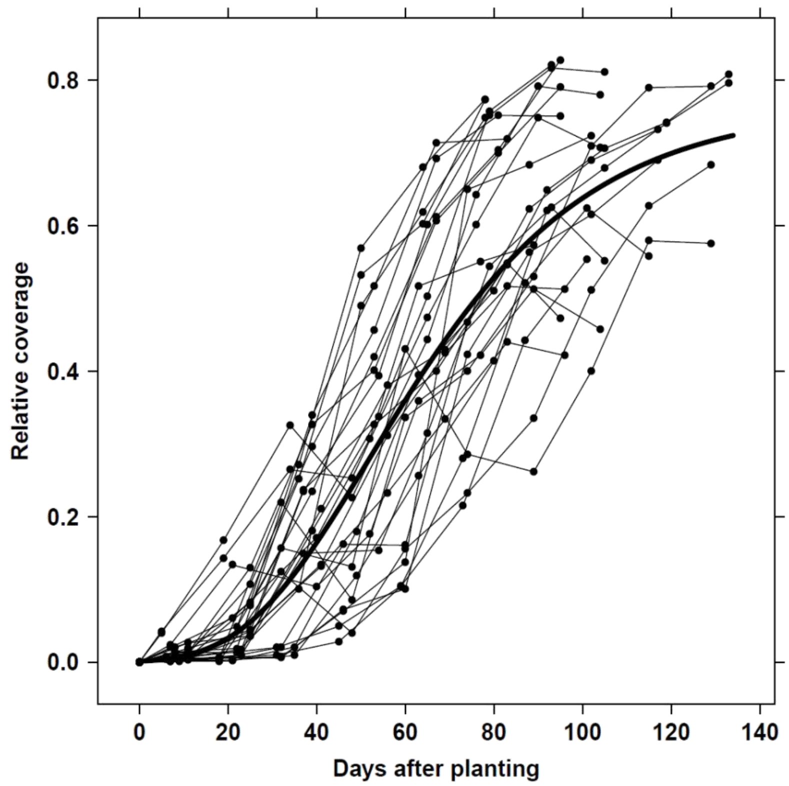
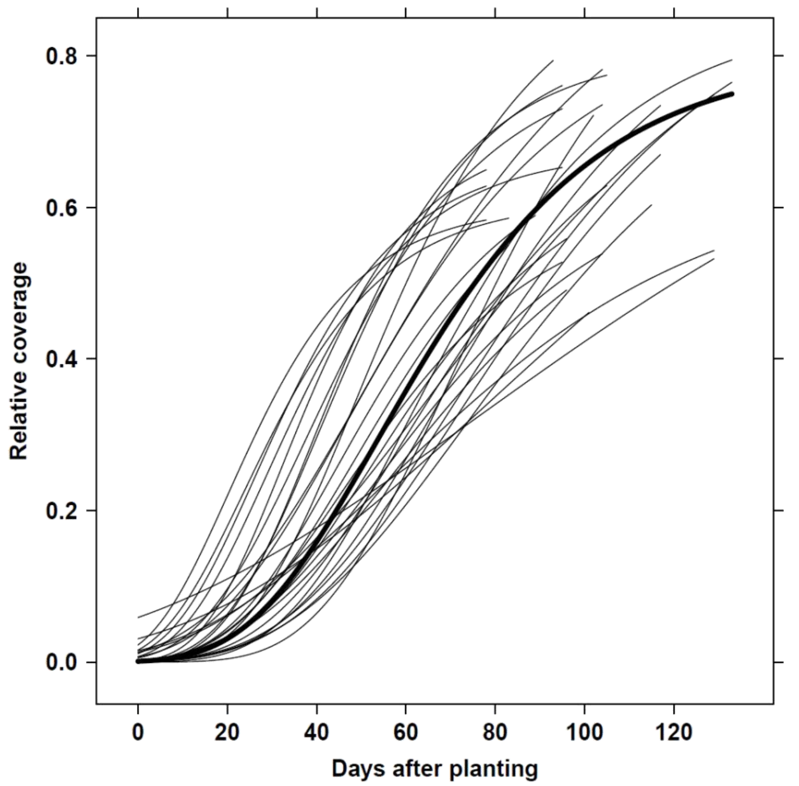
Nonlinear mixed models

Overall fixed effects, observed data



$$y_{ij} = a \times \exp^{\left(-\exp^{c\times(d-x_i)}\right)}$$

Nonlinear mixed model



$$y_{ij} = (a + u_{aj}) \times \exp^{\left(-\exp^{(c+u_{cj})\times(d+u_{dj}-x_{ij})}\right)} + e_{ij}$$

Greenhouse tomato system, Colombia
Non-linear mixed models

- Crop planted all over the country
- Tomato production area: 11304 ha
- 30% under protected conditions
- Yield: 5 – 6 kg plant^{-1}

- Simple plastic greenhouses
- Naturally ventilated
- No active climate control is present
- Planted under soil conditions
- High wire training system

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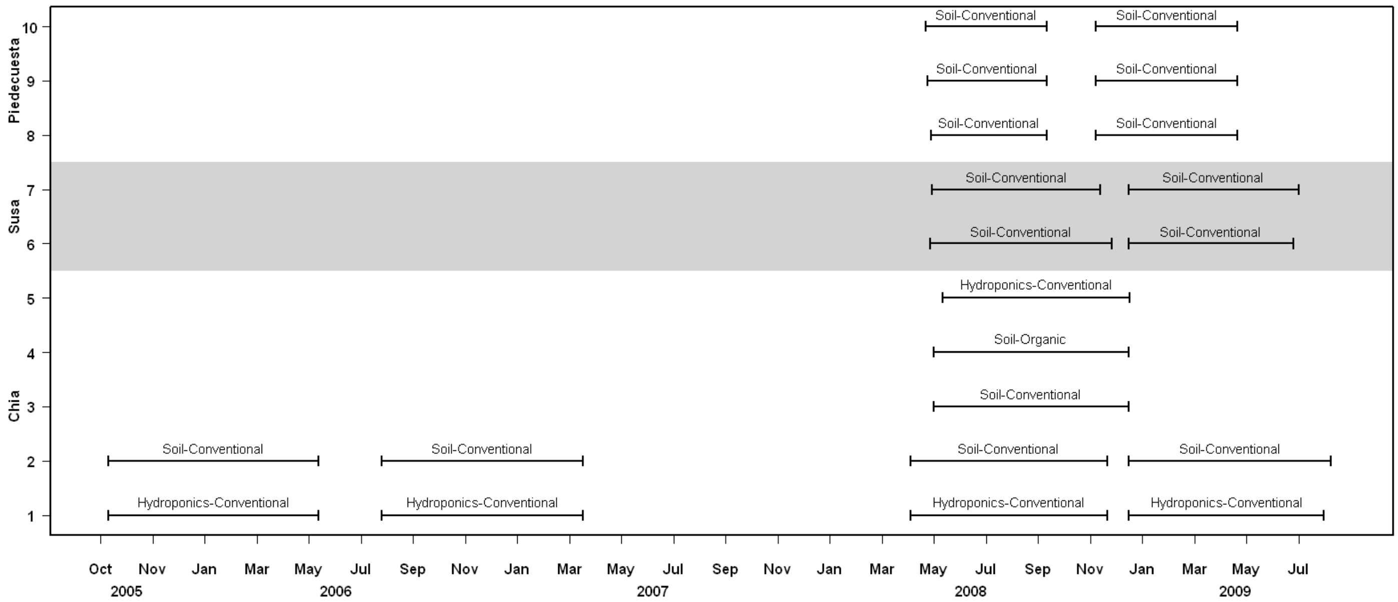
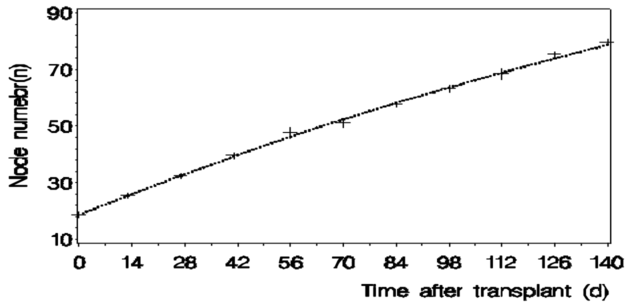
Greenhouse tomato systems

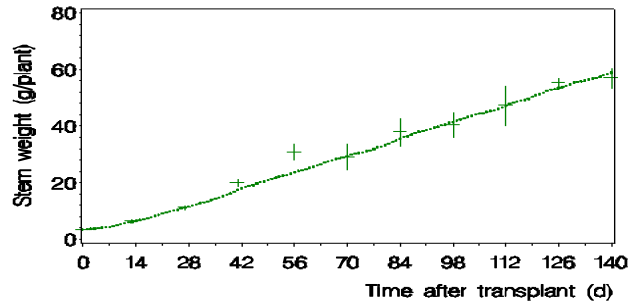


- Three locations Chia, Susa and Piedecuesta
- Greenhouses area between 320 and 1632 m^2

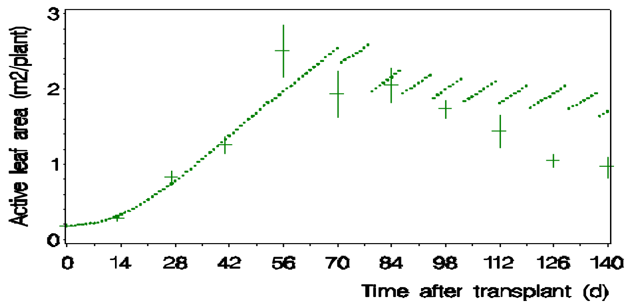
Systems approaches
Tomgro model calibrated for the Bogota savanna



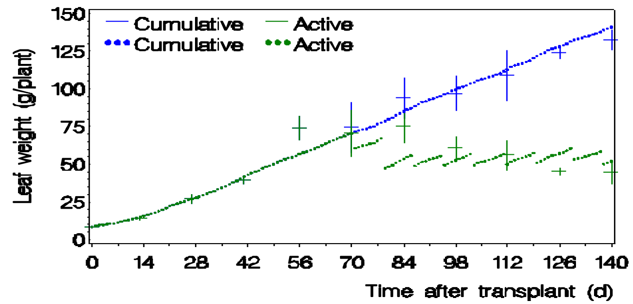
a plant development



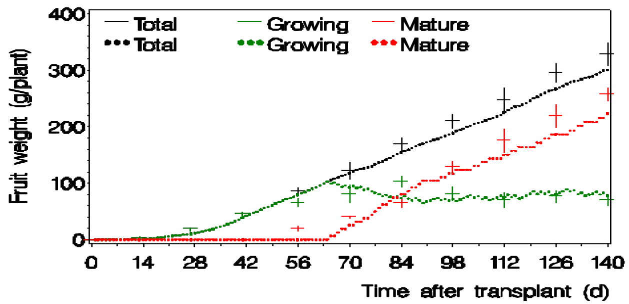
b: stem weight



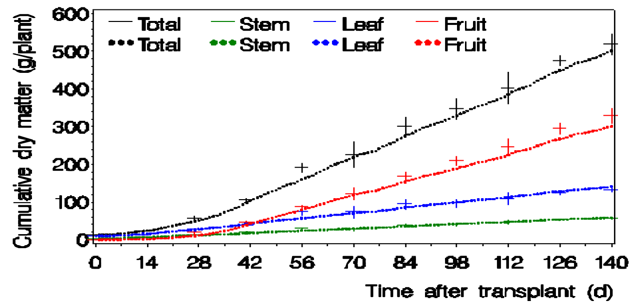
c: active leaf area



d: total and active leaf weight



e: total, growing and mature fruit weight



f: total dry matter and distribution

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Nonlinear mixed models with grouping structures or several dependent variables

Dataset: Greenhouse tomato production systems - Colombia

Observed yield ⟷ **Potential yield (modelled with Tomgro)**

$$y_{ij} = (a + u_{i1}) \times \exp^{\left(-\exp^{c \times (d + u_{i2} - \text{dat})}\right)} + e_{ij}$$

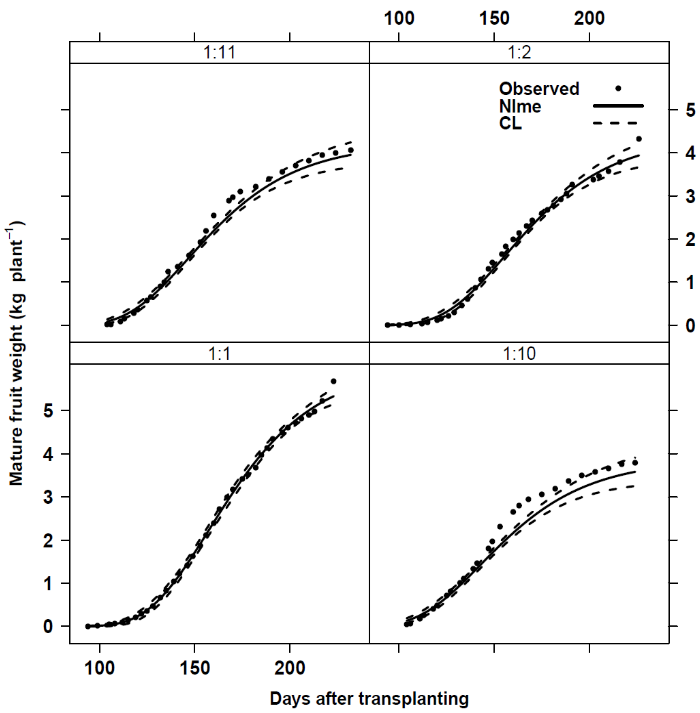
Gompertz growth function

Nonlinear mixed models

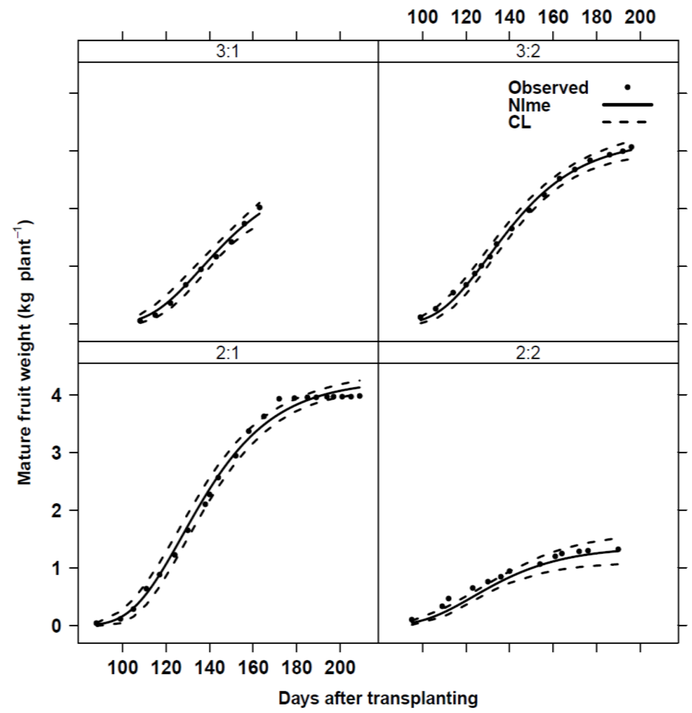
Observed yield

$$y_{ij} = (a + u_{i1}) \times \exp^{\left(-\exp^{c \times (d + u_{i2} - \text{dat})}\right)} + e_{ij}$$

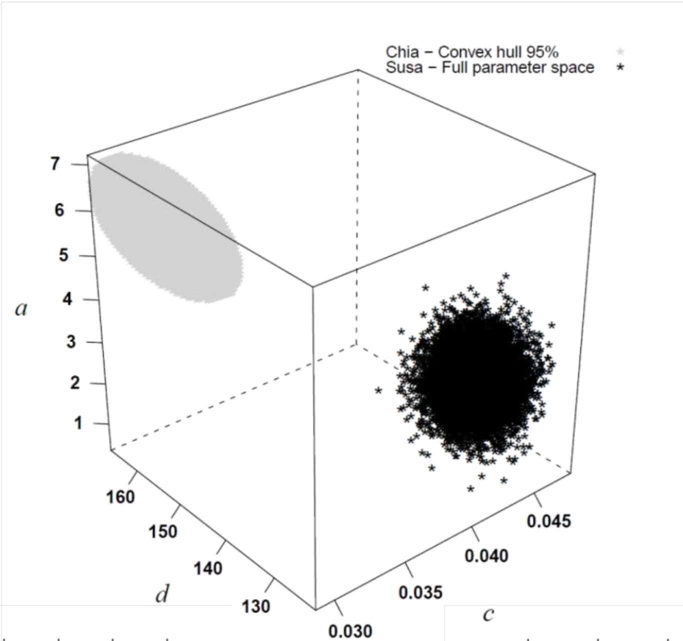
Chia



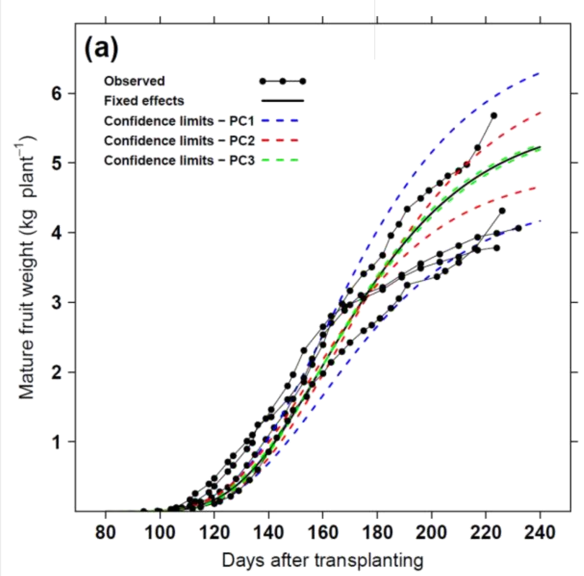
Susa



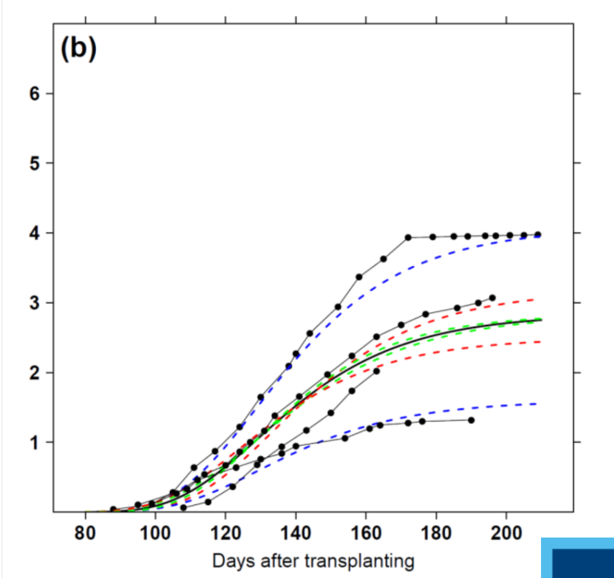
Nonlinear mixed models



Chia



Susa



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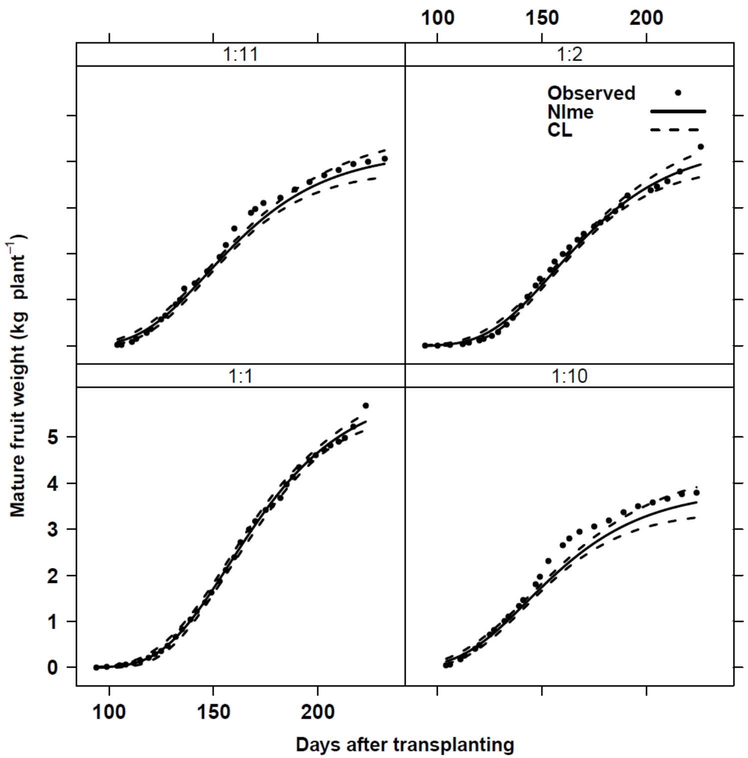
Nonlinear mixed models

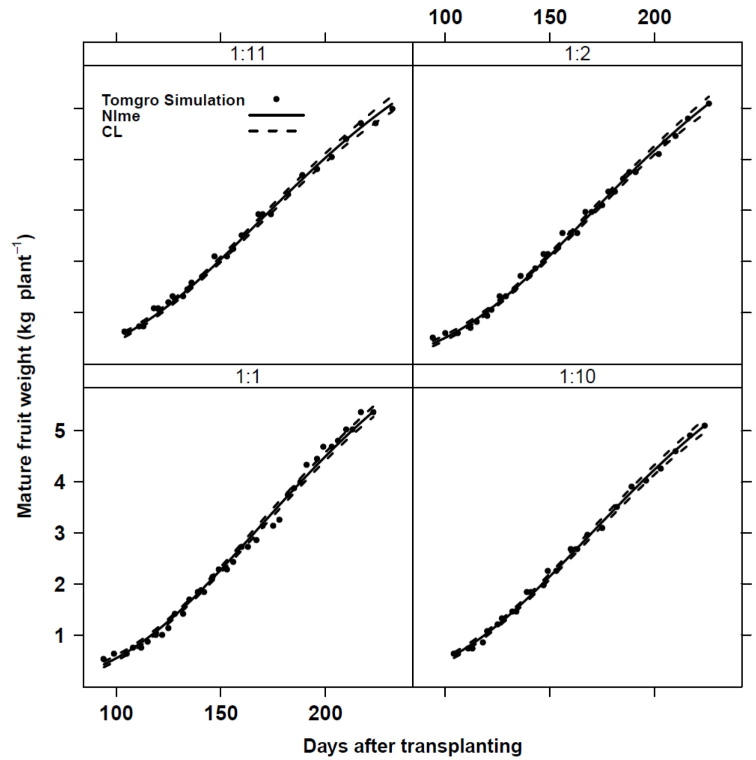
Chia - Observed

$$y_{ij} = (a + u_{i1}) \times \exp^{\left(-\exp^{c \times (d + u_{i2} - \text{dat})}\right)} + e_{ij}$$



Chia – Simulated (TOMGRO-model)

$$y_{ij} = (a + u_{i1}) \times \exp^{\left(-\exp^{c \times (d - \text{dat})}\right)} + e_{ij}$$



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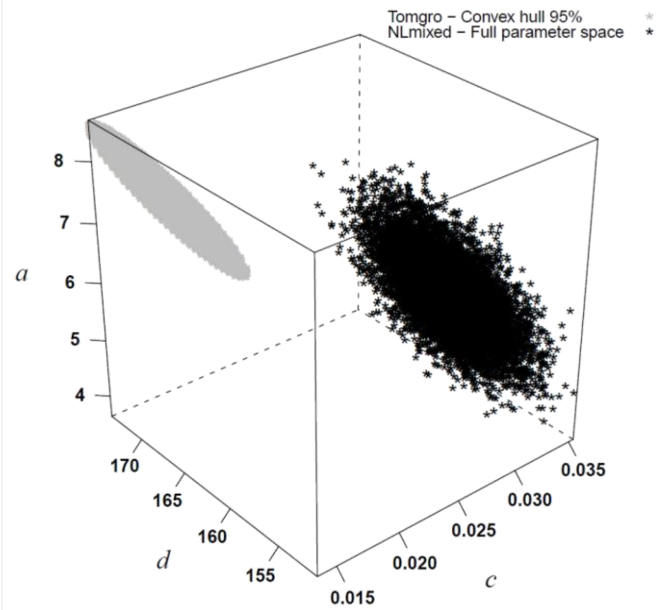
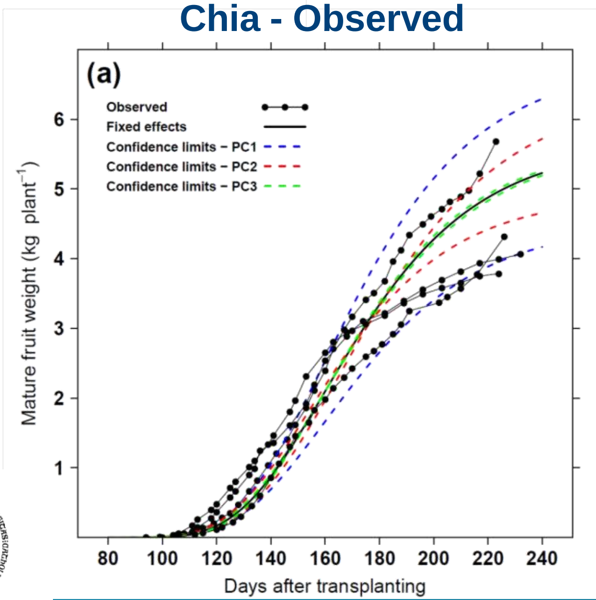
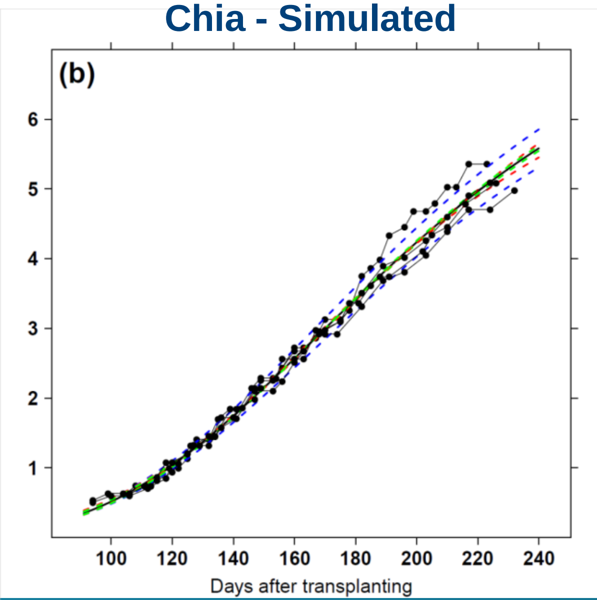
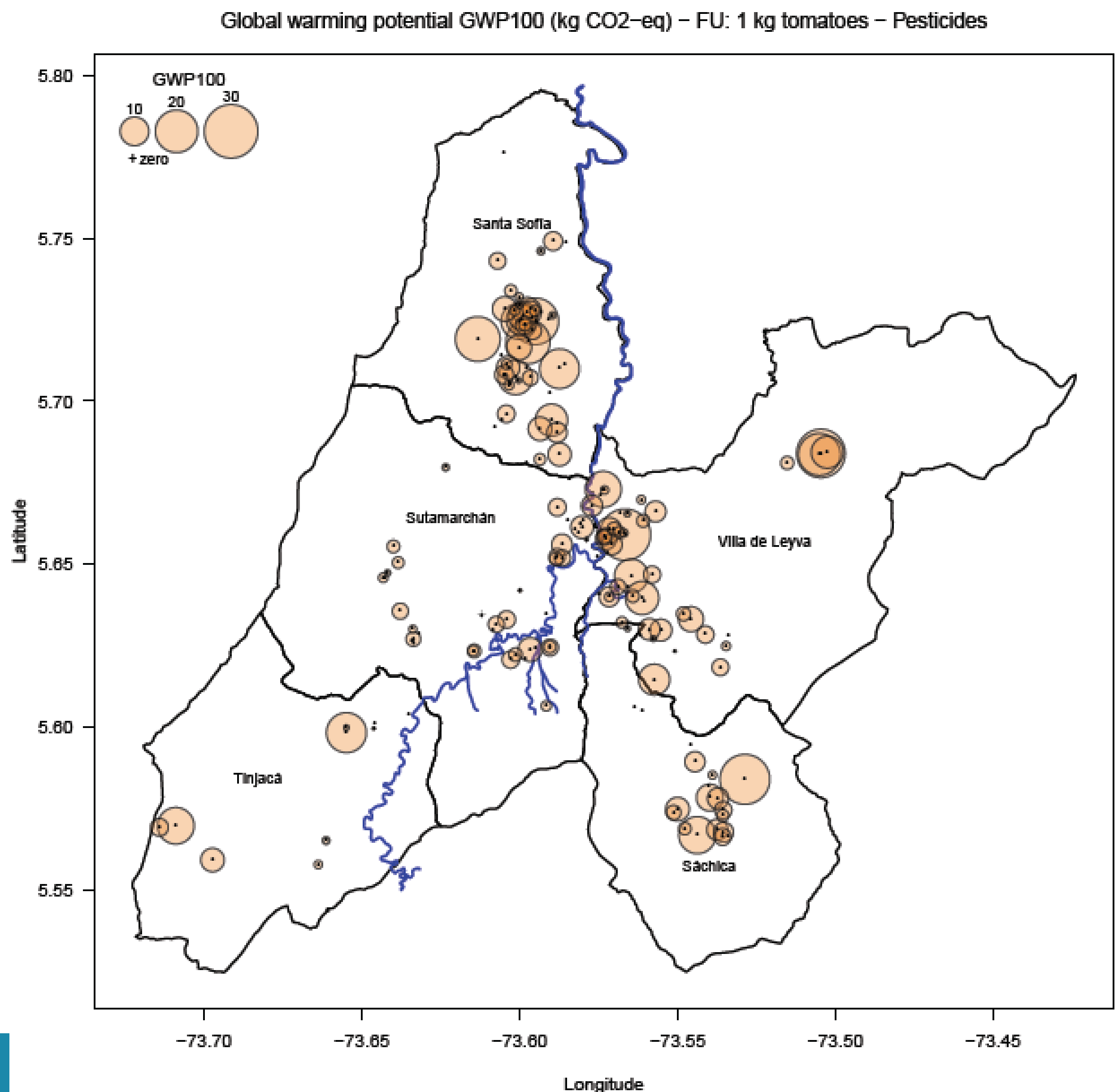
Nonlinear mixed models







Environmental Impact Assessment



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Conclusions

- Model based investigation of technical sustainability
  - Many methodologies are possible
  - Very simple and straightforward to very complex
  - Mission of sustainability research?
  - Static, time invariant ⇔ dynamic
  - Statistical models ⇔ system dynamical model

Thank you for your attention