Modelling land-use change in response to scenarios

Technical Skills Course, International Training Network project Changes

13 September 2012, Dr Sophie Rickebusch

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Content & learning outcome

- What are models?
  - Purpose
  - Development
- Parsimonious (simple) models: Kaya identity
- Including scenarios in models:
  - Land-use models: RUG, IMAGE
  - Integrated assessment models: IMAGE 2, CLIMSAVE IAP

You will have a basic knowledge of what (land-use) models are and how scenarios can be integrated into them

My painting is visible images which conceal nothing; they evoke mystery and indeed when one sees one of my pictures, one asks oneself this simple question 'What does that mean?' René Magritte, 1947

Examples of model purposes

- Describe the dynamic behaviour of a system
- Quantify cause and effect
- Investigate interactions (feedbacks)
- Develop quantitative scenarios
- Determine and quantify uncertainties
- Make a tool to experiment

Rationale for modelling a system

- Rationale for any model = scientific desire to capture the **essence** and remove or reduce the **redundant aspects** of the system under study
- What is essential and what is redundant, i.e. the level of reduction required, depends to a large extent on the **questions being asked**
- The result is a 'model' of reality that is more or less realistic

Important steps in model development (1)

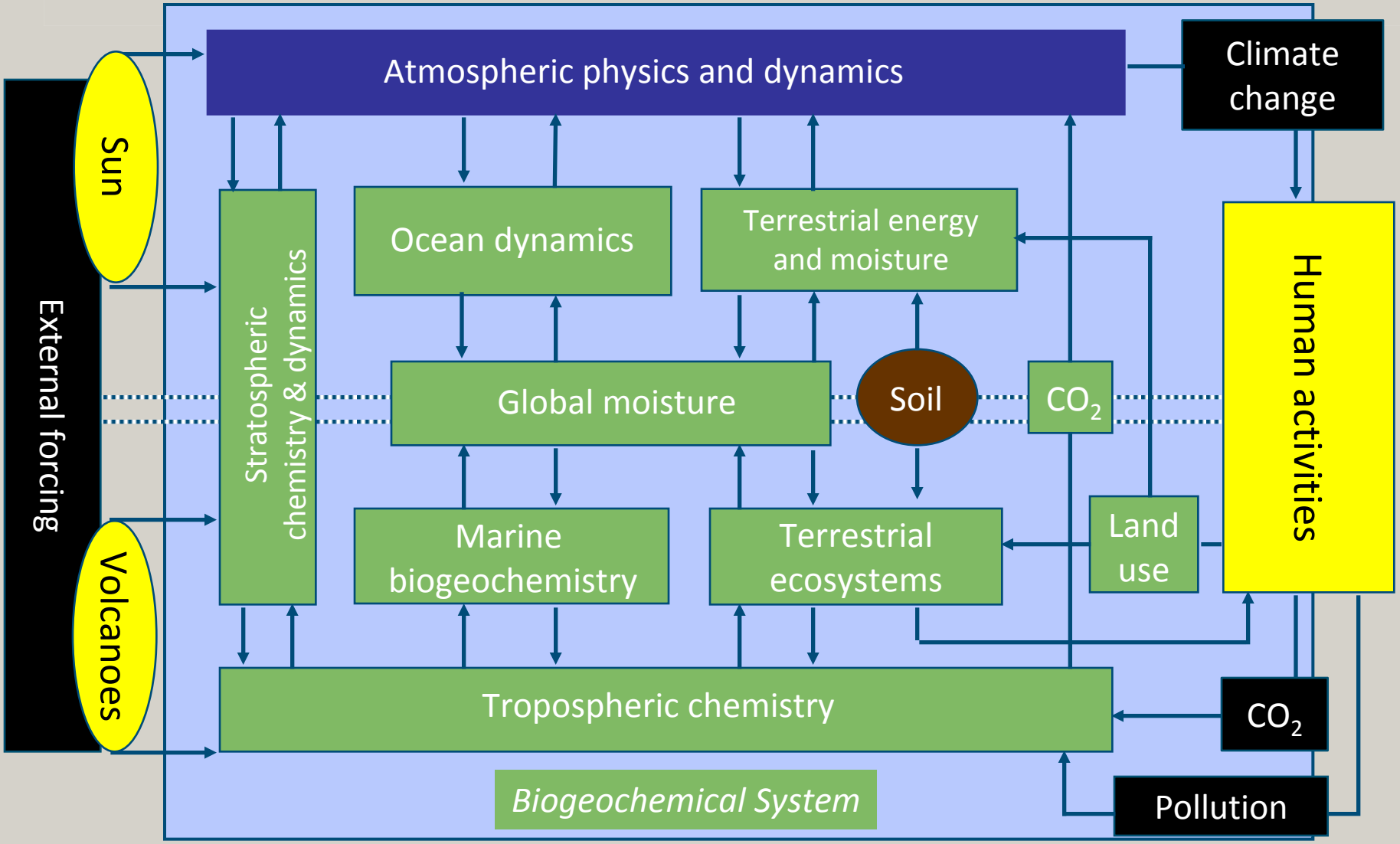
- System conceptualisation
  - DPSIR, wiring diagrams etc.
- Determining empirical relationships between different input and model factors
- Determining change over time (and space) of the different input and model factors
- Model prototyping
  - modelling software (e.g. STELLA, SIMILE)
  - programming language

Important steps in model development (2)

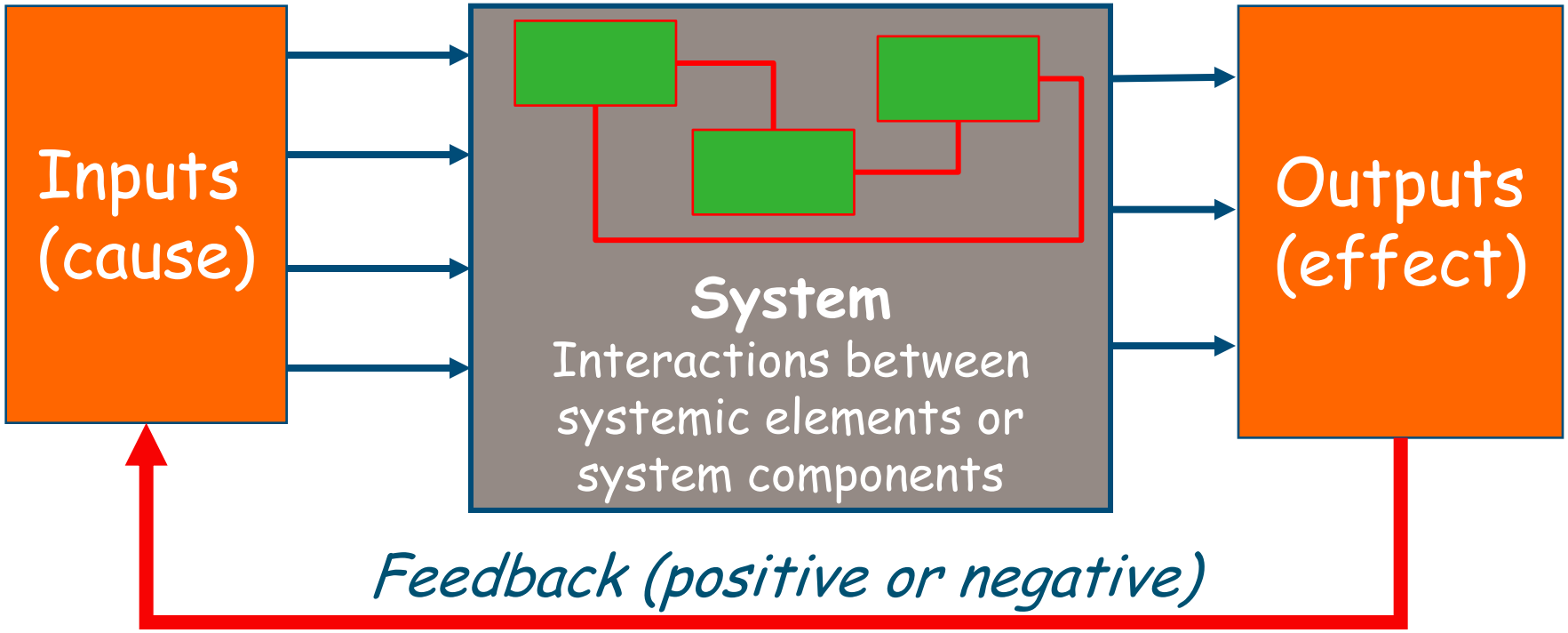
- Model testing
  - does it perform as we expect?
- Validation
  - does it mimic the system dynamics from independent datasets?
- Uncertainty and sensitivity analysis
  - which factors most strongly determine the output?
- Model and data comparisons
  - benchmarking, peer-review
- Model experimentation and scenarios

Conceptualisation of the Earth System:

Bretherton Diagram (1988)



Defining relationships in the system (external and internal factors)



- We want to know the links between cause and effect
- Exploring and quantifying all these links = systems approach

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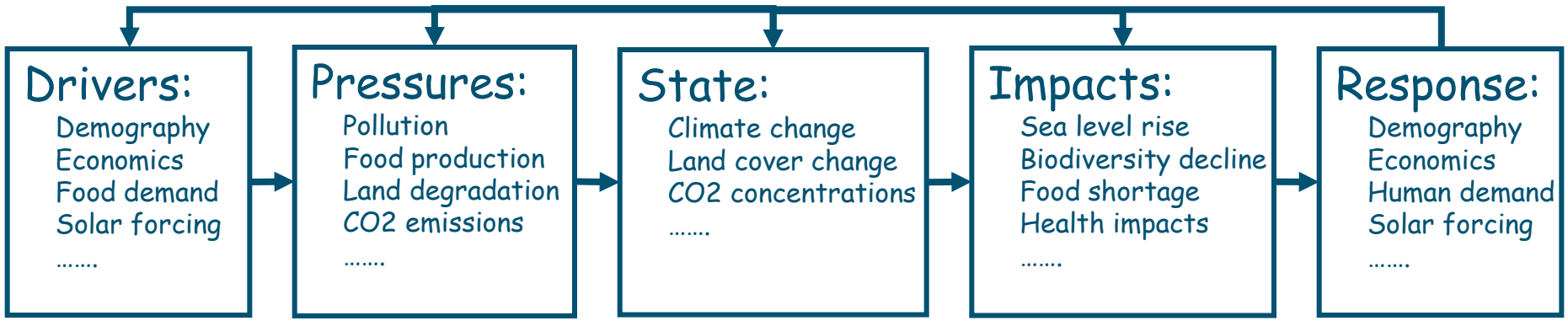
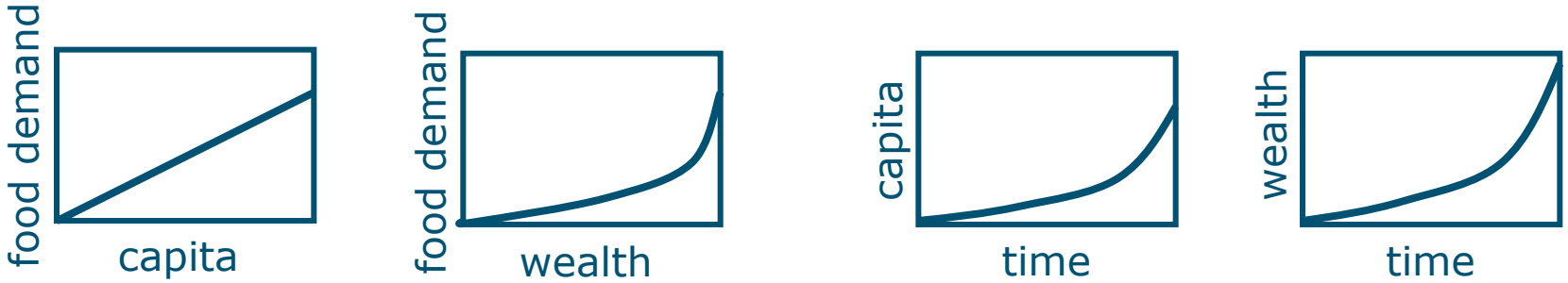
The causal chain (DPSIR) and empirical relationships



When you model, you have to make the relationships between individual drivers, pressures and other variables explicit.



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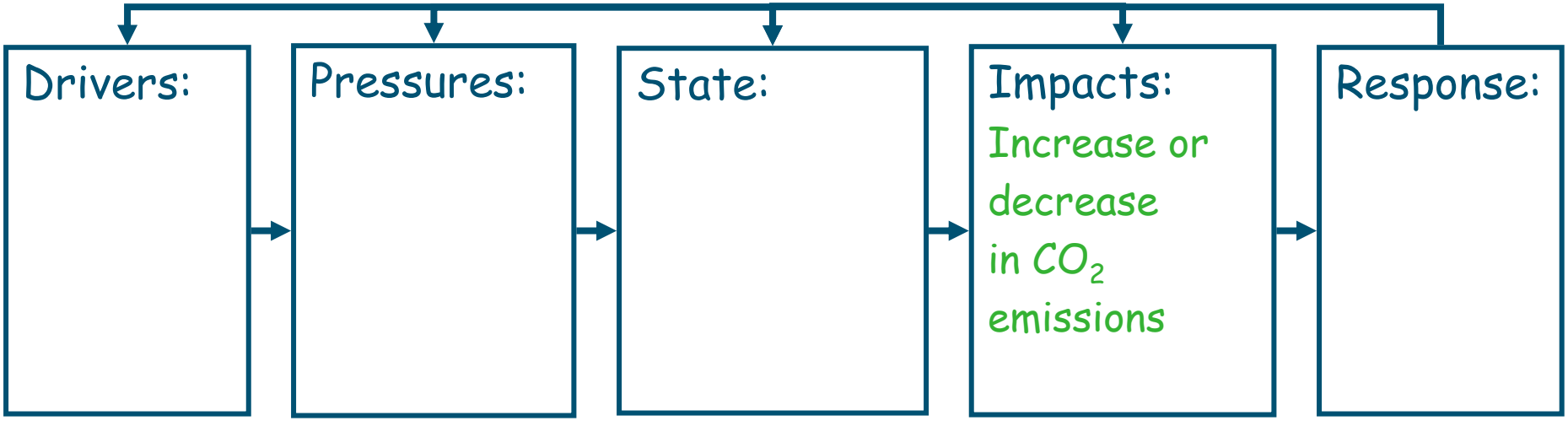
Example: the Kaya identity

The challenge: what factors are needed to model CO_2 emissions from energy use?



Developing a parsimonious model

$$CO_2 = CO_2$$

$$CO_2 = POP/POP \bullet CO_2$$

$$CO_2 = POP/POP \bullet GDP/GDP \bullet CO_2$$

$$CO_2 = POP/POP \bullet GDP/GDP \bullet EU/EU \bullet CO_2$$

$$CO_2 = \underbrace{\underbrace{POP}_{\text{Population}} \bullet \underbrace{GDP/POP}_{\text{Affluence}} \bullet \underbrace{EU/GDP}_{\text{Energy intensity}} \bullet \underbrace{CO_2/EU}_{\text{Carbon intensity}}}_{\text{The KAYA identity}}$$

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KAYA through time

Population

Affluence

Energy intensity

Carbon intensity

CO2 emissions

past **future**

Combining parsimonious models with geographic information

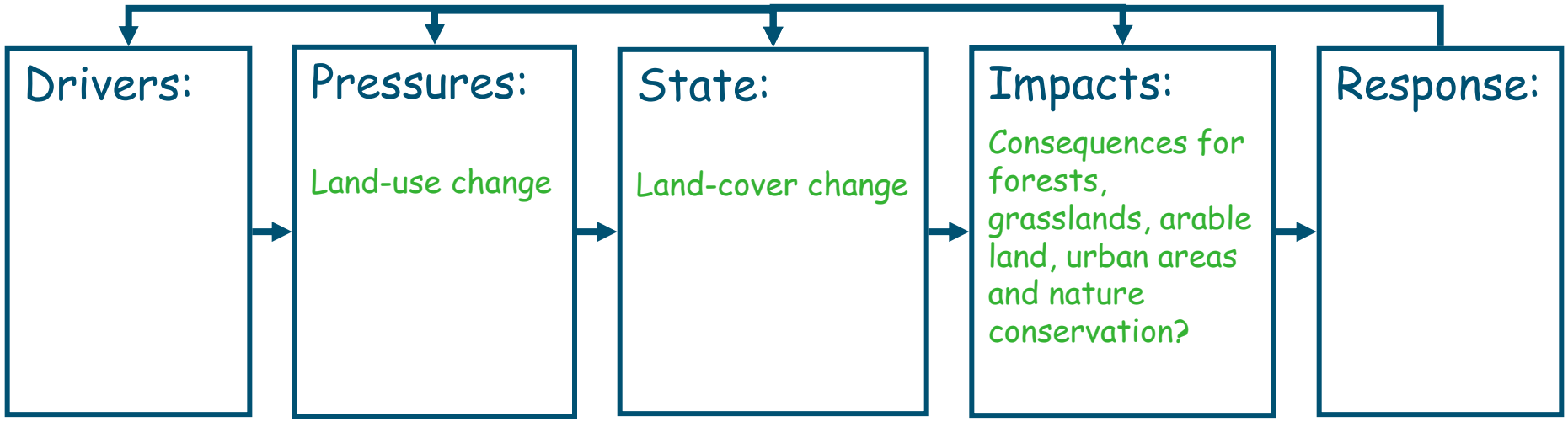
A more complex challenge

We want to develop a model which provides answers to the following questions:

- How will future European land-use develop?
- What are the major trends?
- What are its consequences for forests, grasslands, arable land, urban areas and nature conservation?

What factors should be included in this type of model and how should they be linked?

The results of this challenge



How to implement the method?

Which drivers affect land-use and what is their spatial allocation?

- Spatial drivers:
  resource competition, rural and environmental policy & climate change
- Non-spatial drivers:
  all the rest but especially demand and supply

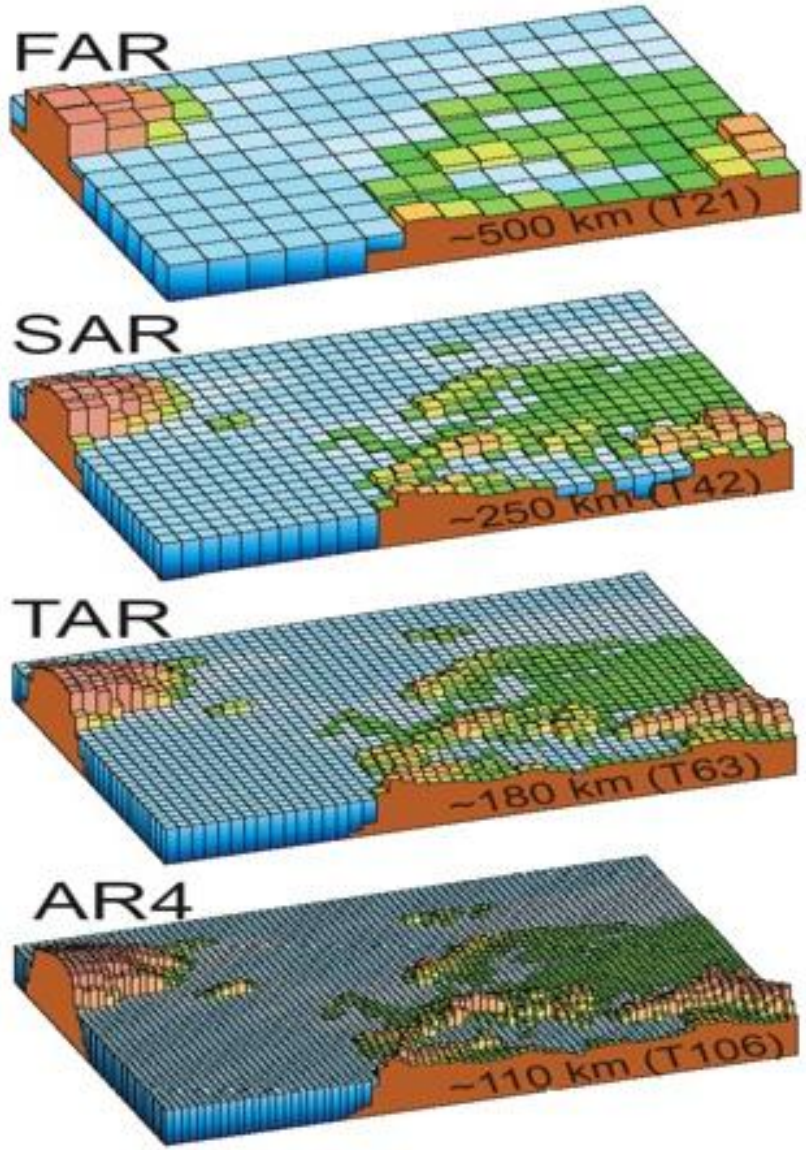
Spatial data: resolution in GCMs

1980s
(500 x 500 km)

Early 1990s
(250 x 250 km)

Late 1990s
(180 x 180 km)

Current resolution
(110 x 110 km)



Doubling the resolution requires halving the temporal resolution.
This leads to 2•2•2•2 =16 more calculations!

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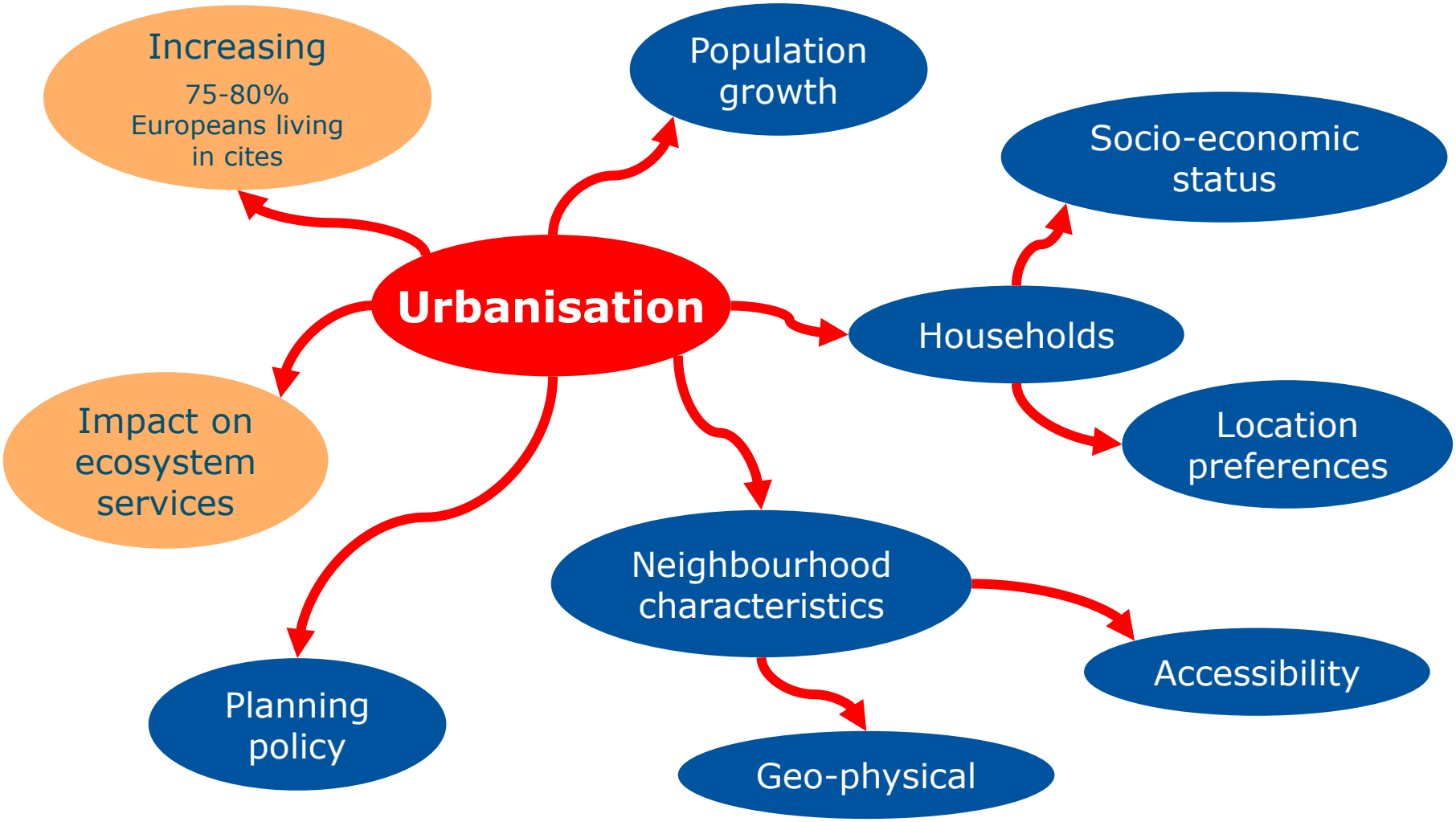
The Regional Urban Growth (RUG) model

Urbanisation



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PLUREL scenarios

Private enterprise / economic values

Global / macro & top-down dynamic

Regional / local & bottom-up dynamic

A1 - *hyper-tech*

- fast economic growth
- high population growth
- few constraints on urbanisation
- shock: rapid ICT development

A2 - *extreme water*

- regional economic development
- medium population growth
- local-level spatial planning
- shock: extreme drought & flood events

B1 - *peak oil*

- government-led sustainable development
- low population growth
- environmental & social consciousness
- shock: soaring oil prices

B2 - *fragmentation*

- local policies for sustainable development
- medium population growth
- fragmented society: enclaves by age group, ethnicity…
- shock: social exclusion

Public / social & environmental values

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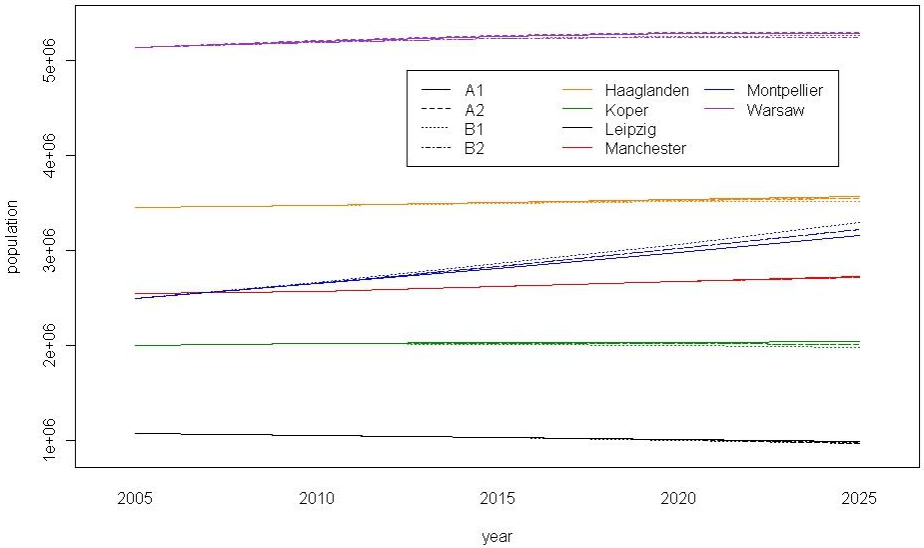
RUG - main inputs

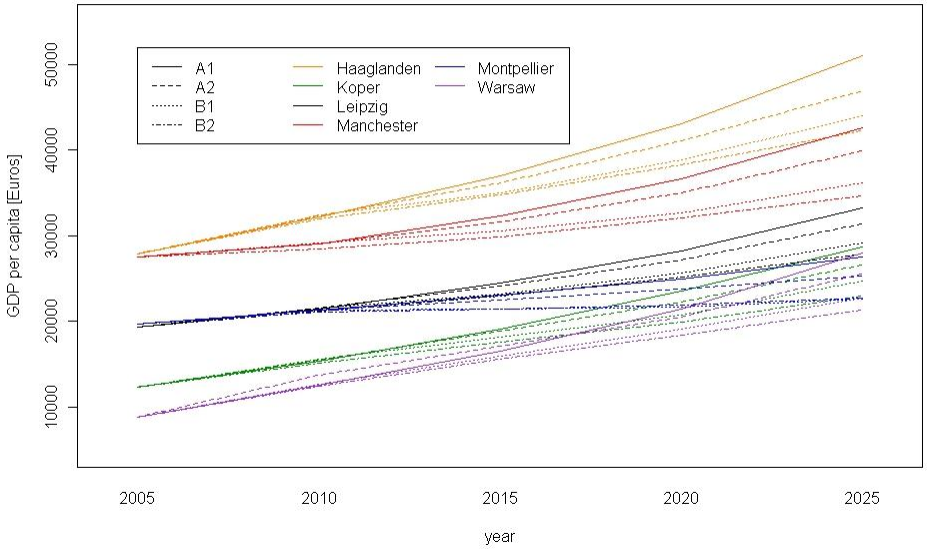
Population & GDP change ⇨ increase in proportion of artificial surfaces

pr.art.surf = ƒ(pop, GDP.cap, urb.typ, country)

adjusted R^2 = 0.75

NUTS 2





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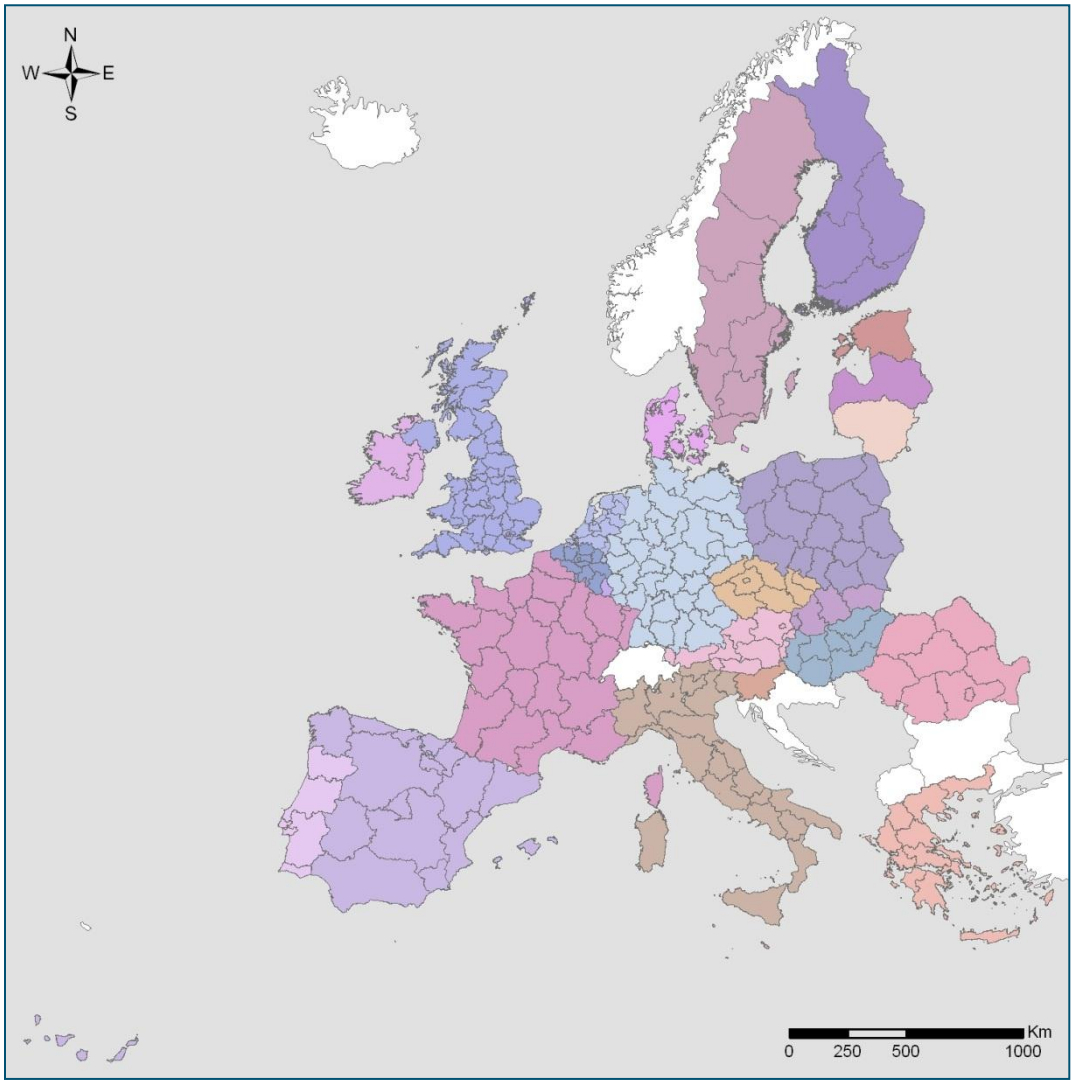
RUG - overview



- EU-27, minus Bulgaria & Cyprus
- Simulation by NUTS 2 region
- 1 km grid
- Time steps: 2015, 2025
- Planning, accessibility, physical constraints (e.g. flooding), etc. ⇨ distribution of urban areas

NUTS 2 → **1 km**

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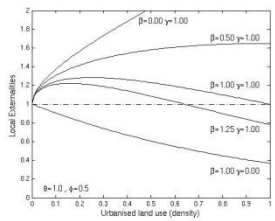
RUG - allocation variables

local externalities

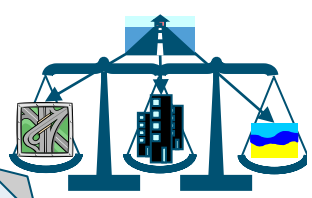
$$LX_{ij} = e^{\left(\gamma.L_{ij}^{\phi} - \beta.L_{ij}^{\theta}\right)}$$

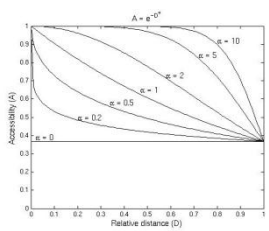


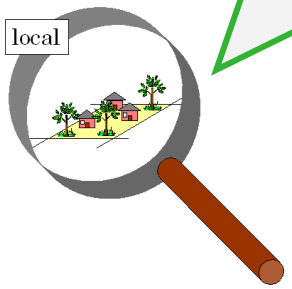
Household preferences

accessibility

$$A_{ij} = \sum_{d} w_d.e^{-\left(\frac{D_{d,ij}}{D_{d,max}}\right)^{\alpha_d}}$$

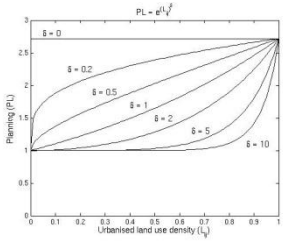






concentration

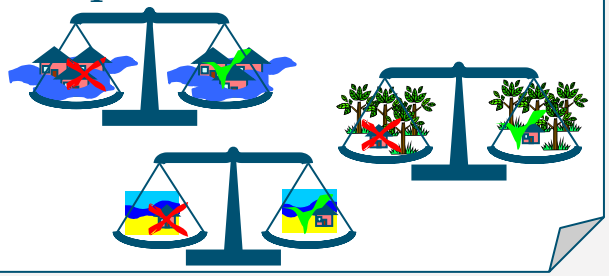
$$PL_{ij} = e^{(L_{ij})^{\delta}}$$



Planning preferences

restrictions

presence/absence



PLUREL scenarios ⇨ RUG parameters

		baseline	hyper-tech (A1)		extreme water (A2)		peak oil (B1)		social fragments (B2)	
externalities	β (green)	2	+	4	-	1	--	0.5	++	6
	γ (red)	0.5	0	0.5	0	0.5	0	0.5	0	0.5
nearest city	weight	5	0	5	+	6	++	7	+	6
	slope	2	--	0.5	-	1	+	3	0	2
primary city	weight	0.5	+	1	+	1	++	2	-	0.3
	slope	1	--	0.5	0	1	+	3	+	3
coast	weight	0.1	0	0.1	--	0.02	-	0.05	+	0.5
	slope	1	0	1	0	1	-	0.5	-	0.5
compaction		0.2	--	0	-	0.1	++	1	+	0.5
flood zones		N	N				Y		Y	
protected areas		N	N				Y		Y	

Flood risk makes coast less attractive

Shift from car to public transport ⇨ concentration in larger centres

- Qualitative interpretation of scenario storylines
- Quantitative translation ⇨ expert judgement

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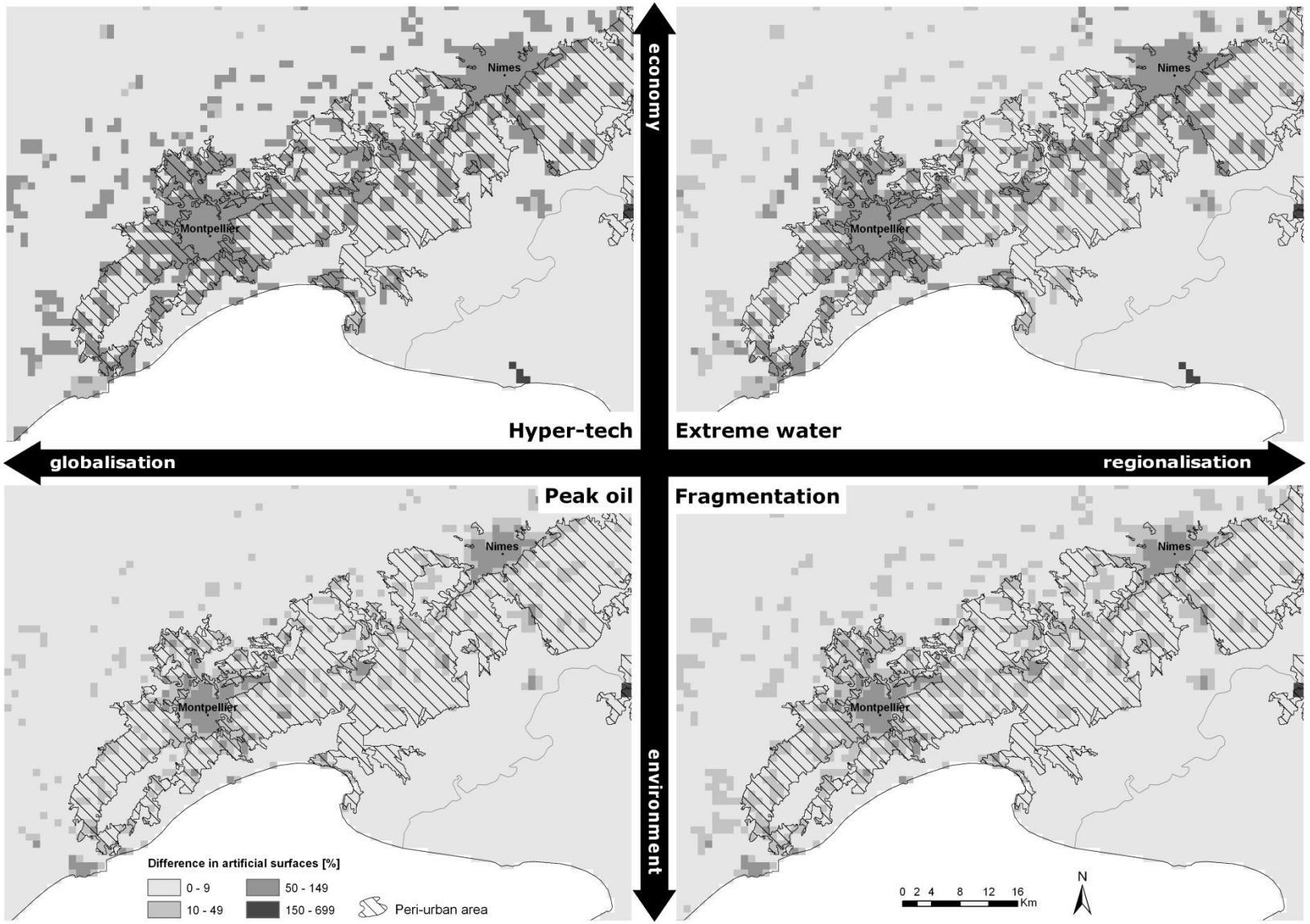
RUG output example: Montpellier 2025



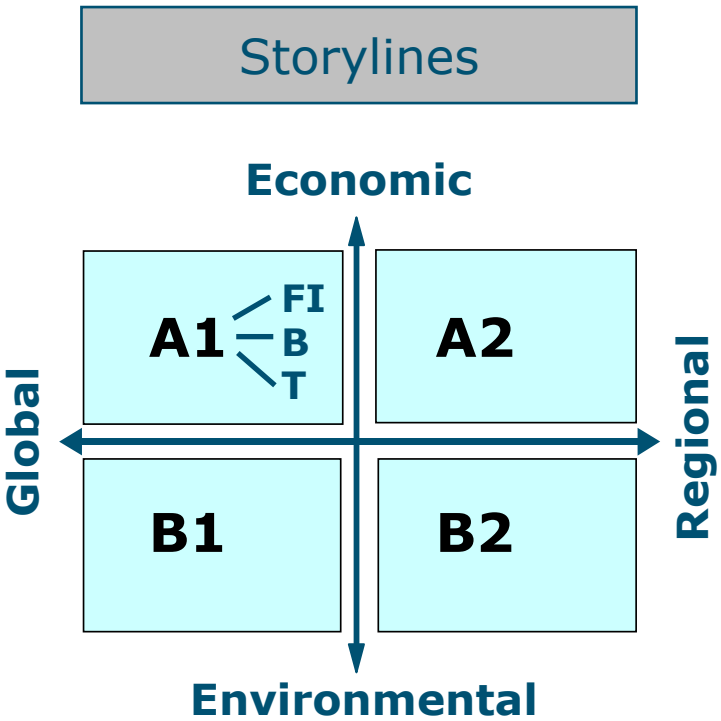
Pop
⇗⇗

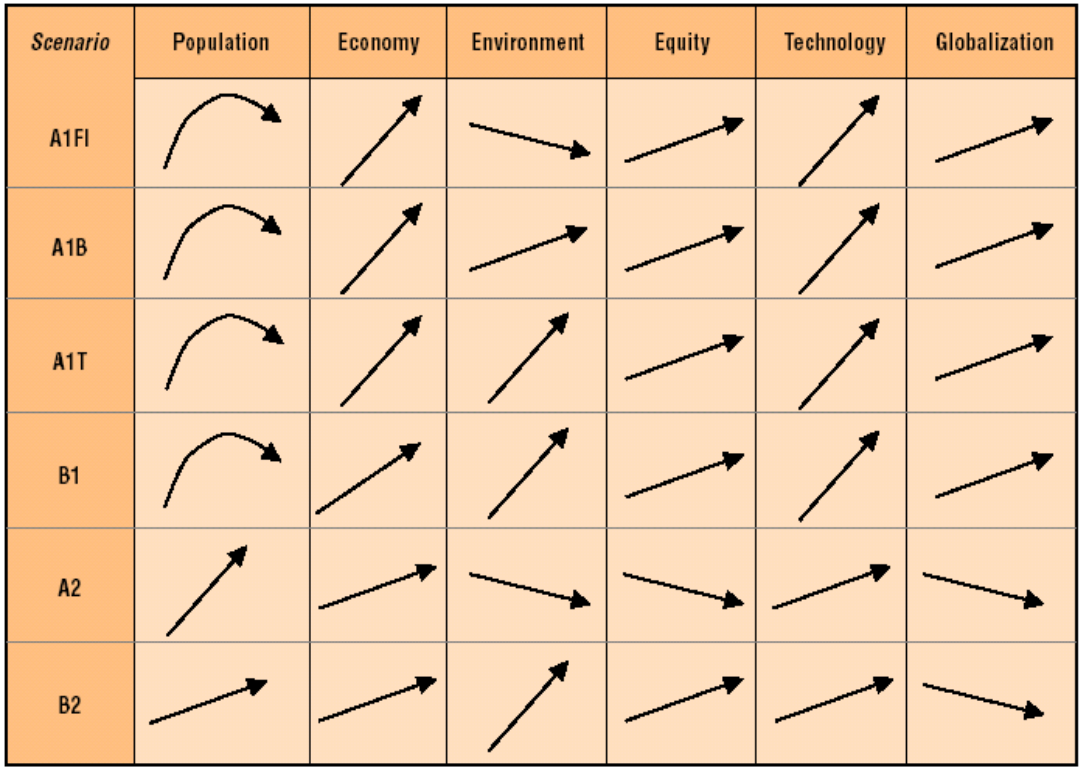
GDPc
⇗/⇨

A multiple land-use model

The IMAGE model

Scenarios: the IPCC SRES framework





Land-use scenario development for the EU: the ATEAM project

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An agricultural land use change model

Based on a simple supply and demand function:

$$\frac{L_t}{L_{t_0}} = \frac{D_t}{D_{t_0}} \cdot \frac{P_{t_0}}{P_t} \cdot \frac{O_{r,t}}{O_{r,t_0}}$$

L …	Agricultural land use *[ha]*
t …	Time
t_0 …	start moment, baseline
D …	Demand for production *[t]*
P …	Productivity *[t/ha]*
O …	Overproduction, relative *[-]*

$$L_t = L_{t_0} \cdot \frac{D_t}{D_{t_0}} \cdot \frac{P_{t_0}}{P_t} \cdot \frac{O_{r,t}}{O_{r,t_0}}$$

Unknown parameters to estimate

Estimation of parameters ⇨ historic trends (1960-2000)

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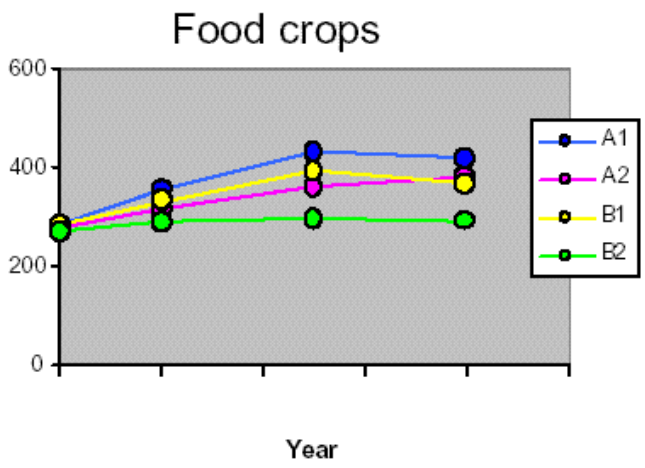
IMAGE demand values

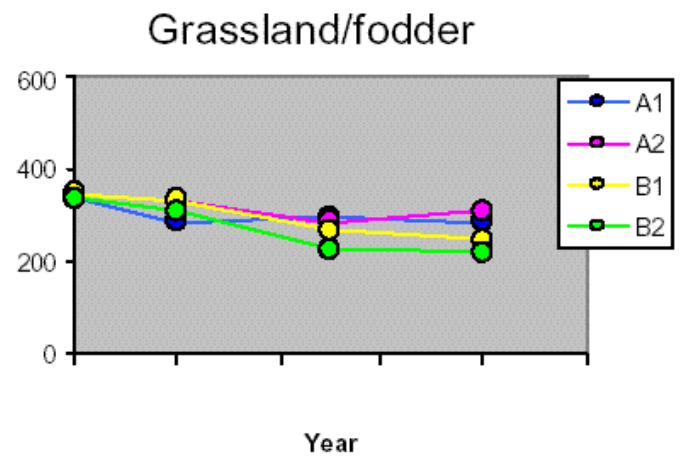
Approach

$$\frac{L_t}{L_{t_0}} = \boxed{D_t} \cdot \frac{P_{t_0}}{P_t} \cdot \frac{O_{r,t}}{O_{r,t_0}}$$

IMAGE model

Estimated future demand





Productivity changes

Approach

$$\frac{L_t}{L_{t_0}} = \frac{D_t}{D_{t_0}} \cdot \frac{P_{t_0}}{\boxed{P_t}} \cdot \frac{O_{r,t}}{O_{r,t_0}}$$

$$P_t = P_{t_0} r_{p_{t-t_0}}$$

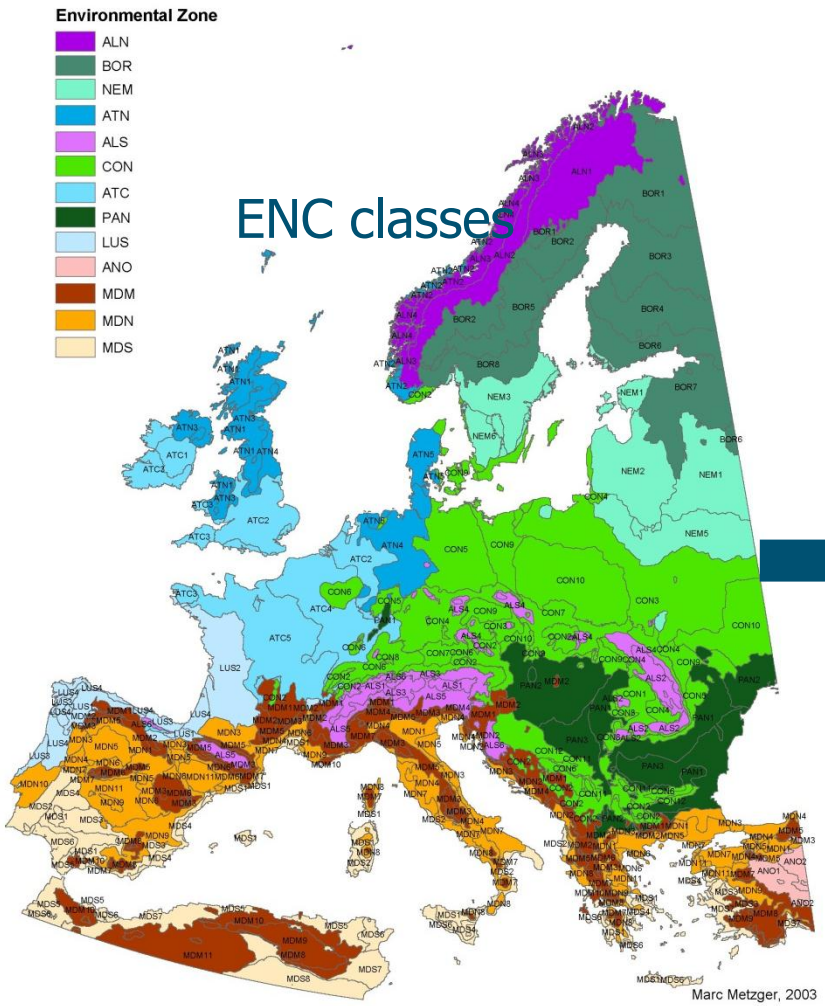
$$r_{p_{t-t_0}} = g(\Delta CO_2, \Delta C, \Delta T)_{t-t_0}$$

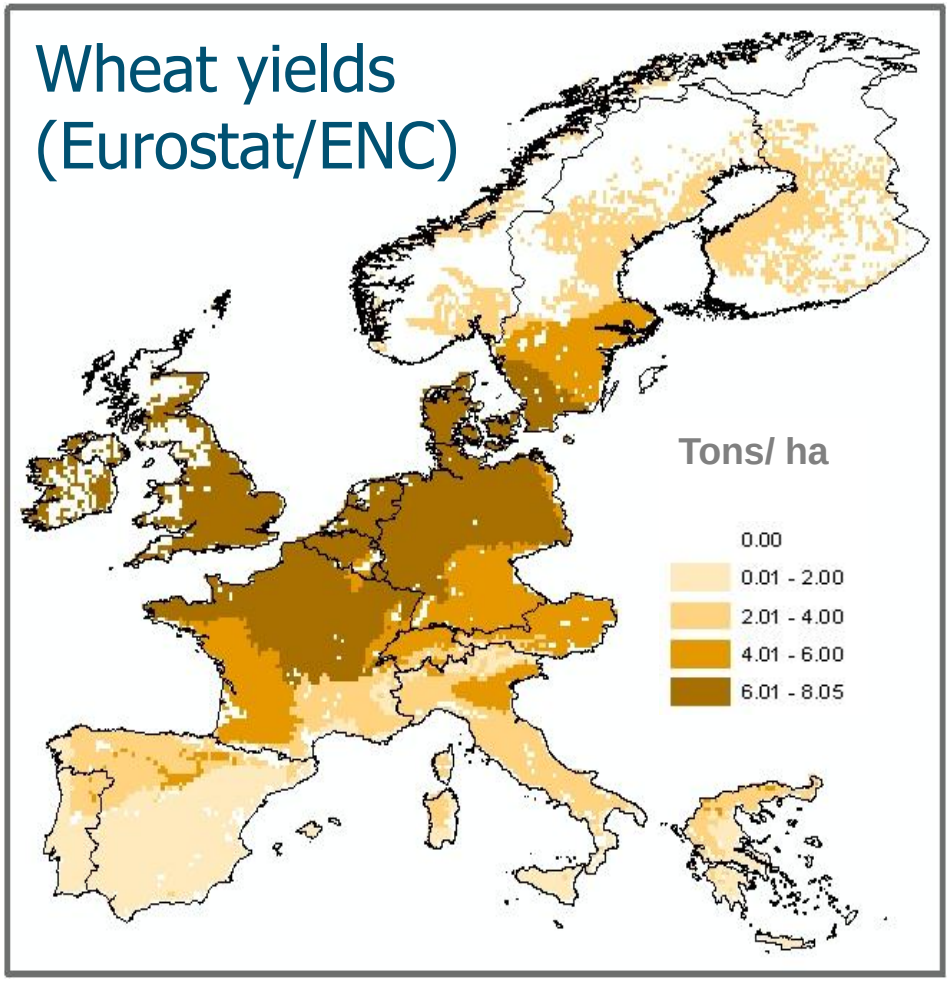
P ...	Productivity *[t/ha]*
r_p ...	Relative change in productivity *[-]*
CO_2 ...	Atmospheric CO_2 concentration
C ...	Climate
T ...	Technology

$$P_t = P_{t_0} + ((P_{t,C} - P_{t_0}) + (P_{t,CO_2} - P_{t_0}) + (P_{t,T} - P_{t_0}))$$

$$\frac{P_{t_0}}{P_t} = \frac{1}{1 + ((P_{t,C}/P_{t_0} - 1) + (P_{t,CO_2}/P_{t_0} - 1) + (P_{t,T}/P_{t_0} - 1))}$$

Estimating climate effects





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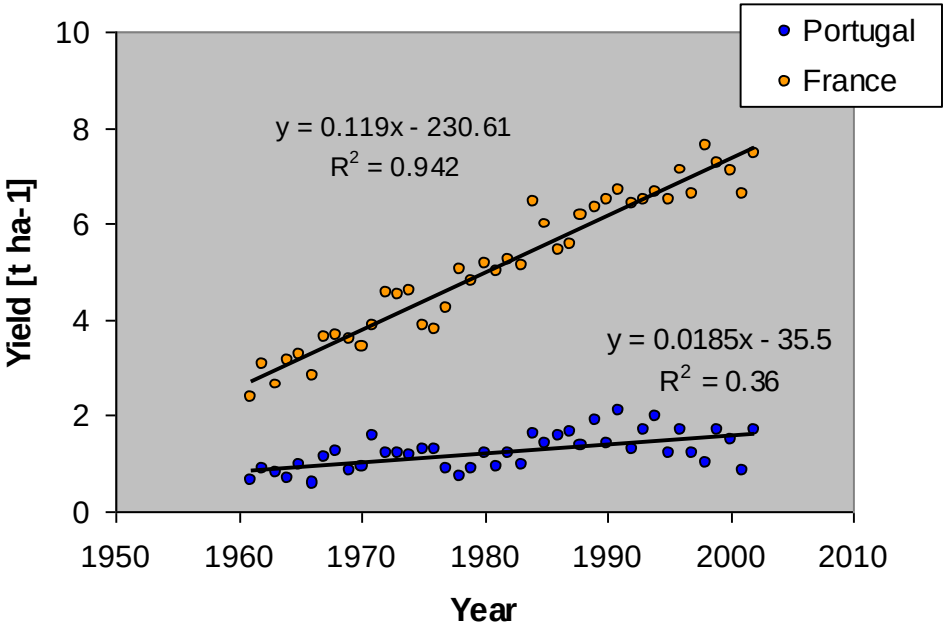
Technology effect

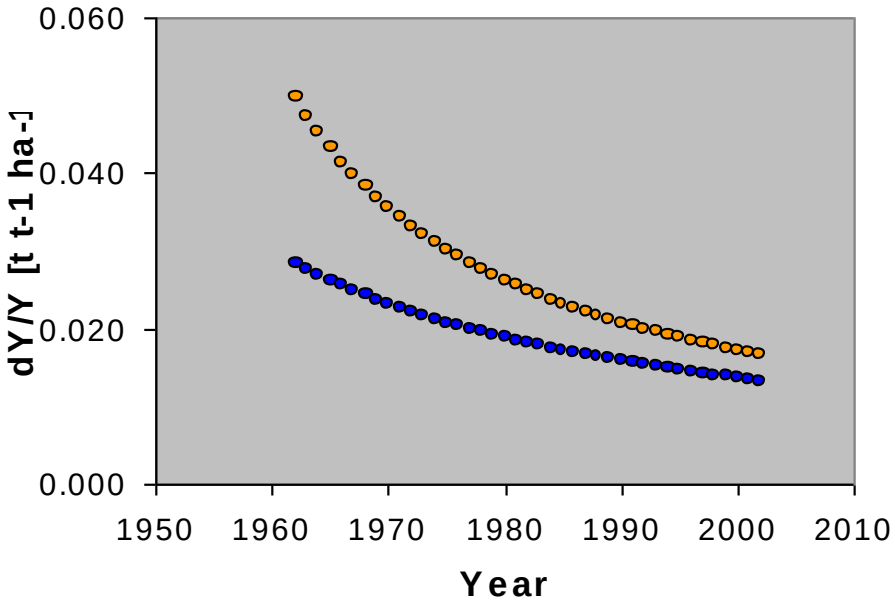
- Quantifying future changes in crop yields arising from technology and management change - how?
- For example, relative change in yields

France and Portugal, 1961-2002

Wheat yield [t/ha] vs. time [yr]



Relative change dY/Y vs. time

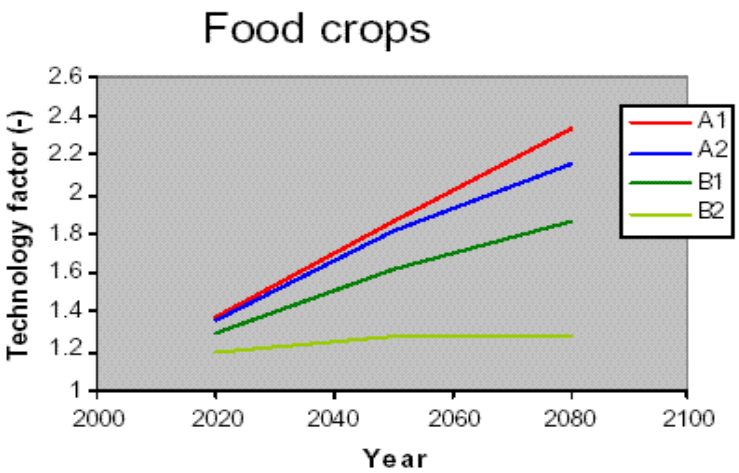


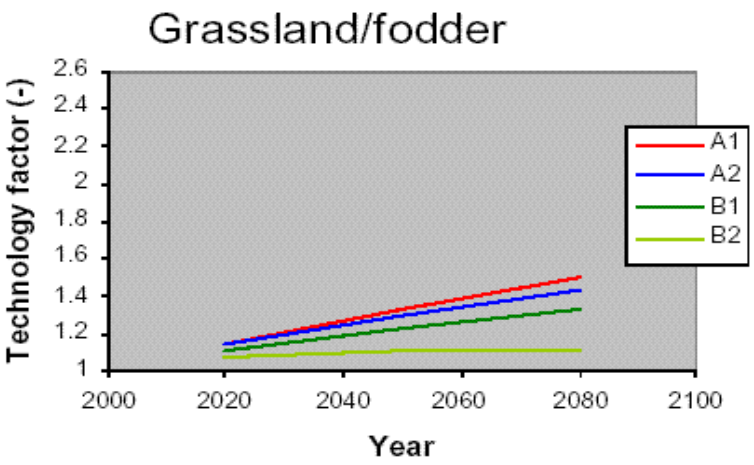
Technology change factors

Approach

$$\frac{P_{t_0}}{P_t} = \frac{1}{1 + ((P_{t,C} / P_{t_0} - 1) + (P_{t,CO_2} / P_{t_0} - 1) + (P_{t,T} / P_{t_0} - 1))}$$

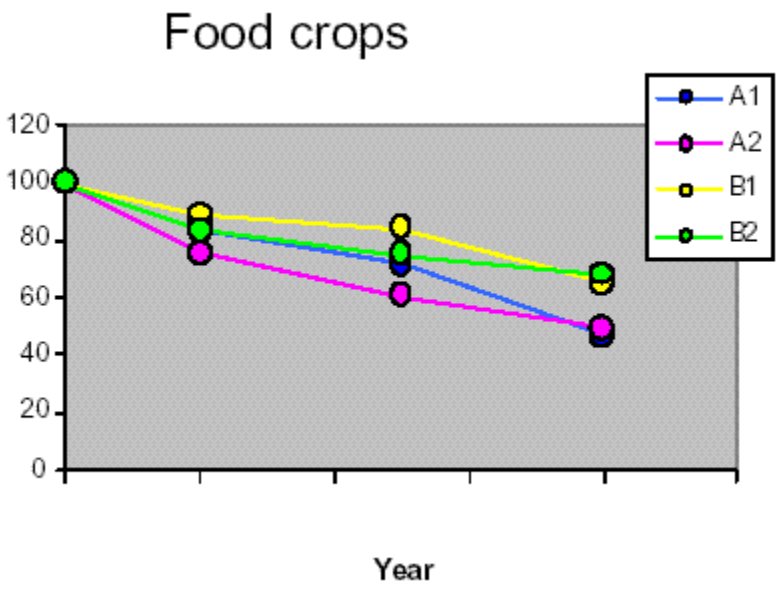
Technology factors

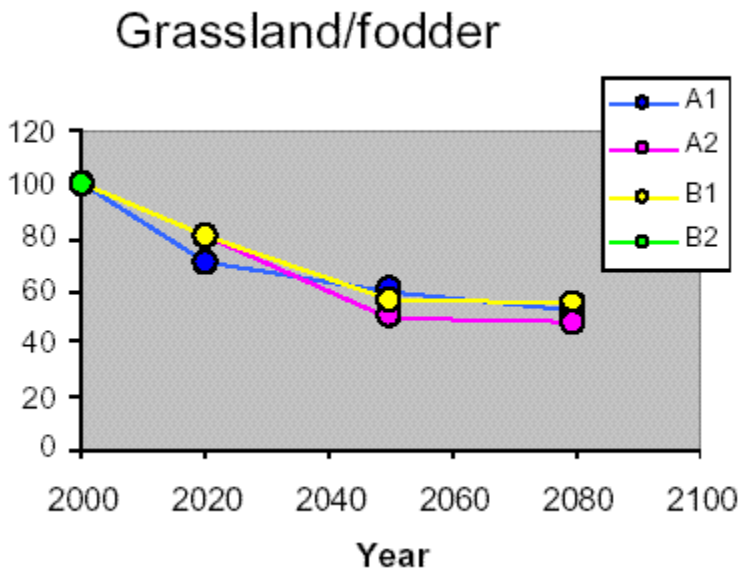




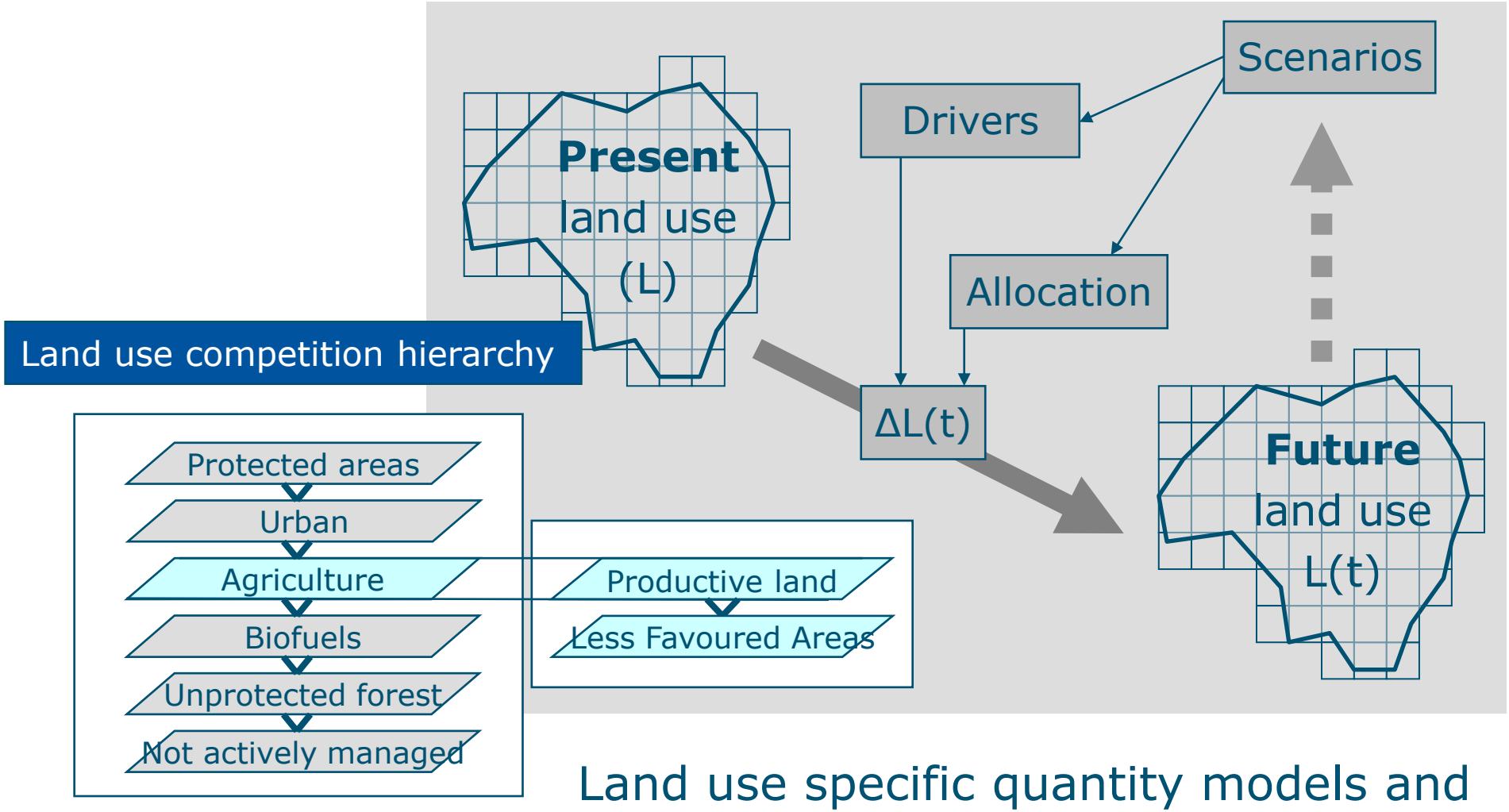
European change quantities

- 50% decline in agricultural (food) production areas by 2080!
- But... what about the spatial allocation of these quantities?





Spatial allocation



Land use specific quantity models and spatial allocation rules

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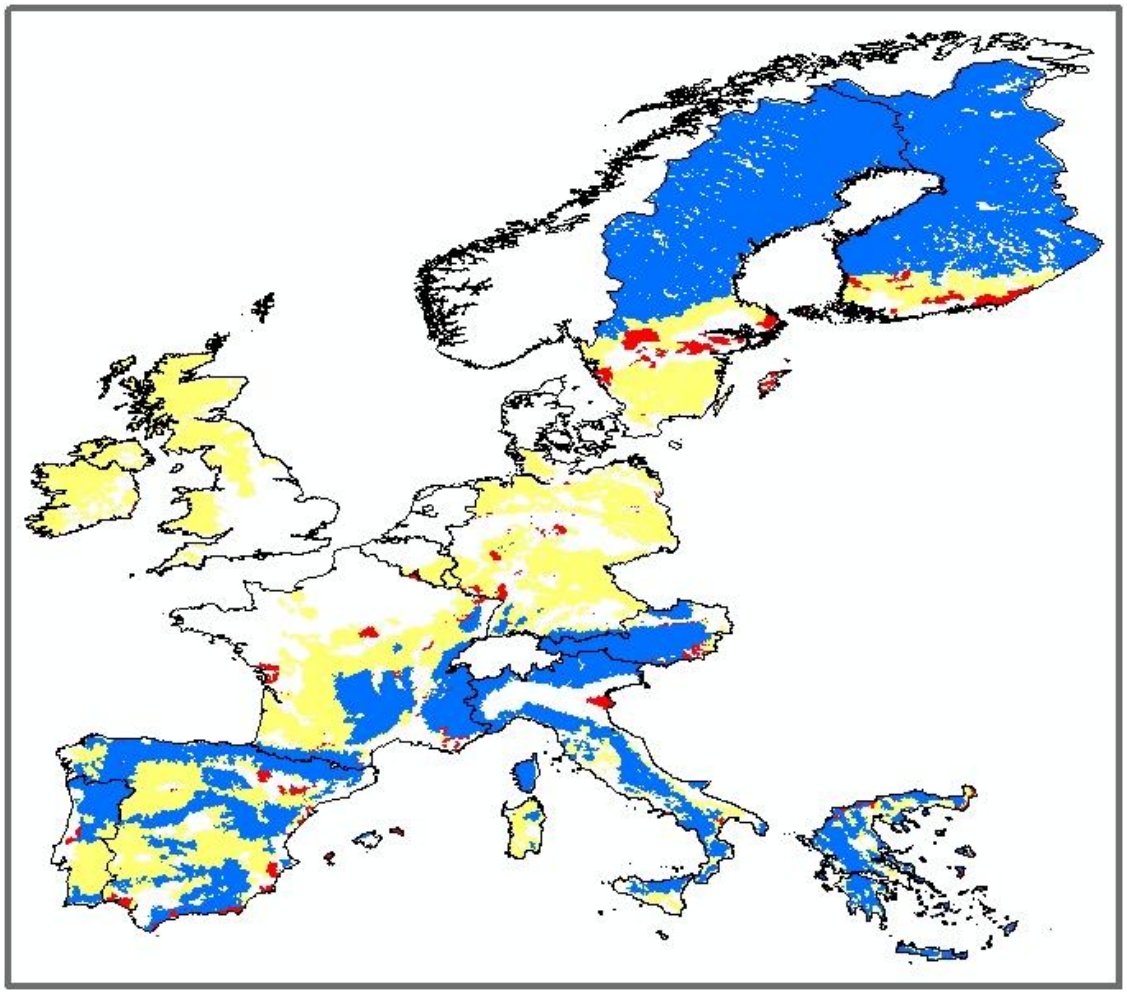
Less Favoured Areas



Non-optimal locations

- **Mountain/hill areas**
- **Areas with handicaps**
- **Less Favoured Areas**

Source: EC DG Agriculture

Scenario spatial allocation rules

A1

No oversupply
Optimal locations
(non LFAs)

A2

No oversupply
Equal spatial change
(regional)

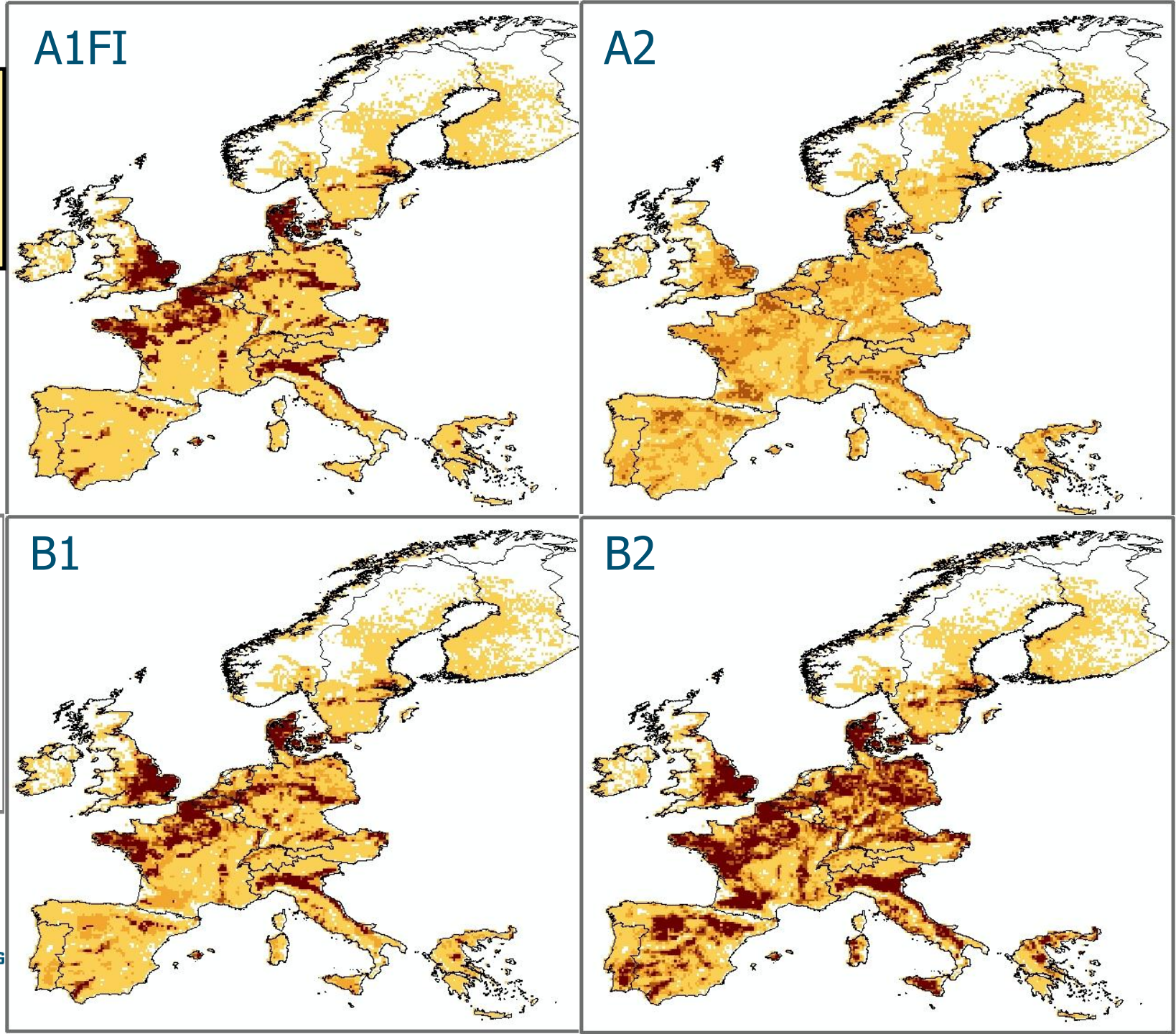
B1

Oversupply
Optimal location of
arable land
No change in grassland

B2

Oversupply
No change in areas

Crop land in 2080 (HADCM3)

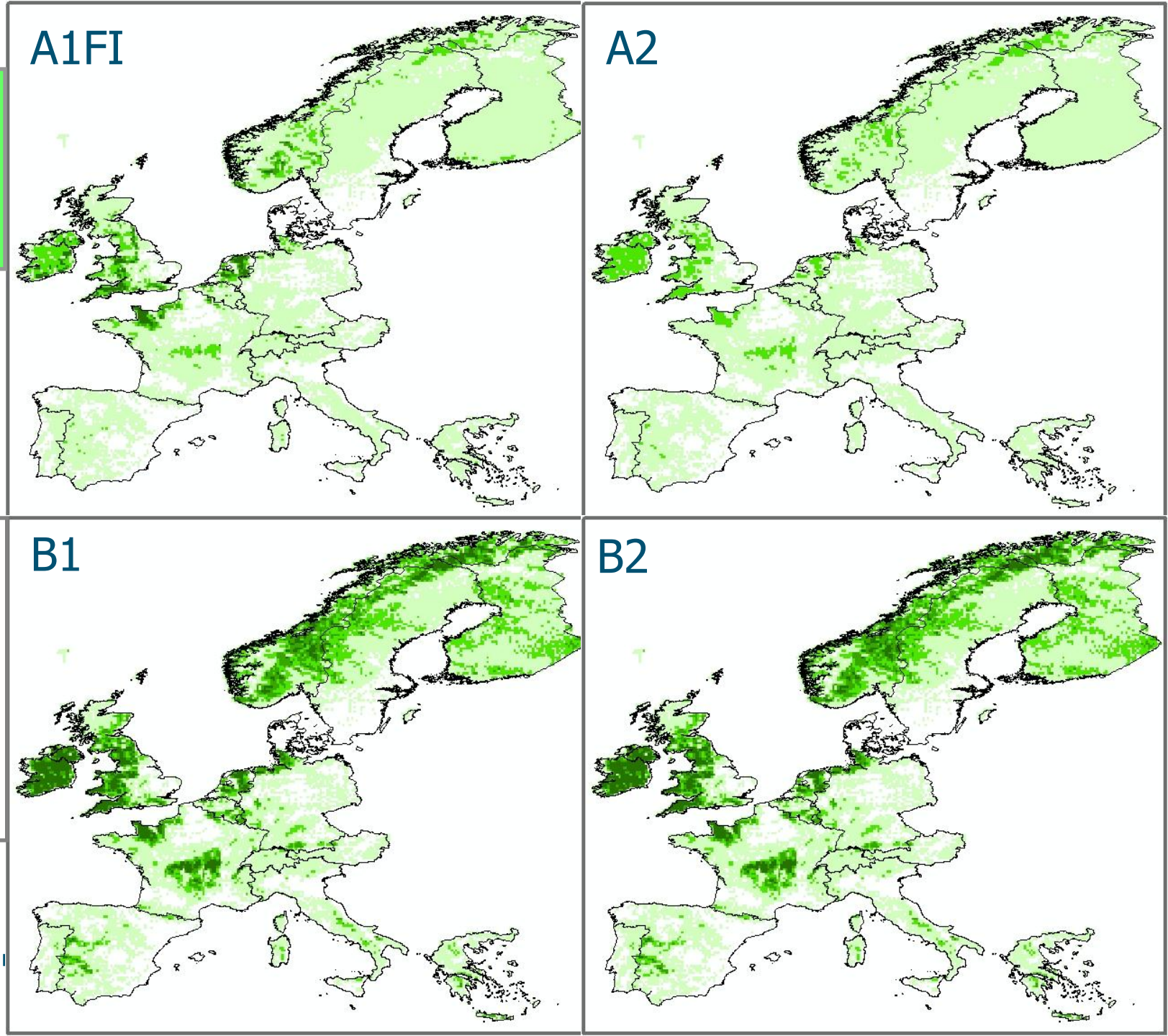


Percentage of arable land per ATEAM cell

- 0
- 1 - 25
- 26 - 50
- 51 - 75
- 76 - 100

WAG

Grass land in 2080 (HADCM3)

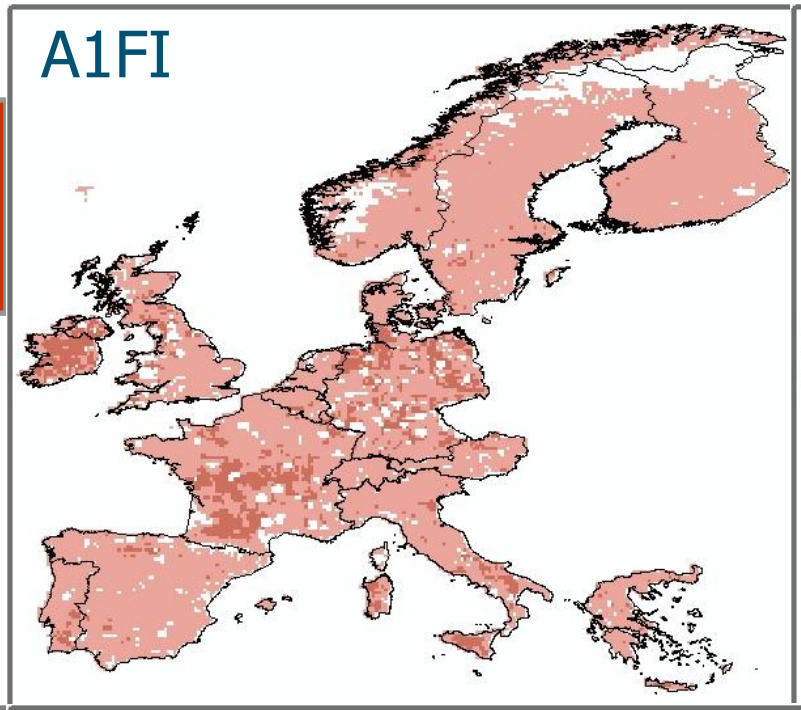


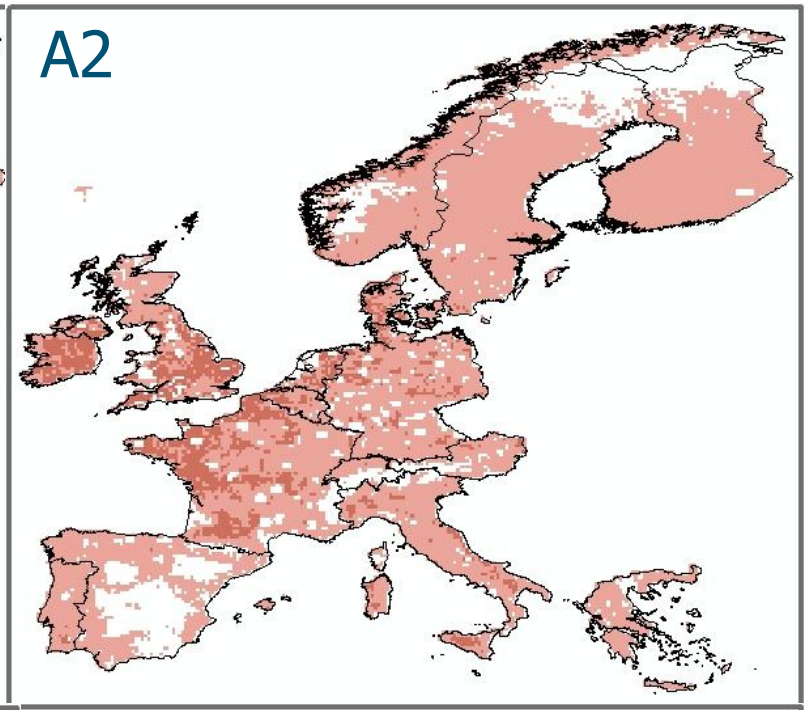
Percentage of grassland per ATEAM cell

- 0
- 1 - 25
- 26 - 50
- 51 - 75
- 76 - 100

WAGI

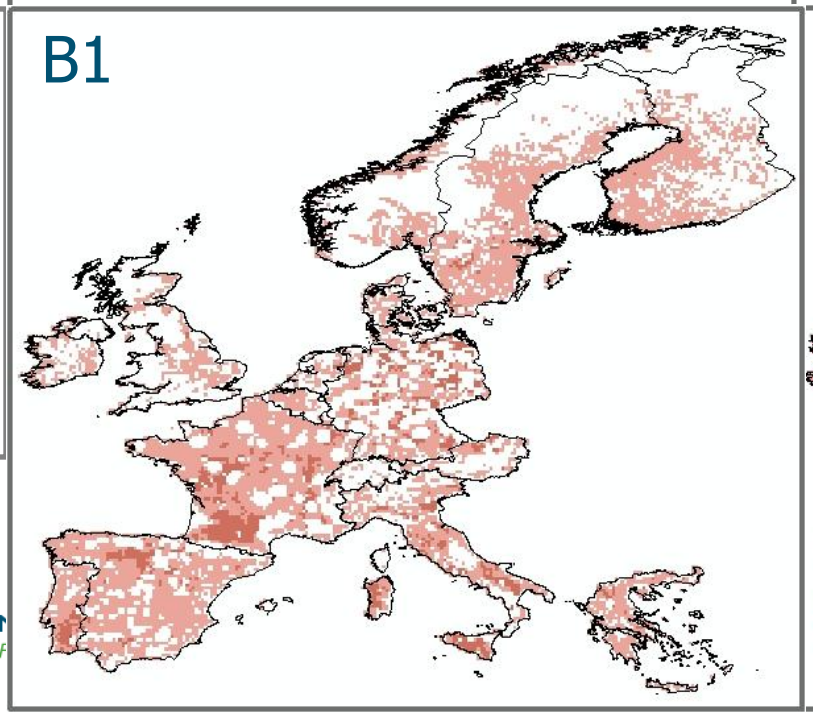
Biofuels in 2080 (HADCM3)

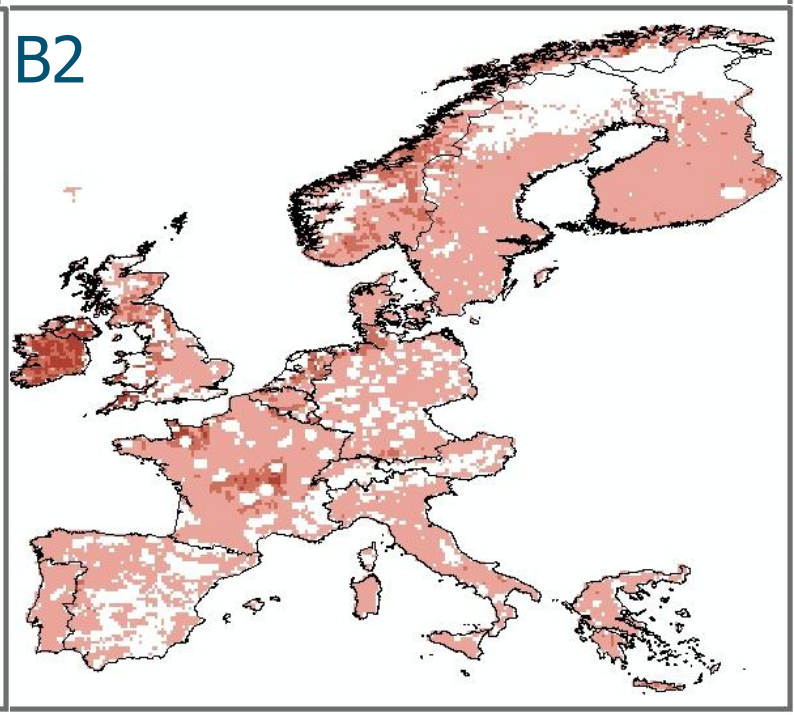




Percentage of biofuels per ATEAM cell

- 0,00
- 0,01 - 25,00
- 25,01 - 50,00
- 50,01 - 75,00
- 75,01 - 100,00





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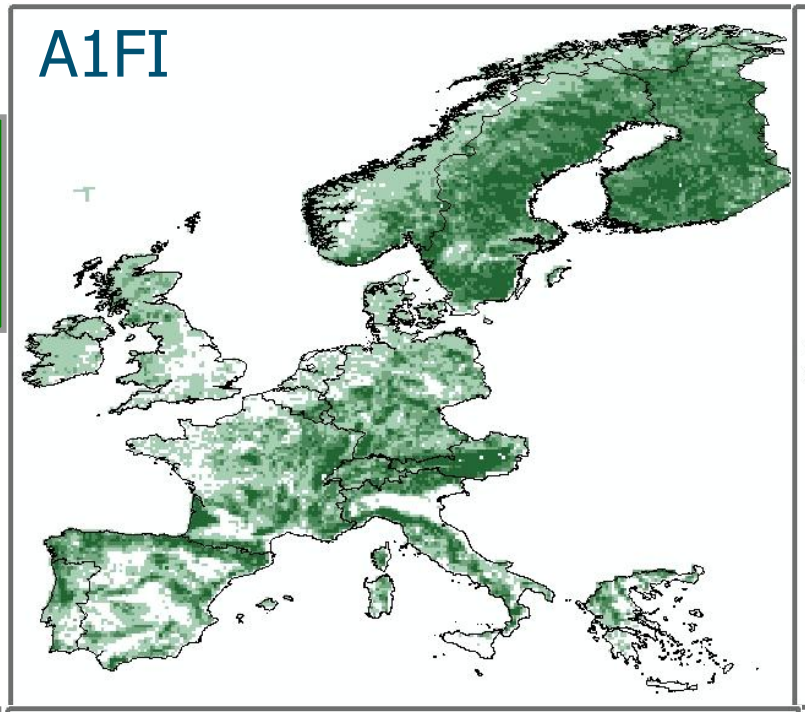
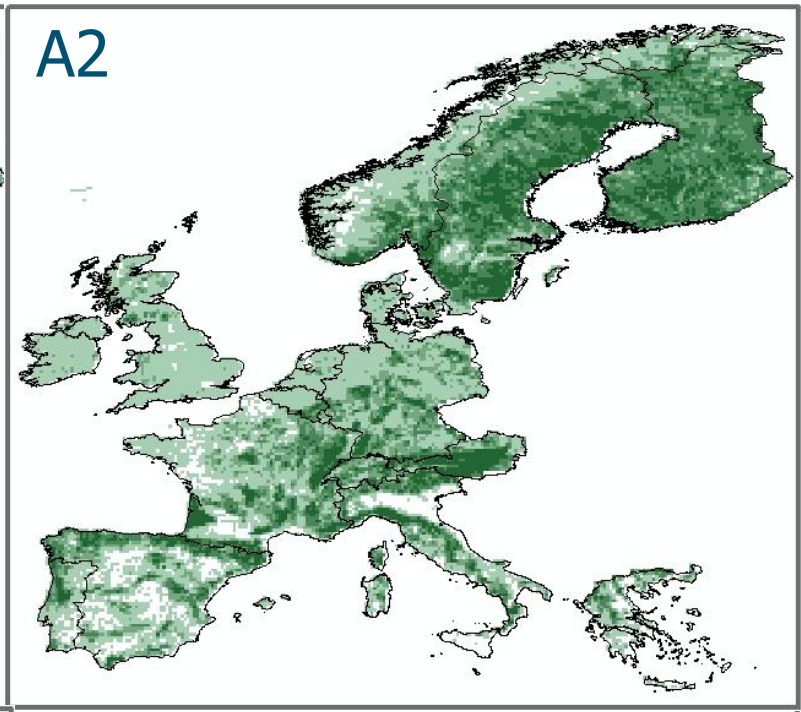
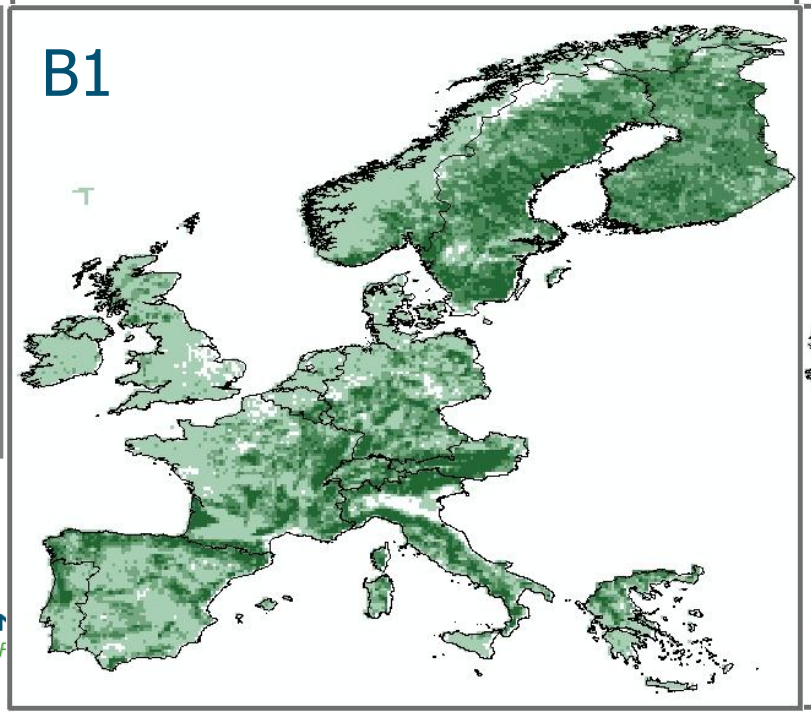
Forest in 2080 (HADCM3)

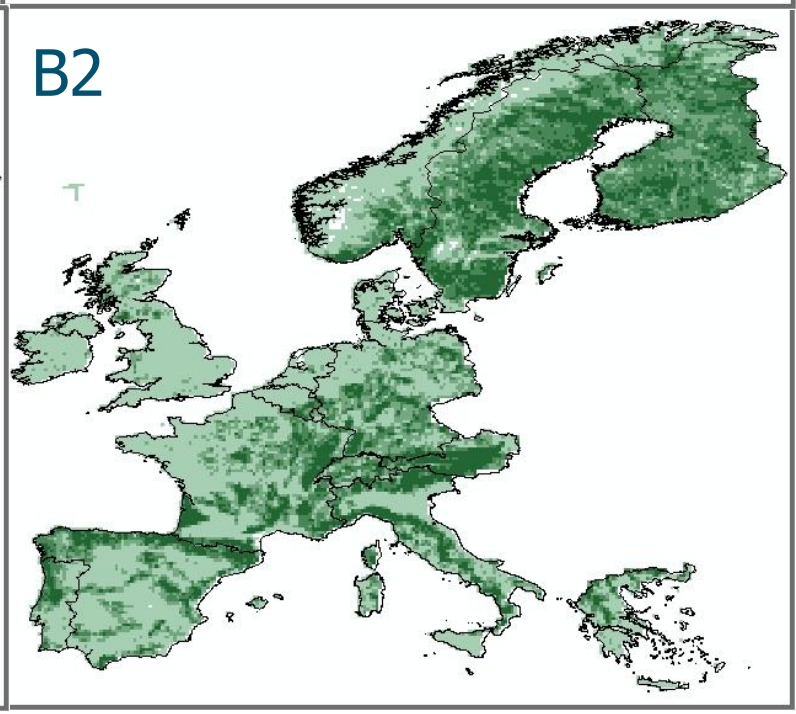




Percentage of forest per ATEAM cell

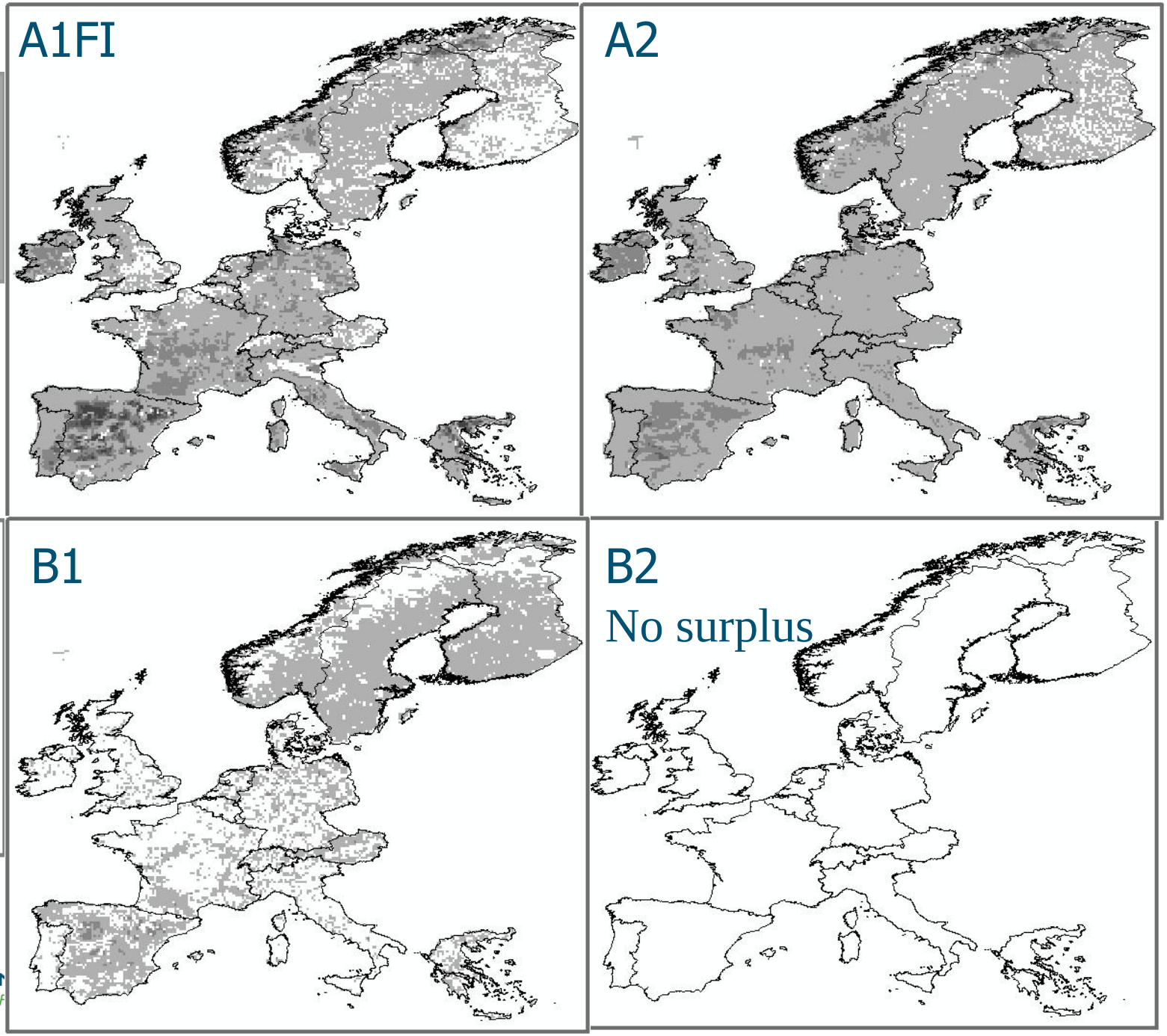
- 0
- 1 - 25
- 26 - 50
- 51 - 75
- 76 - 100





WAGEN

Surplus land in 2080 (HADCM3)



Percentage of surplus land per ATEAM cell

- 0,00
- 0,01 - 25,00
- 25,01 - 50,00
- 50,01 - 75,00
- 75,01 - 100,00

So what happens to all this spare land?

- More energy crops?
- Even more forests?
- Abandonment (i.e. more trees & shrubs)?
- Nature and biodiversity (i.e. probably more trees & shrubs)?
- Recreation (hobby horses and golf courses)?

- How much?
- Where do you allocate it?

Integrated Assessment models

Modelling the social and natural aspects of global change

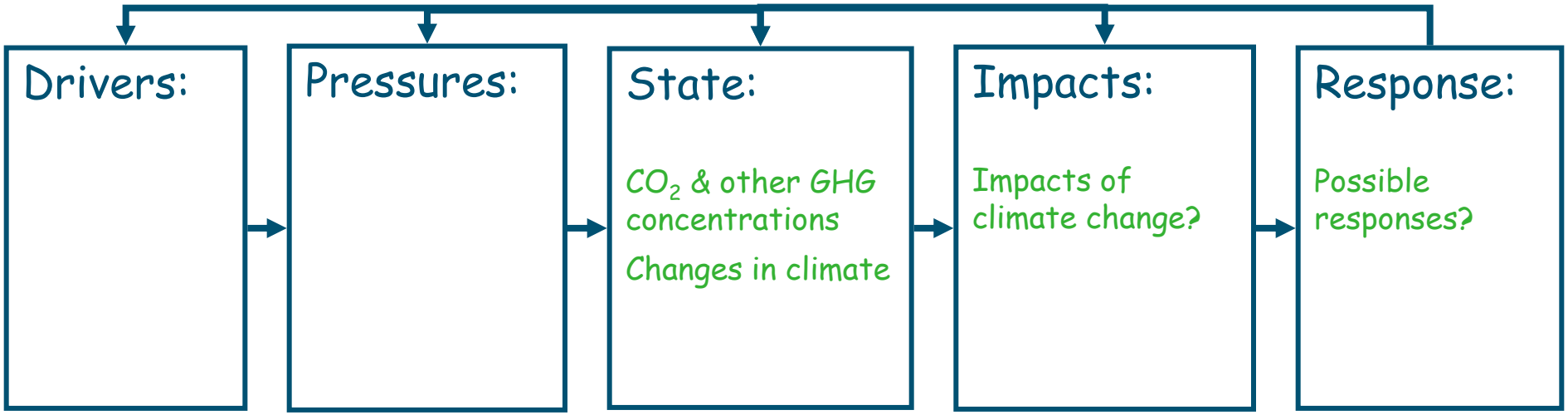
A final, complex challenge

We want to develop a model which provides answers to the following questions:

- How will the future concentrations of all GHG develop?
- How does an increase in concentrations affect the climate?
- What are the major impacts of these changes?
- What can we do about it?

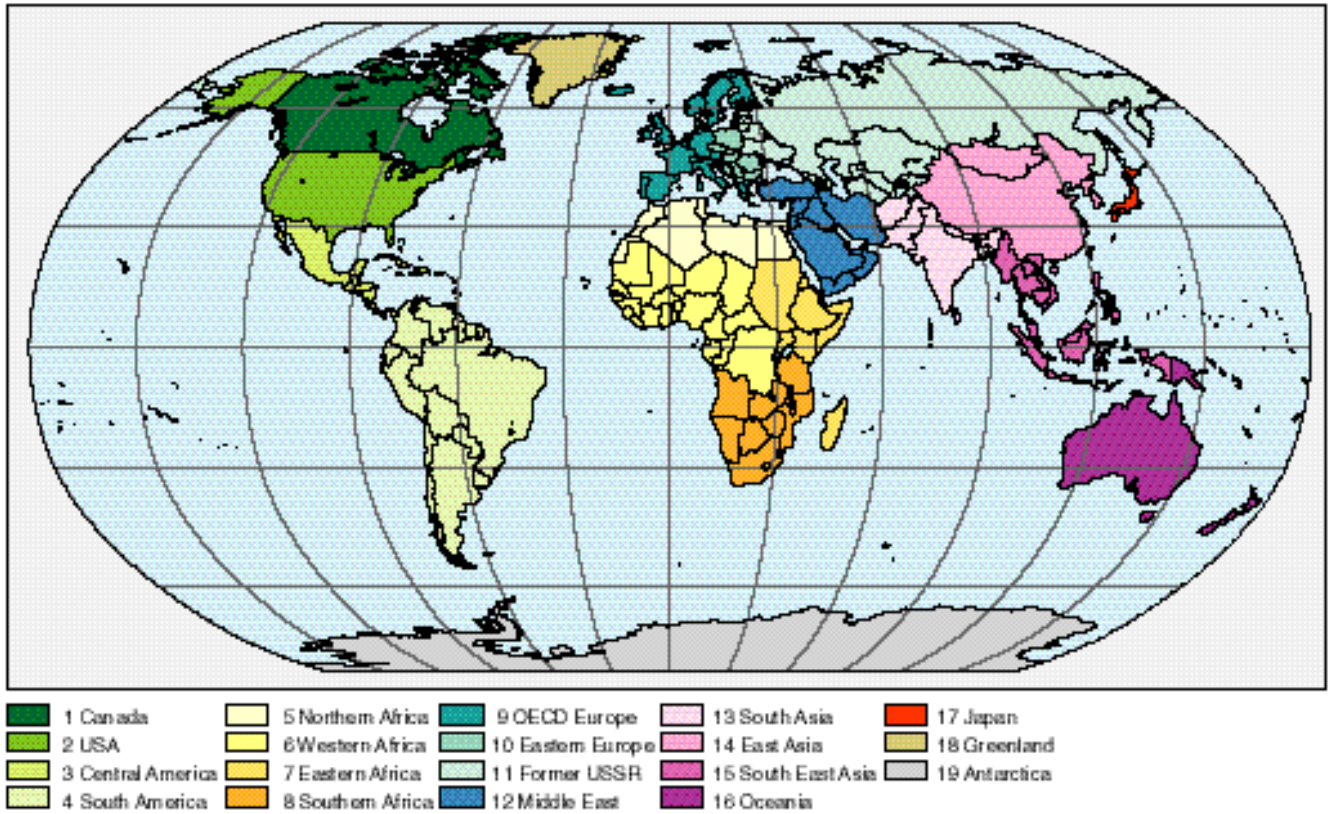
What components should be included in this model and how should they be linked?

Discussion results



A global integrated assessment model

The IMAGE 2 model



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Objectives of IMAGE 2

Scientific goals:

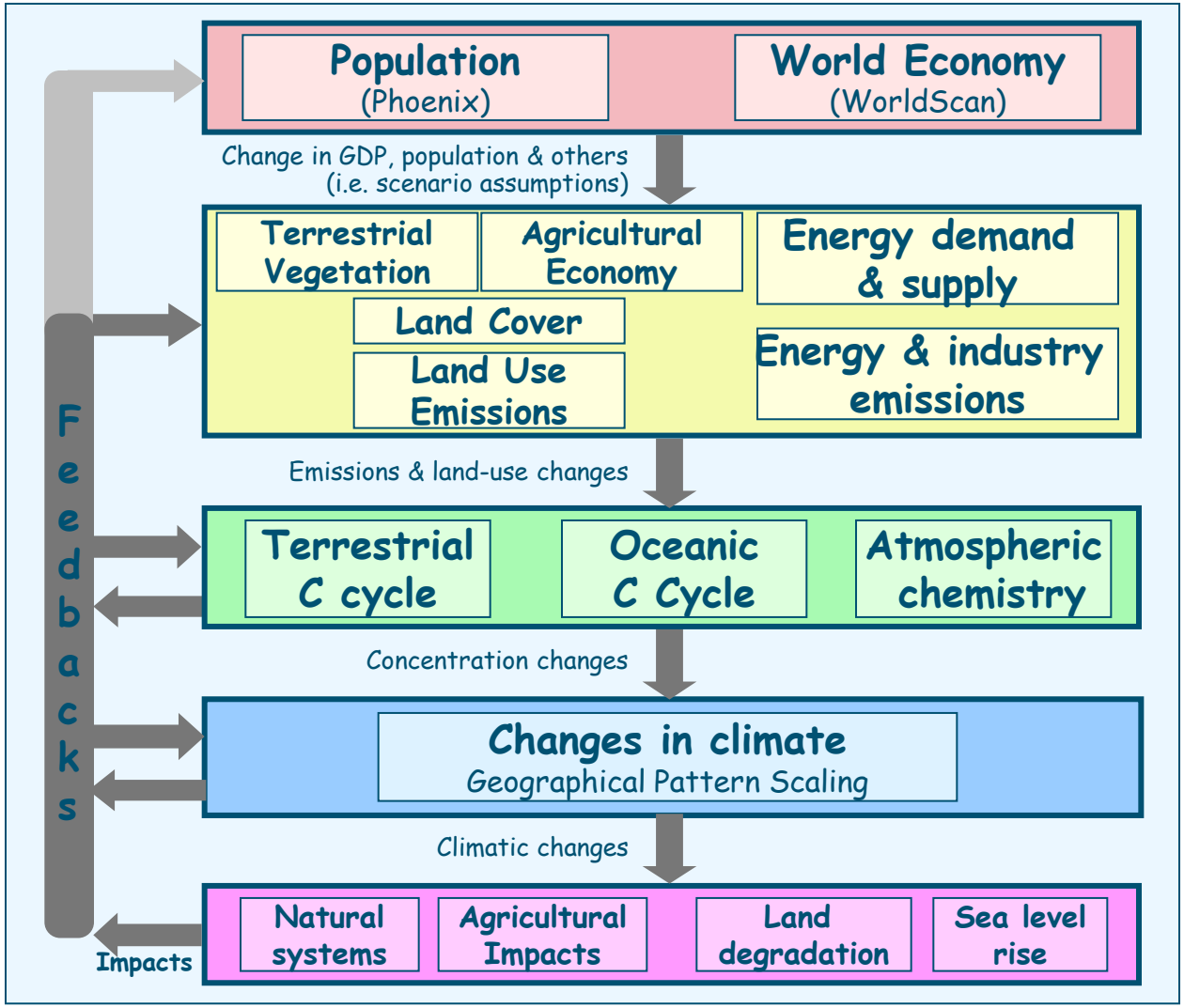
- Assess relative importance of different linkages in the climate system
- Analyse strength of different interactions and feedbacks
- Estimate major sources of uncertainty in such a complex system
- Assist in identifying gaps in understanding the climate system

Policy Goals:

- Link science to policy-making aspects of global change regionally and geographically
- Analyse influence of economic, demographic and technological trends on global change and its impacts
- Provide a dynamic and long-term perspective of global change

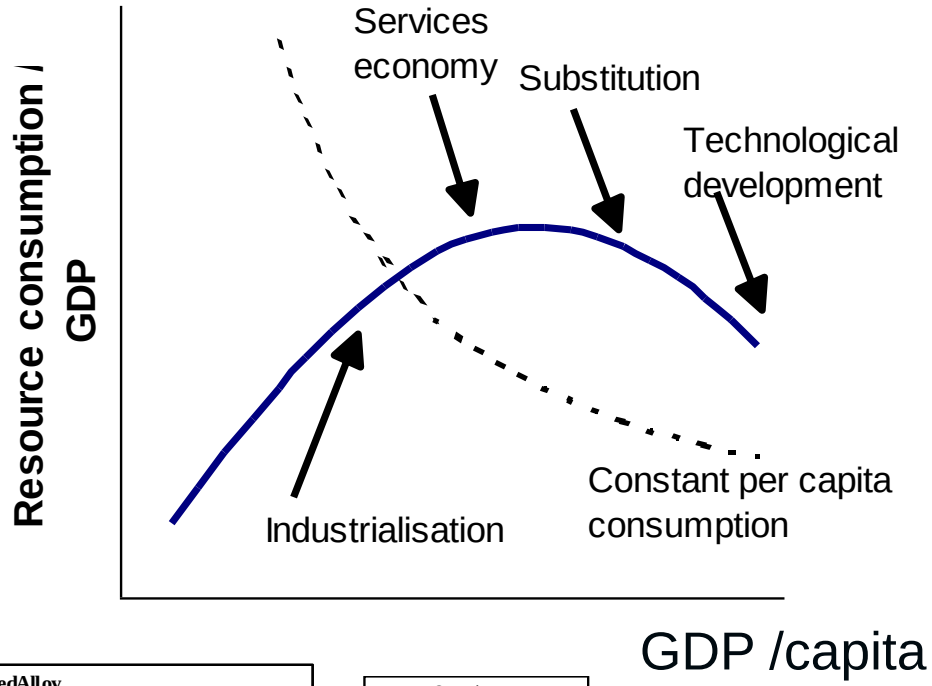
IMAGE = Integrated Model to Assess the Global Environment

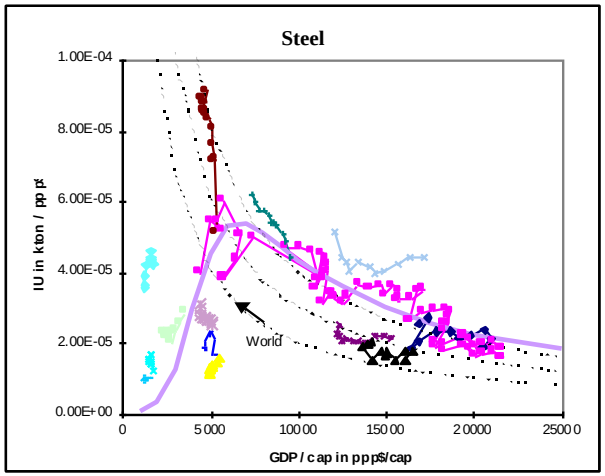
Structure of IMAGE 2

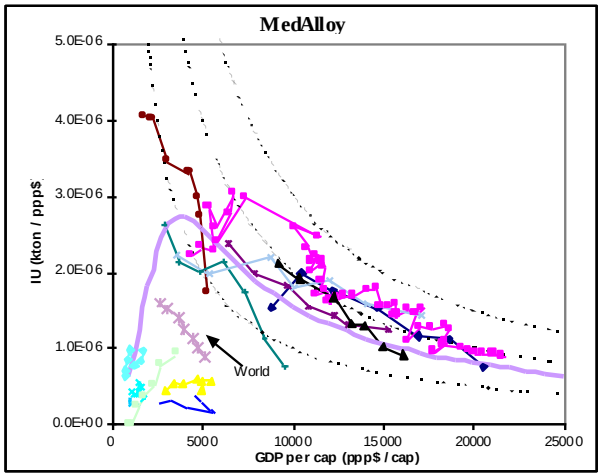


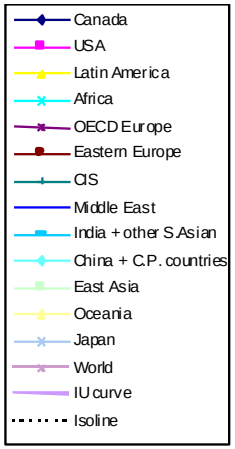
Theory and empirical data

Example:
resource use as a function of activity level

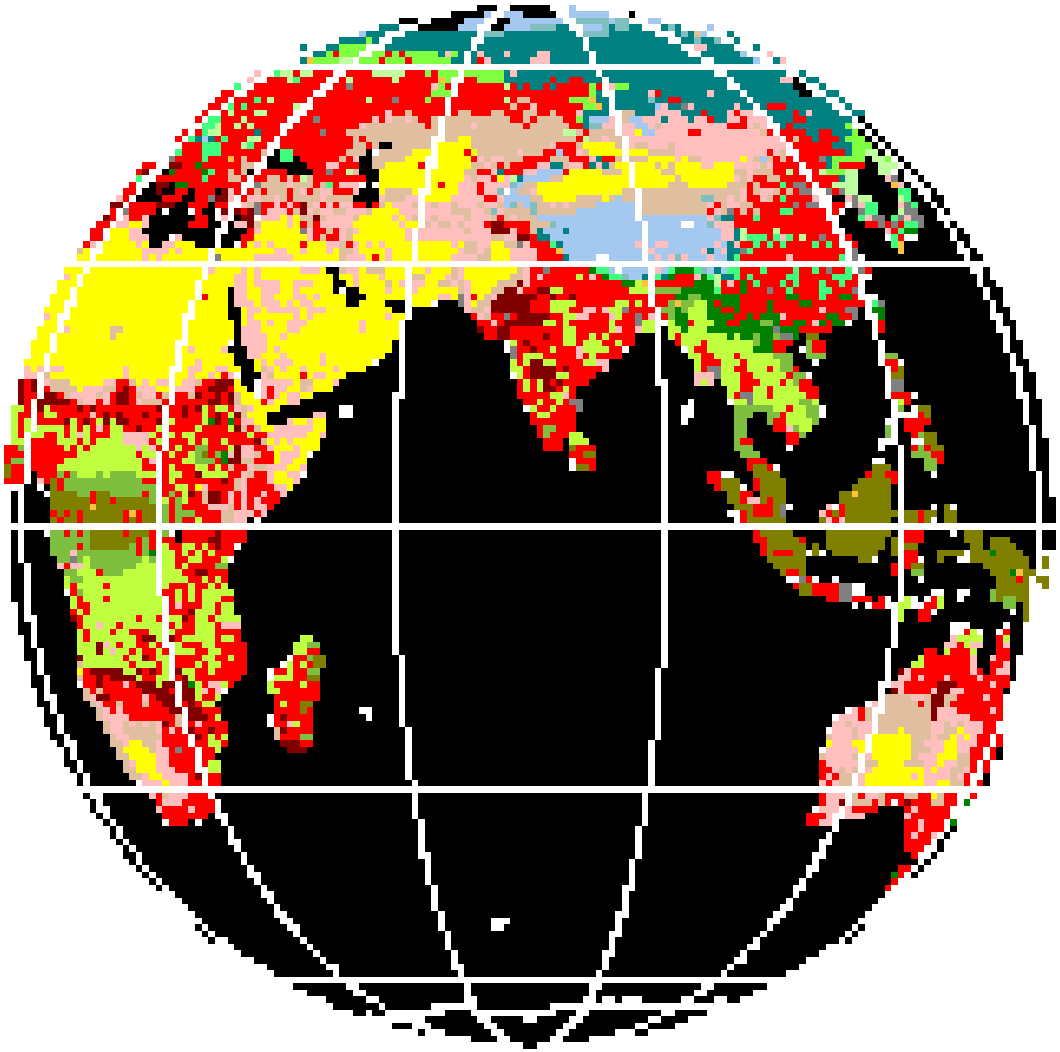


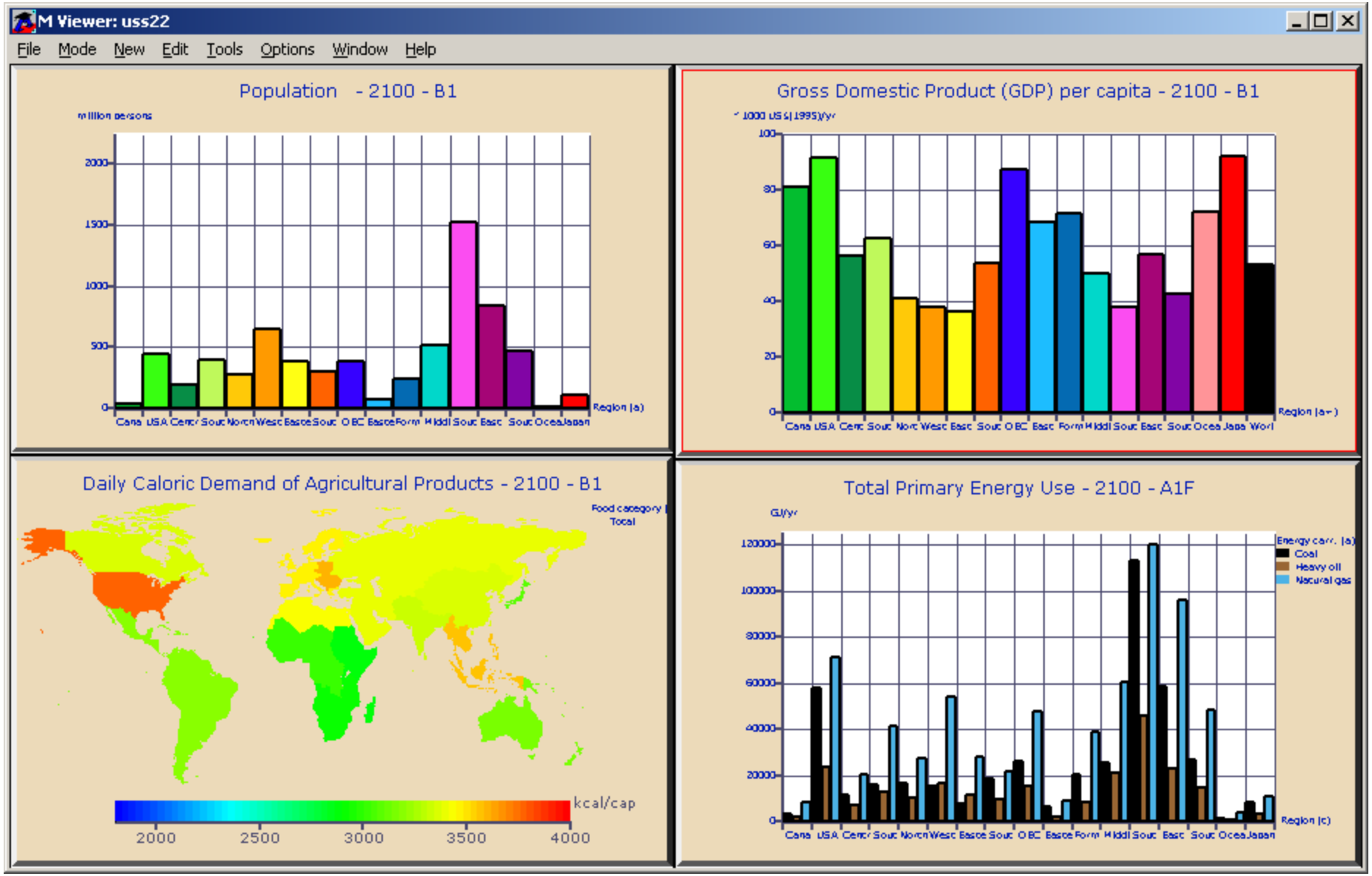






0.5 x 0.5° grid for environmental factors





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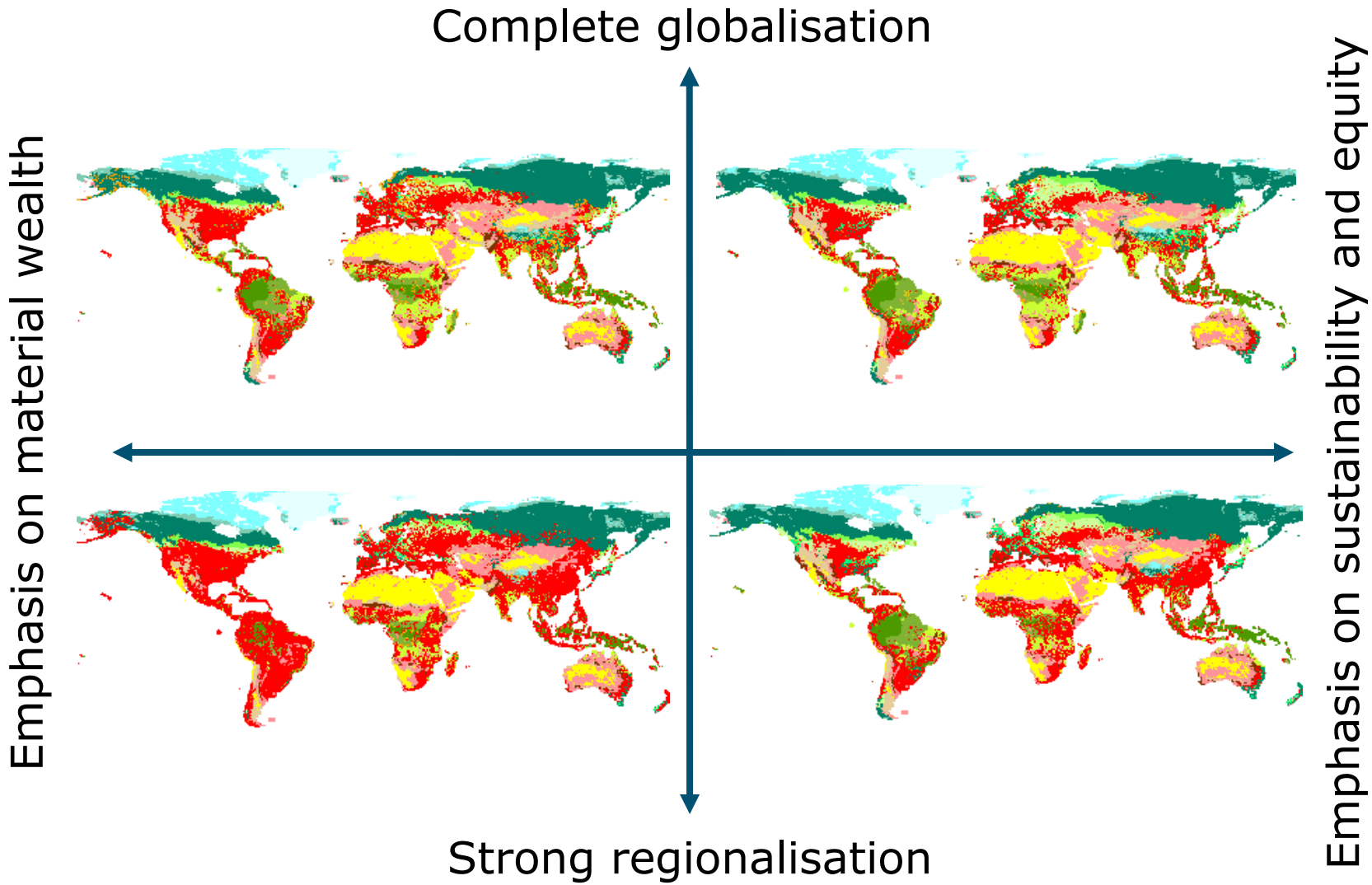
The IPCC scenarios: land cover in 2100



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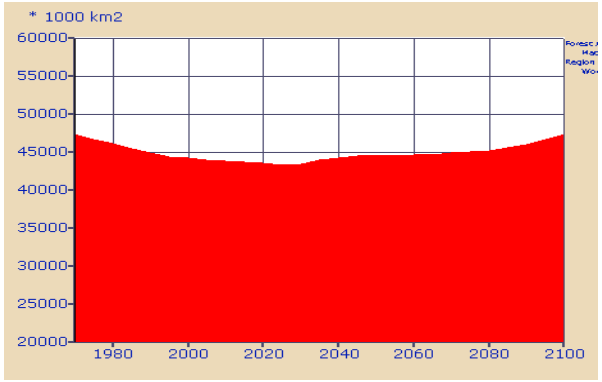
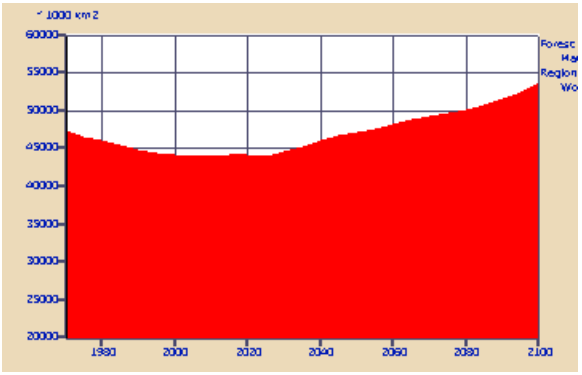
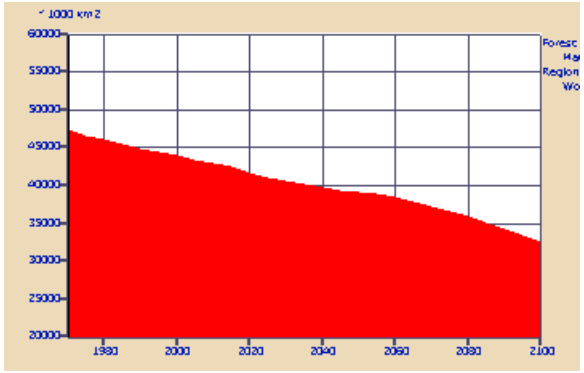
Forest area

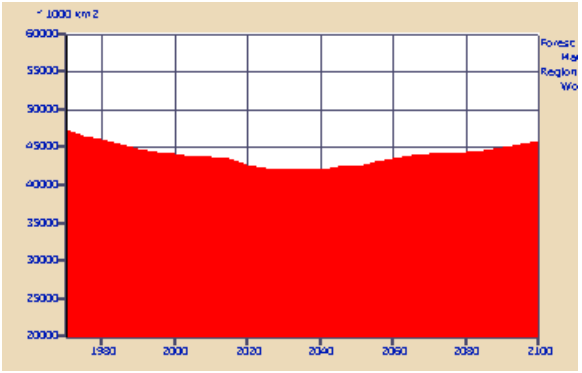
Complete globalisation

Emphasis on material wealth









Emphasis on sustainability and equity

Strong regionalisation

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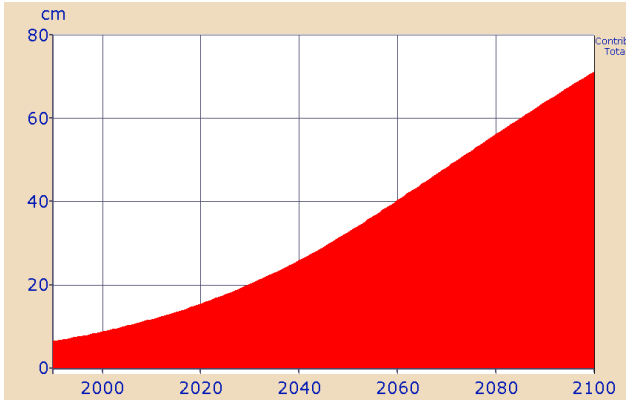
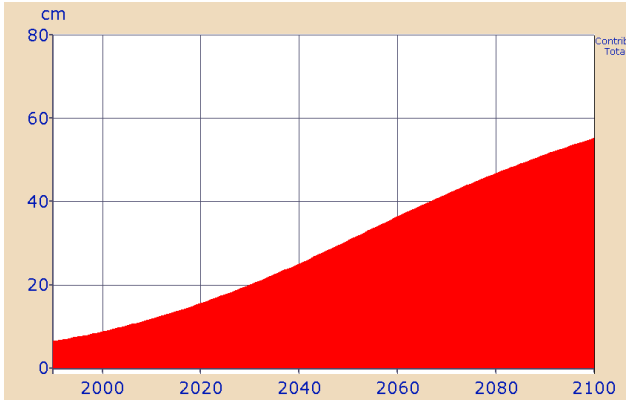
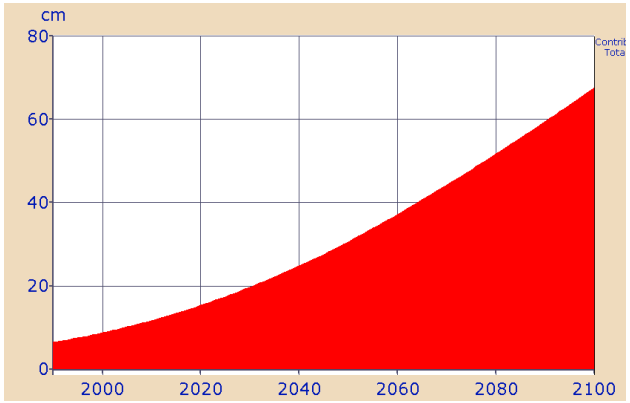
Sea-level rise

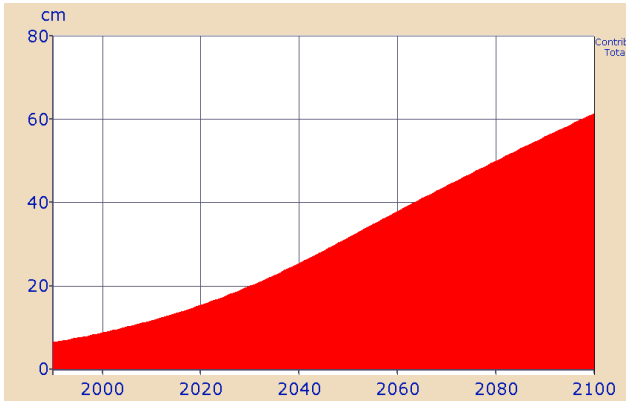
Complete globalisation

Emphasis on material wealth









Emphasis on sustainability and equity

Strong regionalisation

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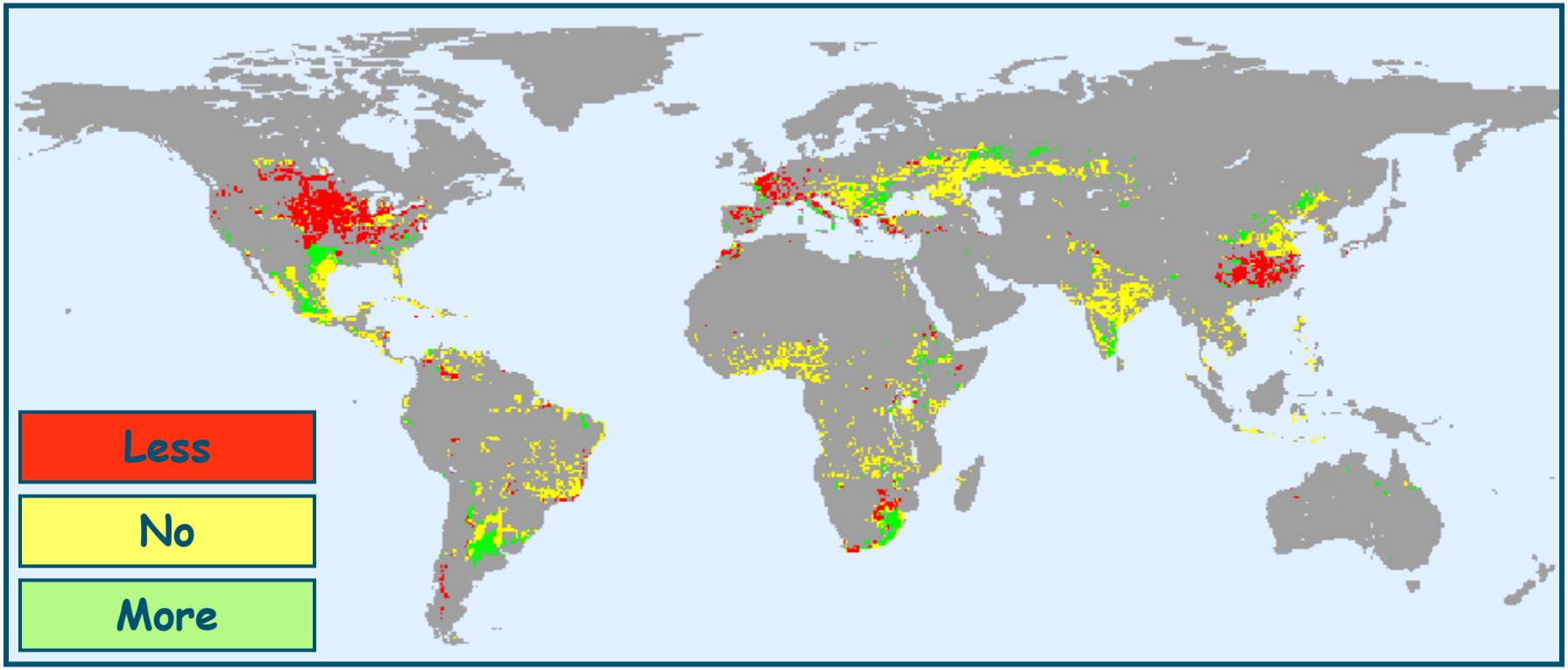
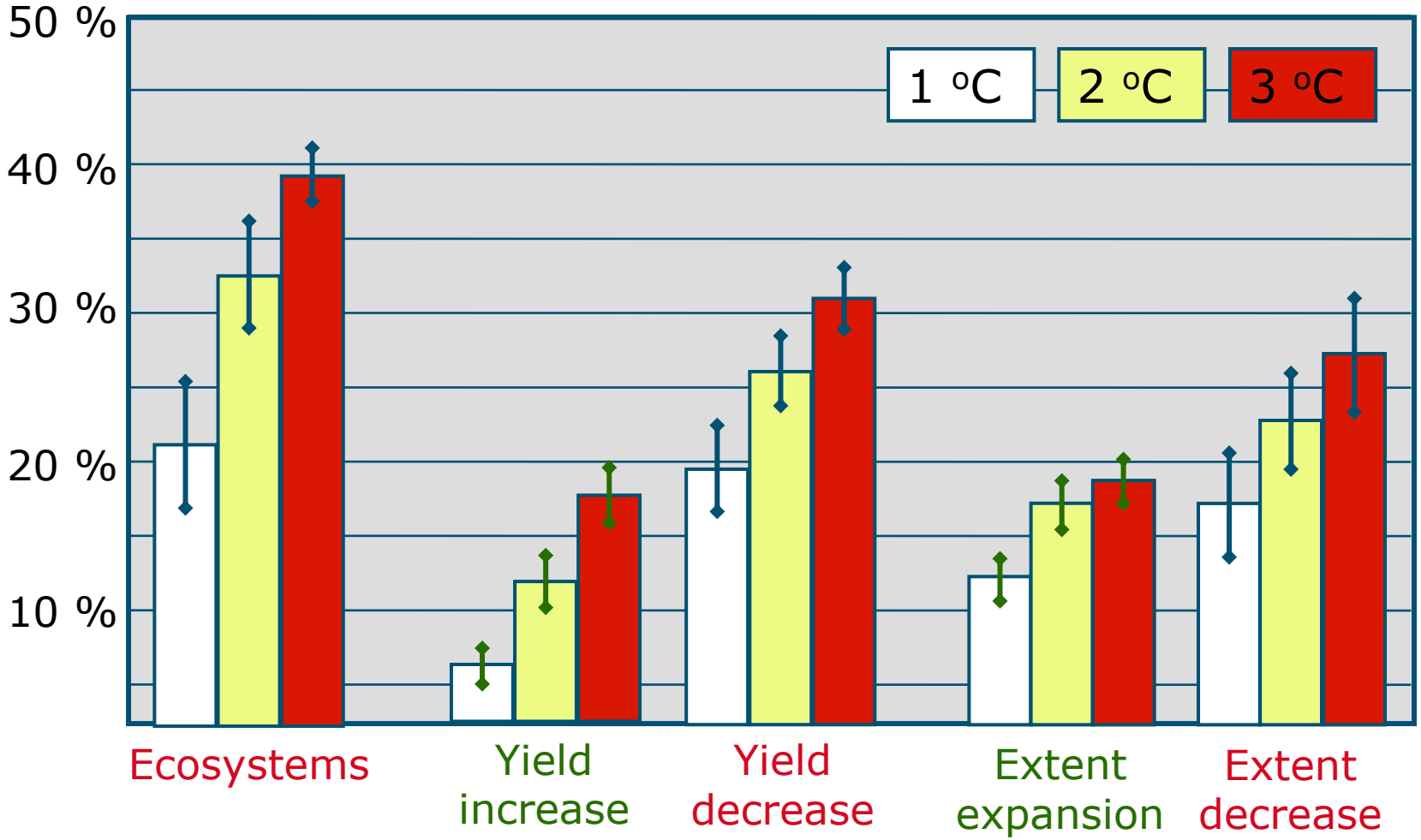
Impact on the yield of corn



The regional yield can change: some regions improve while others decline (mainly driven by drought)

How do risks evolve globally?



Impacts are expressed as the percentage of area affected
Reference is the current area (crops) or the total amount of land (ecosystems).

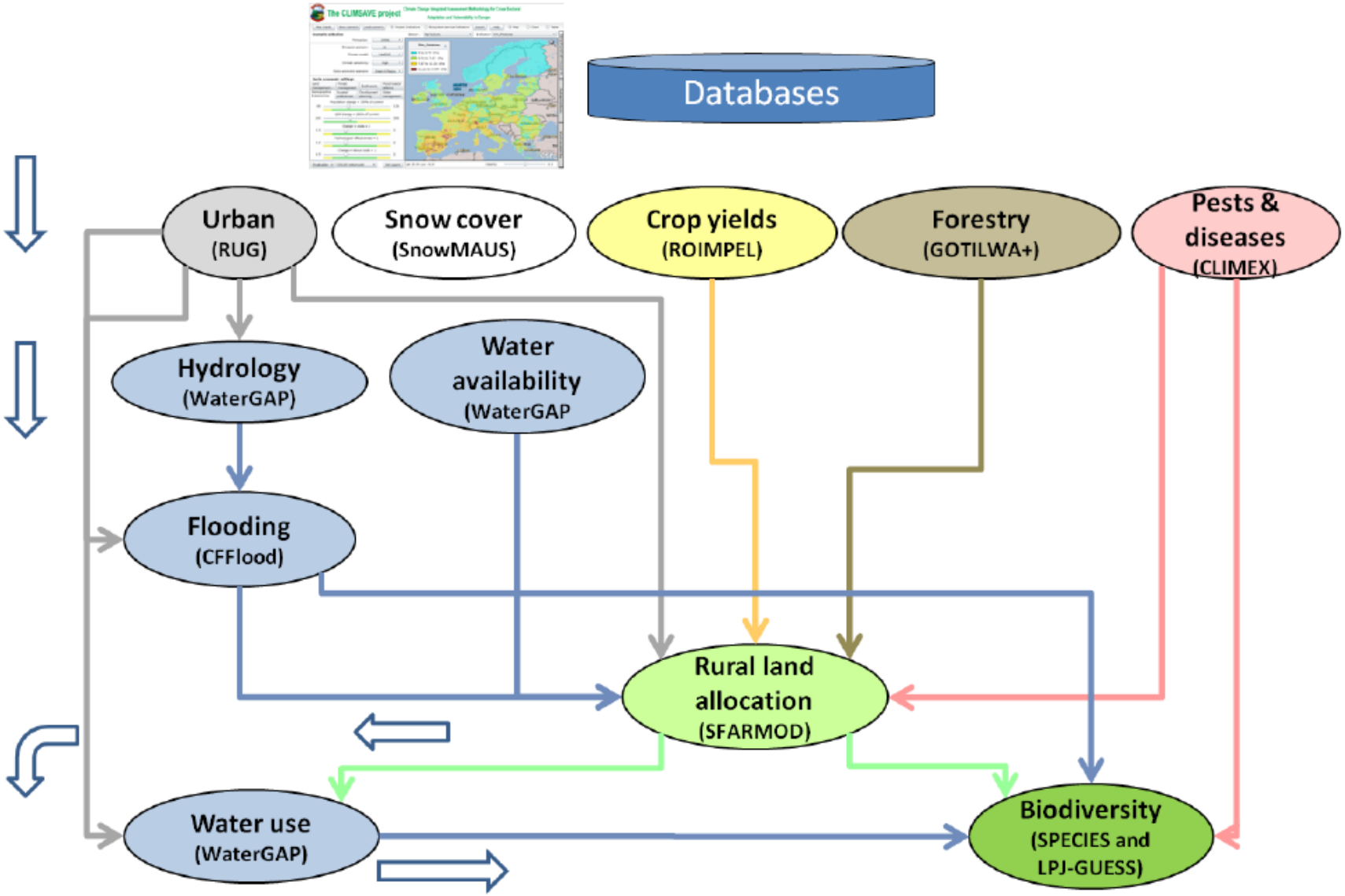
Major scientific insights

- Feedbacks are important
- Large differences in impacts between different regions and sectors
- Social and natural science aspects equally important
- Early action creates flexibility, is cheaper, may even be beneficial and will most likely only yield gradual changes
- Delayed action deepens problems, cripples many response options and could yield sudden changes

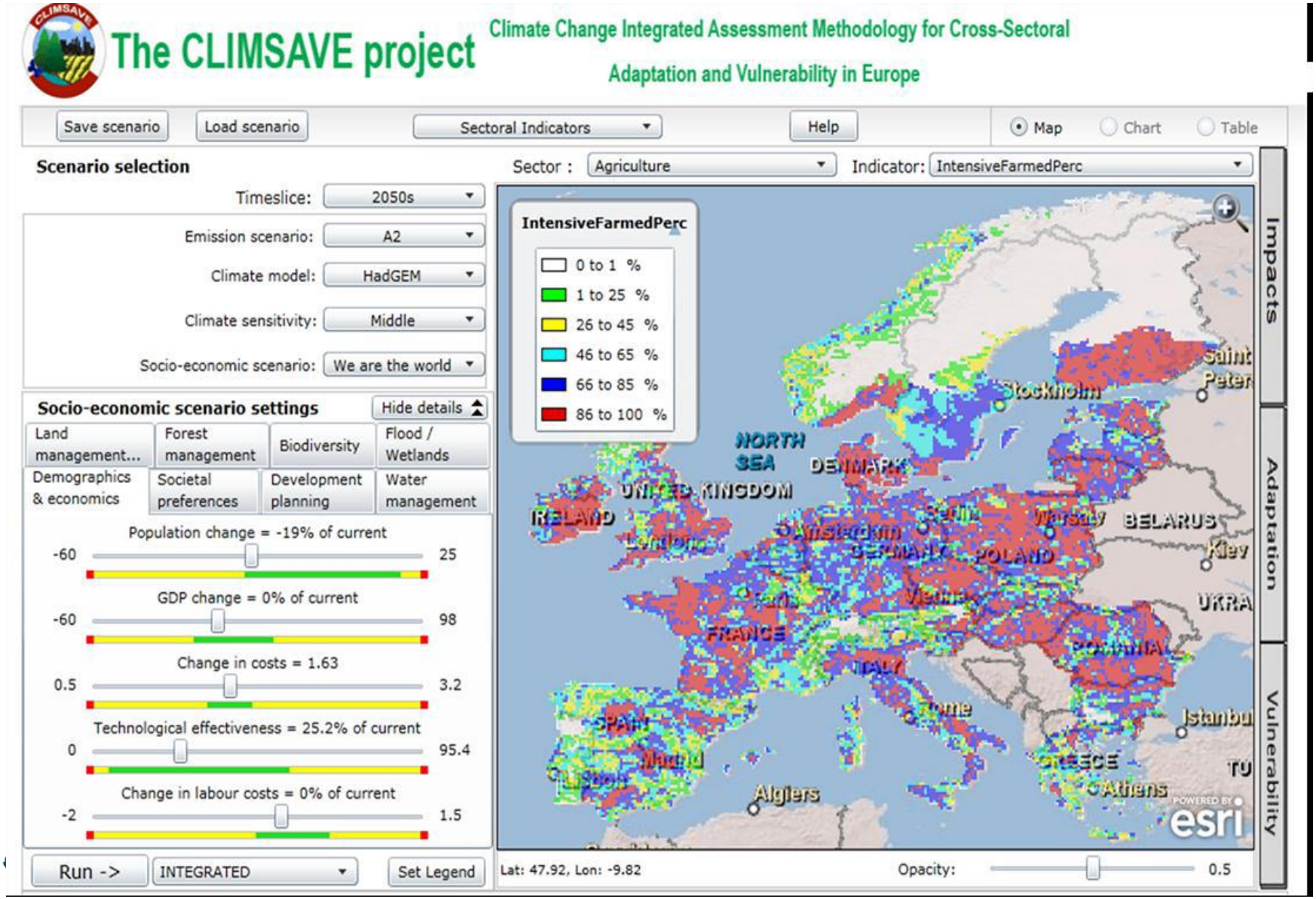
CLIMSAVE Integrated Assessment Platform

- Web-based IAP to allow stakeholders to explore climate change impacts and responses
- Constraint: run-time must be short!
- Solution: uses meta-models, i.e. simpler models which mimic the full model
- Coverage: EU/EEA/Switzerland
- Resolution: 10 x 10’
- Still work in progress - see www.climsave.eu

CLIMSAVE IAP: meta-model linkages



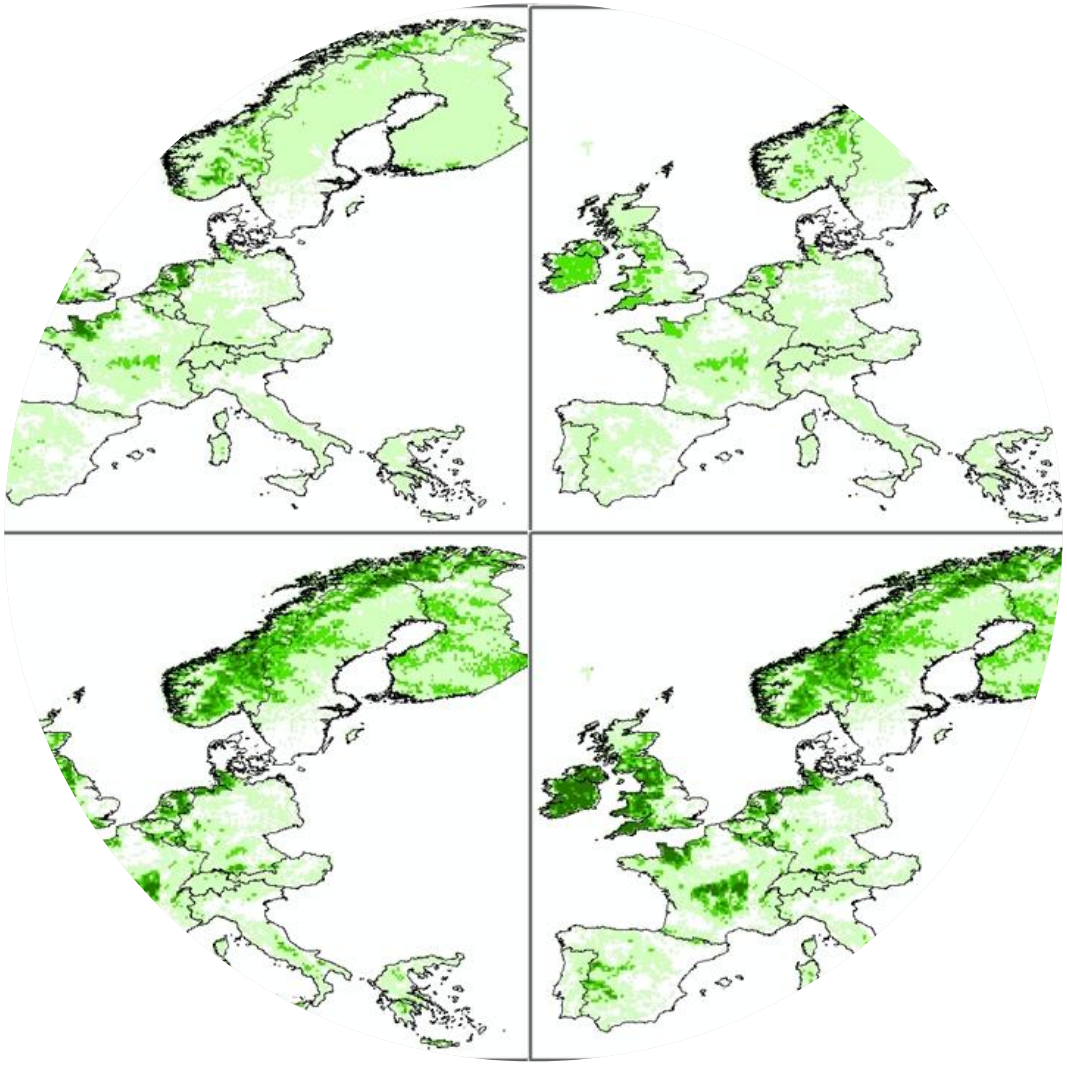
CLIMSAVE IAP: preview



Summary

- Models can be simple or very complex
  - all have their uses, simple ones may be part of more complex models
- Land-use models combine global and spatial variables
- To use scenarios in land-use models, you need to draw from the storylines:
  - future variable values
  - allocation rules (e.g. as parameters)
- Values and allocation rules can be derived from past trends, theory, expert/stakeholder judgement,...

Any questions?



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