# Ecosystem and bioclimatic modelling in a global change perspective


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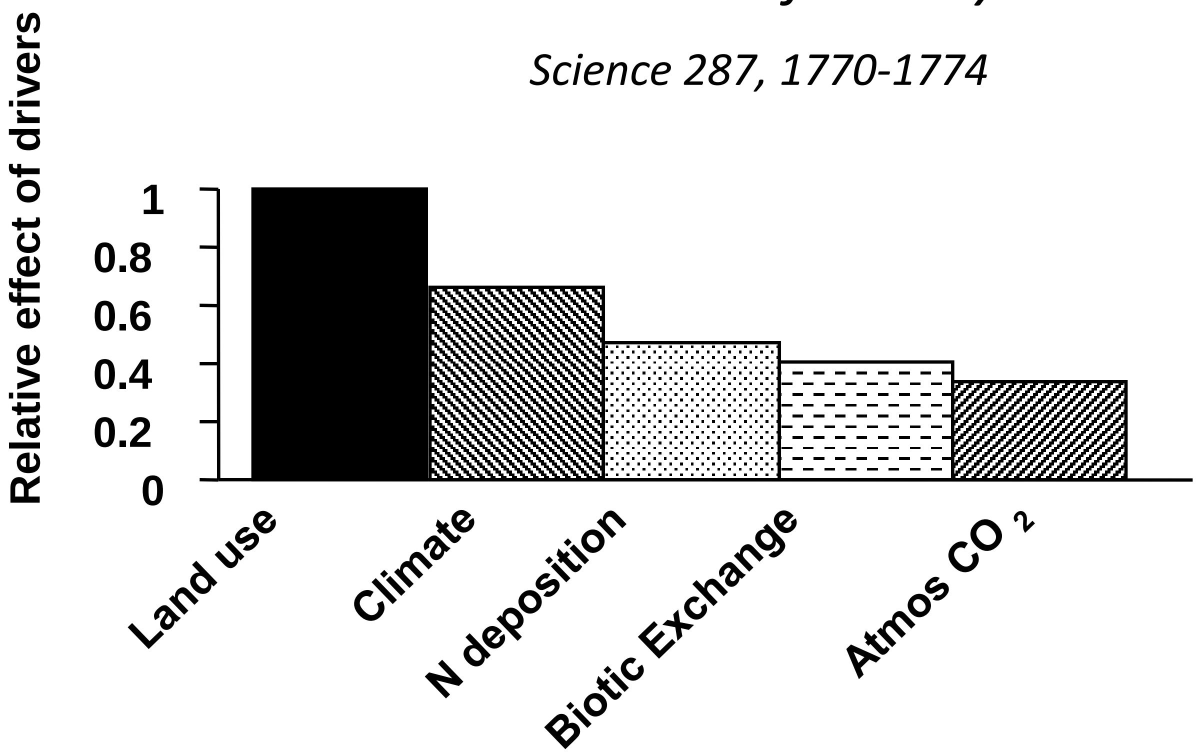
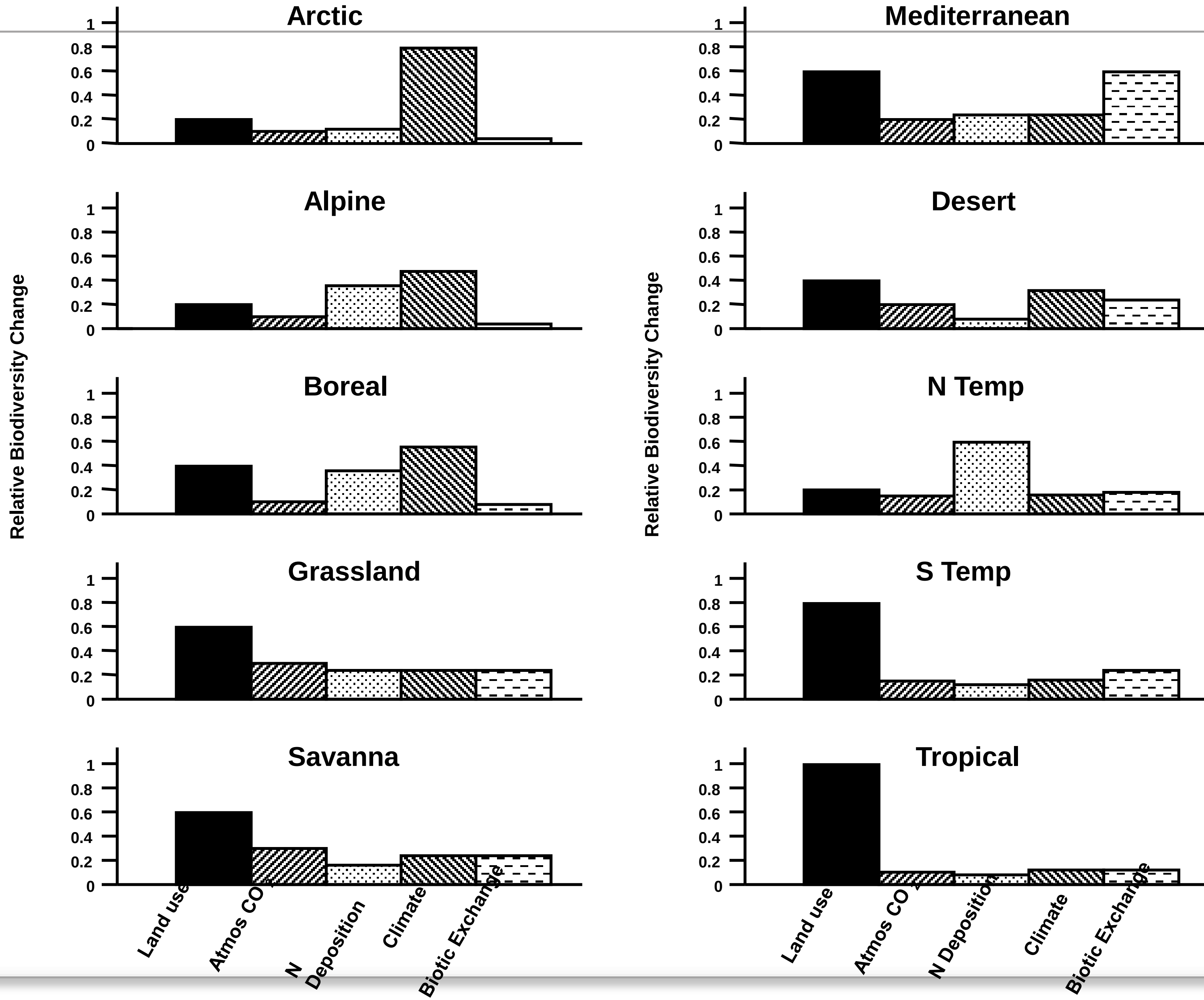
- Climate change and scenarios
- Bioclimatic modelling – statistical and process-based and examples
- Ecosystem dynamics – the role of $CO_2$
- Modelling ecosystem dynamics
- Examples

# Contents

*Sala et al. 2000 Global biodiversity scenarios for the year  2100*

*Science 287, 1770-1774*

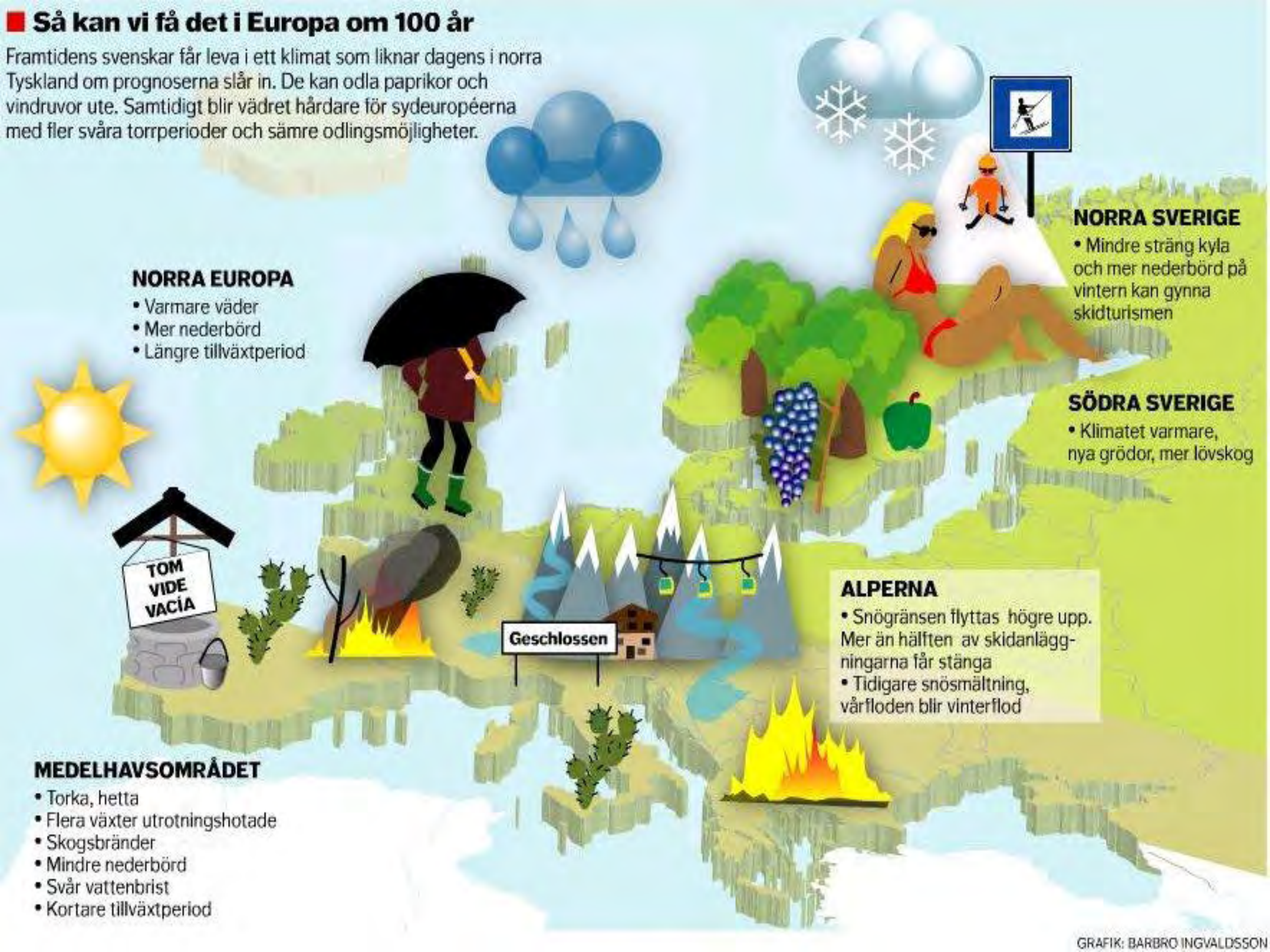




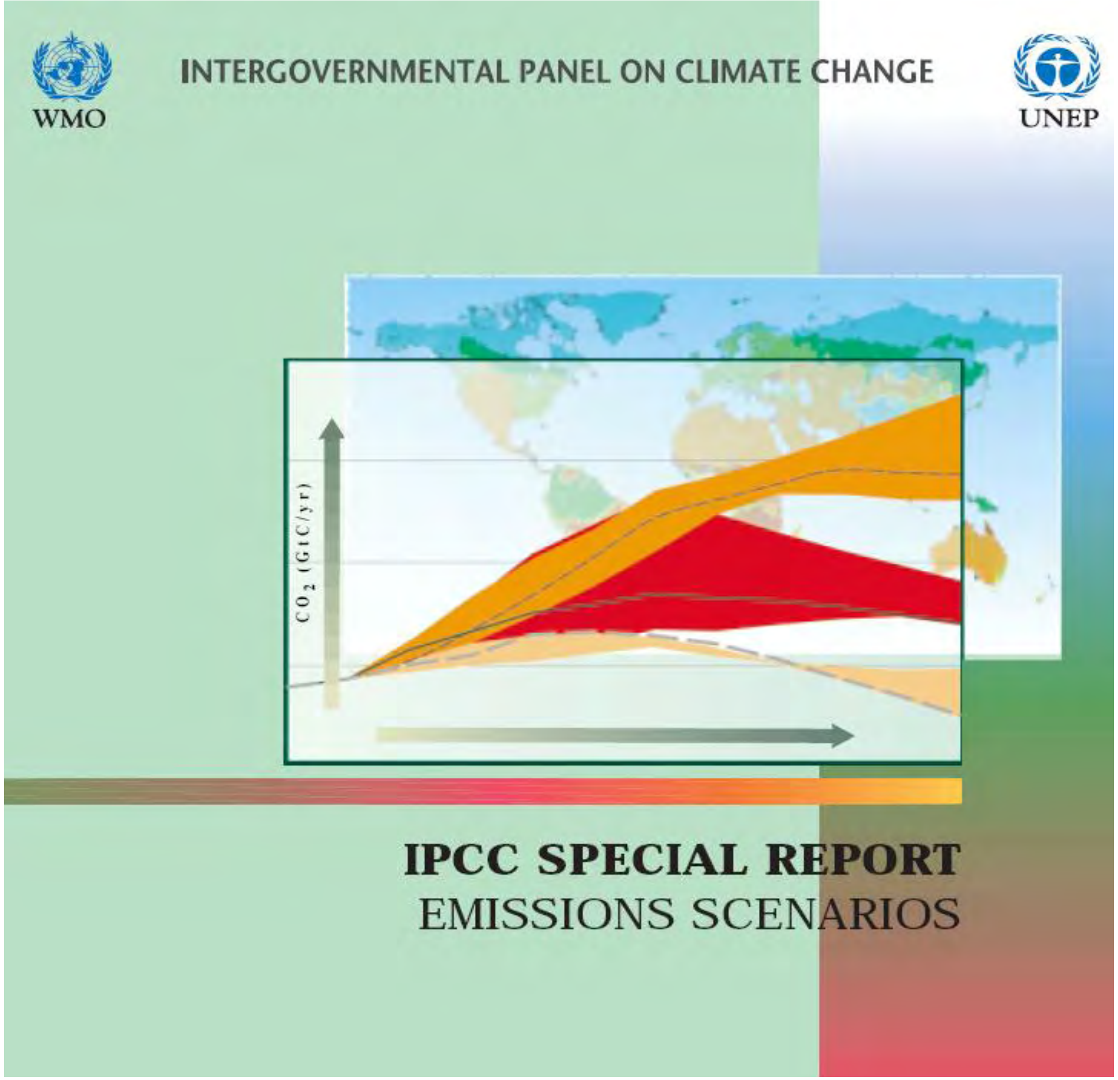
Arctic
Mediterranean
Alpine
Desert
Boreal
N Temp
Grassland
S Temp
Savanna
Tropical
Relative Biodiversity Change
0
0.2
0.4
0.6
0.8
1
Land use
Atmos CO 2
N Deposition
Climate
Biotic Exchange

## Så kan vi få det i Europa om 100 år

Framtidens svenskar får leva i ett klimat som liknar dagens i norra Tyskland om prognoserna slår in. De kan odla paprikor och vindruvor ute. Samtidigt blir vädret hårdare för sydeuropéerna med fler svåra torrperioder och sämre odlingsmöjligheter.



# Greenhouse gas emissions



# IPCC SRES SCENARIOS

- *IPCC Special Report on Emission Scenarios*
- 4 storylines describe the relationship between the forces driving the emissions (greenhouse gases and aerosols)
- 40 Scenarios with a mix demographic, economic and technology drivers

## IPCC SRES SCENARIOS

- A1 storyline: very rapid economic growth,global population peaks 2050 and then declines. New and more efficient technologies. Convergence among regions, reduction in differences in per capita income
- Includes 3 groups A1FI – fossil intensive A1T – non-fossil energy sources, A1B balanced energy

## IPCC SRES SCENARIOS

- B1 storyline – convergent world with same population peak as in A1 – but rapid changes towards a service and information economy – clean and resource efficient technologies – global solutions to economics, social and environmental sustainability

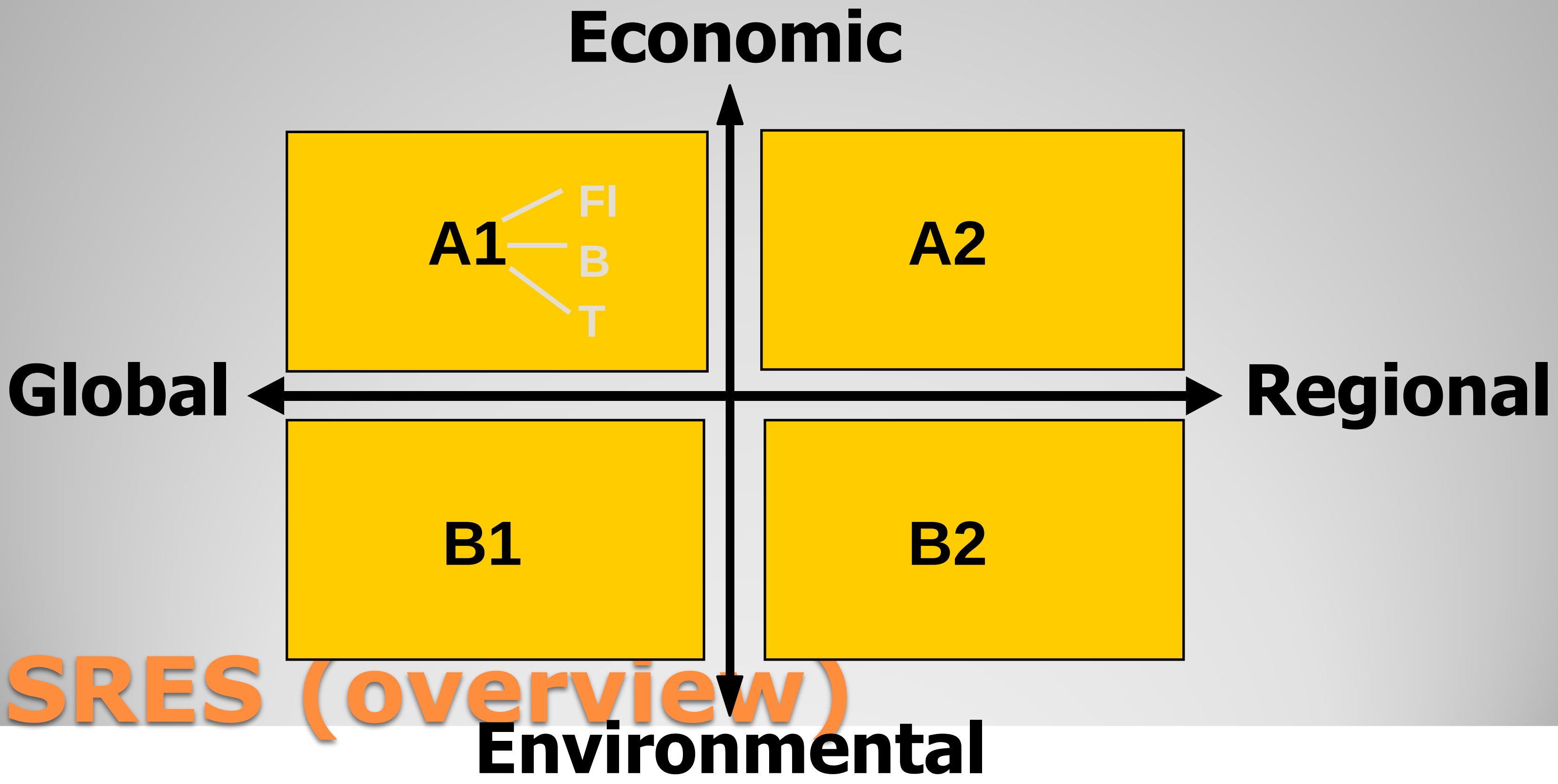
## IPCC SRES SCENARIOS

- A2 storyline – a heterogenous world, self reliance, local identities, fertlity patterns converge very slowly so increasing population. Economics primarily regionally oriented, percapita growth more fragmented

## IPCC SRES SCENARIOS

- B2 storyline – world of local solutions to economic, social and environmental sustainability. Continuously increasing population but lower than A2, intermediate levels of economic development, less rapid and more diverse technological change
- Local and regional levels

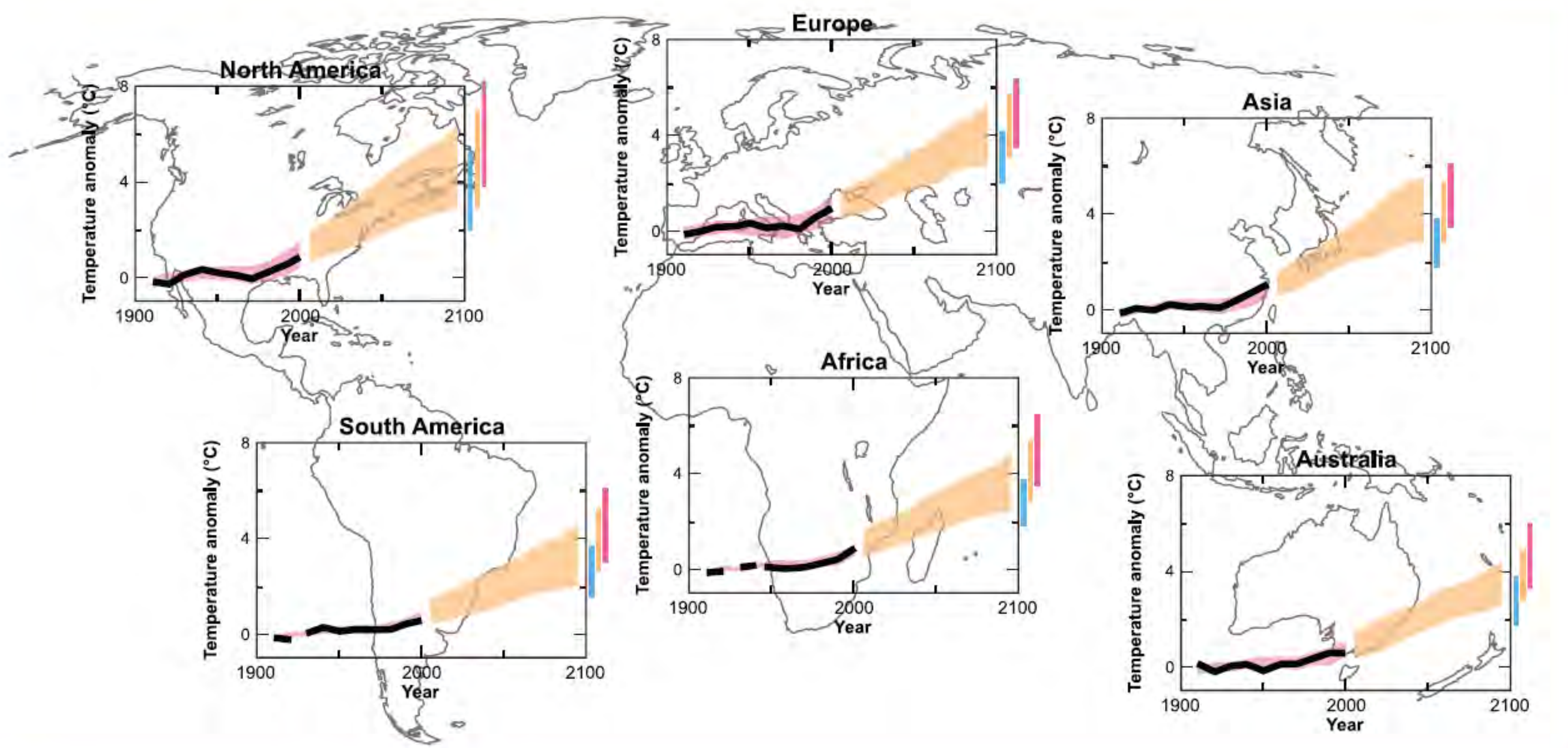
# SRES (overview)

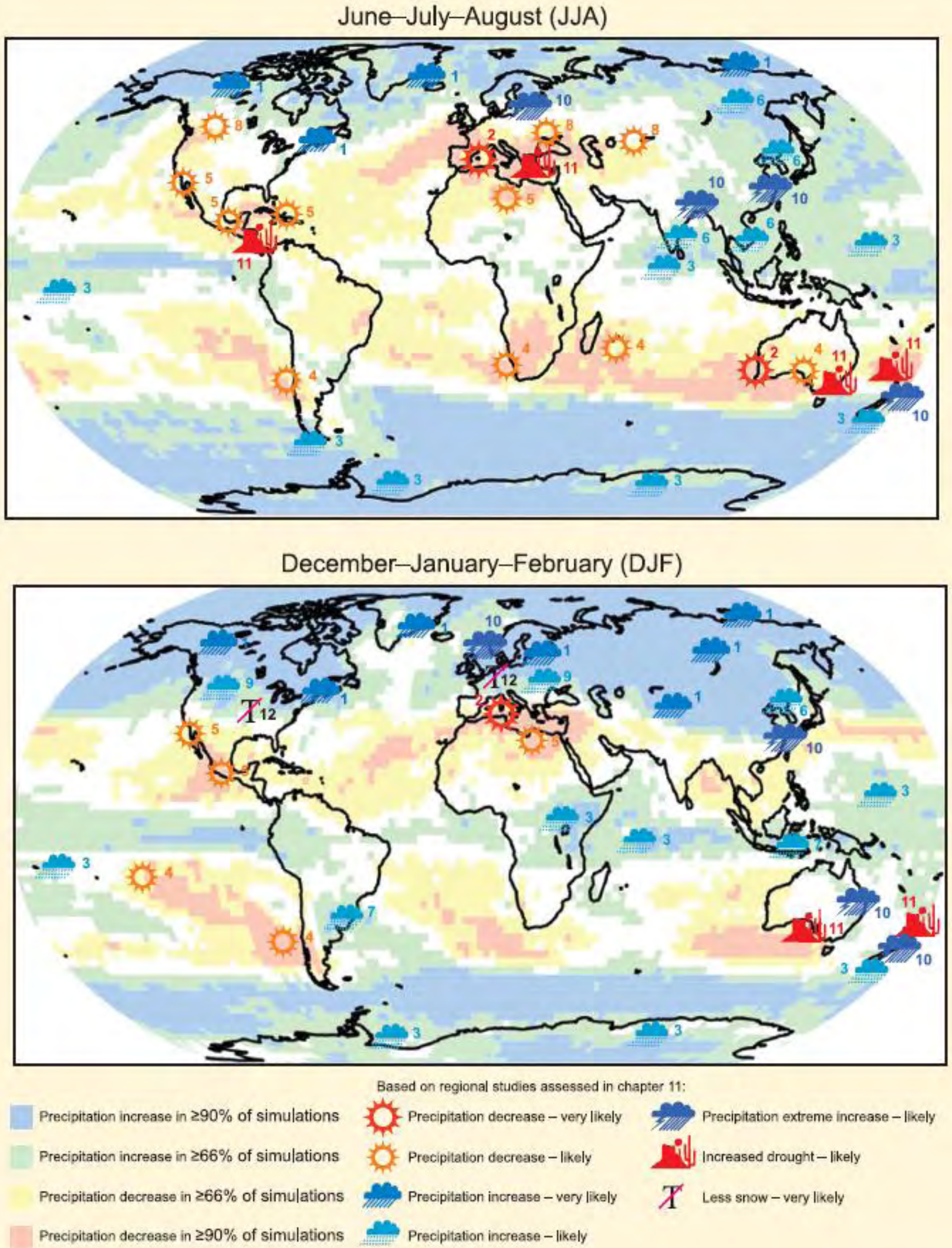


# Regional Climate Projections

IPCC 2007

**Box 11.1, Figure 1.** *Temperature anomalies with respect to 1901 to 1950 for six continental-scale regions for 1906 to 2005 (black line) and as simulated (red envelope) by MMD models incorporating known forcings; and as projected for 2001 to 2100 by MMD models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red). The black line is dashed where observations are present for less than 50% of the area in the decade concerned. More details on the construction of these figures are given in Section 11.1.2.*






**Box 11.1, Figure 2.** *Robust findings on regional climate change for mean and extreme precipitation, drought, and snow. This regional assessment is based upon AOGCM based studies, Regional Climate Models, statistical downscaling and process understanding. More detail on these findings may be found in the notes below, and their full description, including sources is given in the text. The background map indicates the degree of consistency between AR4 AOGCM simulations (21 simulations used) in the direction of simulated precipitation change.*

Changes in precipitation (mean and extremes), drought and snow (SRES A1B).

IPCC 2007

Species respond to many aspects of the environment, but individualistically – they all have their own multidimensional environmental hyperspace

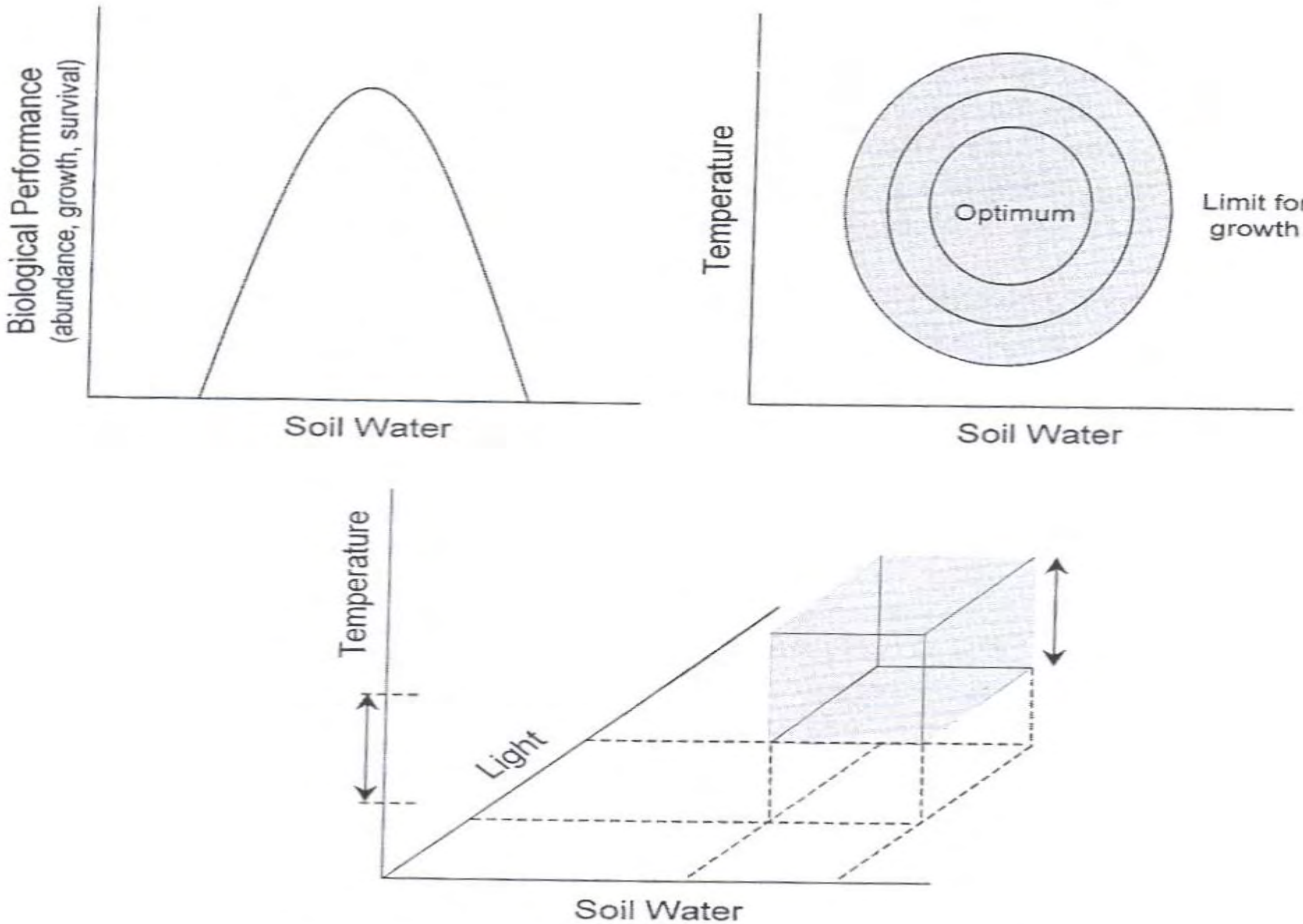



*Figure 10.2.* Tolerance of a species in relation to environmental conditions. Top left: Response to soil water. Top right: Response to soil water and temperature showing the range of conditions for which growth can occur and is optimal. Bottom: Range of conditions along three dimensions (soil water, temperature, light) over which growth is possible.

# Risk from shifting climate space

Ohlemüller, R., Gritti, E.S., Sykes, M.T. & C.D. Thomas (2006). Towards European climate risk surfaces: the extent and distribution of analogous and non-analogous climates 1931-2100. ***Global Ecology and Biogeography, 15, 395-405***.

- five biologically relevant climate variables (10' grid)
- 1945 (1931-1960) as last pre-warming reference period
- for each grid cell:

  - how much area in Europe with pre-warming analogous conditions

  - distance to these areas

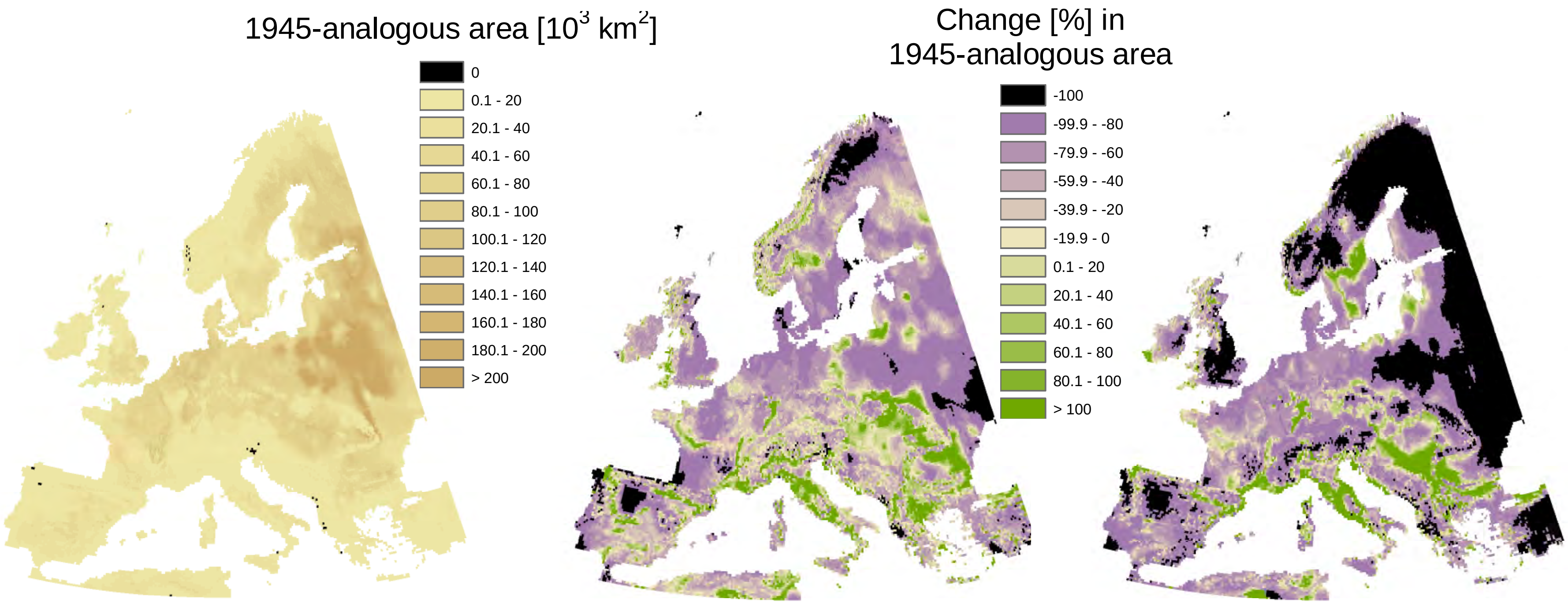
  - direction to these areas

Table 1 The five primary climate variables, their units and three tolerance ranges (*TR*) investigated. Tolerance ranges define the range (±) within which the future climate in a grid cell was considered analogous to 1945 conditions

| | | | Tolerance range (*TR*) | | |
|---|---|---|---|---|---|
| Code | Climate variable | Unit | narrow | medium | wide |
| Tm | Mean annual temperature | °C | ±0.1 | ±1.0 | ±2.0 |
| Tc | Mean temperature coldest month | °C | ±0.1 | ±1.0 | ±2.0 |
| GDD5 | Growing degree days > 5 °C | °C | ±25 | ±250 | ±500 |
| Pa | Mean annual precipitation | mm | ±10 | ±50 | ±100 |
| Pd | Annual water deficit | mm | ±10 | ±50 | ±100 |

# **Area** with pre-warming analogous conditions

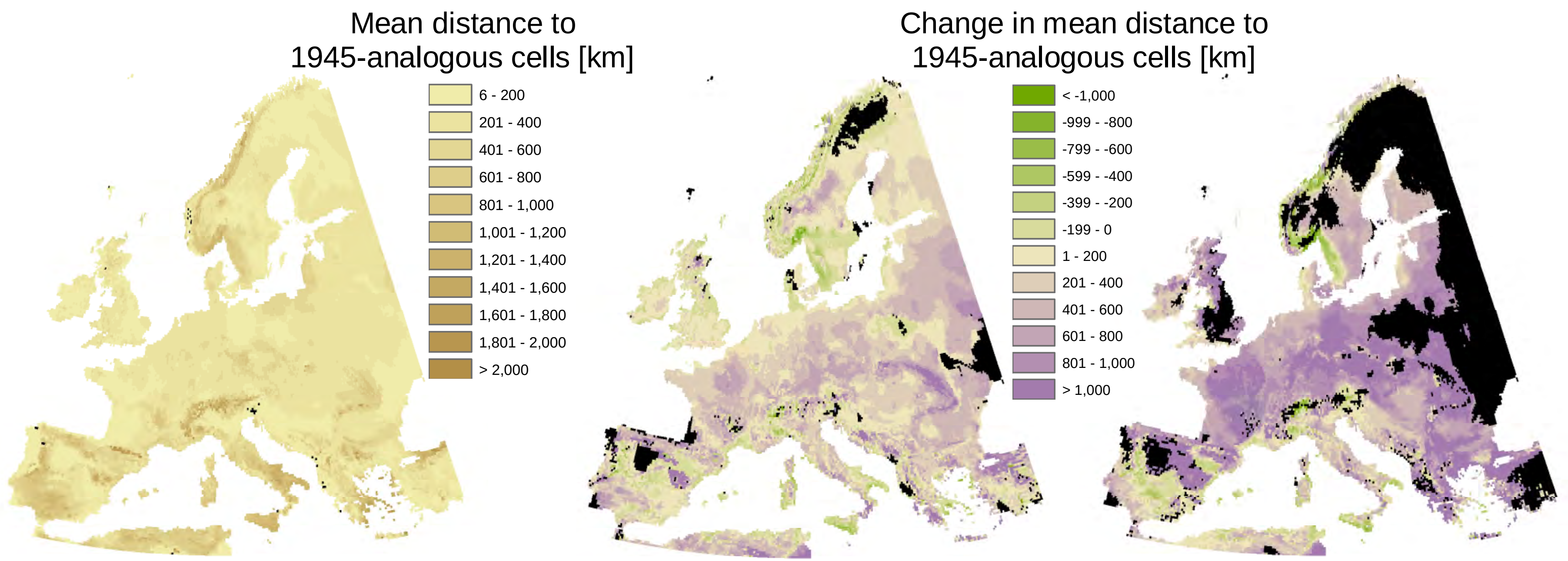
**1945** **+2°C** **+4°C**




= disappearing climates

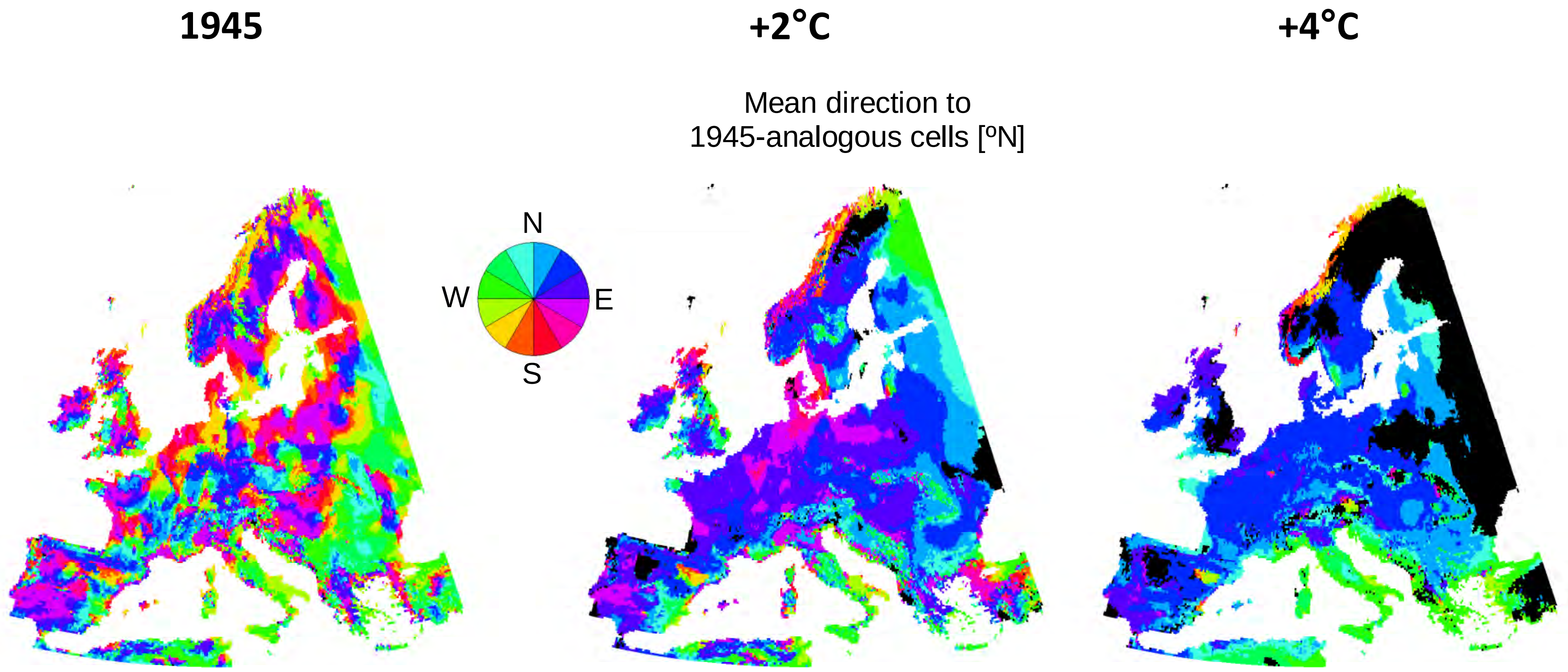
# **Distance** to areas with analogous climates

**1945** **+2°C** **+4°C**




= disappearing climates

# **Direction** to areas with analogous climates



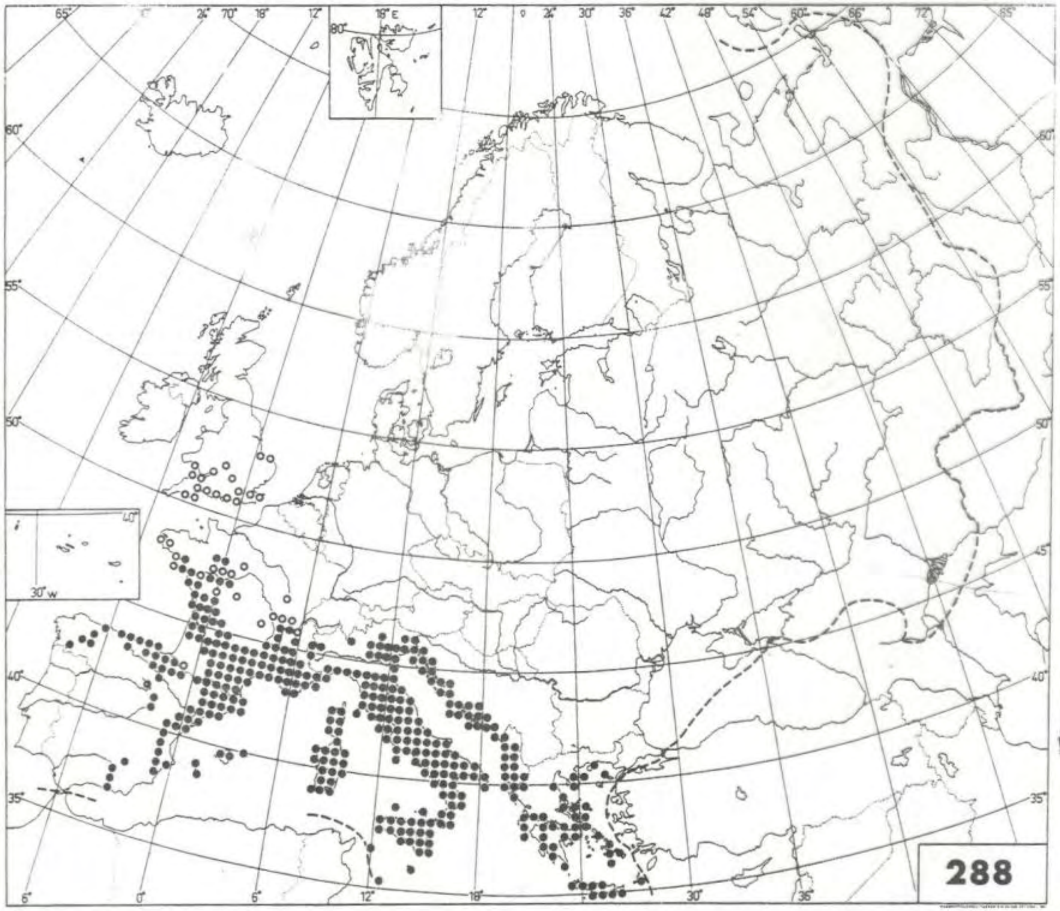

= disappearing climates

# Statistical methods to assess species responses

Bioclimatic envelope models
Species distribution models
Habitat models
Ecological niche-based modelling

- Can be used for many species (1000s) over a wide range of species e.g. plants, animals, insects
- Assumes equilibrium with “current” climate
- Uses “current” digitised species distributions
- Uses statistics on the spatial distribution of climate variables to define a climate envelope that best describes a species “current” range.
- This envelope used to project a species distribution under different climate scenarios

# Statistical methods




Quercus ilex

Example species dataset:
Atlas Florae Europaeae
*Jalas & Suominen 1972-1991*

*A digitised version*

CTA/CART- Classification and regression tree analysis
GLM – Generalised linear models
GAM – Generalised additive models
Locally weighted regressions
ANN - Artificial neural networks
GARP – Genetic algorithm for rule-set prediction
MARS – Multivariate adaptive regression splines
GBM – Generalised boosted models
MAXENT – Maximum entropy method
Random Forests Analysis

# Statistical methods (2) e.g.

**Table 1** Examples of the statistical techniques, and their abbreviations, applied in bioclimatic envelope modelling

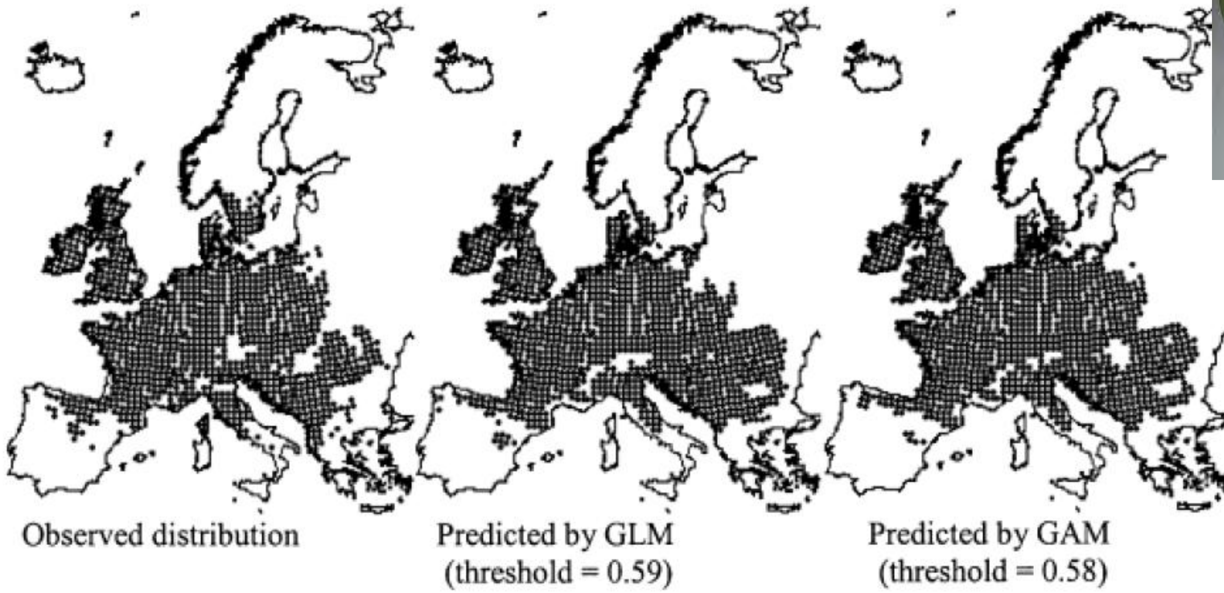
| Study | Modelling methods |
|---|---|
| Brereton *et al.*, 1995; Beaumont and Hughes, 2002 | BIOCLIM |
| Kadmon *et al.*, 2003; Meynecke, 2004; Beaumont *et al.*, 2005 | |
| Box *et al.*, 1993; 1999; Crumpacker *et al.*, 2001 | 'The Florida Model' |
| Walker and Cocks, 1991 | HABITAT |
| Carpenter *et al.*, 1993 | DOMAIN |
| Baker *et al.*, 2000 | CLIMEX |
| Skov and Svenning, 2004; Svenning and Skov, 2004 | Fuzzy minimal rectilinear envelope modelling |
| Iverson and Prasad, 1998; 2001; 2002 | Classification and regression tree analysis (CTA / CART / RTA) |
| Guisan and Theurillat, 2000; Price, 2000 | Logistic regression/binomial GLM |
| Bakkenes *et al.*, 2002; Burns *et al.*, 2003 | |
| Leathwick *et al.*, 1996; Midgley *et al.*, 2003 | GAM |
| Araújo *et al.*, 2004; Luoto *et al.*, 2005 | |
| Beerling *et al.*, 1995; Huntley *et al.*, 1995; 2004 | Locally weighted regression |
| Hill *et al.*, 1999; 2002 | (local regression/loess) |
| Berry *et al.*, 2002; Pearson *et al.*, 2002; 2004 | ANN |
| Peterson, 2001; Anderson *et al.*, 2002a; 2002b | GARP |
| Peterson *et al.*, 2002a; 2002b; 2004 | |
| Prasad and Iverson, 2000 | MARS |
| Gavin and Hu, 2005 | GM-SMAP |
| Thuiller, 2003; 2004; Araújo *et al.*, 2005a; 2005b | GLM, GAM, CTA, ANN |
| Thuiller *et al.*, 2005a; 2005b | |

ANN = artificial neural networks; GAM = generalized additive models; GARP = genetic algorithm for rule-set prediction; GLM = generalized linear models; GM-SMAP = Gaussian mixture distributions and multiscale segmentation; MARS = multivariate adaptive regression splines.

Heikkinen, R.K., Luoto, M., Araújo, M., Virkkala, R., Thuiller, W., & Sykes, M.T.. 2006. Methods and uncertainties in bioclimatic modelling. *Progress in Physical Geography*, 30. 751-777

# Evaluating Performance

- Measure accuracy of prediction – preferably based on independent data e.g. Kappa statistic, Cohen's $\kappa$, AUC values of the ROC statistic, etc
- Comparison of modelling techniques
- Approaches to account for model predictions' variability
  - use a framework of different methods
  - use a consensus analysis (via PCA or cluster analysis) that represents the central tendency across all models considered.




Global Change Biology (2003) **9**, 1353–1362

# BIOMOD – optimizing predictions of species distributions and projecting potential future shifts under global change

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*Centre d'Ecologie Fonctionnelle et Evolutive, Centre National de Recherche Scientifique, 1919 route de Mende, 34293 Montpellier Cedex 5, France*

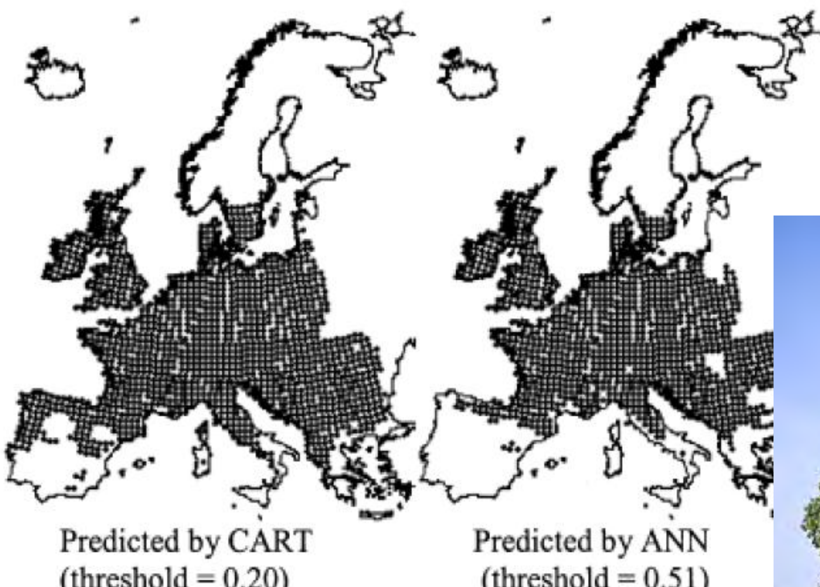
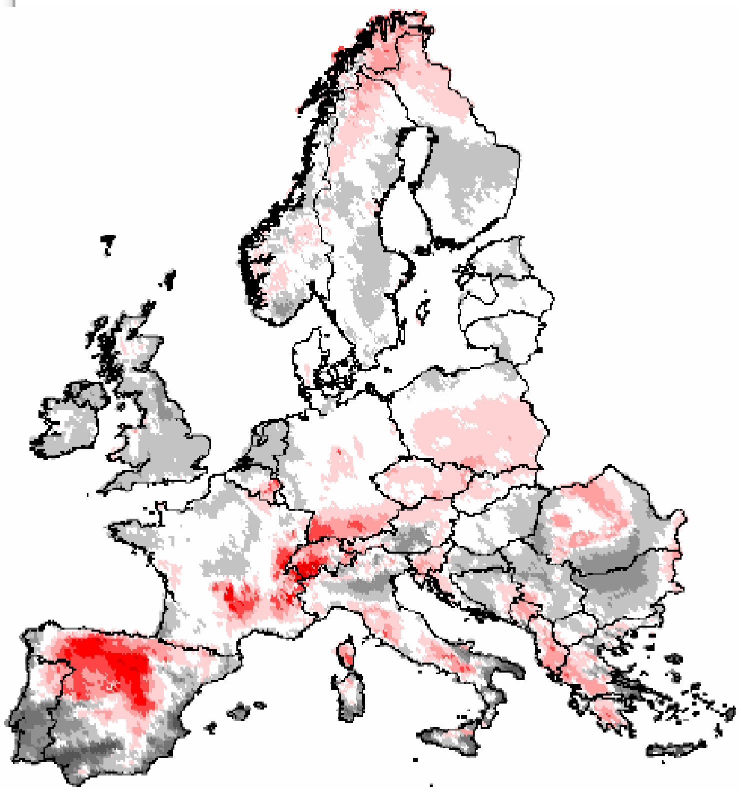
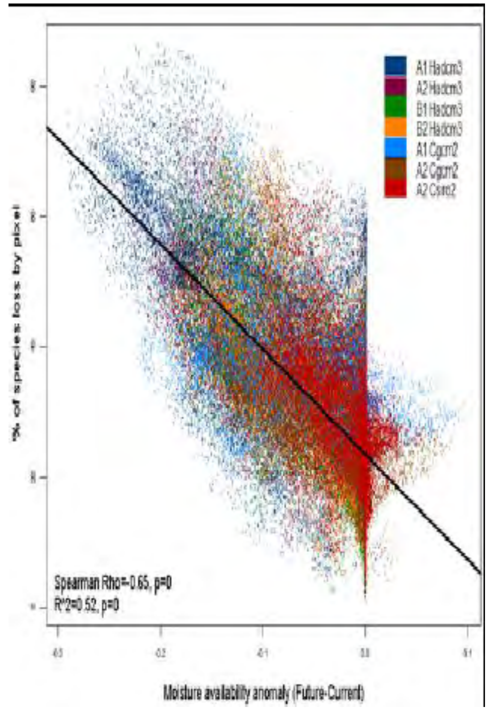



**Fig. 1** Observed and predicted distribution for *Quercus petraea* according to the modelling technique used. The ROC curve and $\kappa$ statistics on evaluation data are the following: GLM (AUC = 0.939; $\kappa$ = 0.74), GAM (AUC = 0.945; $\kappa$ = 0.77), CART (AUC = 0.927, $\kappa$ = 0.76) and ANN (AUC = 0.960; $\kappa$ = 0.79).

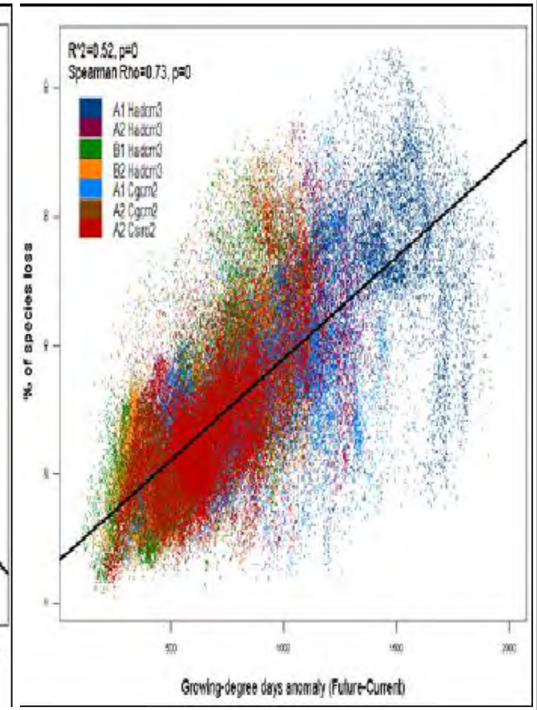
# Statistical based bioclimatic envelope approaches e.g. BIOMOD



Regional projections of residuals from the multiple regression of species loss against GDD and moisture availability index - RED excess species loss, grey a deficit




Moisture availability anomaly




Growing degree days anomaly

Relationships between the % of species loss and anomalies of moisture availability & GDD – different colours different climate change scenarios

1350 plant species, climate: annual, winter, summer precip, annual & min temp. GDD, moisture avail. Index in each 50X50 grid. GLM GAM, CART, ANN % consensus PCA

**Climate change threats to plant diversity in Europe**

**Thuiller, W., Lavorel, S., Araújo M.B., Sykes, M.T. & Prentice I.C. 2005**

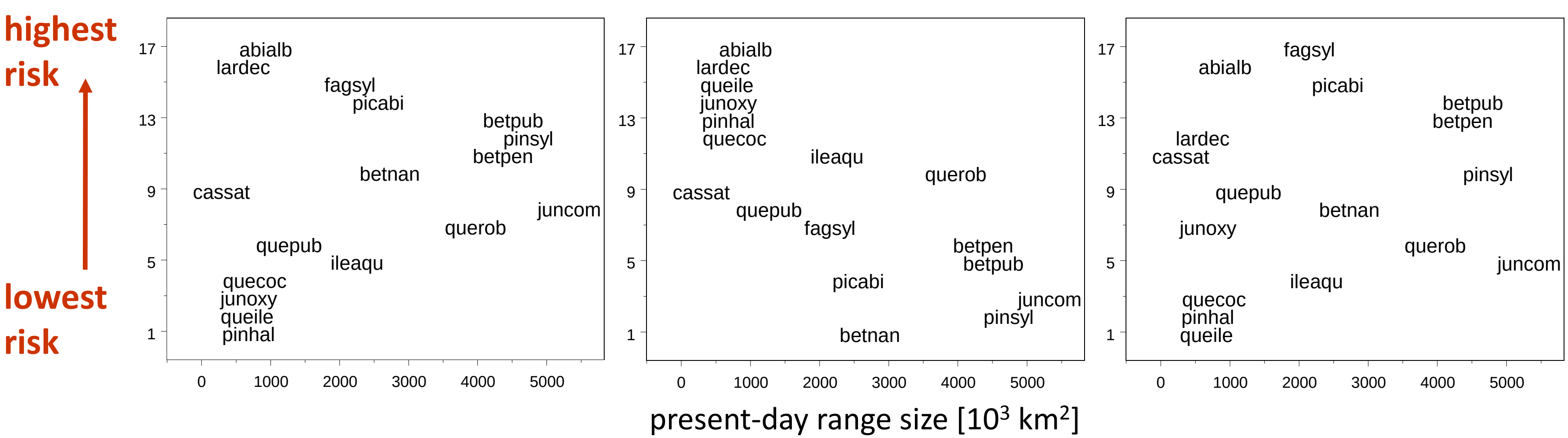
***Proceedings National Academy of Sciences of the United States of America (PNAS) 102 8245-8250***

# Different measures of extinction risk associated with shifting climates by 2095

*Ohlemüller, R., Gritti, E.S. , Sykes, M.T., & Thomas, C.D. (2006). Quantifying components of risk for European woody species under climate change.* ***Global Change Biology, 12, 1788-1799.***

10'x10' climate grid, GAM, CART & GLM models - mostly good agreement between models (showing GAM) – comparing 1945 climate data and species p/a and then used to predict 1995, 2045, 2095 with HADCM3 GCM (scenarios B1/A1Fi)

| Risk measure I | Risk measure II | Risk measure III |
|---|---|---|
| Loss in climatically suitable area | Increase in distance to climatically suitable areas (2095) | Decrease in climatic suitability in already occupied locations |



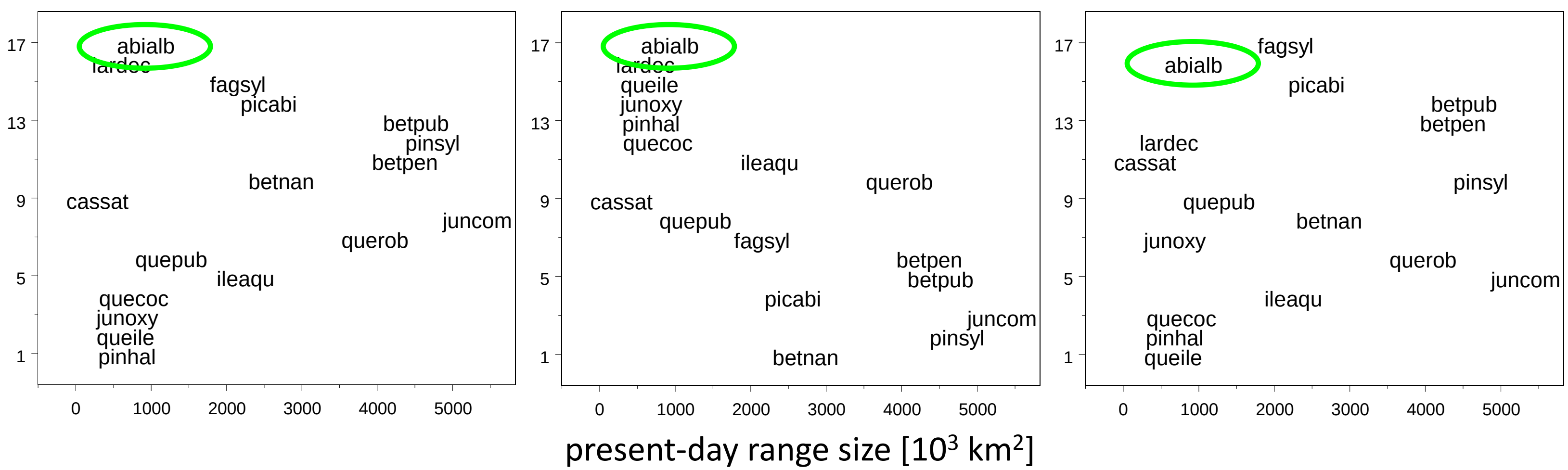


# *Abies alba* (silver fir)

| Risk measure I | Risk measure II | Risk measure III |
| --- | --- | --- |
| Loss in climatically suitable area | Increase in distance to climatically suitable areas | Decrease in climatic suitability in already occupied locations |

highest risk

lowest risk



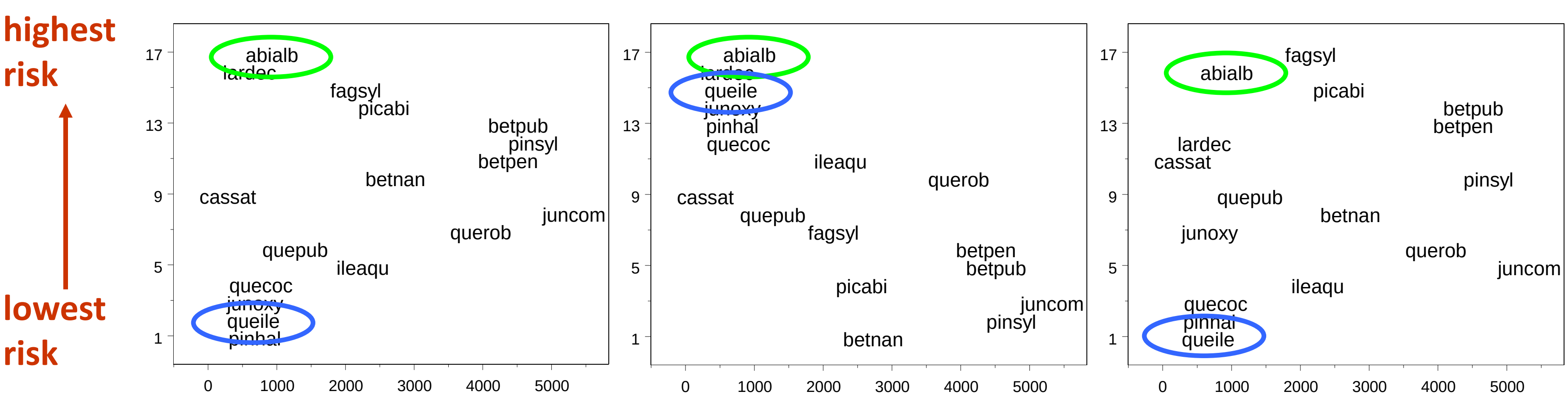
© Renzo Motta

# *Abies alba* (silver fir)

# *Quercus ilex* (holm oak)

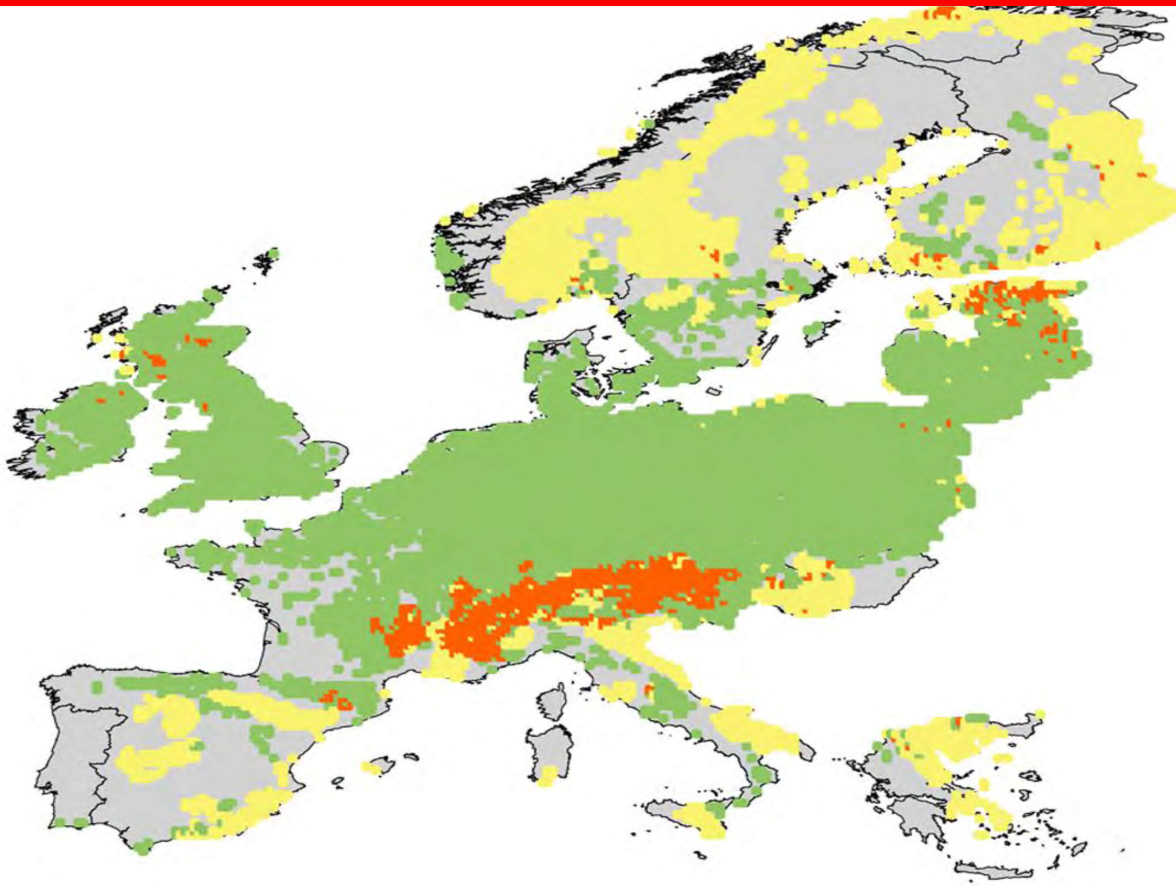
© Brian Ecott

| Risk measure I | Risk measure II | Risk measure III |
| --- | --- | --- |
| Loss in climatically suitable area | Increase in distance to all climatically suitable areas | Decrease in climatic suitability in already occupied locations |




present-day range size [$10^3$ $km^2$]

# Current niche spaces of *Boloria titania* and *Polygonum bistorta*

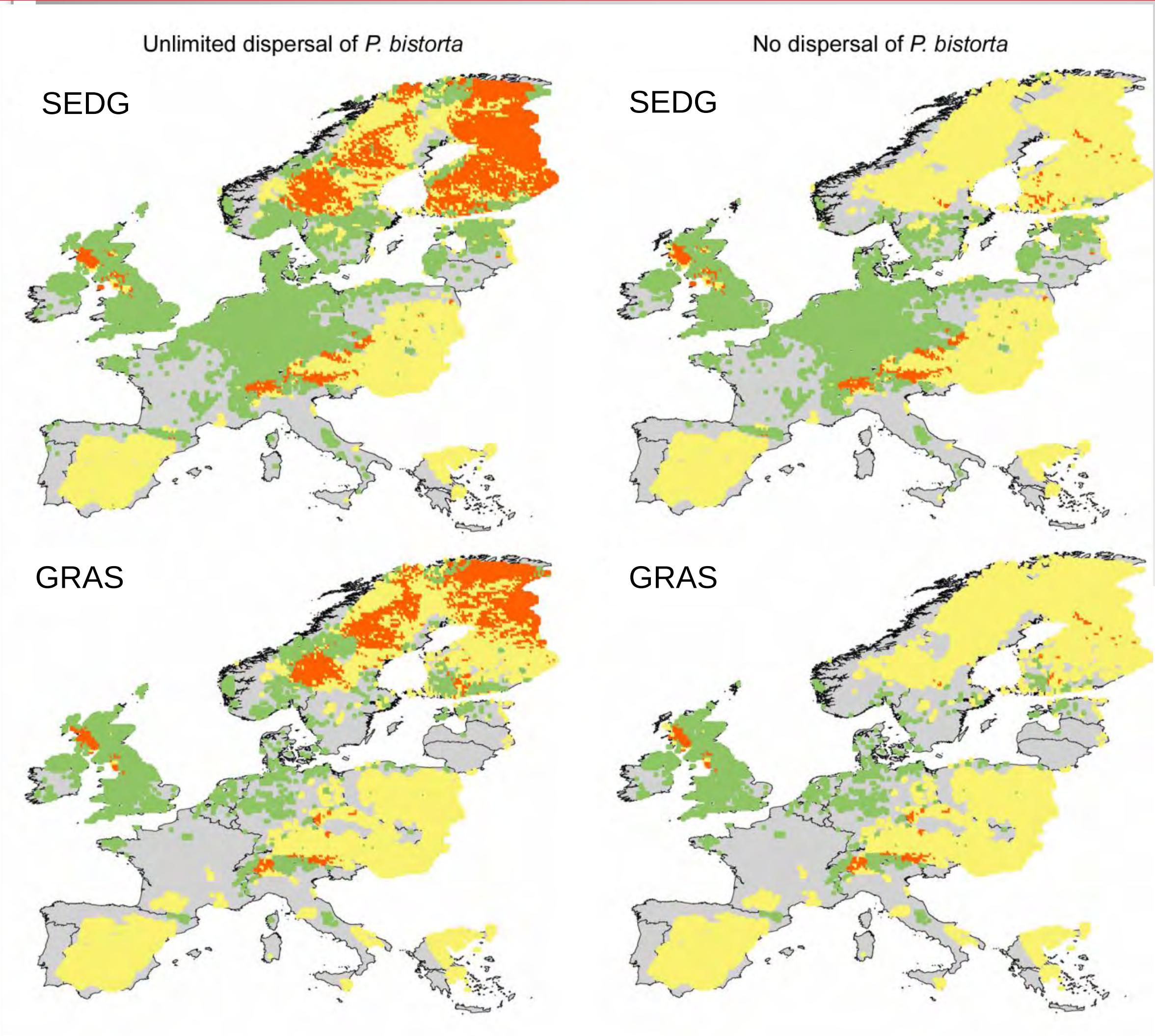



Two separate ecological niche models for the butterfly and its host plant based on climate, land use and soil characteristics. AUC‘s > 0.93

- Niche spaces of *Boloria titania* and *Polygonum bistorta* show today only small areas of overlap.

***Schweiger, O., Settele, J., Kudrna, O., Klotz, S. Kuhn, I. Climate change destabilises ecosystem functioning in press***

# Projected changes in niche space of *Boloria titania* and *Polygonum bistorta for 2080*




- Niche space of *B. titania* would increase
- But mismatch of both niche spaces increases, too
- Serious decrease of overlap in the butterfly's original distribution (Alps and Baltic States).
- Potentially new areas in the north could only be colonised in the unlikely case of high dispersal ability of *P. bistorta*.
- Climate change can disrupt trophic interactions.

*P. bistorta*
*B. titania*
Overlap

- See Thuiller 2003, 2004 GCB, Thuiller et al. 2003 JVS, Seguardo & Araújo 2004 , Heikkinen et al 2006 etc

No single method that can be used with reliability in the majority of studies – but some approaches are more reliable (e.g. GAM, ANN, MARS)

Many models are species-dependent and thus using one or a few models over many species is fraught

Variability between methods greater under future climate scenarios

Multi-model frameworks to find the “best” model – the consensus approach might be better – BUT?

# So what about statistical models any good ?
# 1. Model dependent results

- Are species in equilibrium with current climate ?
- Model dependent results
- Climate data/land use data uncertainties
- Sampling a species climatic range ??
- Downscaling
- Bioclimatic parameter choice
- Problems of scale
- Stóchastic events, extreme events
- Non-analogue futures
- Extinction lags
- Genetic differences at range boundaries
- Fragmentation
- Dispersal/migration
- The effect of changing CO2 (fertilisation and water balance)
- Changing competitive relationships
- Increasing nitrogen deposition
- Changing phenology
- Invasive species

**BIG question – Are broad scale results relevant for Biodiversity conservation policy??**

# 2. Many uncertainties and assumptions

- Phenology models
- Bioclimatic models /BIOME/SPECIES range shift models

# Physiologically based equilibrium approaches

# Phenology

Phenology- timing of events through the year.

Climate driven changes:

e.g. earlier budburst/leaf drop

earlier flowering times

earlier appearance of butterflies

earlier breeding in birds and amphibians

earlier arrival of migrating birds

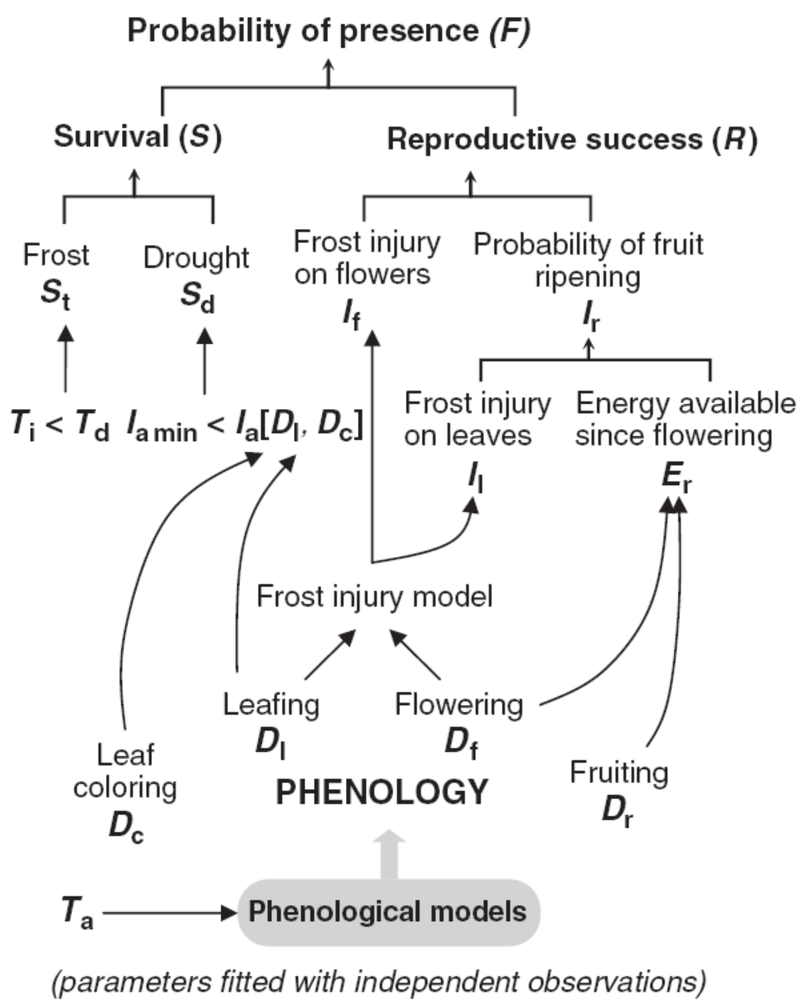



**Fig. 1** Description of PHENOFIT. $T_a$, average daily temperature; $T_i$, minimum daily temperature; $D_l$, date of leafing; $D_f$, date of flowering; $D_r$, date of fruiting; $D_c$, date of leaf coloring; $I_a[D_l; D_c]$, moisture index between leafing and leaf coloring; $I_{a\,min}$, minimal moisture index (species dependent); $I_l$, leaves frost injury index; $E_r$, available energy since flowering; $I_f$, flowers frost injury index; $I_r$, index of fruit maturation; $S$, probability to survive; $S_t$, probability to survive frost; $S_d$, probability to survive drought.

Global Change Biology (2005) **11**, 1493–1503, doi: 10.1111/j.1365-2486.2005.00996.x

# Sensitivity analysis of the tree distribution model PHENOFIT to climatic input characteristics: implications for climate impact assessment

XAVIER MORIN and ISABELLE CHUINE
*Centre d'Ecologie Fonctionnelle et Evolutive, Equipe BIOFLUX, CNRS, 1919 route de Mende, 34293 Montpellier cedex 5, France*

PHENOFIT – a process based model that predicts species distributions

Based on principle that adaptation of a tree species to its environment strongly depends on the synchronization of its development timing to seasonal variations in climate.

Output – a probability of presence of an adult individual after several years

Calculated as the product of its probability to survive until the next reproductive season and to be able to produce viable seeds – reproductive success)

Chuine & Beaubien 2001: Phenology is a major determinant of temperate tree range Ecol Letts 4:500-510

PROCESS-BASED MODELING OF SPECIES' DISTRIBUTIONS: WHAT LIMITS TEMPERATE TREE SPECIES' RANGE BOUNDARIES?

Xavier Morin,[1,3] Carol Augspurger,[2] and Isabelle Chuine[1]

*Ecology*, 88(9), 2007, pp. 2280–2291


Probability of presence of different species simulated with PHENOFIT
Area with Δs observed ranges

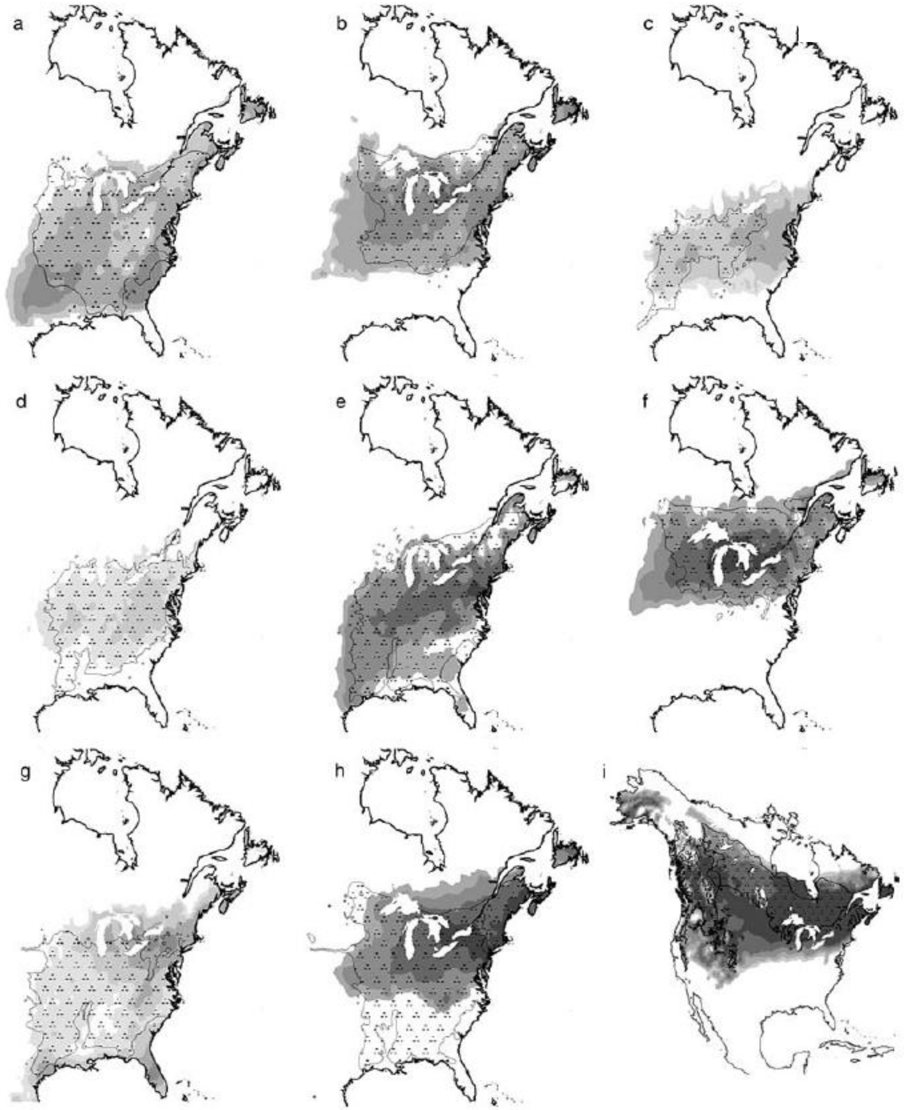
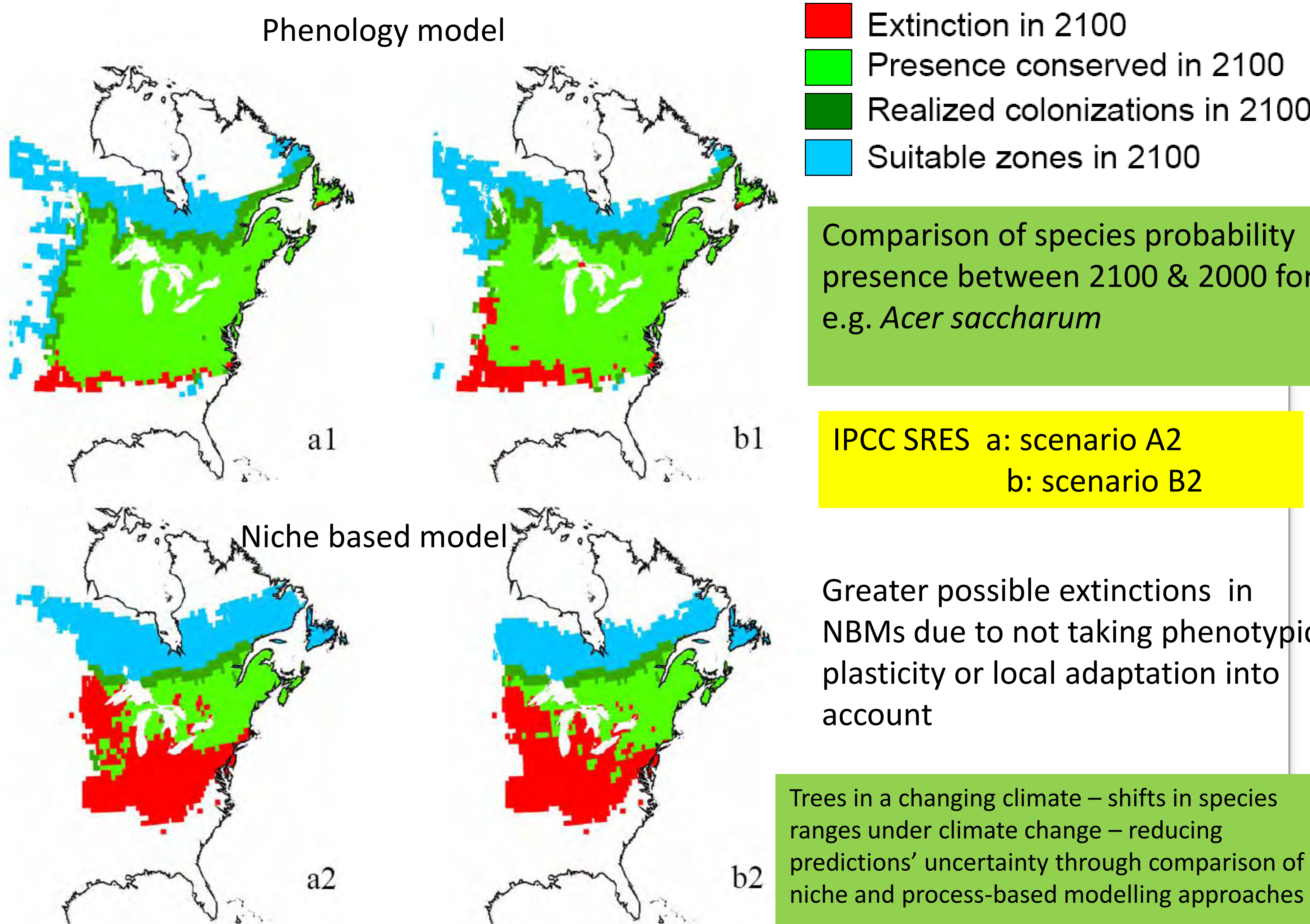



Fig. 1. Probability of presence (above SPT [specific presence threshold], see Table 1) simulated with PHENOFIT (Chuine and Beaubien 2001) for: (a) *Acer saccharinum*; (b) *Acer saccharum*; (c) *Aesculus glabra*; (d) *Carya ovata*; (e) *Fraxinus americana*; (f) *Fraxinus nigra*; (g) *Juglans nigra*; (h) *Ostrya virginiana*; (i) *Pinus contorta*; (j) *Pinus monticola*; (k) *Populus deltoides*; (l) *Populus tremuloides*; (m) *Quercus bicolor*; (n) *Quercus macrocarpa*; (o) *Salix nigra*; (p) *Sassafras albidum*; and (q) *Ulmus americana*. Note that the distribution of *Pinus banksiana* (sister species of *Pinus contorta*) is also shown in panel (i) on the eastern part of the continent. Values can range from 0 to 1. Area with triangles corresponds to the observed species' distribution.




Comparison of species probability presence between 2100 & 2000 for e.g. *Acer saccharum*

IPCC SRES a: scenario A2
b: scenario B2

Greater possible extinctions in NBMs due to not taking phenotypic plasticity or local adaptation into account

Trees in a changing climate – shifts in species ranges under climate change – reducing predictions' uncertainty through comparison of niche and process-based modelling approaches

*Xavier Morin & Wilfried Thuiller – Ecology in revision*

- BIOME (PFTs) – plant functional types – generalised grouping based around function – global maps – BIOME 1, 3, 4
- STASH species used currently plants and then currently less than 40 –regional/continental maps
- These approaches are concerned with responses to the environment at a physiological level
- Assumes a number of bioclimatic variables to be important for a species survival e.g. winter cold kills – (mean coldest month), e.g. drought reduces growth ( AET/PET) etc
- Still basically correlative
- Some added features related to amount (NPP – Biome3) or likely degree of establishment at any site (STASH)

# More physiologically-based range shift/bioclimatic equilibrium approaches

- One of the first bioclimatic models – a model of individual species distributions and productivity
- **Using 12 monthly values of mean temperature, precipitation and cloudiness –**
- **Downscaled to daily values to get bioclimatic variables and growth multipliers**
- **Defines grid climate and compares species bioclimatic requirements to define p/a and likely productivity**
- **Gridded output at** regional to continental scale

- Bioclimatic variables representing distinct *physiological limiting* mechanisms:
- Minimum temperature tolerance (mean coldest month temp;
- Growing season length - complete life cycle (GDD);
- Chilling requirements for budburst e.g. Beech;
- Drought tolerance AET/PET

# Bioclimatic Equilibrium Modelling – STASH

***(Sykes, Prentice & Cramer 1996, Sykes & Prentice 1995, Walther, Birger & Sykes 2005, Giesecke et al. 2007, Walther et al. 2007)***

- A period of chilling, before budburst can take place, is required for some deciduous boreal and temperate trees e.g. *Fagus sylvatica*
- Presumed to be an adaptation to weather variability and late frosts
- Use the negative exponential relationship between GDD to budburst and length of the chilling period from Murray, Cannell & Smith 1989

# STASH Chilling Requirements

LUNDS UNIVERSITET

- Effects of temperature & drought on assimilation & respiration thru multipliers (see Forska gap model 1993 paper) in the range 0-1 giving likely degree of establishment at any site (STASH)
- Species - a parabolic response to daily temperature between −4 & 36°C (pine & spruce) and other species between −4 & 42°C (see Larcher 1983)
- Growth rates do not decline at range limits – especially in the south – species can increase growth rates until an ON-OFF switch kills them

## ON-OFF switches

Minimum mean coldest month temperature (surrogate for Abs min)

Max mean coldest month temperature (e.g. Spruce −1.5C a surrogate for ? Snow )

Minimum values for alpha a drought index (AET/PET)

Minimum GDD

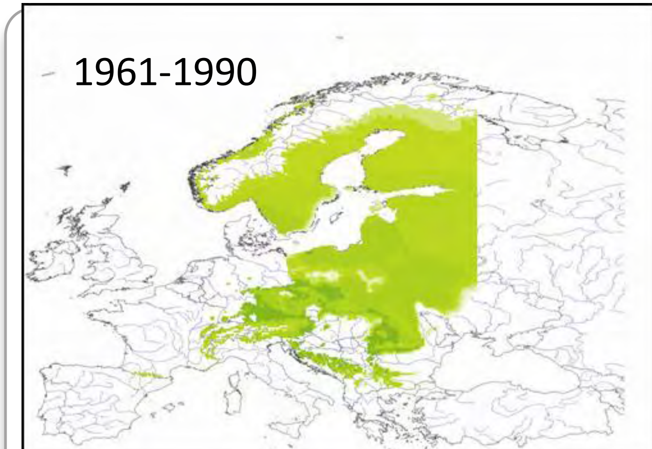
# STASH – effects on growth and ON-OFF switches

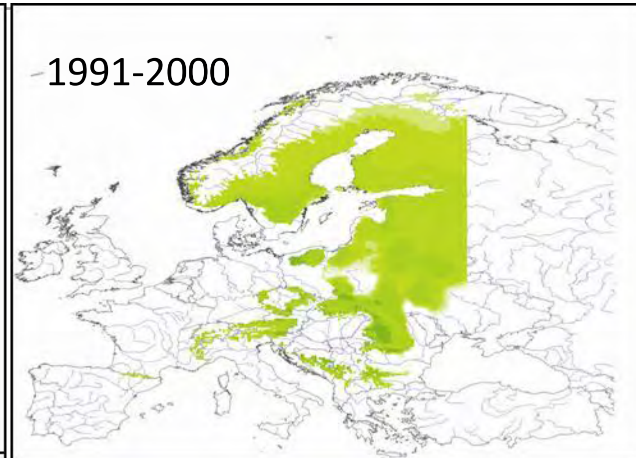
LUNDS UNIVERSITET

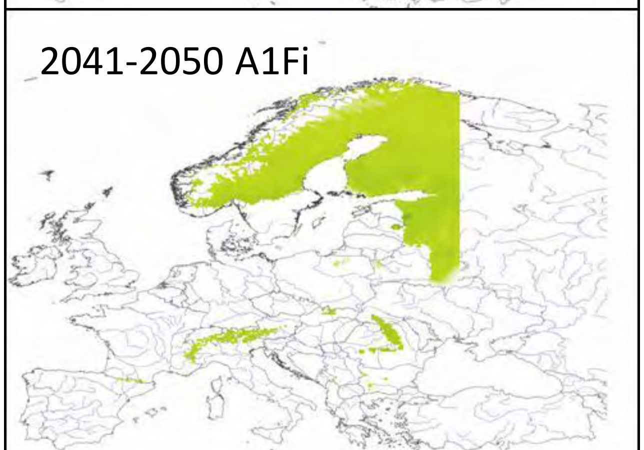
TABLE 1. Bioclimatic parameters for north European tree species.

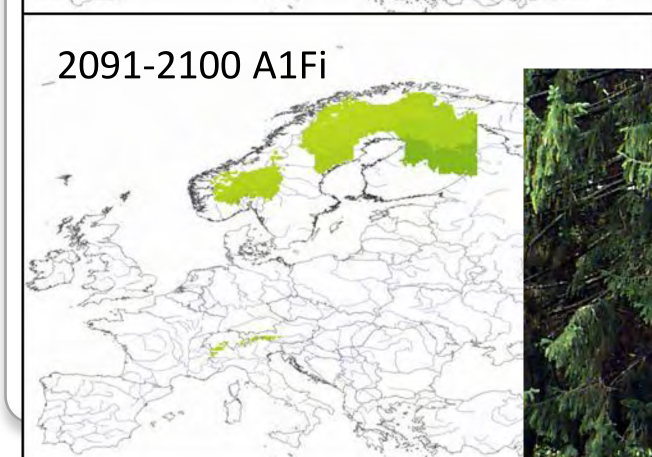
| Species | min $\alpha^*$ | min $T_c$ | max $T_c$ | min GDD* | $b$ | $k$ |
|---|---|---|---|---|---|---|
| Evergreen conifers | | | | | | |
| *Picea abies* (L.) Karsten | 0.85 | | −1.5 | 600 | 100 | 0.05 |
| *Pinus sylvestris* L. | 0.70 | | −1 | 500 | 100 | 0.05 |
| *Juniperus communis* L. | 0.55 | | | 150 | 100 | 0.05 |
| *Taxus baccata* L. | 0.50 | −5 | | 1000 | 100 | 0.05 |
| Evergreen broad-leaved | | | | | | |
| *Ilex aquifolium* L. | 0.50 | −0.5 | | 1100 | 100 | 0.05 |
| Deciduous broad-leaved | | | | | | |
| *Acer platanoides* L. | 0.75 | −16 | 0.5 | 1150 | 100 | 0.05 |
| *Alnus incana* (L.) Moench | 0.75 | | −2.5 | 430 | 100 | 0.05 |
| *Betula pendula* Roth | 0.70 | | | 700 | 500 | 0.02 |
| *Betula pubescens* Ehrh. | 0.77 | | | 150 | 100 | 0.05 |
| *Carpinus betulus* L. | 0.70 | −8 | 5 | 1100 | 1200 | 0.0075 |
| *Corylus avellana* L. | 0.55 | −15 | | 800 | 450 | 0.02 |
| *Fagus sylvatica* L. | 0.65 | −3.5 | 6 | 990 | 1150 | 0.0065 |
| *Fraxinus excelsior* L. | 0.65 | −16 | 6 | 1100 | 100 | 0.05 |
| *Populus tremula* L. | 0.60 | | 6 | 400 | 100 | 0.05 |
| *Quercus petraea* (Mattuschka) Liebl. | 0.67 | −3.5 | 6.5 | 1150 | 100 | 0.05 |
| *Quercus robur* L. | 0.65 | −16 | | 1100 | 100 | 0.05 |
| *Sorbus aucuparia* L. | 0.60 | | | 300 | 100 | 0.05 |
| *Tilia cordata* Millar | 0.70 | −18 | 5 | 830 | 1250 | 0.0065 |
| *Ulmus glabra* Hudson | 0.65 | −15 | | 850 | 100 | 0.05 |

# Some species parameters



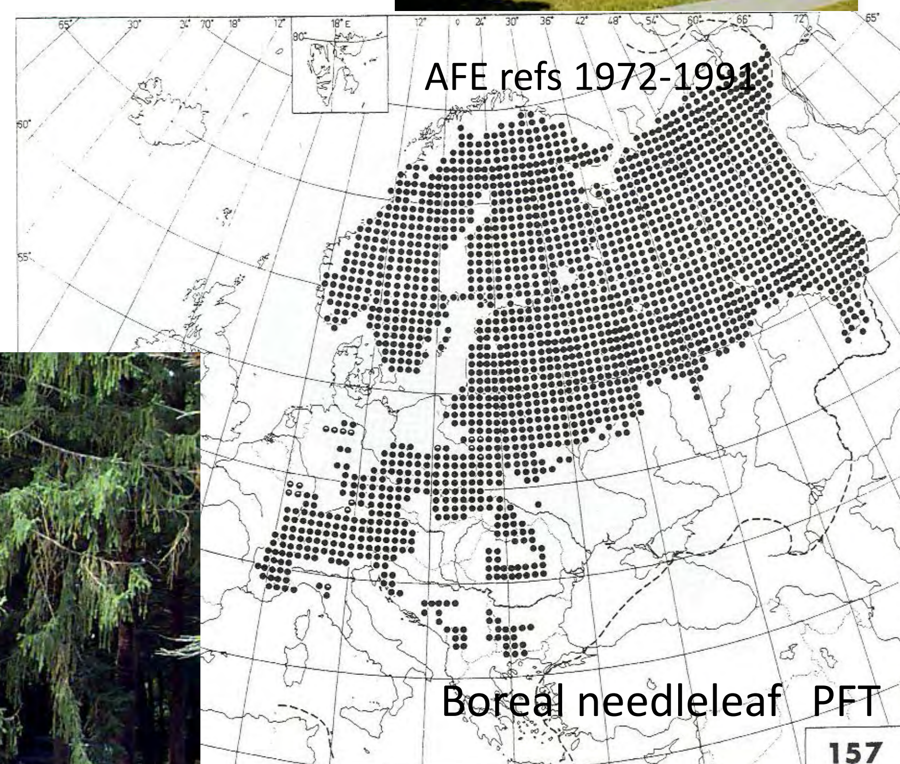



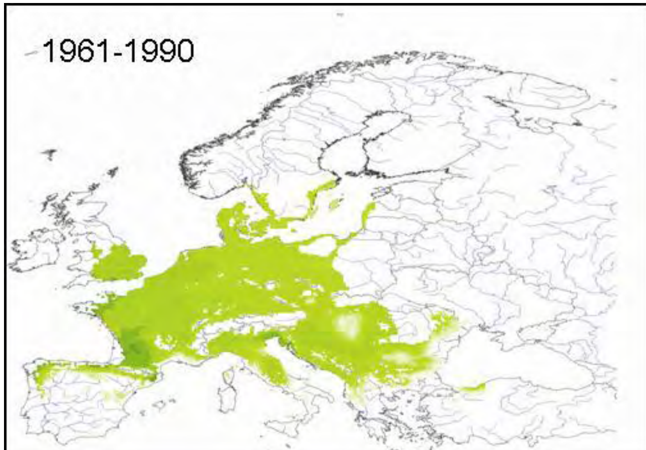



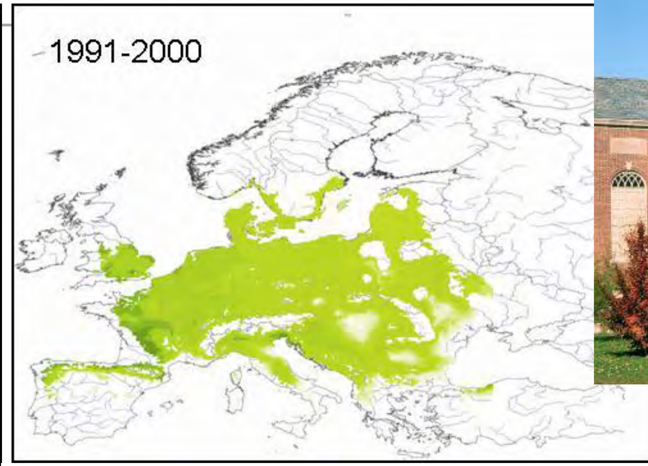




0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10

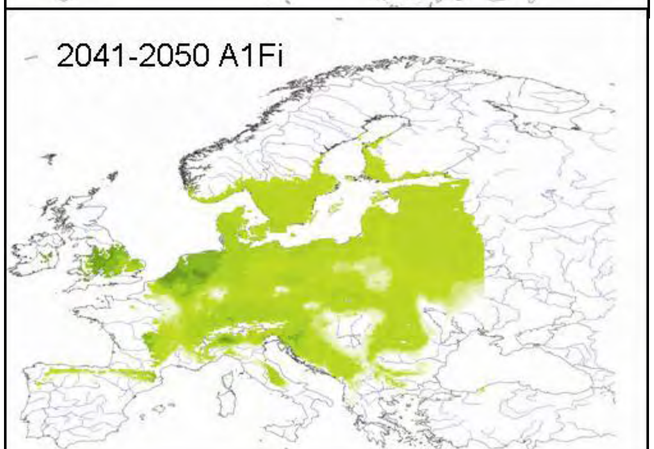
# Picea abies



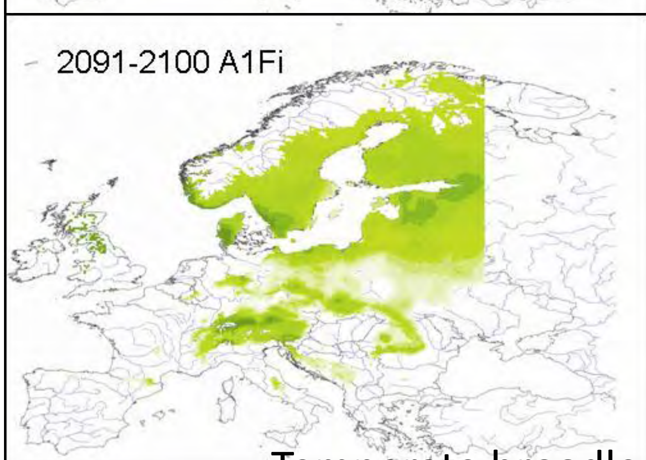



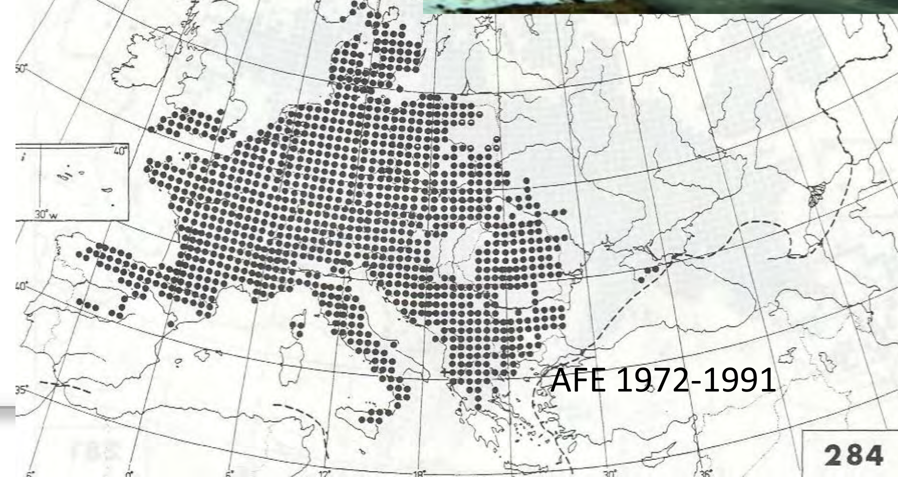




## Fagus sylvatica




- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 - 10



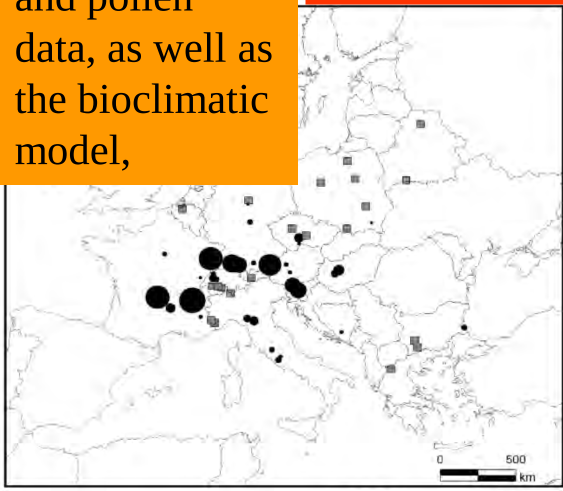

AFE 1972-1991

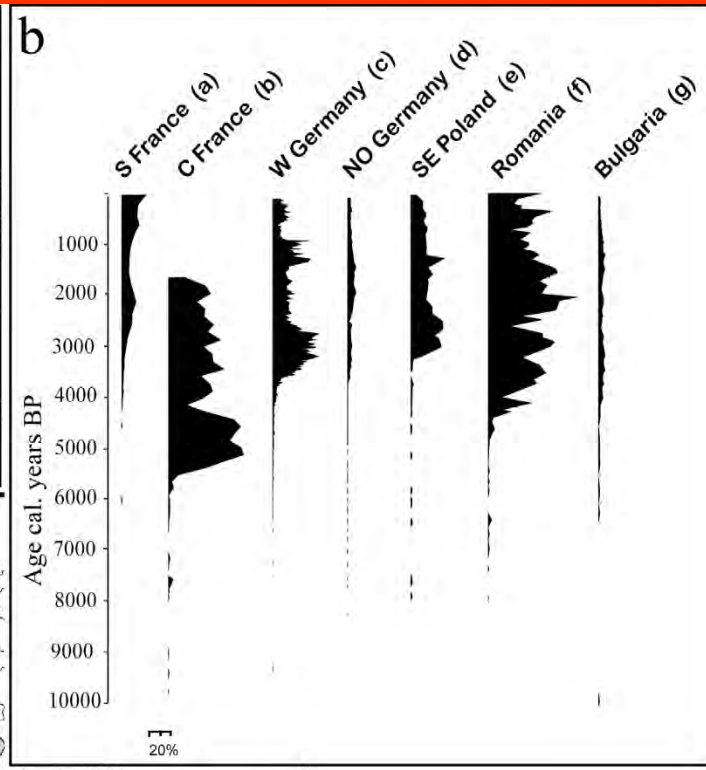
Temperate broadleaf deciduous PFT

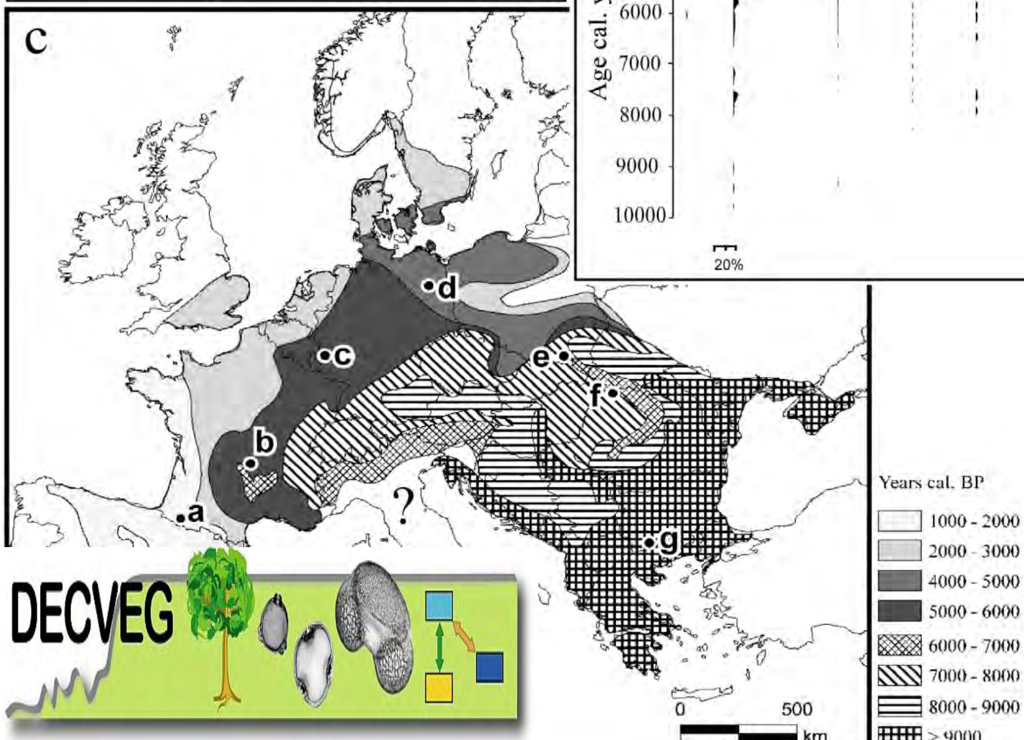
NB: Uncertainties in the climate and pollen data, as well as the bioclimatic model,

# Towards an understanding of the Holocene distribution of Fagus sylvatica (L) *Giesecke et al. 2007 J. Biogeography 34, 118-131*

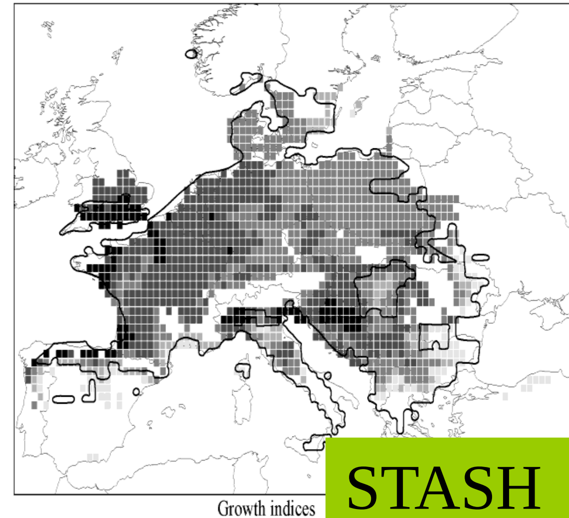
## An equilibrium approach



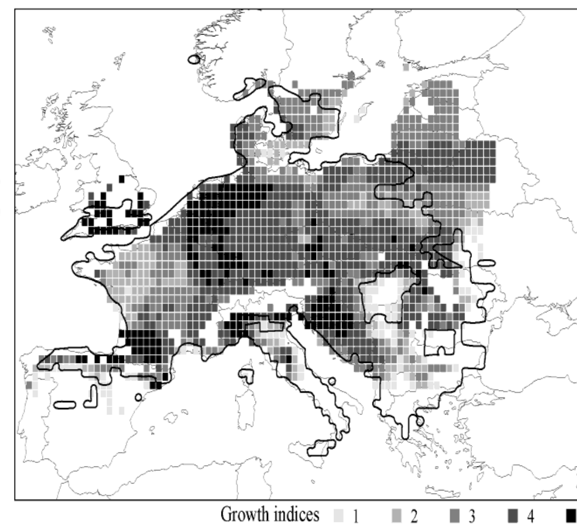




DECVEG




STASH

6000BP GEN2




6000BP ECHAM

# Ecosystem dynamics and climate change

Drivers of change in ecosystems

$CO_2$ concentration increases

Climate change

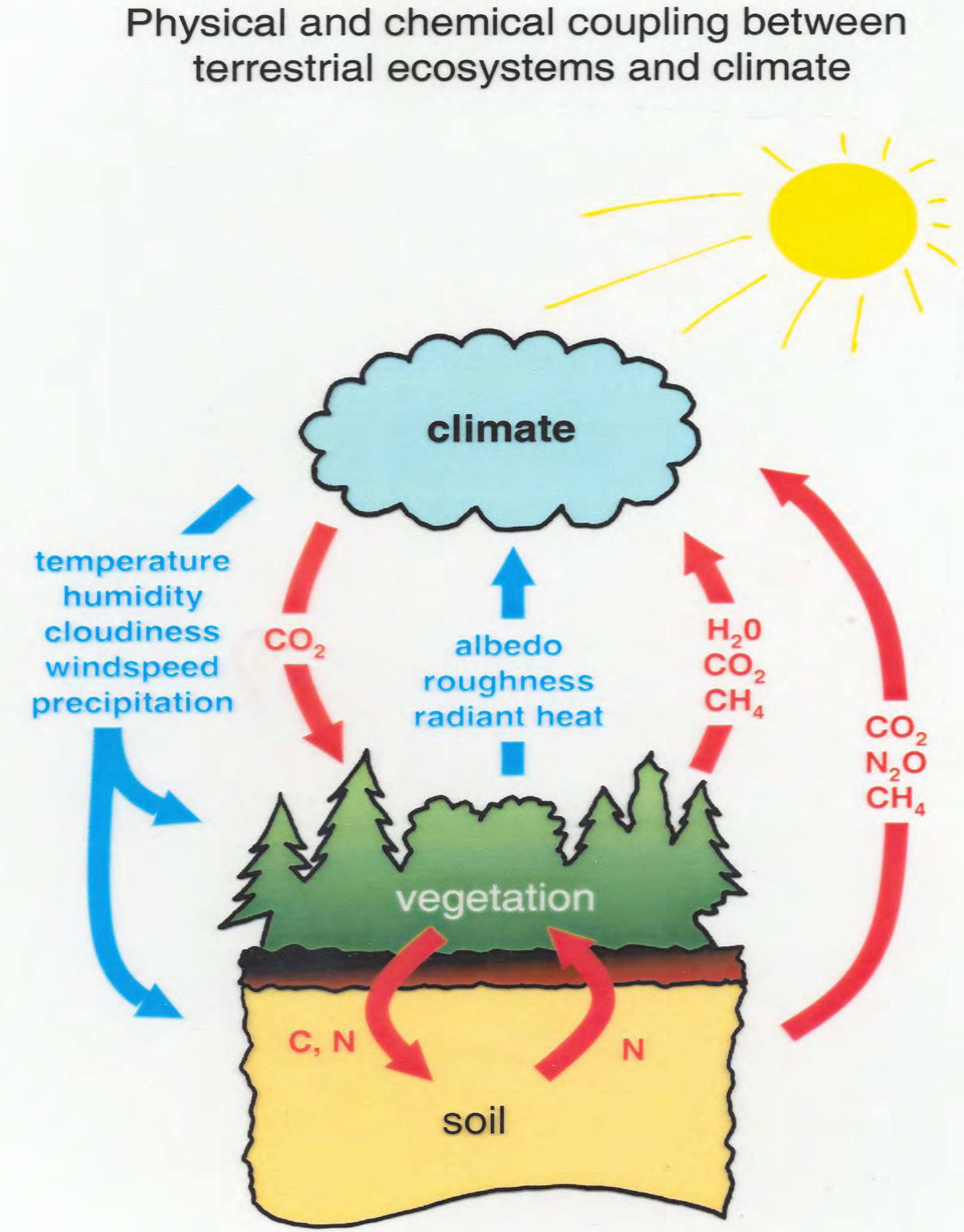
Land use change

Exotic species

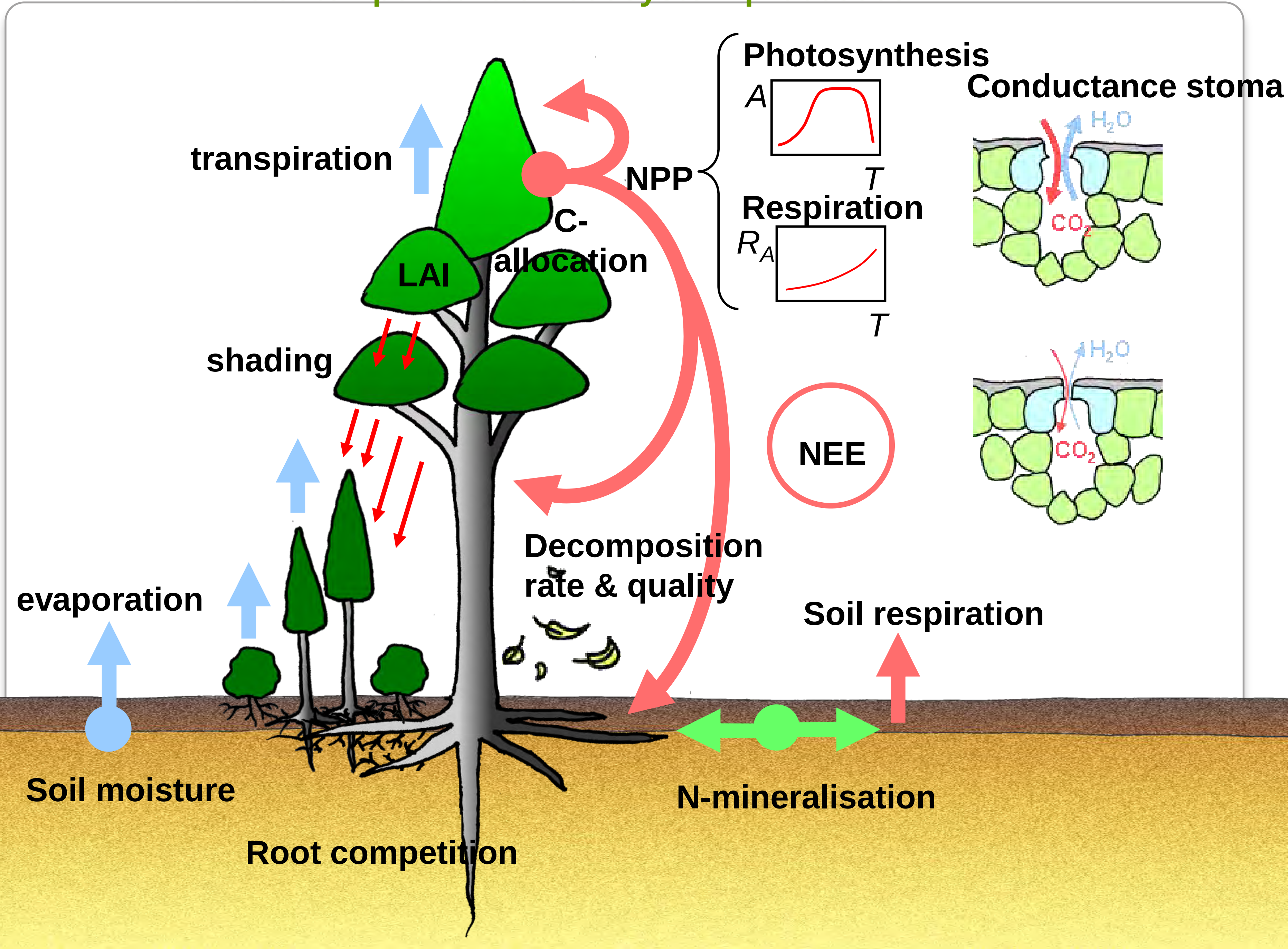
N deposition

Disturbance

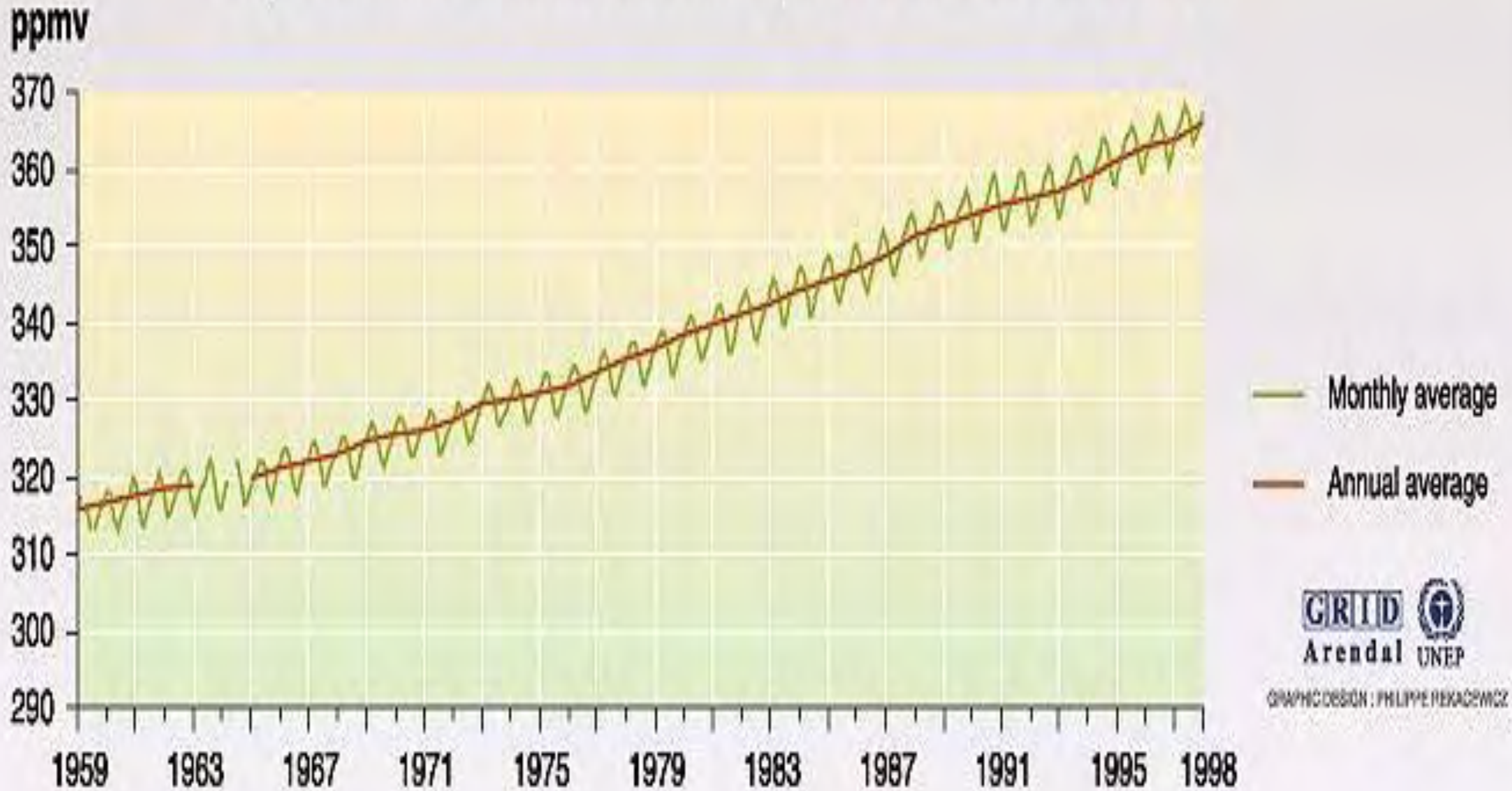
TIME



# Influence of temperature on ecosystem processes

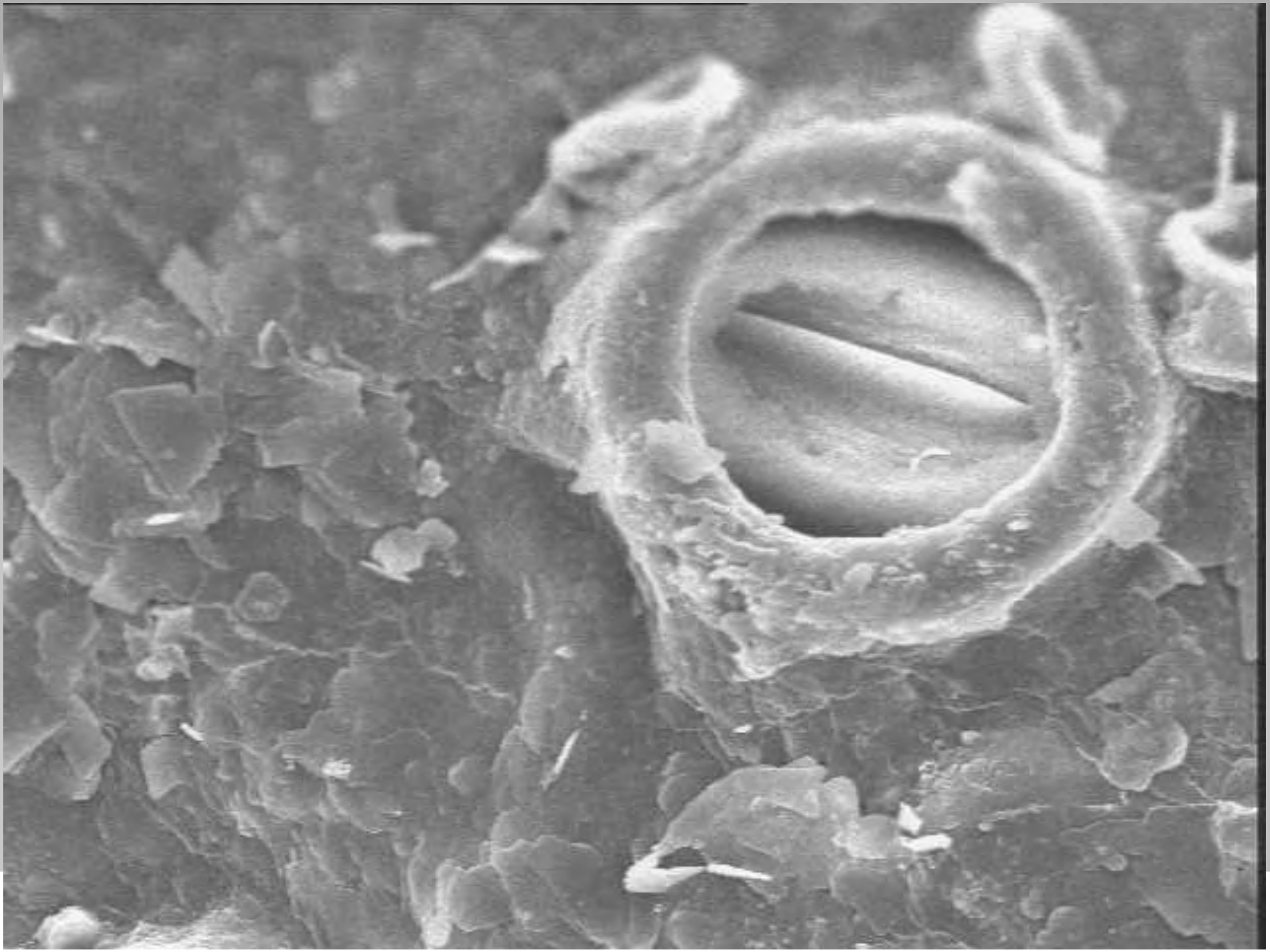


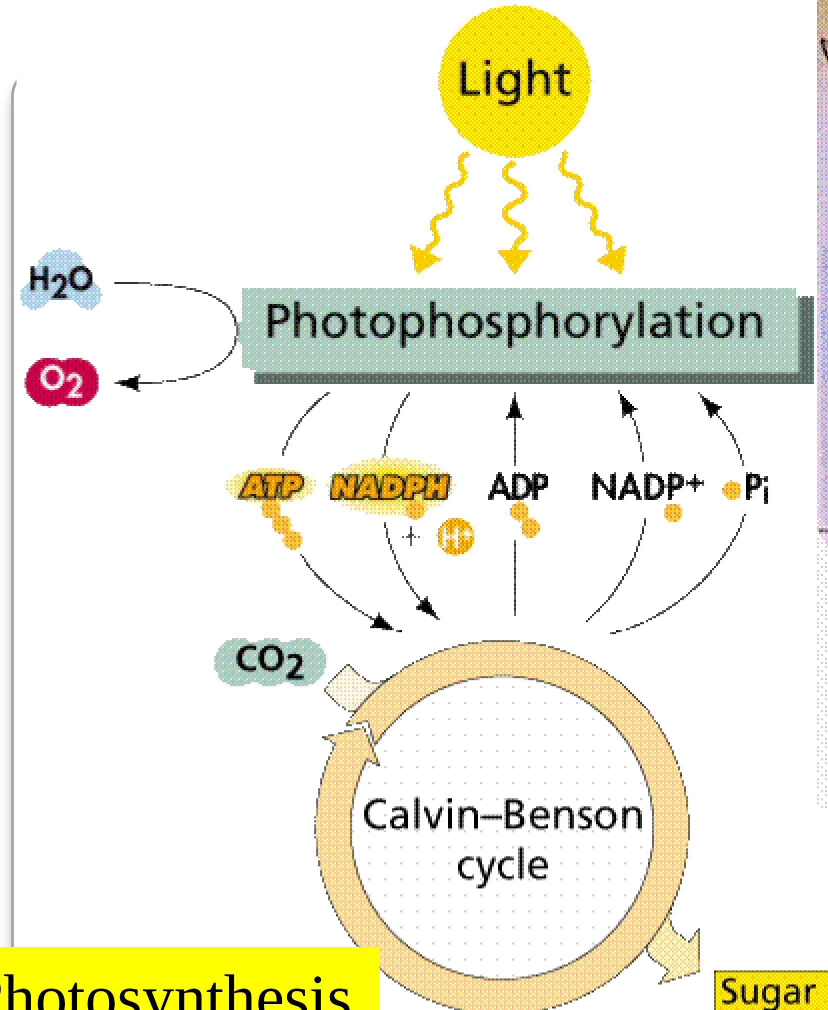
# $CO_2$ concentration in the atmosphere: Mauna Loa curve

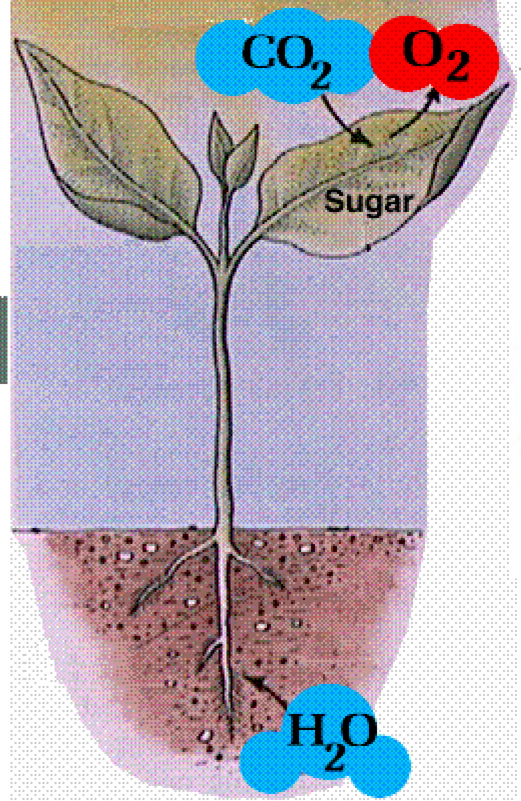


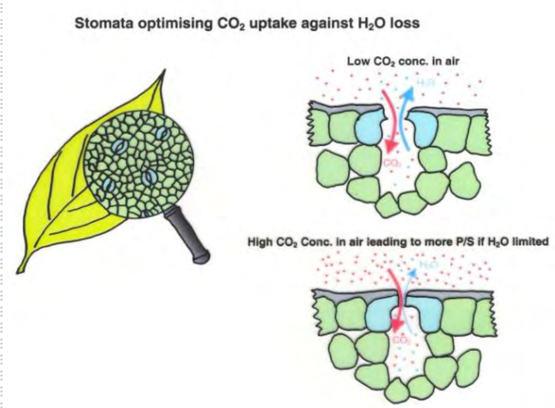

Source : Scripps Institution of oceanography (SIO), University of California, 1998.

# $CO_2$ is a resource for plants





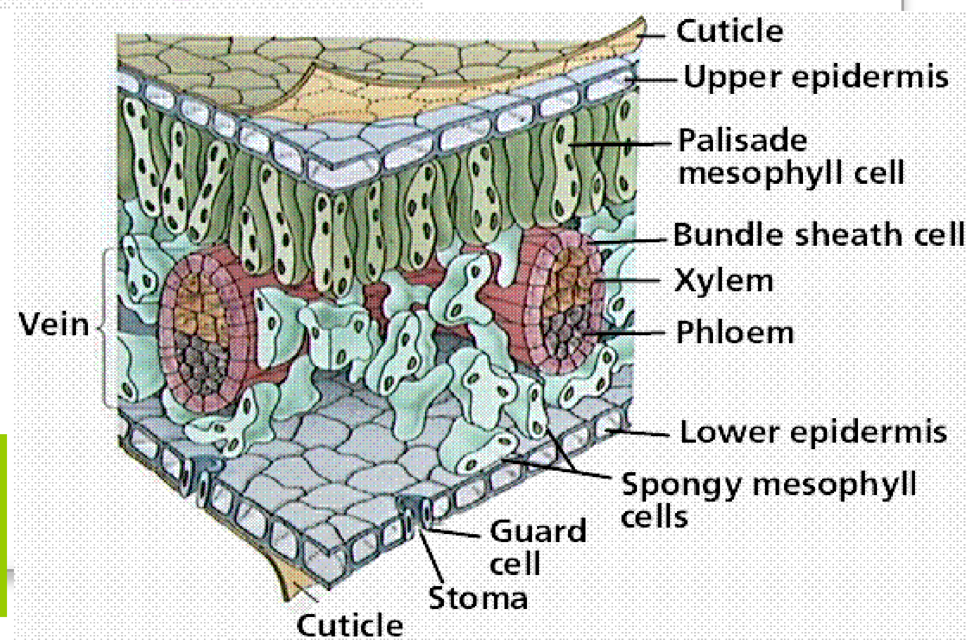

# Photosynthesis

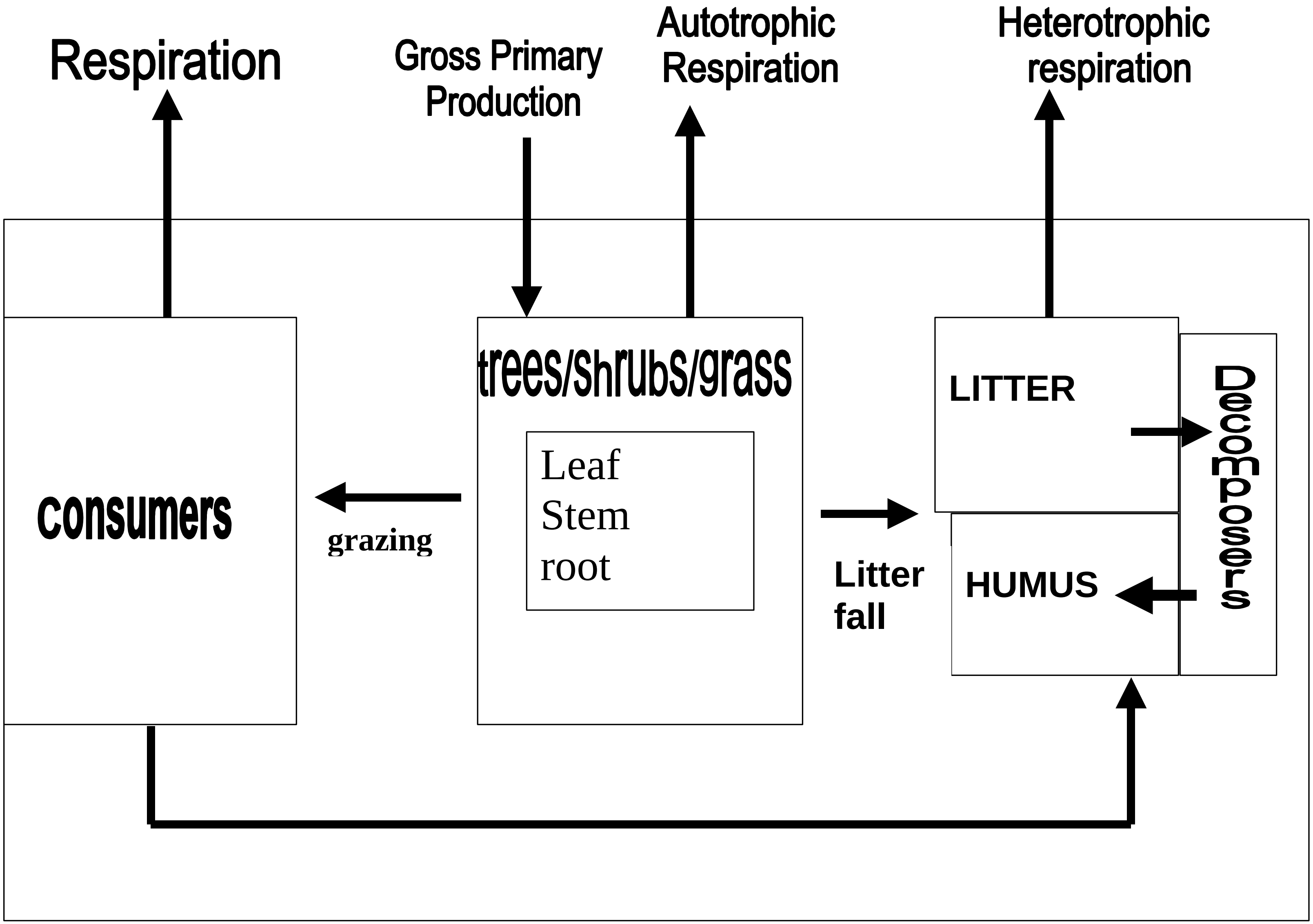
$6CO_2$+$6H_2O$+photons gives $C_6H_{12}O_6$ + $6O_2$

glucose

# Respiration

$C_6H_{12}O_6$+$6O_2$ gives $6CO_2$+$6H_20$ + energy (kJ)






# Flows of carbon

- $CO_2$ fertilisation effects
- Important in some biomes e.g. Dry grasslands, Mediterranean etc
- WUE & Increased Carbon dioxide

# Increasing Carbon Dioxide – direct effects

# $CO_2$ direct effects

*Ainsworth & Long 2005 What have we learned from 15 years of free-air CO2 enrichment (FACE) ? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2.*

*New Phytologist 351-371*

**Table 1** Large-scale free-air $CO_2$ enrichment (FACE) facilities used in this review

| Site | Location | Elevated $[CO_2]$ | Site description reference | Ecosystem | First year of exposure (p |
|---|---|---|---|---|---|
| Aspen FACE FACTS 2 | Rhinelander, WI, USA 45°36′-N, 89°42′-W | Ambient + 200 | Dickson *et al.* (2000) | Aspen forest | 1998 |
| BioCON Cedar Creek | Cedar Creek, MN, USA 45°24′-N, 93°12′-W | 550 | Reich *et al.* (2001) | Natural prairie grassland | 1998 |
| ETH-Z FACE Swiss FACE | Eschikon, Switzerland 47°27′-N, 8°41′-E | 600 | Zanetti *et al.* (1996) | Managed grassland | 1993 |
| FACTS 1 Duke Forest | Orange County, NC, USA 35°58′-N, 70°5′-W | Ambient + 200 | Hendrey *et al.* (1999) | Loblolly pine forest | 1996 |
| Maricopa FACE | Maricopa, AZ, USA 33°4′-N, 111°59′-W | 550* Ambient + 200† | Lewin *et al.* (1994) | Agronomic $C_3$ and $C_4$ crops | 1989 |
| Nevada Desert | Mojave Desert, NV, USA 36°49′-N, 115°55′-W | 550 | Jordan *et al.* (1999) | Desert ecosystem | 1997 |
| Oak Ridge | Roane County, TN, USA 35°54′-N, 84°20′-W | Ambient + 200 | Norby *et al.* (2001) | Sweetgum plantation | 1998 |
| Pasture FACE | Bulls, New Zealand 40°14′-S, 175°16′-E | 475 | Edwards *et al.* (2001) | Managed pasture | 1997 |
| POPFACE | Viterbo, Italy 42°37′-N, 11°80′-E | Ambient + 200 | Miglietta *et al.* (2001) | Poplar plantation | 1999 |
| Rapolano Mid FACE | Chianti Region, Italy 43°25′-N, 11°35′-E | 560–600 | Miglietta *et al.* (1997) | *Vitis vinifera* *Solanum tuberosum* | 1995 |
| Rice FACE | Shizukuishi town, Japan 39°38′-N, 140°57′-E | Ambient + 200 | Okada *et al.* (2001) | *Oryza sativa* | 1998 |
| SoyFACE | Champaign, IL, USA 40°02′-N, 88°14′-W | 550 | | *Glycine max* *Zea mays* | 2000 |

The Brookhaven National Laboratory (BNL) injection method is described in detail by Hendrey *et al.* (1993) and Lewin *et al.* (1994). Pure C injection methods are described by Miglietta *et al.* (2001) and Okada *et al.* (2001). A detailed map of all FACE experiments, and links to individual websites, are given at the Carbon Dioxide Information Analysis Center website: http://cdiac.esd.ornl.gov/programs/FACE/whereisface.html.
*1989–94; †1996–2000.

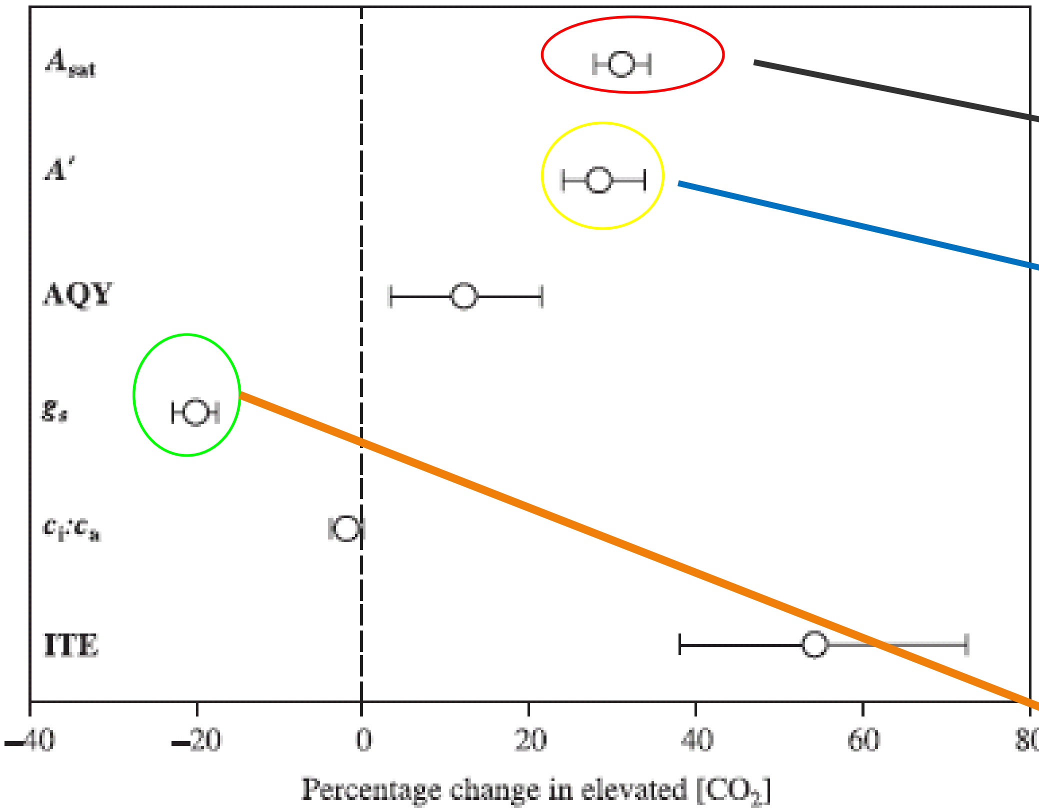



Fig. 1 Mean response to elevated [$CO_2$] (±95% CI) of light-saturated $CO_2$ uptake ($A_{sat}$), diurnal carbon assimilation ($A'$), apparent quantum yield of $CO_2$ uptake (AQY), stomatal conductance ($g_s$), ratio of intercellular ($c_i$) to atmospheric $CO_2$ concentration ($c_a$), and instantaneous transpiration efficiency (ITE). Number of species, FACE experiments and individual observations for each response are given in Appendix 2.

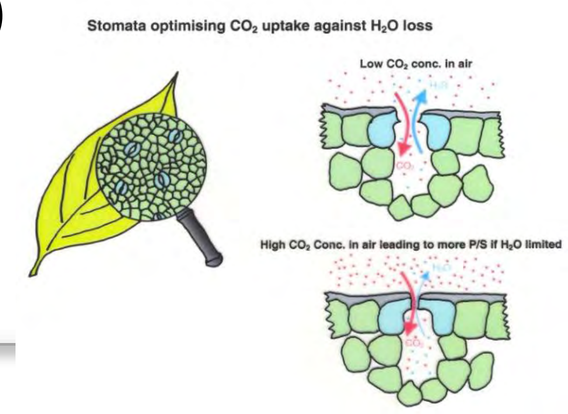
Elevated CO2 increased light saturated photosynthetic rate by 31%

Diurnal Ps carbon assimilation increased by 28%

Across all experiments and all species

-------------------------

Stomatal conductance ($g_s$) Averaged over 40 spp declined by 20% in elevated CO2)




Ainsworth & Long 2005

Ainsworth & Long 2005

# C3 functional groups

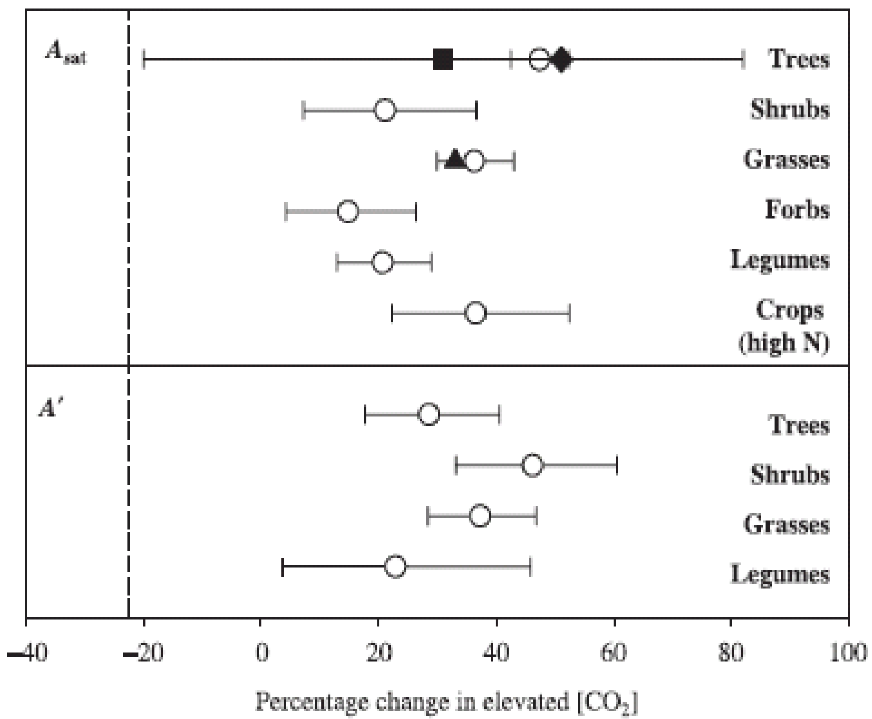



**Fig. 3** Comparative photosynthetic responses of different $C_3$ functional groups to elevated [$CO_2$]. Results from: ○, this meta-analysis; ■, a meta-analysis of tree species (Curtis & Wang, 1998); ◆, a meta-analysis of European tree species (Medlyn *et al.*, 2001); ▲, a meta-analysis of $C_3$ grasses (Wand *et al.*, 1999). Number of species, FACE experiments and individual observations for each response in our meta-analysis are given in Appendix 2.

Trees more responsive than grass, forbs, legumes and crops

NB however FACE trees are young and rapidly growing trees

Mature trees ?

Ainsworth & Long 2005

# Acclimation responses – overall low

To maintain a balance in N and other resources allocated to Ps reactions species acclimate to elevated CO2 – acclimation occurs and its different between different functional groups

Accentuated acclimation under N-limitation

BUT FACE decrease in N leads only to a marginal decrease in response to elevated CO2

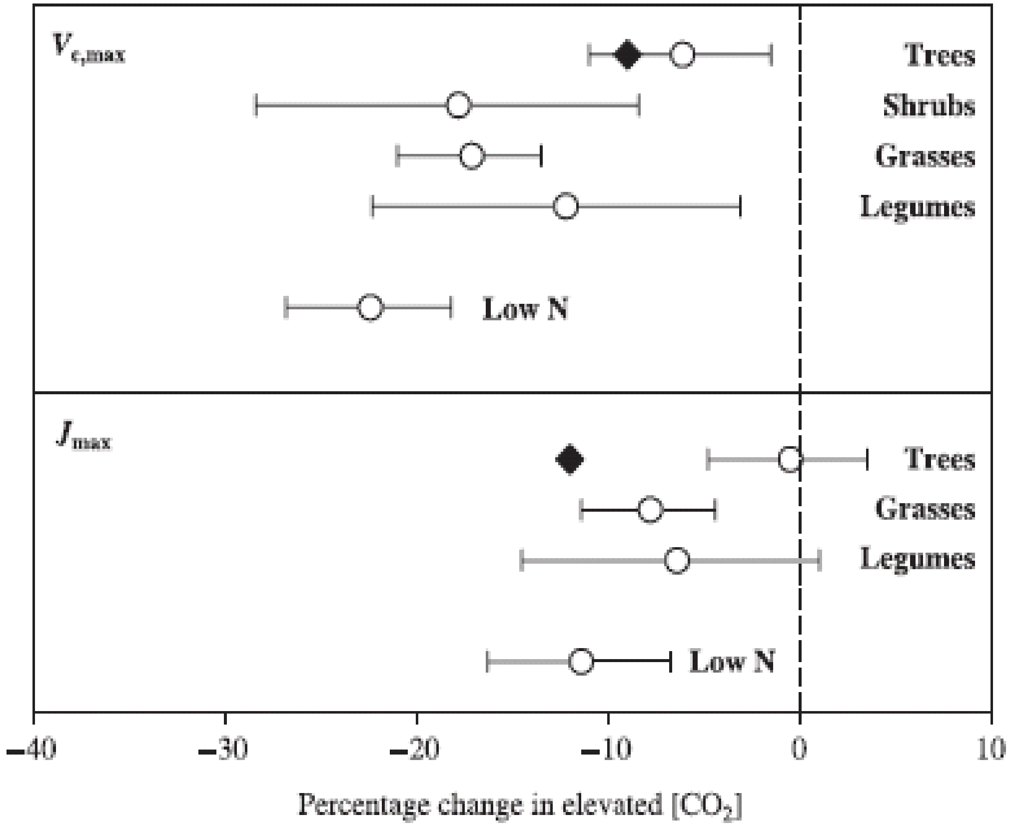
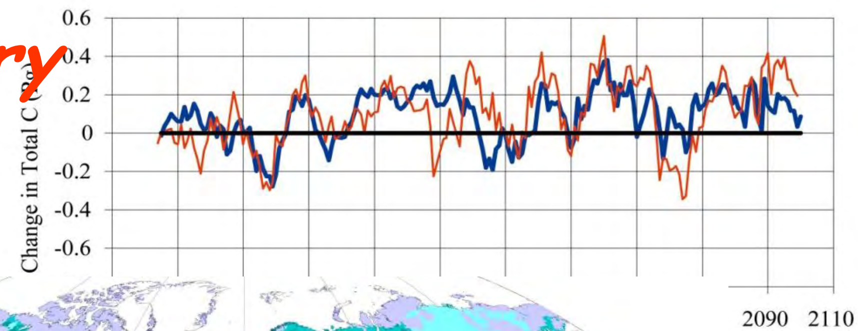


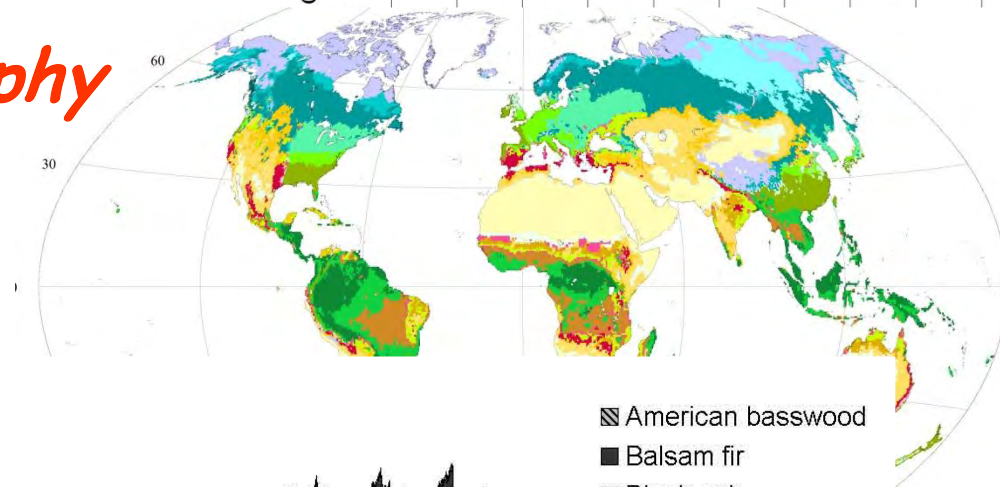

**Fig. 6** Comparative acclimation responses of different $C_3$ functional groups to elevated [$CO_2$]. Results from: ○, this meta-analysis; ◆, a prior meta-analysis of European tree species (Medlyn *et al*., 2001). Number of species, FACE experiments and individual observations for each response are given in Appendix 2.

# Dynamic Ecosystem modelling

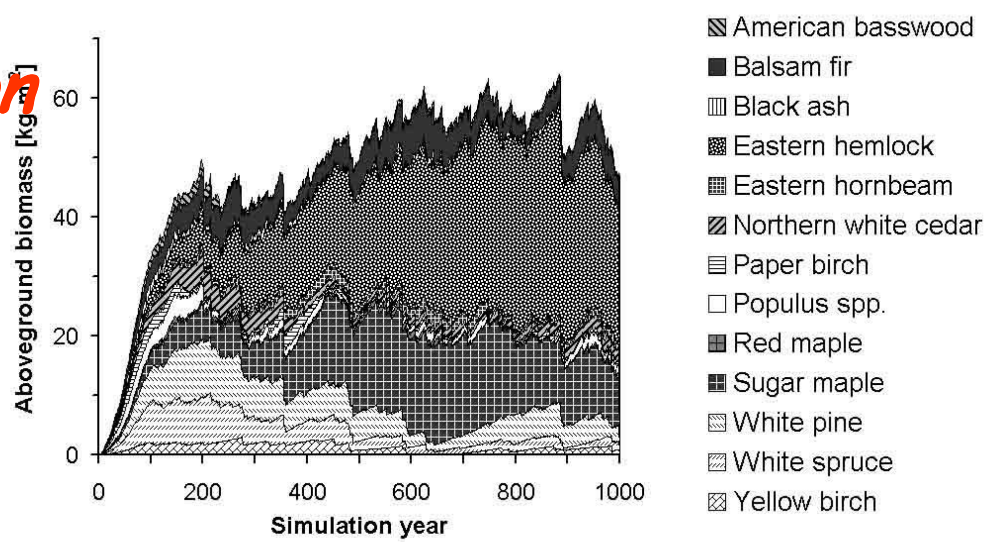
Biogeochemistry




Biogeography




Population Ecology

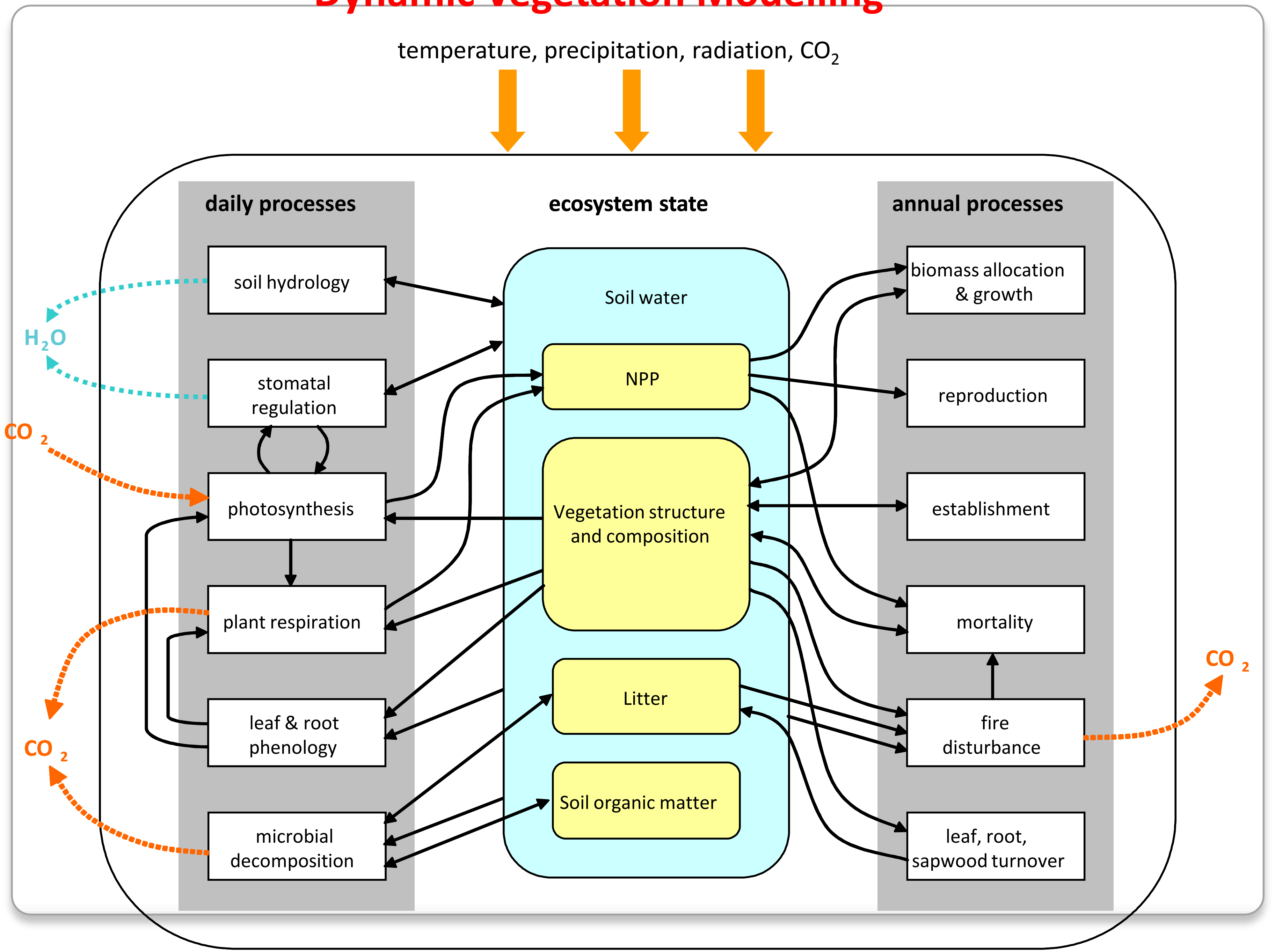



Plant Physiology

Scaling

$$6H_2O + 6CO_2 \xrightarrow{h\upsilon} (CH_2O)_6 + 6O_2$$

# Dynamic Vegetation Modelling



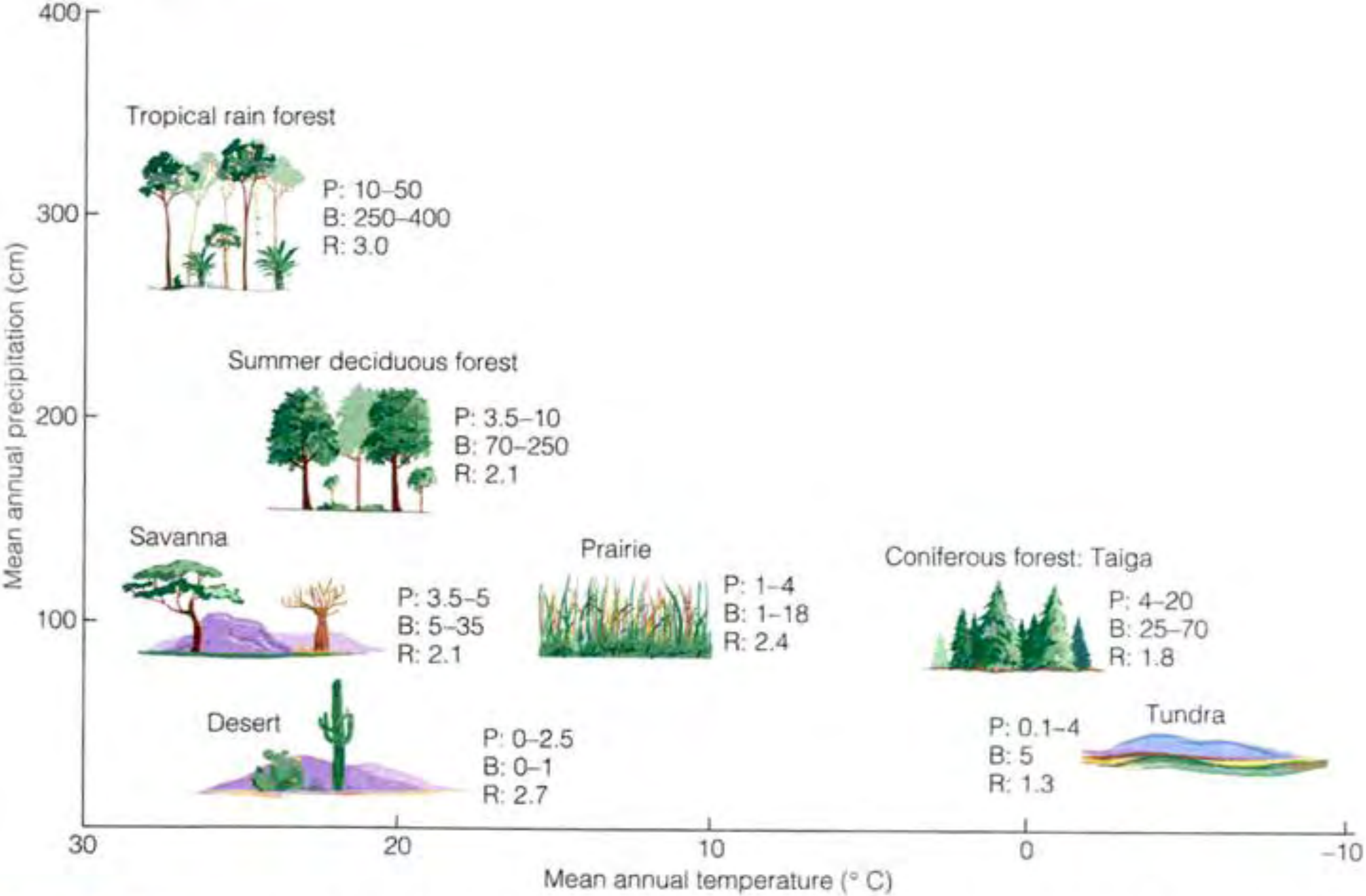
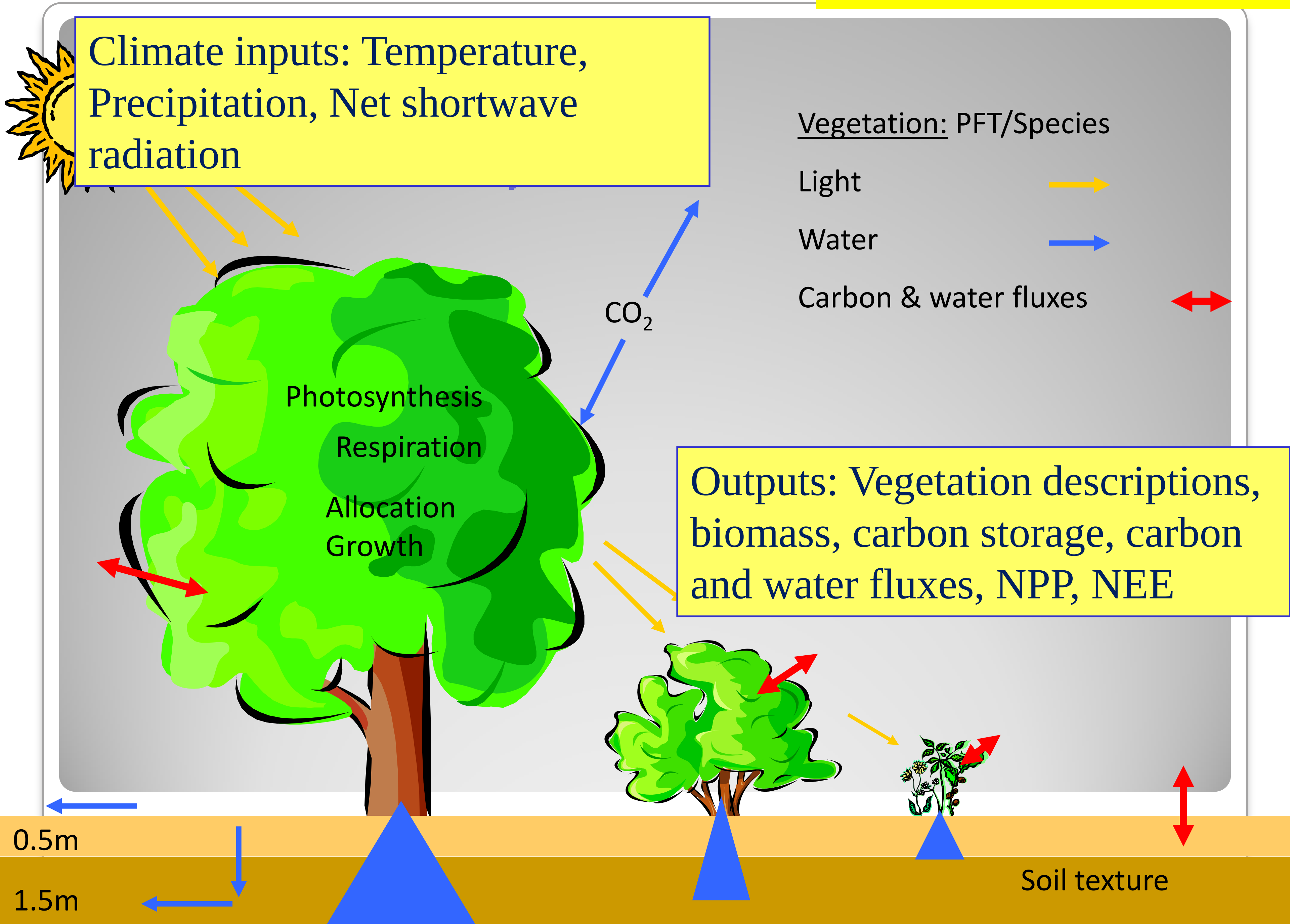



**Figure 23.5** Distribution of primary production, standing biomass, and radiation input relative to rainfall and temperature. P = primary production (tn/ha); B = biomass (tn/ha); R = PAR solar radiation (kcal/m$^2$/yr). (Adapted from J. R. Etherington, *Environmental and Plant Ecology*, 2nd ed., p. 355. New York, John Wiley, 1975. Used by permission.)

Smith, R.L., Smith, T.M., 1998. Elements of Ecology. Addison Wesley Longman, Inc., Menlo Park, California.

# LPJ-GUESS framework



*Sitch et al. GCB 2003 etc*

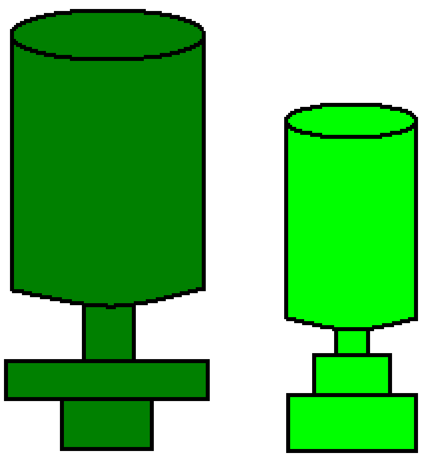
*Global to Continental scale*

*Smith et al. 2001, Hickler et al. 2004 etc etc*

*Patch to landscape to regional scale*

## LPJ-DGVM population mode

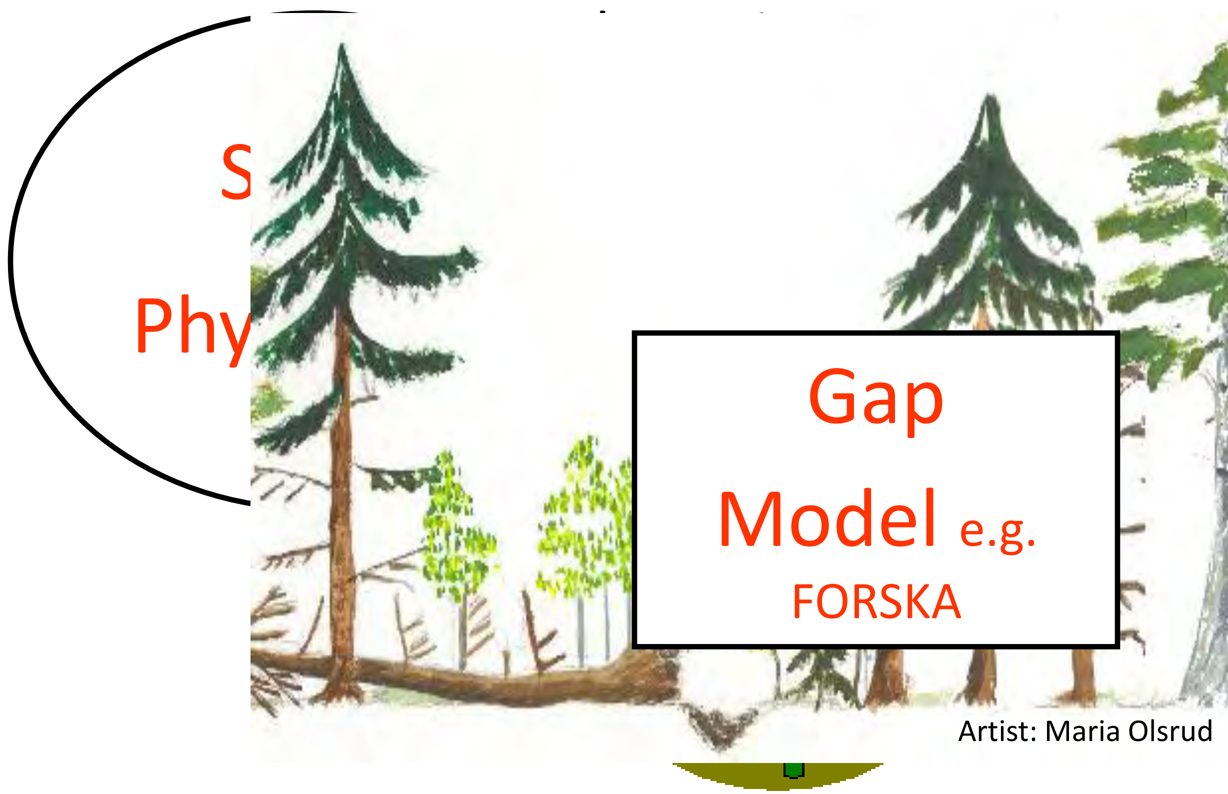
- Average individuals
- No age structure



PFT 1 PFT 2

## GUESS
cohort mode

- Age structure **SPECIES/PFTS**



# LPJ-GUESS DYNAMIC VEGETATION MODEL

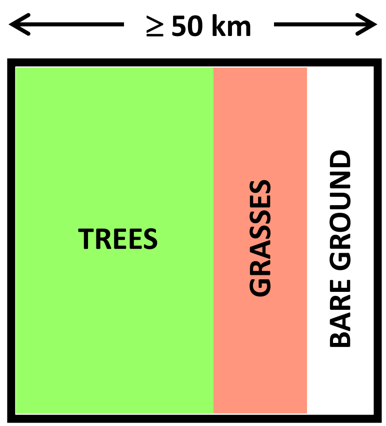
**AREA-BASED MODELS**
**POPULATION MODE (LPJ-DGVM)**

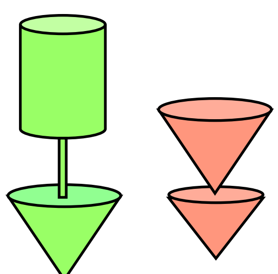
- **computationally efficient**
- **area-averaging assumption valid at regional but not finer scales**
- **simplistic vegetation dynamics**

**INDIVIDUAL-BASED MODELS**
**COHORT MODE (GUESS)**

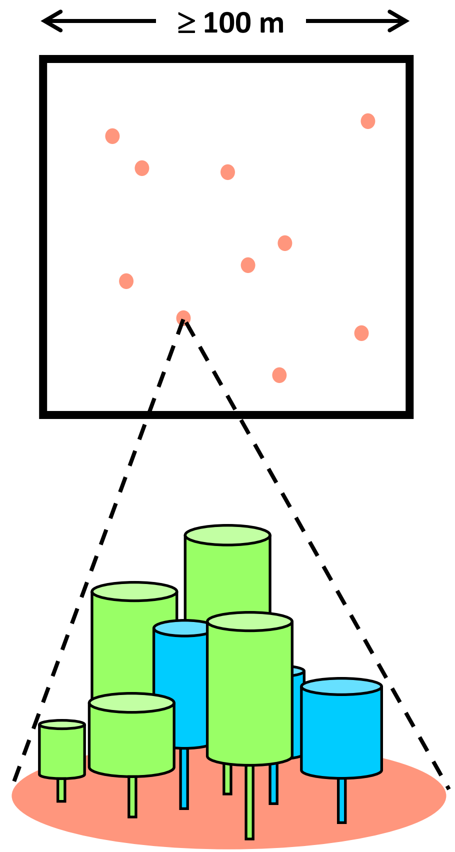
- **computationally demanding**
- **valid at local-landscape scale and upscaleable to region to continental**
- **mechanistic vegetation dynamics**

Plant functional types PFTs



**An average individual for each PFT**
**NO cohorts**




PFTs OR Species

**Cohort or age classes for different PFTs/Species**

# IF NOT SPECIES THEN PLANT FUNCTIONAL TYPES (PFTs)

Physignomy (tree/grass)

Phenology (evergreen/deciduous)

Bioclimatic Limits (cold and heat tolerance)

Physiology (*e.g.* $C_3$/$C_4$ photosynthesis)

*e.g.* ”Temperate summergreen broadleaved tree”

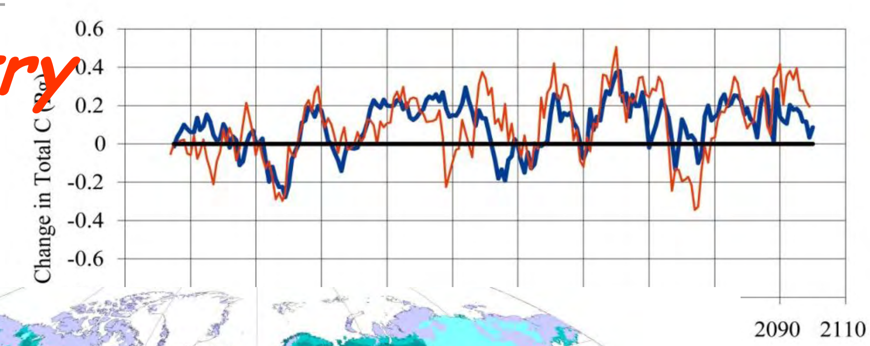
(*e.g. Fagus sylvatica*)

## PLANT FUNCTIONAL TYPES

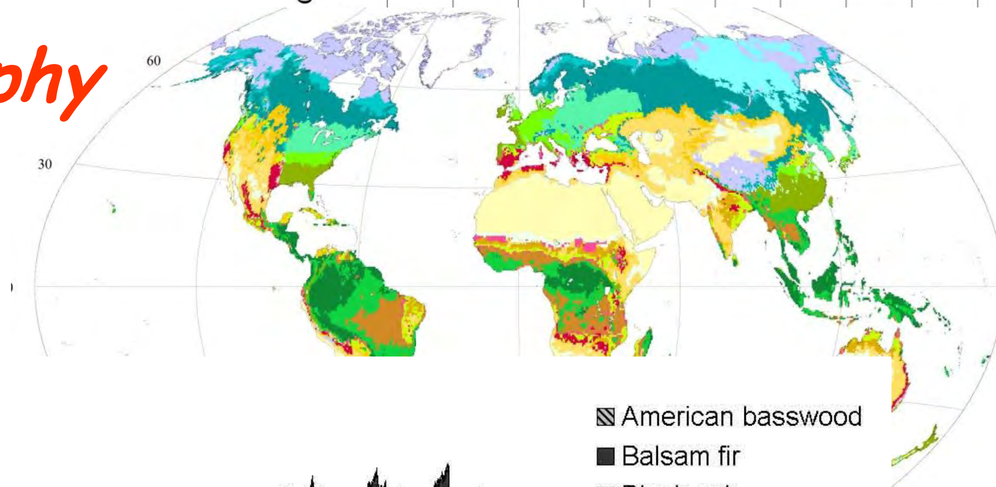
Compete for dominance in the 'carbon market'

| PARAMETER | Needleleaved evergreen | shade-intolerant broadleaved summergreen | shade-tolerant broadleaved summergreen | grass |
|---|---|---|---|---|
| max establishment rate | | | | |
| light requirement for establishment | | | | |
| leaf phenology class | | | | |
| allocation to stems | | | | |
| fraction of roots in upper/lower soil layer | | | | |

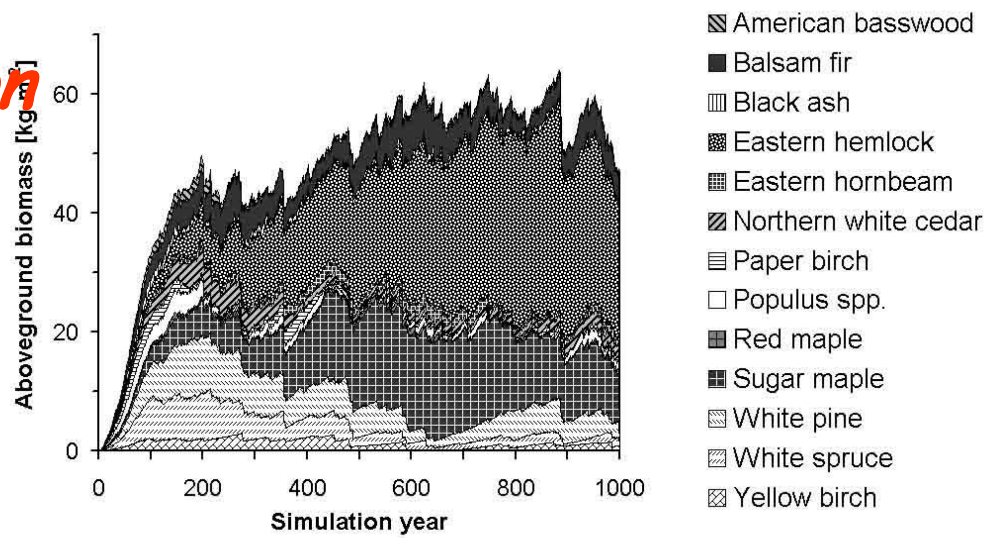
Biogeochemistry




Biogeography




Population Ecology




Plant Physiology

$$6H_2O + 6CO_2 \xrightarrow{h\,\upsilon} (CH_2O)_6 + 6O_2$$

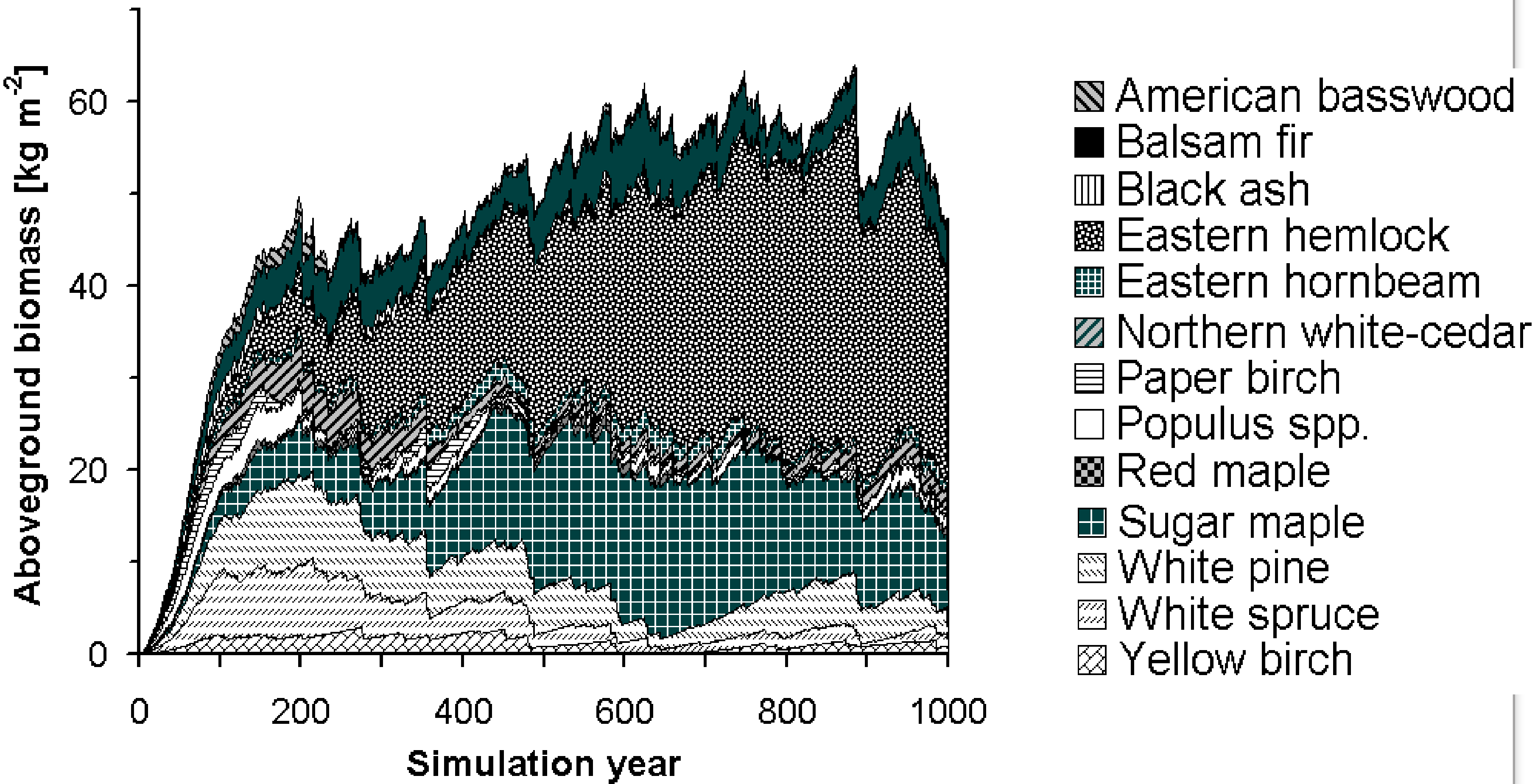
Scaling

# Vegetation dynamics

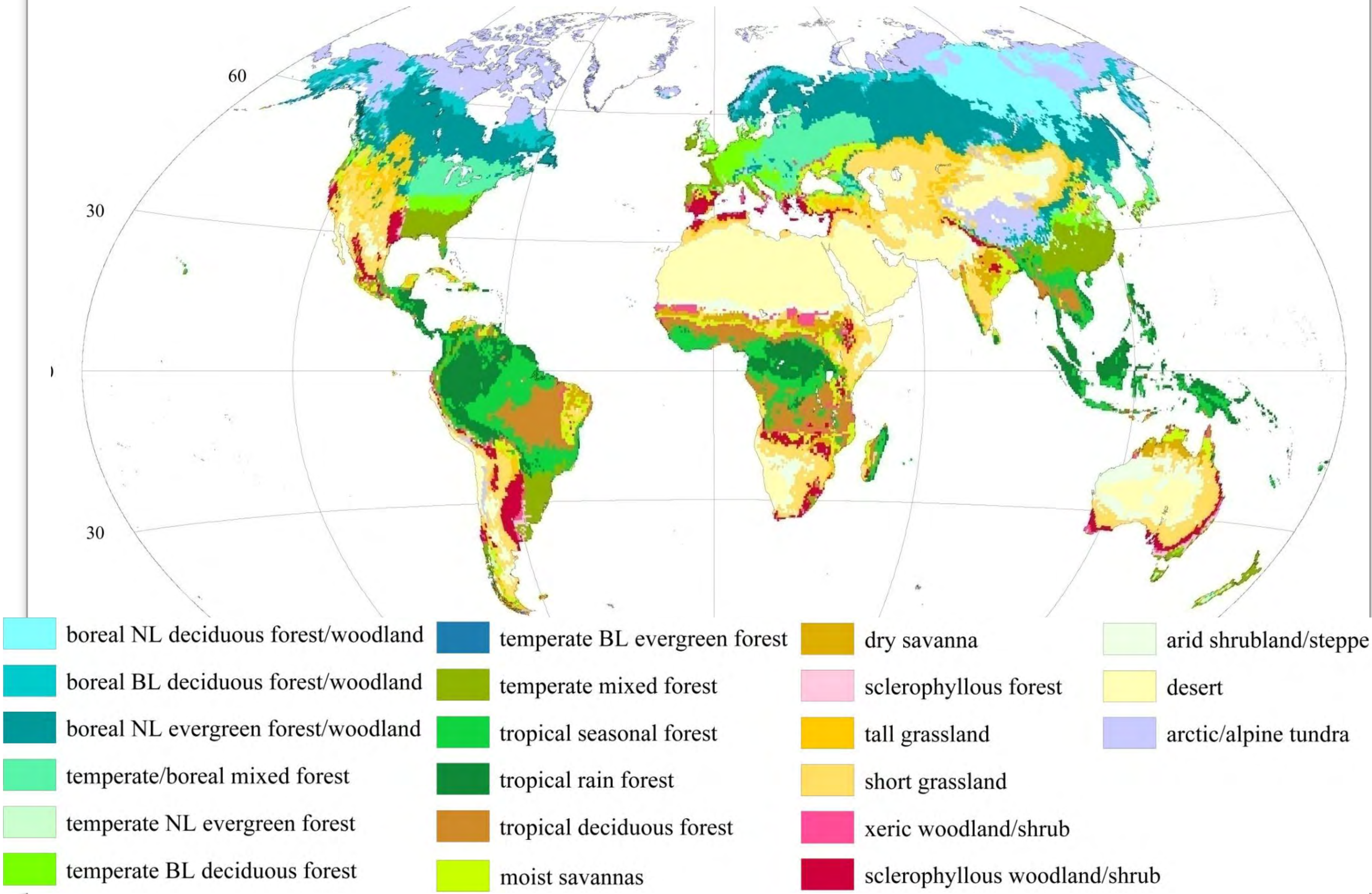
herbaceous vegetation light-demanding pioneer trees initial cohort of shade-tolerant trees

mixed-species, multi-aged and of shade-tolerant trees regeneration in treefall gap

# Vegetation dynamics

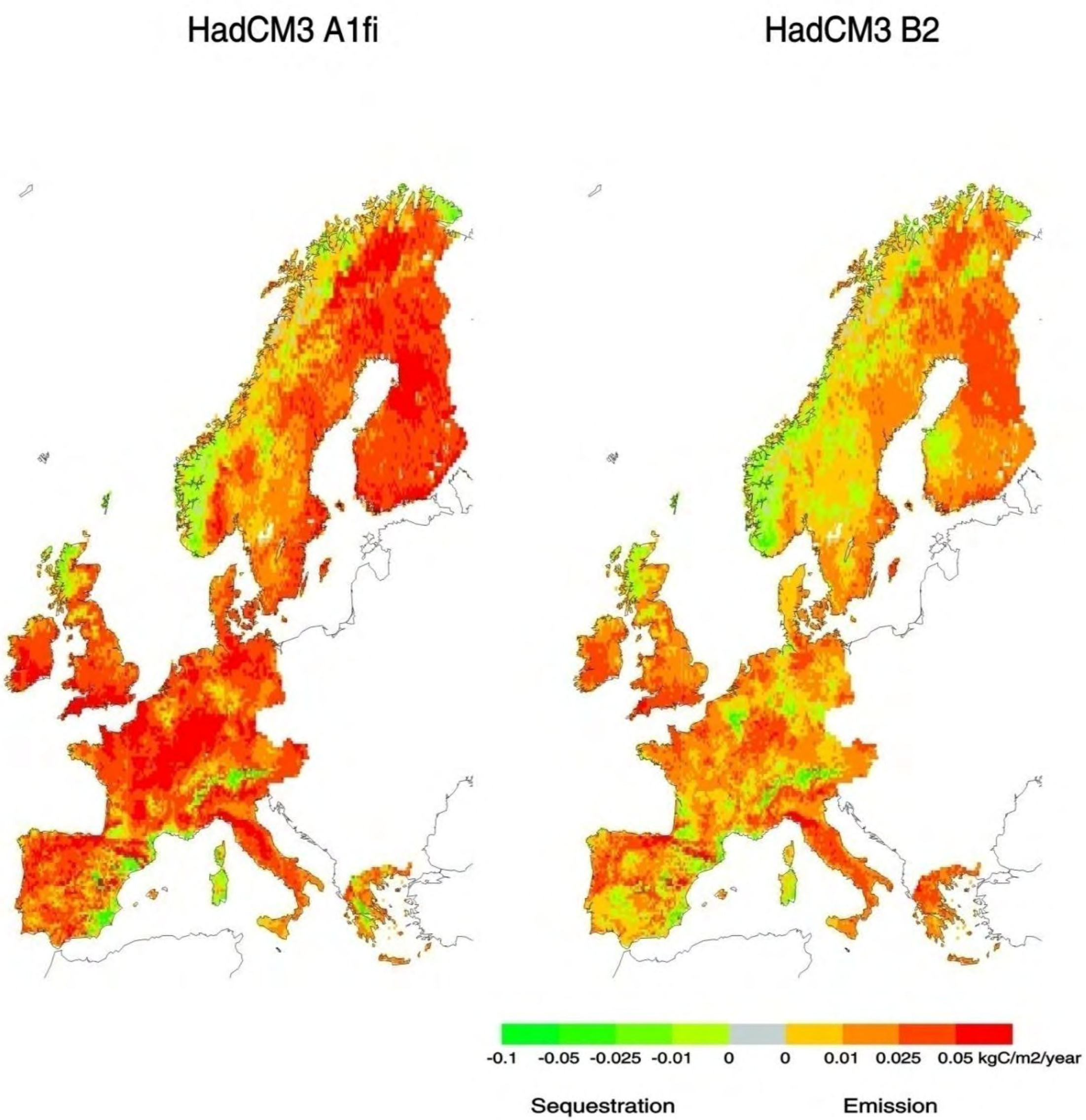


# Biogeography

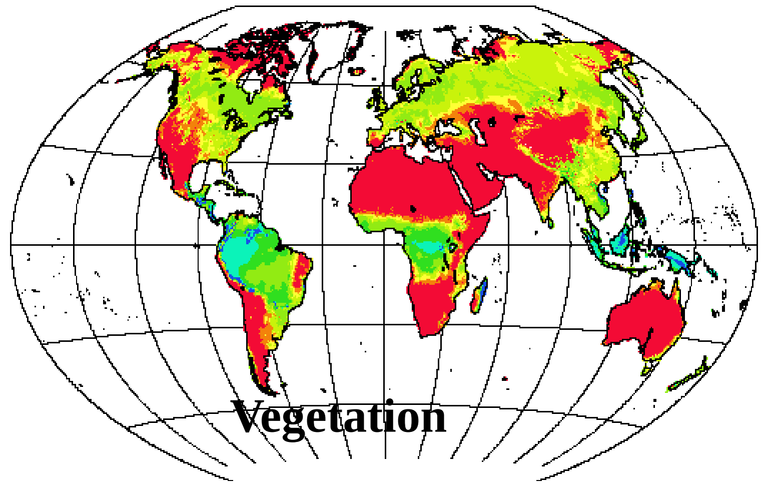



NL = needle-leaved; BL = broadleaved

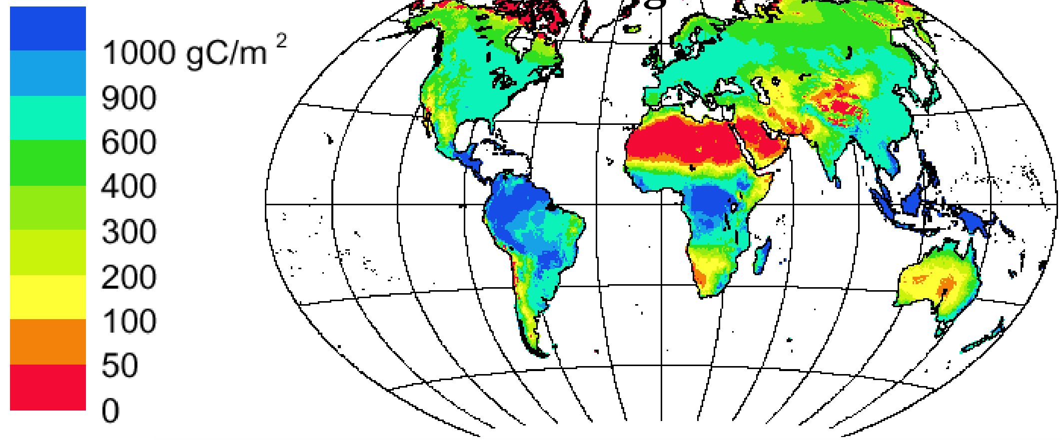
# Biogeochemistry

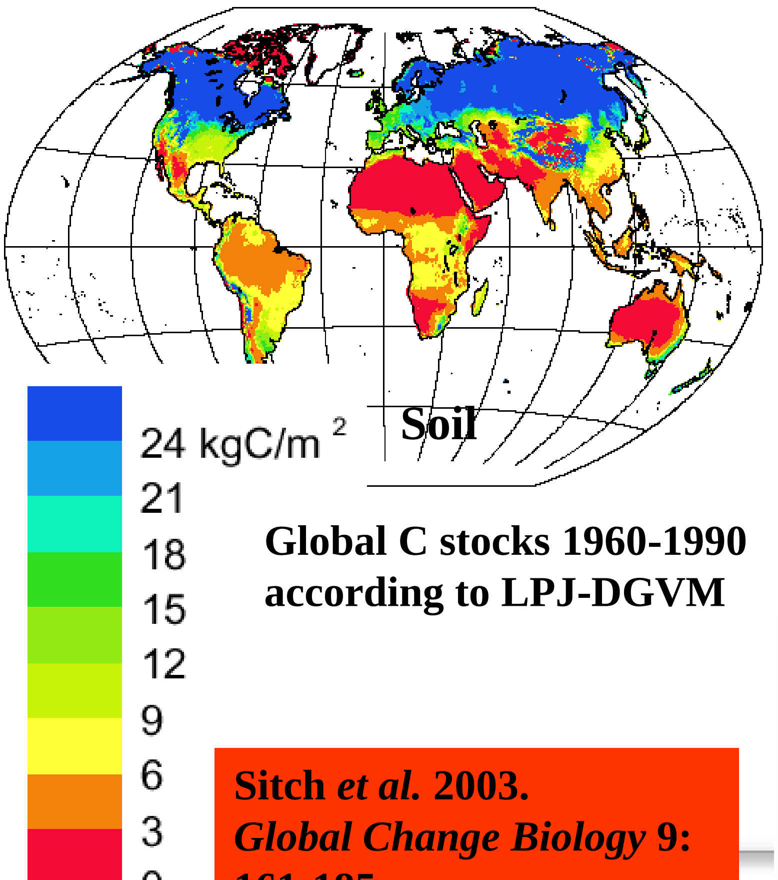


# Applications using an ecosystem model to address impacts of climate change



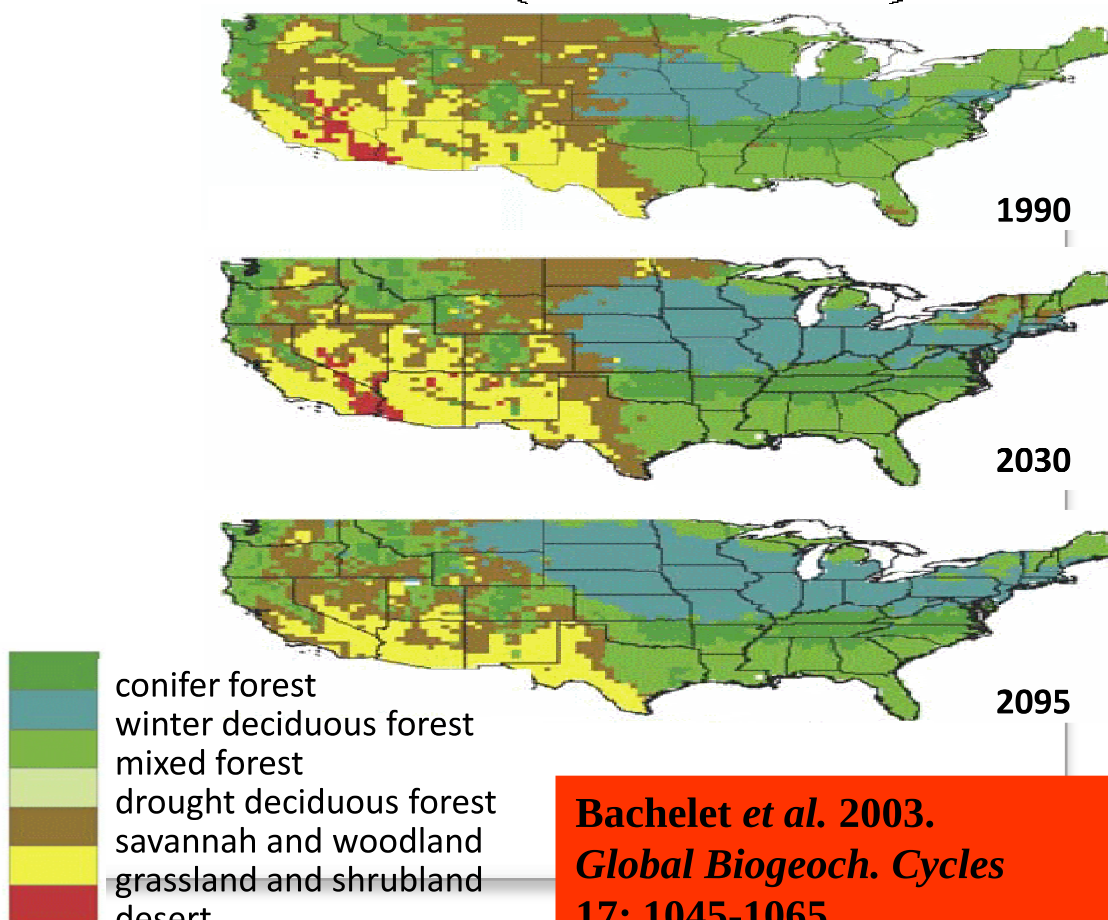

Global NPP 1960-1990 according to LPJ-DGVM




Global C stocks 1960-1990 according to LPJ-DGVM

**Sitch *et al.* 2003.**
***Global Change Biology* 9: 161-185**




**Bachelet *et al.* 2003.**
***Global Biogeoch. Cycles* 17: 1045-1065**

Using LPJ-GUESS (POPULATION MODE) & Regional Climate Model output driven by data from one or more GCMs.

Land use was simulated using observed present day land use (CORINE/PELCOM)

*Morales et al. 2007 Changes in European ecosystem productivity and carbon balance driven by regional climate model output.* ***Global Change Biology 13: 108-122***

RCMs: SMHI Rossby centre – RCAO,

DMI – HIRHAM RCM, GKSS – CLM

UK Hadley HadRM3H, MPI – REMO

GCMs Hadley –HadAM3H & ECHAM4/OPYC3

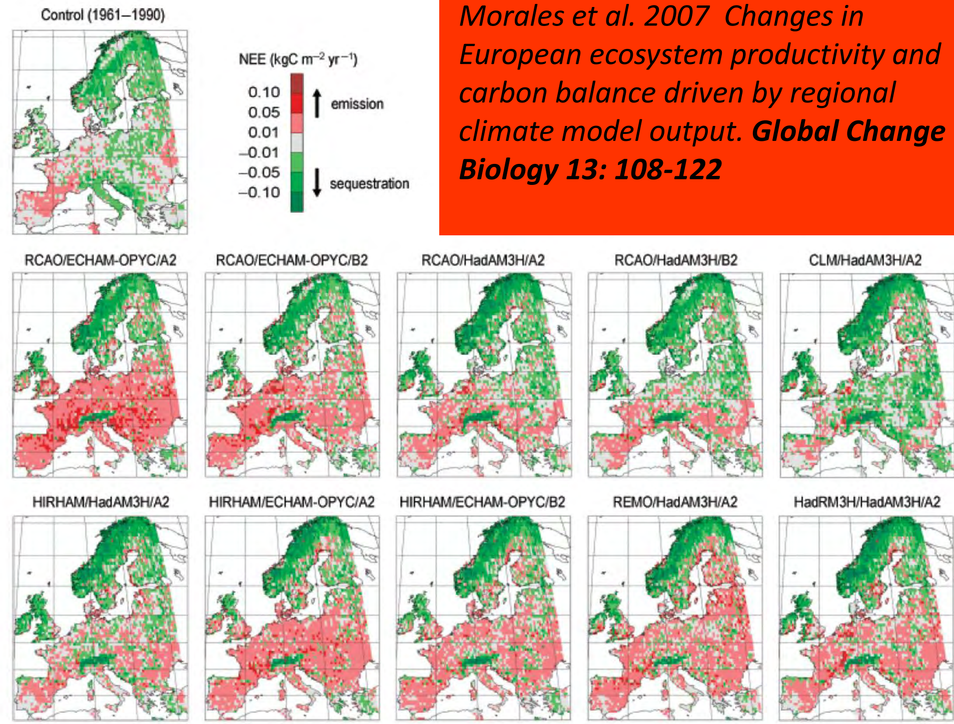



**Fig. 5** Net ecosystem carbon exchange (NEE) for the scenario period 2071–2100 simulated by LPJ-GUESS under the 10 regional climate model-generated climate scenarios. Results for the control period 1961–1990 are included for comparison. Negative values represent an uptake of carbon by terrestrial ecosystems.

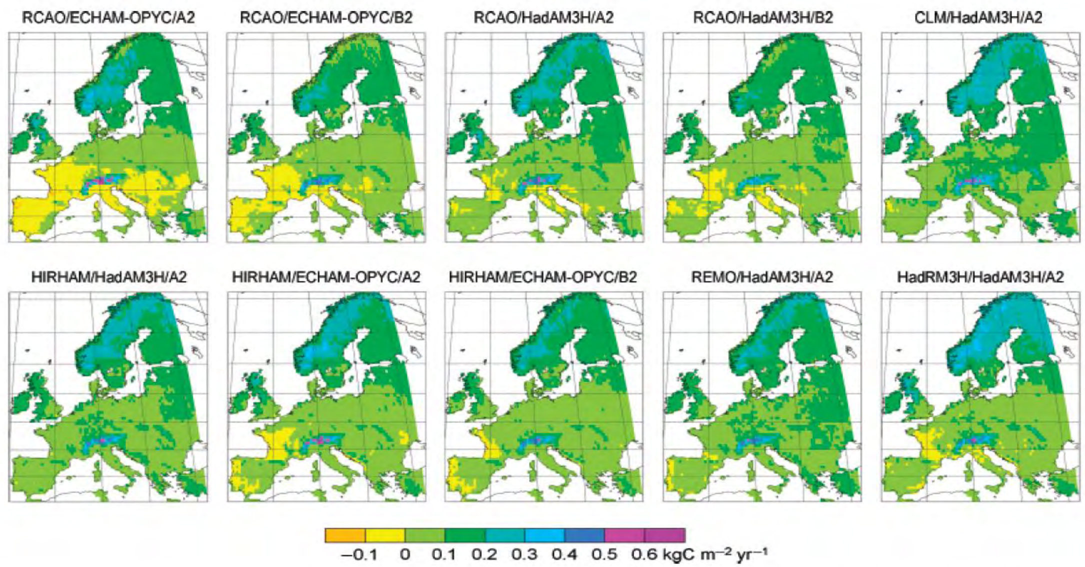



**Fig. 3** Net primary production changes by 2071–2100 compared with the control period (1961–1990) simulated by LPJ-GUESS under the 10 regional climate model-generated climate scenarios.

Different impacts between north and south Europe

S. Europe growing season water deficits

N Europe – changes in growing season length

Choice of GCM boundary conditions more important than RCM

Between 1991-2100 modelled impacts on carbon balance range from a sink of 11.6GtC to a source of 3.3 Gtc

The Sahel has become greener

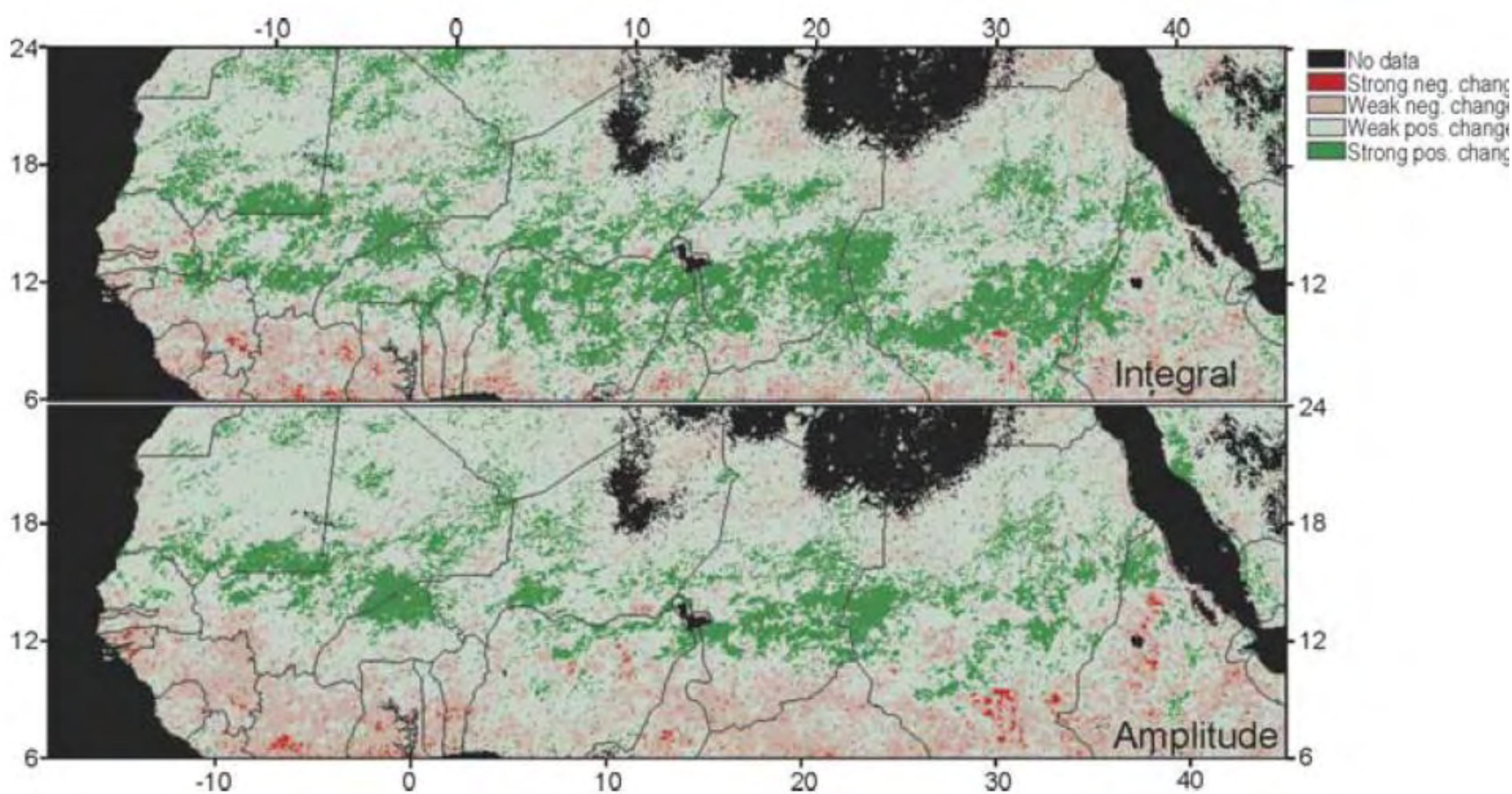



**Figure 4.** Trend in integrated NDVI (top) and amplitude (bottom) 1982–1999.

Eklundh and Olsson et al. 2003

**Precipitation controls Sahel greening trend. Hickler et al. 2005**

***Geophysical Research letters 32 L21415***

Using:

NDVI dataset from NOAA/AVHRR – peak NDVI values for growing seasons 1982-1988

LPJ-DGVM driven by monthly data (CRU05)

Factorial experiments changing different driving variables – temp, precip, sunshine, CO2

**Results – model produced overall trends in greenness – Fig 1**

**Precipitation almost alone explains changes (CO2 minor) – Fig 3**

**Therefore anthropogenic forcing not required to explain greening trend**

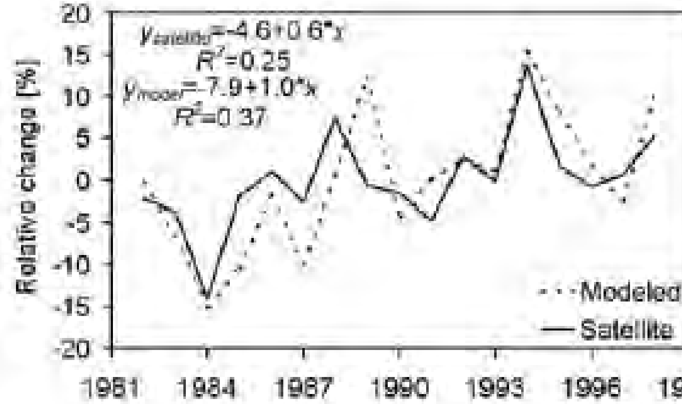



**Figure 1.** Relative changes (compared to the 1982–1998 mean) of satellite-derived peak-season NDVI and modeled peak-season leaf area index (LAI), averaged over the Sahel.

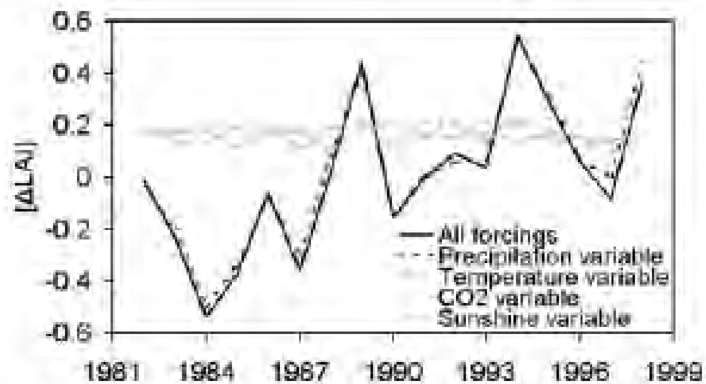
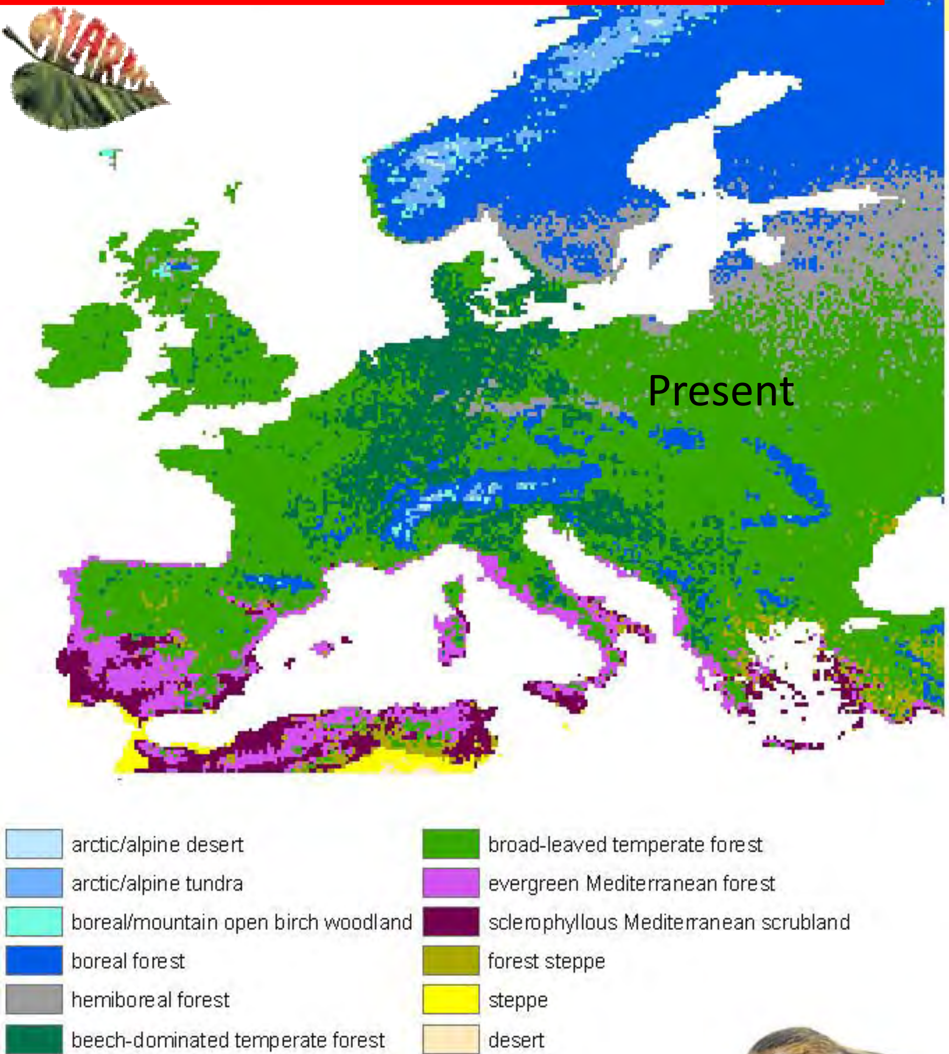
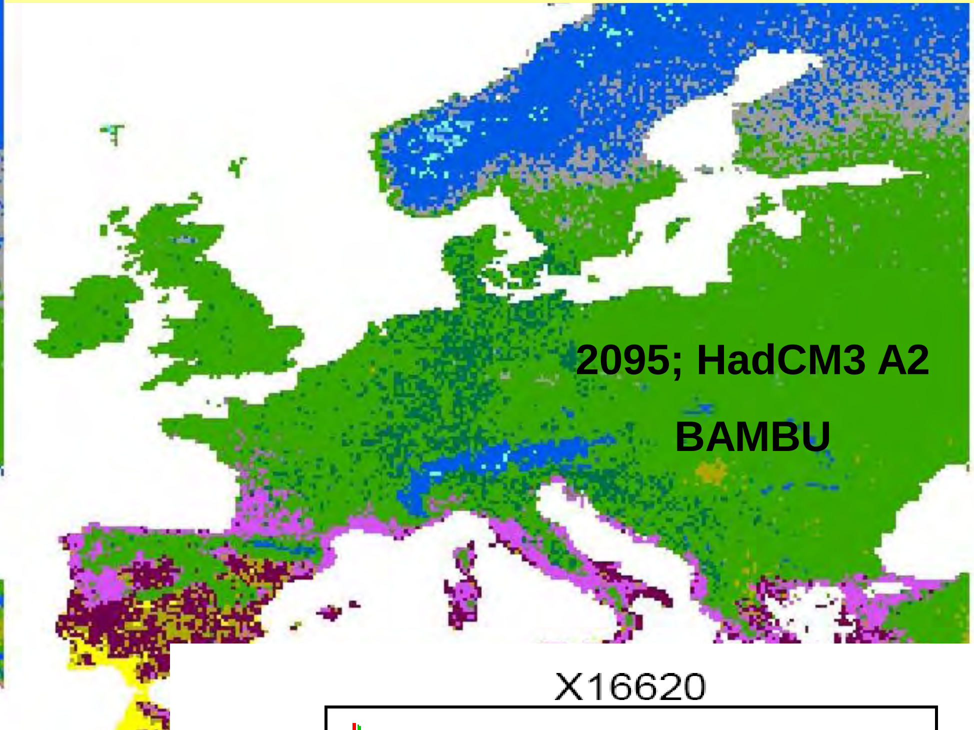


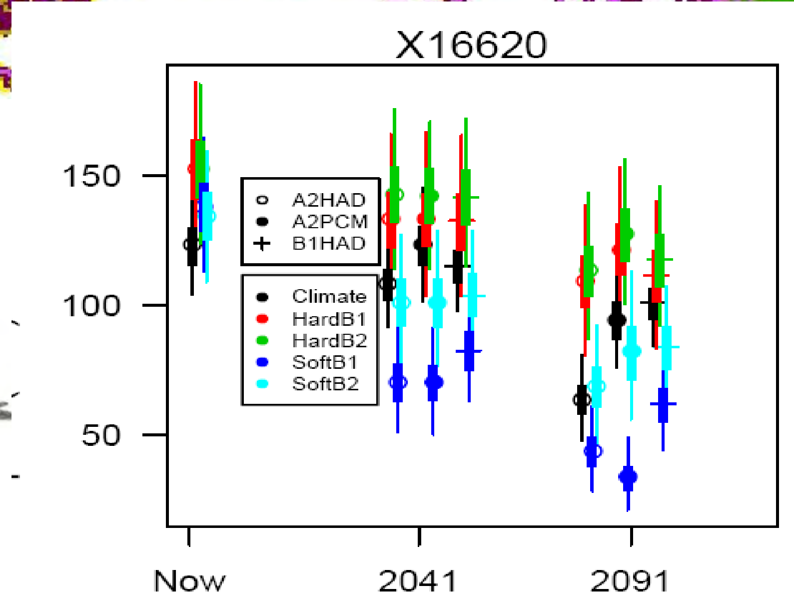

**Figure 3.** Modeled LAI anomalies, relative to the mean value for 1982–1998, averaged over the Sahel region. In separate simulations, the model was run either with variation in all climatic inputs (all forcings, i.e., changing temperature, precipitation, relative sunshine and atmospheric $CO_2$ concentration), or varying only one input variable at a time, keeping the remaining input variables constant at 1982–1998 averages.

# Present and future bird envelopes, and changing habitats

## Vegetation/habitats (PNV) simulated by dynamic ecosystem LPJ-GUESS (species level) – time series



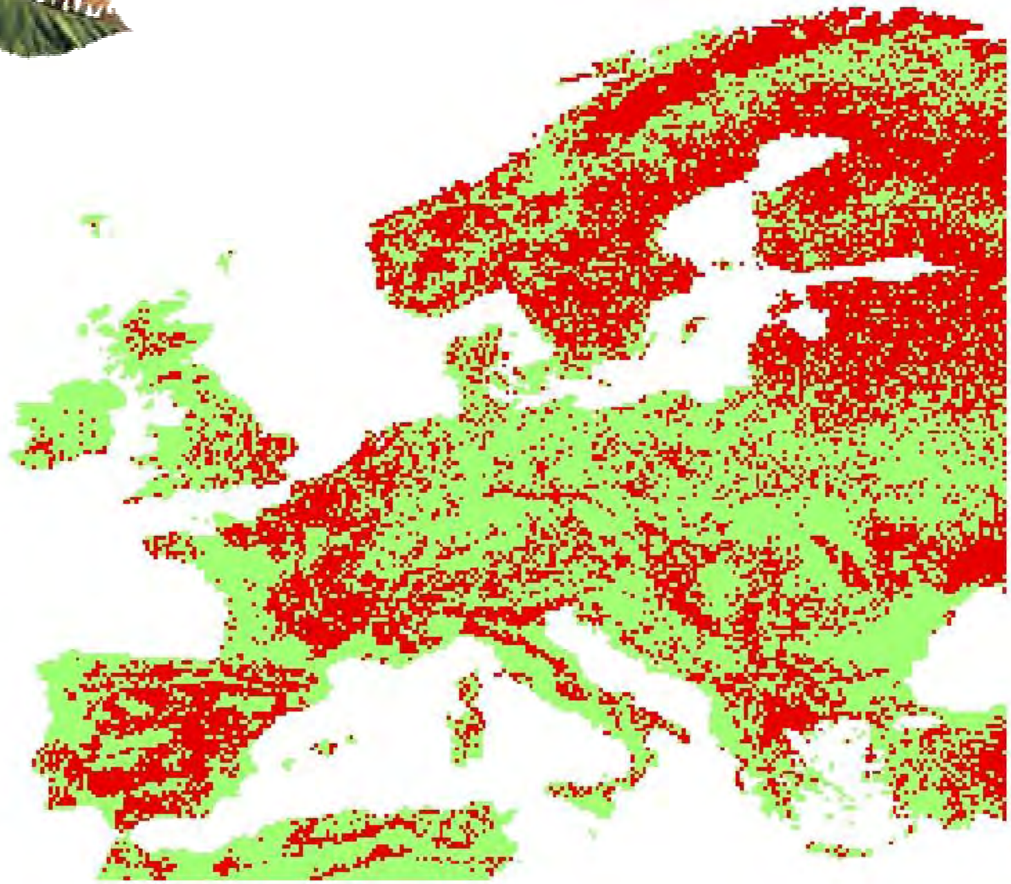



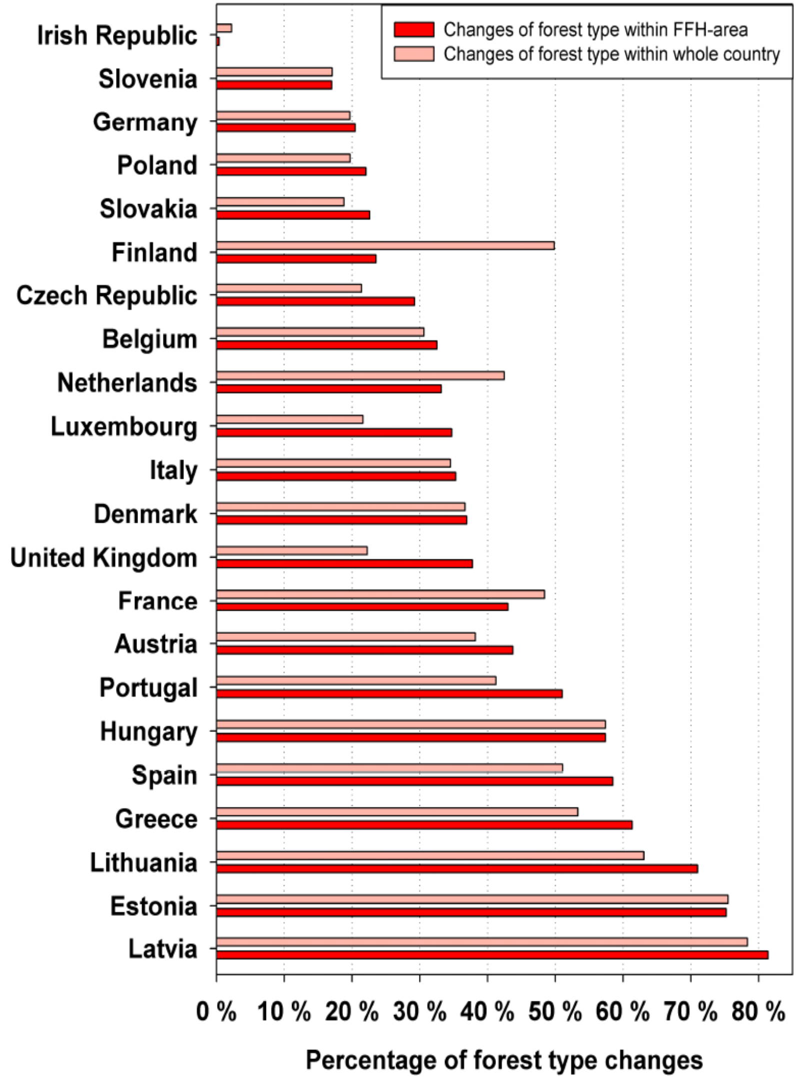

Twite

York, Lund and RSPB

Anderson et al. in prep

# Predicted future vegetation changes in Europe. Grid cells in red change under A2.

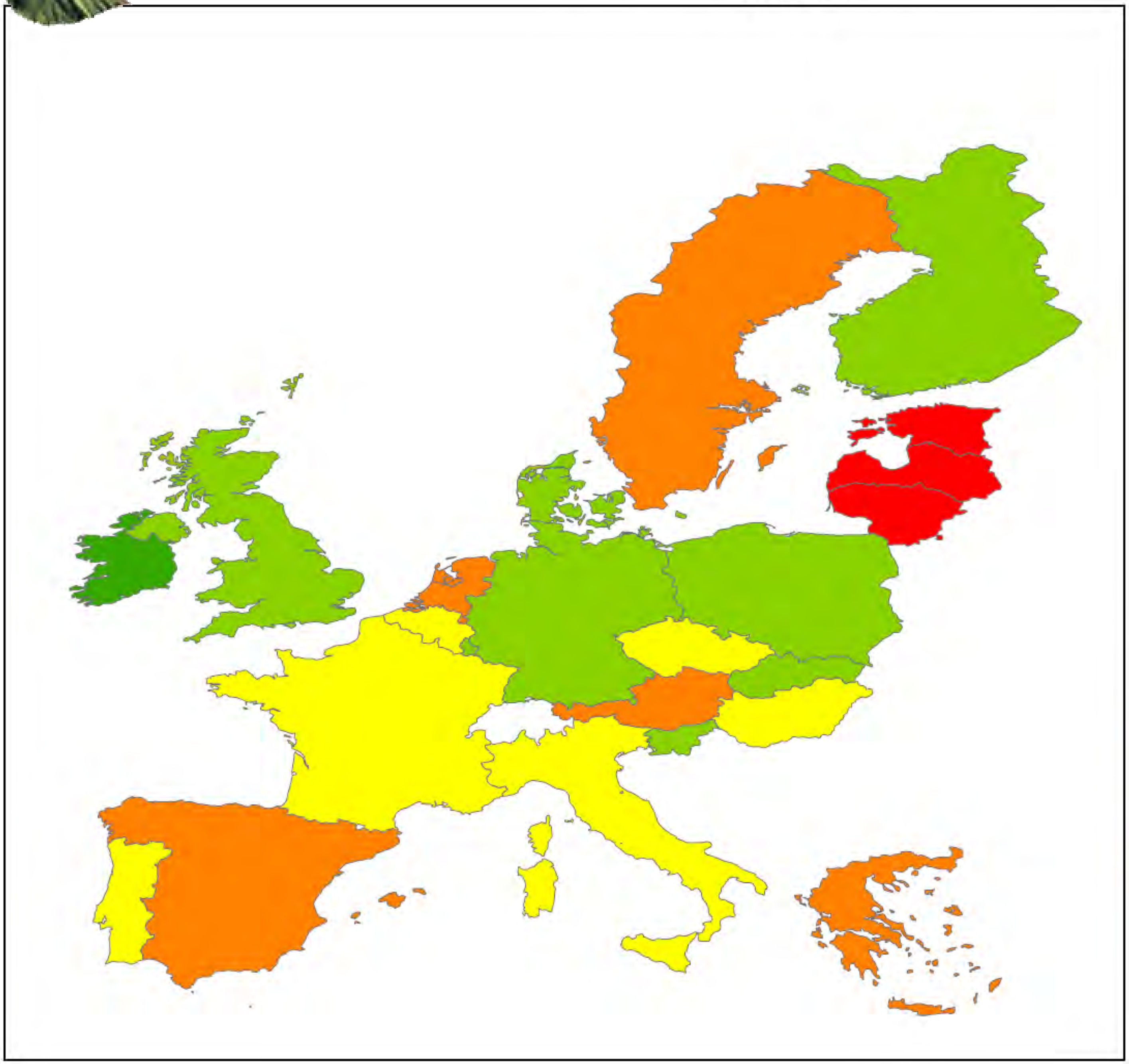





Hickler, T. Miller, P., Smith, B., Sykes, M.T. (Lund), Vohland, K. (Potsdam), Kuhn I., (UFZ), Gisecke (Lpool), Franzek, S., Carter, T. (SYKE)

Percentage of forest type changes by country

# Vegetation change in the ffh areas HAD B1




Vegetation Changes in NATURA 2000 sites (using area of change in each country)

SEDG (B1) climate only scenario

# Exporting the ecological effects of climate change

## – developed and developing countries will suffer the consequences of climate change, but differ in both their responsibility and how badly it will affect their ecosystems

Chris. D. Thomas, Ralf Ohlemüller, Barbara Anderson, Thomas Hickler, Paula A. Miller, Martin T. Sykes & John W. Williams 2008
EMBO reports vol 9 Special issue 51-58

EMBO reports

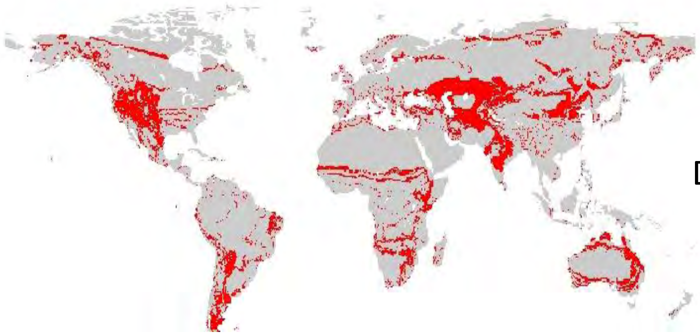
science & society

Used LPJ-DGVM in a moderate warming scenario (B1) to model the changes in Biomes between 1931-1960 “1945” and 2041-2050 “2045”

# The global distribution of risk by 2050

## risk = changes to natural systems

### 1. Biome change yes (red)/no (grey)



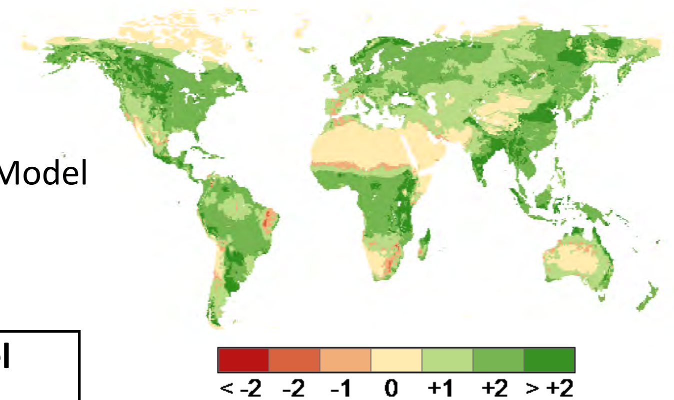
LPJ-GUESS (Lund)

Dynamic Global Vegetation Model

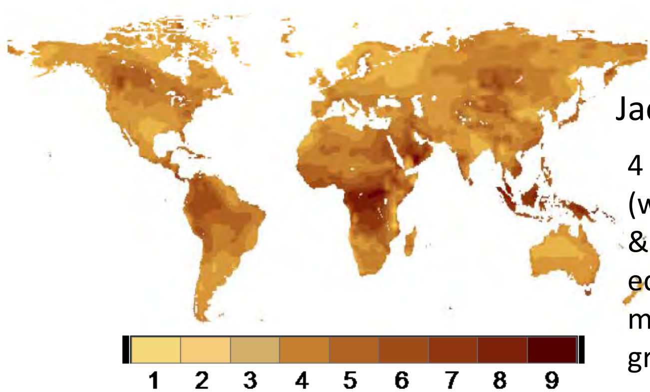
**HadCM3 climate model**

**B1 emission scenario**

### 2. Change in woody LAI



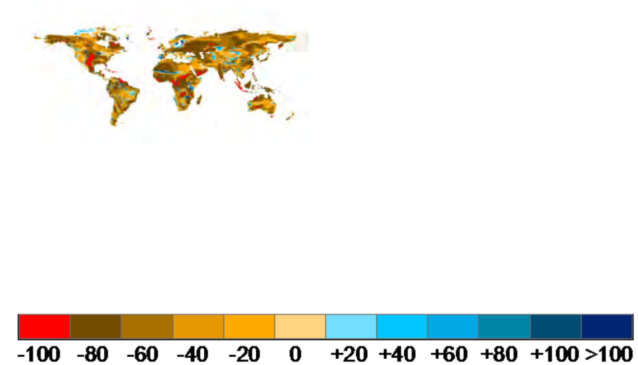

### 3. Climate outside recent range 1931-1960



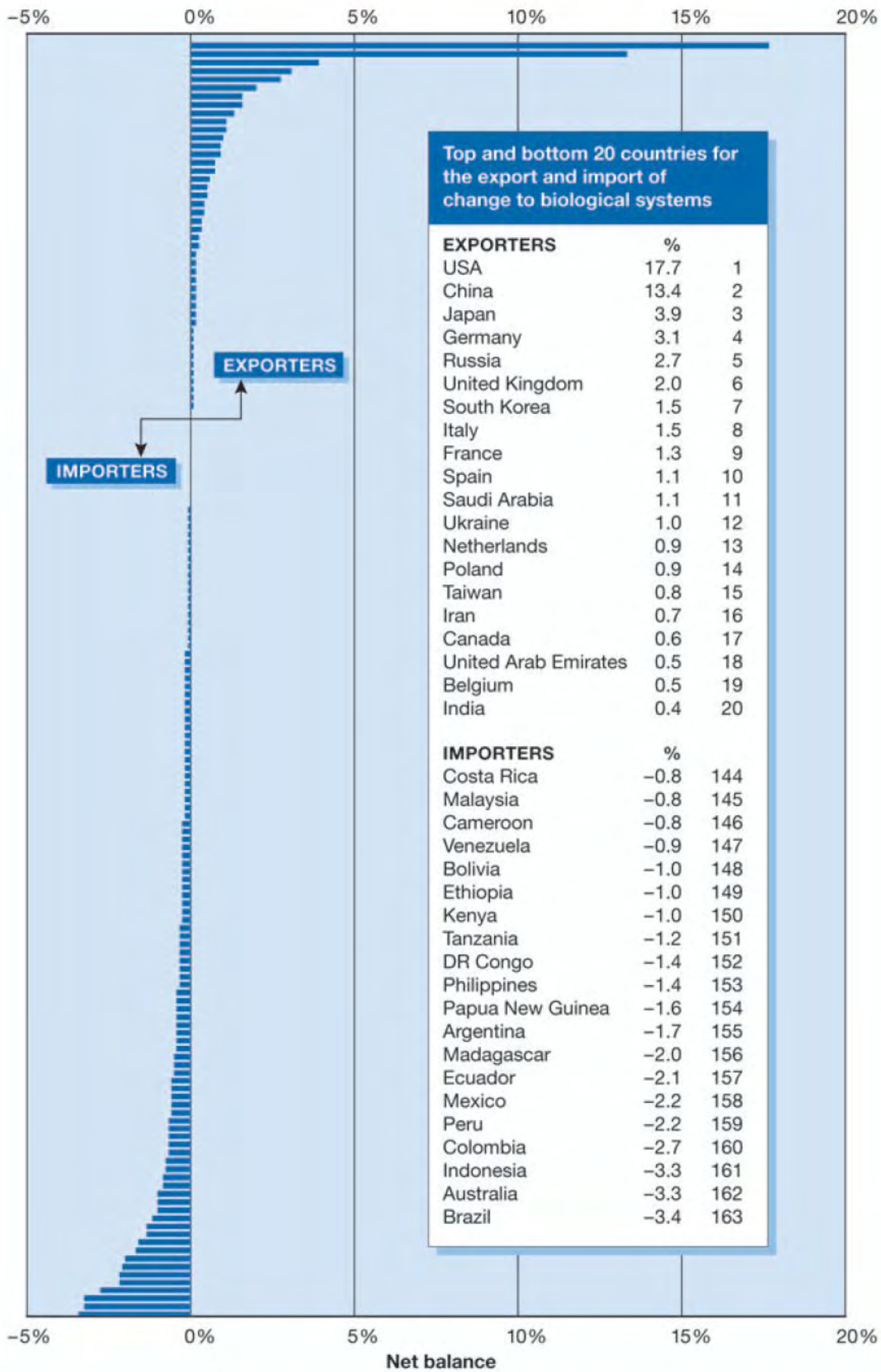

Jack Williams (US)

4 climate variables (winter & summer temp & precip). Weighted equally to produce a measure of change – greatest change in tropics

### 4. Change in analogous area




Distribution of shrinking (brown/red) and expanding (blue)




| EXPORTERS | % | |
|---|---|---|
| USA | 17.7 | 1 |
| China | 13.4 | 2 |
| Japan | 3.9 | 3 |
| Germany | 3.1 | 4 |
| Russia | 2.7 | 5 |
| United Kingdom | 2.0 | 6 |
| South Korea | 1.5 | 7 |
| Italy | 1.5 | 8 |
| France | 1.3 | 9 |
| Spain | 1.1 | 10 |
| Saudi Arabia | 1.1 | 11 |
| Ukraine | 1.0 | 12 |
| Netherlands | 0.9 | 13 |
| Poland | 0.9 | 14 |
| Taiwan | 0.8 | 15 |
| Iran | 0.7 | 16 |
| Canada | 0.6 | 17 |
| United Arab Emirates | 0.5 | 18 |
| Belgium | 0.5 | 19 |
| India | 0.4 | 20 |
| **IMPORTERS** | **%** | |
| Costa Rica | −0.8 | 144 |
| Malaysia | −0.8 | 145 |
| Cameroon | −0.8 | 146 |
| Venezuela | −0.9 | 147 |
| Bolivia | −1.0 | 148 |
| Ethiopia | −1.0 | 149 |
| Kenya | −1.0 | 150 |
| Tanzania | −1.2 | 151 |
| DR Congo | −1.4 | 152 |
| Philippines | −1.4 | 153 |
| Papua New Guinea | −1.6 | 154 |
| Argentina | −1.7 | 155 |
| Madagascar | −2.0 | 156 |
| Ecuador | −2.1 | 157 |
| Mexico | −2.2 | 158 |
| Peru | −2.2 | 159 |
| Colombia | −2.7 | 160 |
| Indonesia | −3.3 | 161 |
| Australia | −3.3 | 162 |
| Brazil | −3.4 | 163 |

**Fig 2** | Global distribution of the export and import of projected changes to natural biological systems through fossil fuel-based $CO_2$ emissions. Positive values indicate that a country exports global change to ecosystems through emissions above any change within the country, and negative values indicate that a country would be a net recipient of ecosystem/biodiversity change. Each bar represents one of 163 countries (excluding Antarctica and Greenland, most small island nations and some others that occupied less than 50% of any 0.5° global grid cell, and a few others for which full data were not available)

All significant relationships indicate that climate change will cause more severe alterations in ecological systems in high biodiversity than in low-biodiversity countries

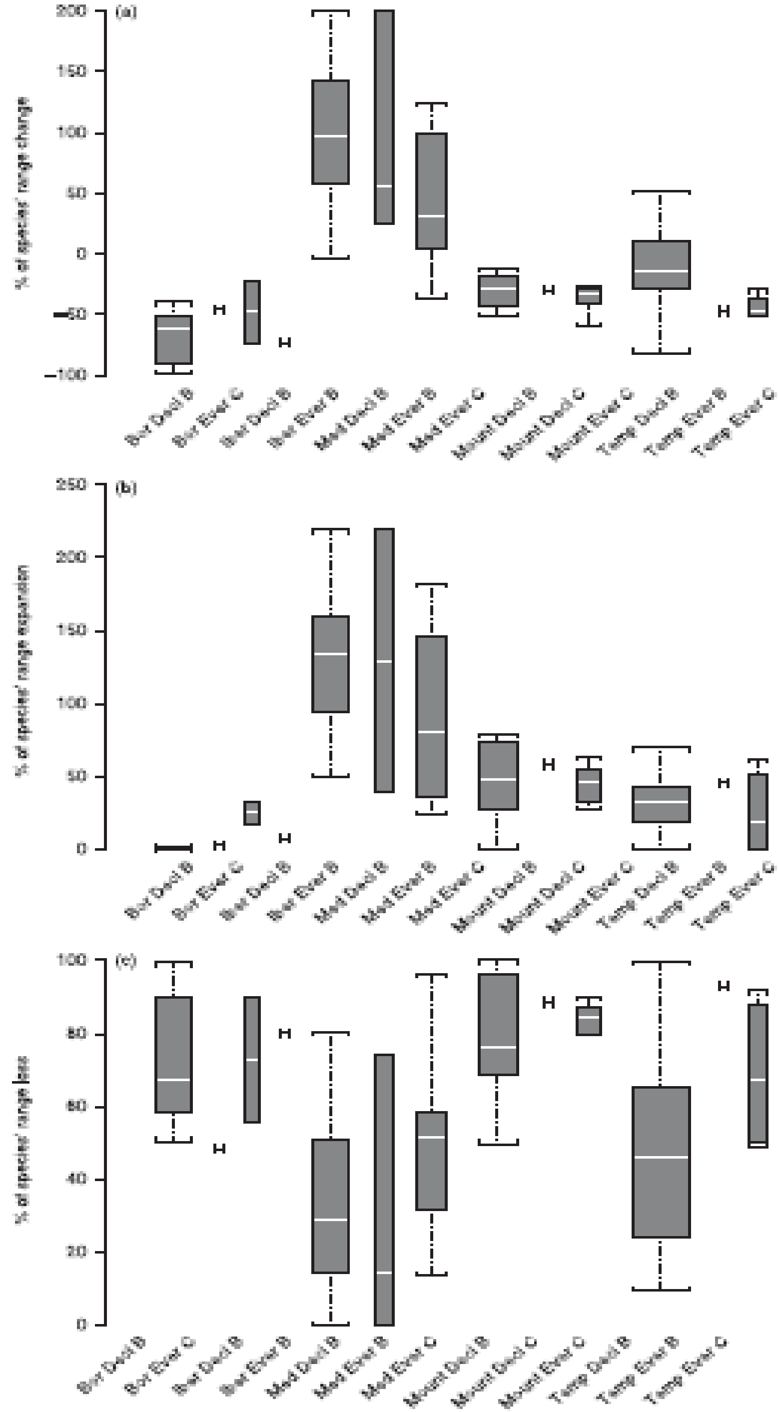
1. Greater changes in future woody cover and climate space in countries with low per capita income and GDP AND lower CO2 emissions.

2. Countries least responsible for climate change and do not have economic means to develop adaptive strategies will experience greatest changes – with severe effects on biodiversity

3. Some countries are exporters of the biological effects of climate change

# Ecosystem and bioclimatic modelling in a global change perspective

Martin T. Sykes
Department Physical Geography & Ecosystems Analysis,
Geobiosphere Science Centre,
Lund University
Sweden
Martin.Sykes@nateko.lu.se




# Using niche-based modelling to assess the impact of climate change on tree functional diversity in Europe

Wilfried Thuiller[1,2,3,4*], Sandra Lavorel[1,4], Martin T. Sykes[5] and Miguel B. Araújo[1,3,6,7]

*Diversity and Distributions, (Diversity Distrib.)* (2006) 12, 49–60

122 trees and tall shrubs using AFE for comparison – then classified into Functional groups (PFTs) and phytogeographic classes e.g. Boreal evergreen coniferous versus mediterranean evergreen coniferous

7 bioclimatic variables = mean annual temperature, mean temperature of coldest month, mean annual precipitation, mean winter precip, mean summer precip, GDD and AET/PET

On a random sample of data for each species GLM, GAM, CTA, ANN models were calibrated and then evaluated against the rest of the data

Simpson's diversity index variation between current and 2080

Functional diversity with and without unlimited migration

Temperate areas lose FD due to loss of broadleaved deciduous and coniferous trees

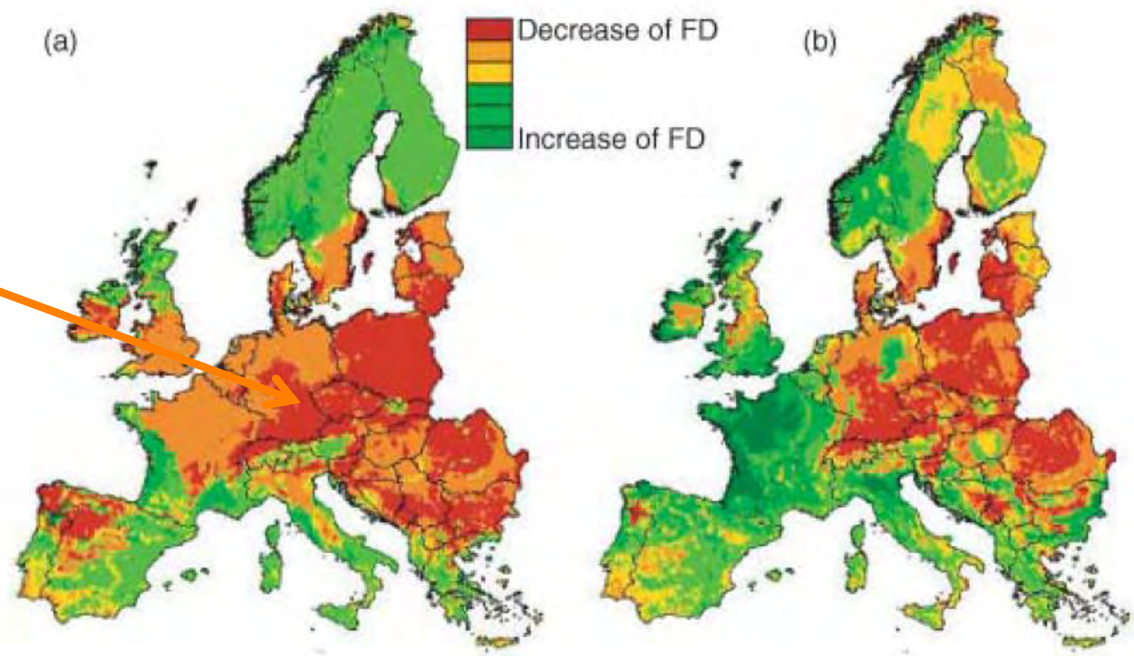



Figure 3 Variability in tree functional diversity under null (a) and unlimited (b) migration assumptions. FD means functional diversity.

No migration

Unlimited migration

# The balance


Biogeophysics group