La modélisation des surfaces continentales en relation avec les changements climatiques

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La modélisation des surfaces continentales en relation avec les changements climatiques

- Why *model* the (terrestrial) biosphere?
- A historical overview
- Data issues
- Critical gaps in understanding
- Intermediate complexity models
- Land use and land use change
- Recent and future applications

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Why model the terrestrial biosphere?

- Scientific curiosity
- Need to assure specific „services“ from the biosphere (risk avoidance)
- Understand the role of the biosphere as part of the coupled Earth system (energy & momentum transfer, biogeochemical cycles, paleo dynamics)
- Observations, experiments & models

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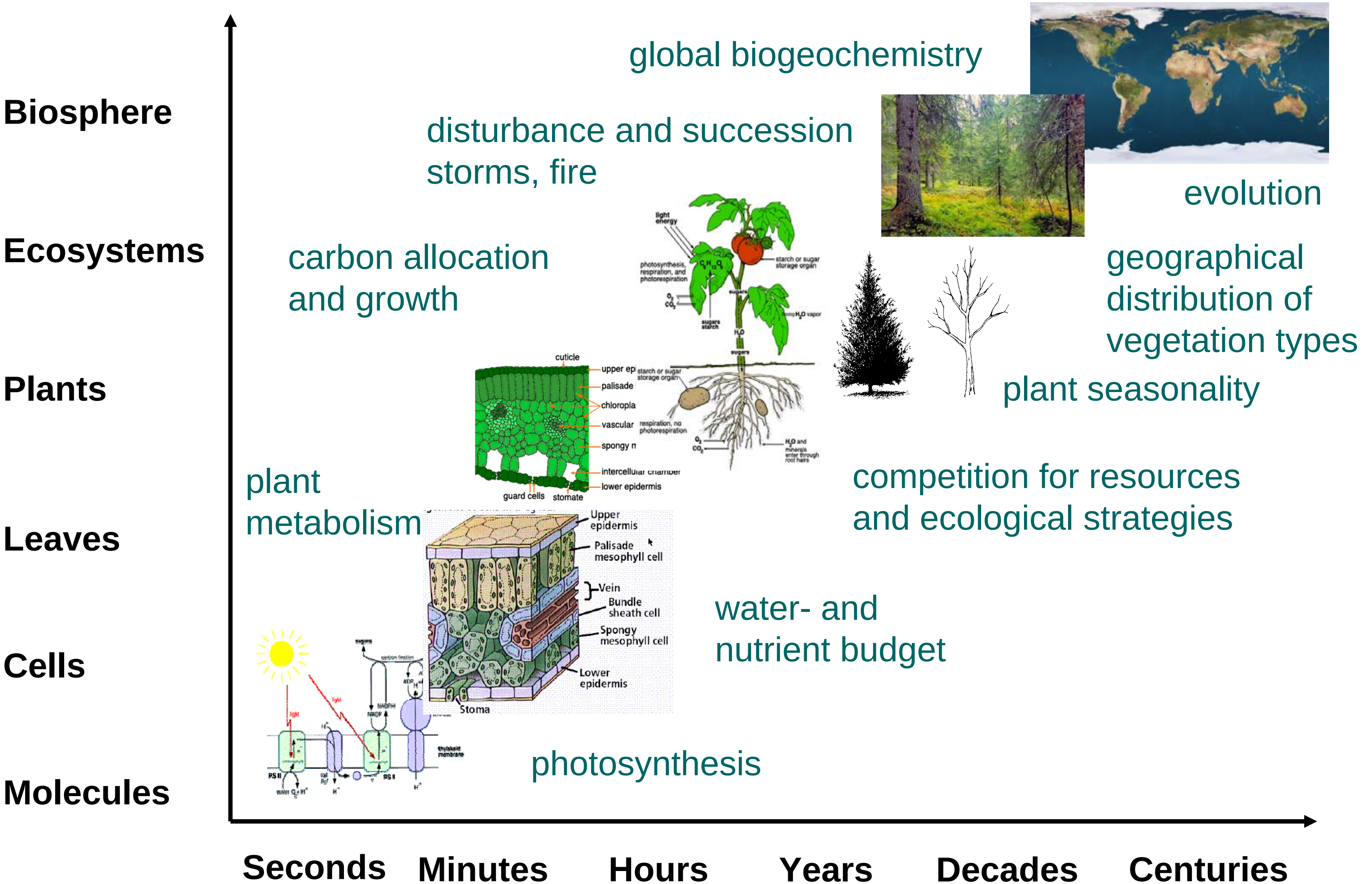
Interacting Scales in Biogeochemistry



From Wolfgang Lucht, PIK

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Some ecosystem services


food production


slope stability


tourist attraction


fire prevention


water storage


biodiversity


pollination


fibre production


fodder production


flood protection


carbon sequestration


beauty


recreation


stabilising micro-climate


game reserve


shelter for life stock

From Dagmar Schröter, Vienna

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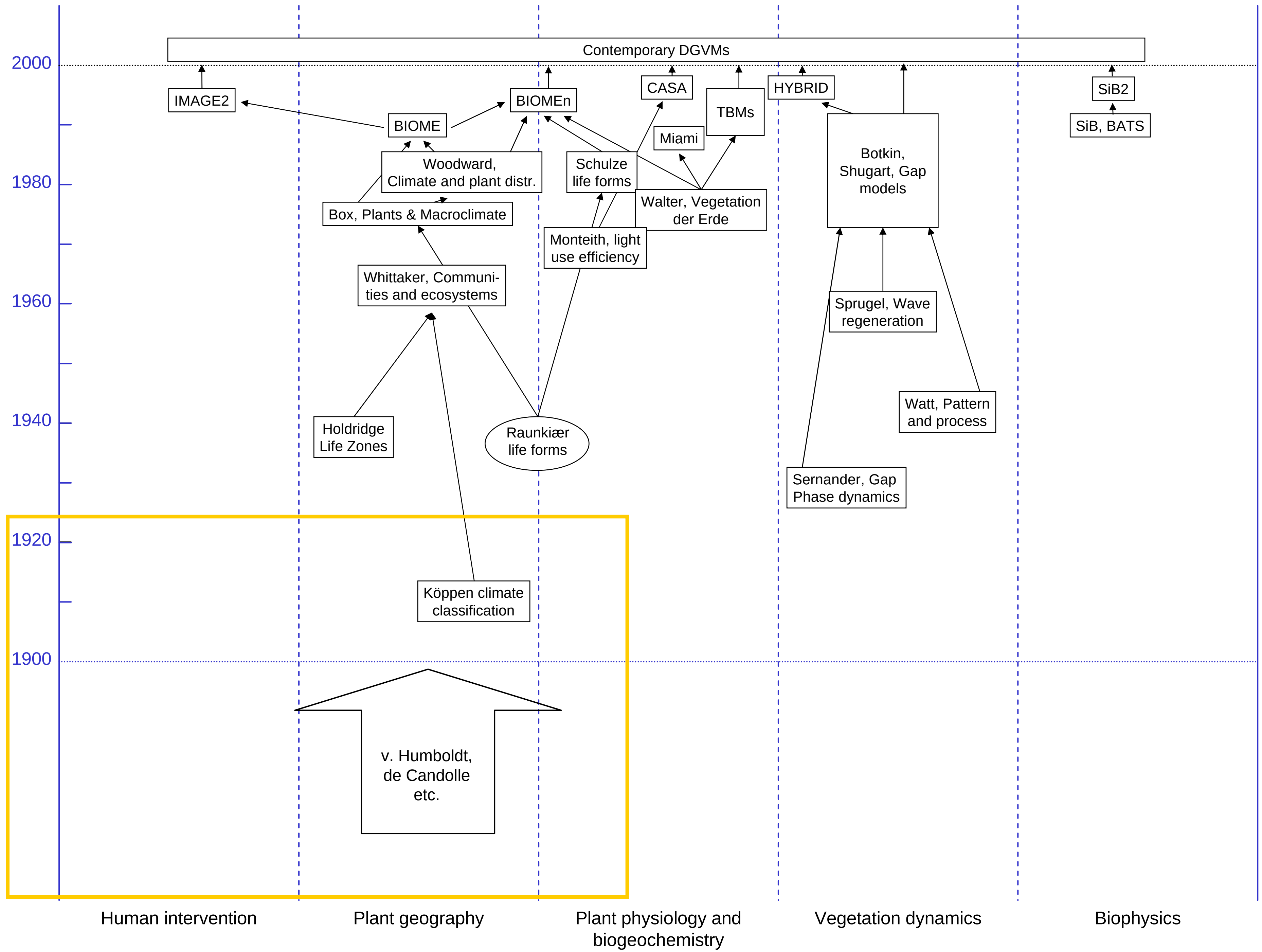

Contemporary DGVMs
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Climate and plant distr.
Schulze
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Walter, Vegetation
der Erde
Botkin,
Shugart, Gap
models
Box, Plants & Macroclimate
Monteith, light
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Whittaker, Communi-
ties and ecosystems
Sprugel, Wave
regeneration
Watt, Pattern
and process
Holdridge
Life Zones
Raunkiær
life forms
Sernander, Gap
Phase dynamics
Köppen climate
classification
v. Humboldt,
de Candolle
etc.
Human intervention
Plant geography
Plant physiology and
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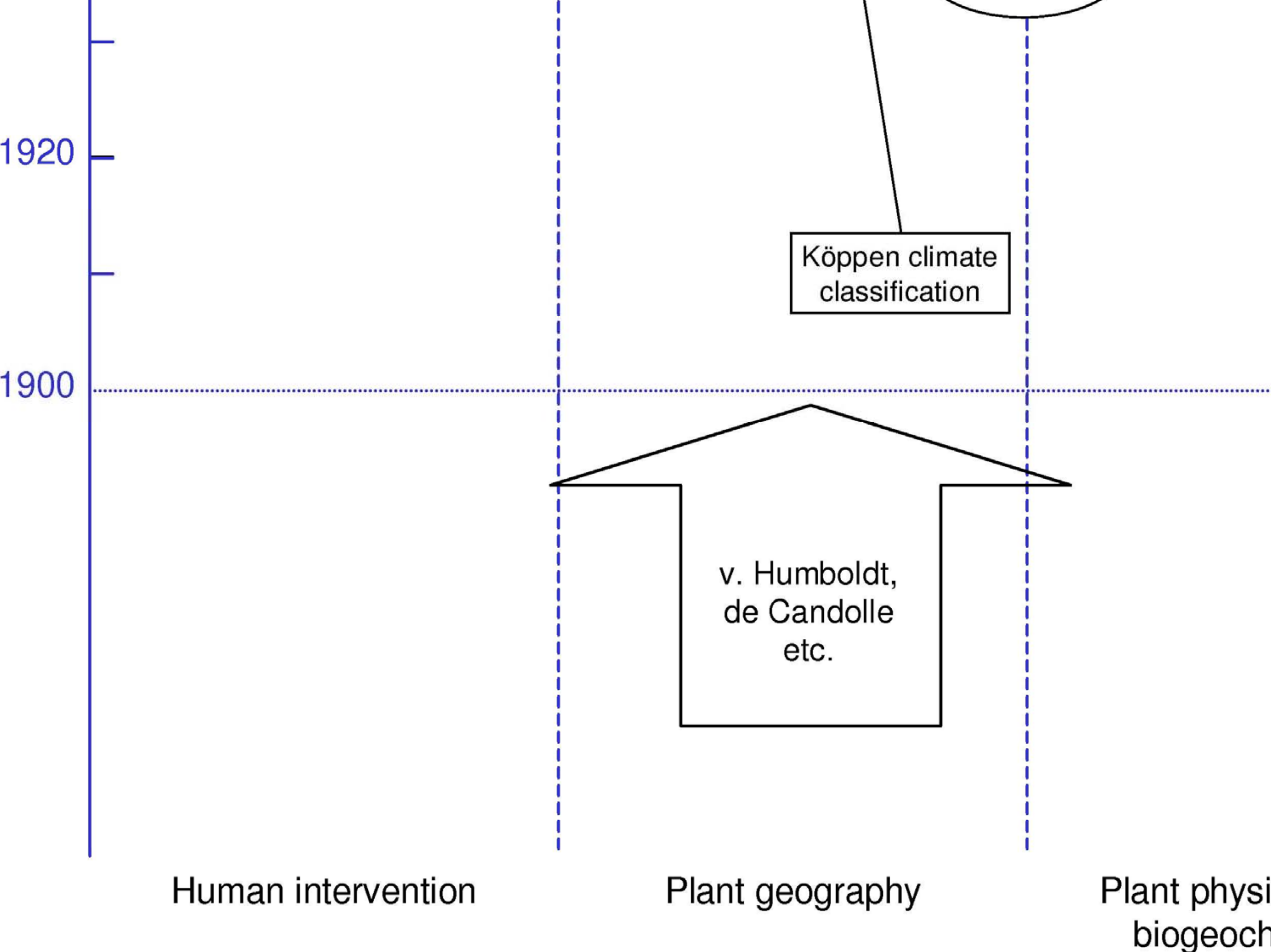
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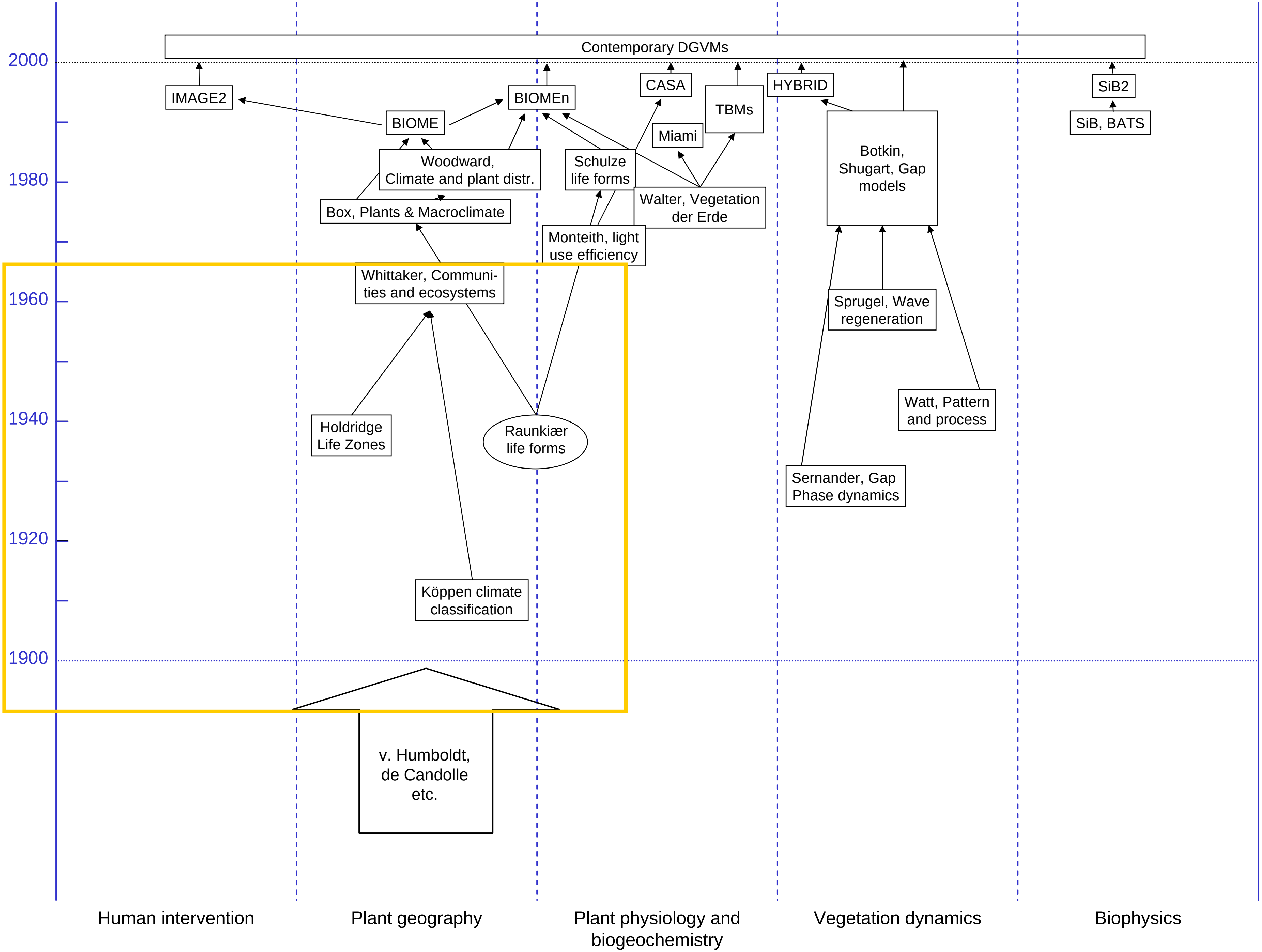

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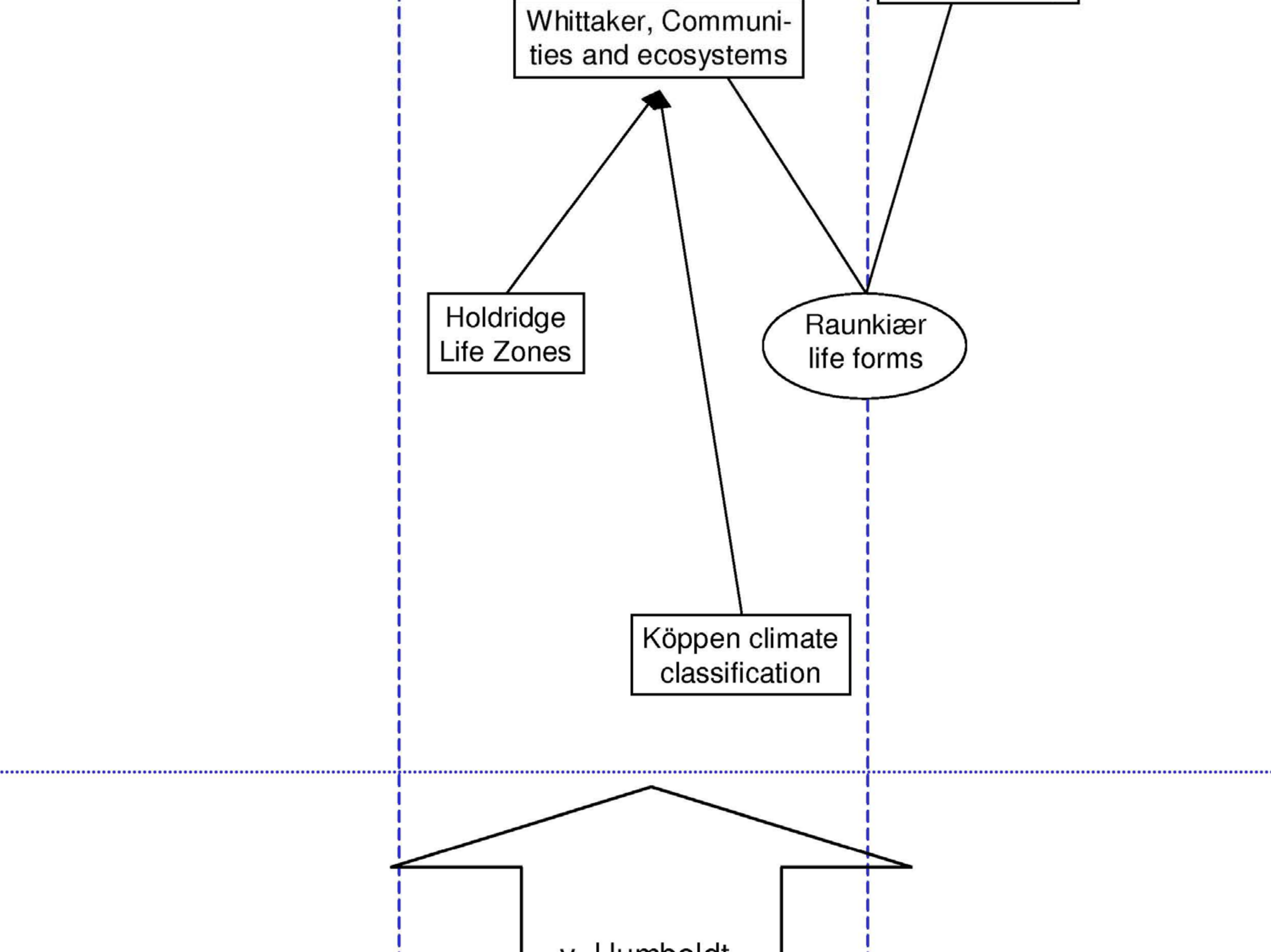

Whittaker, Communi-
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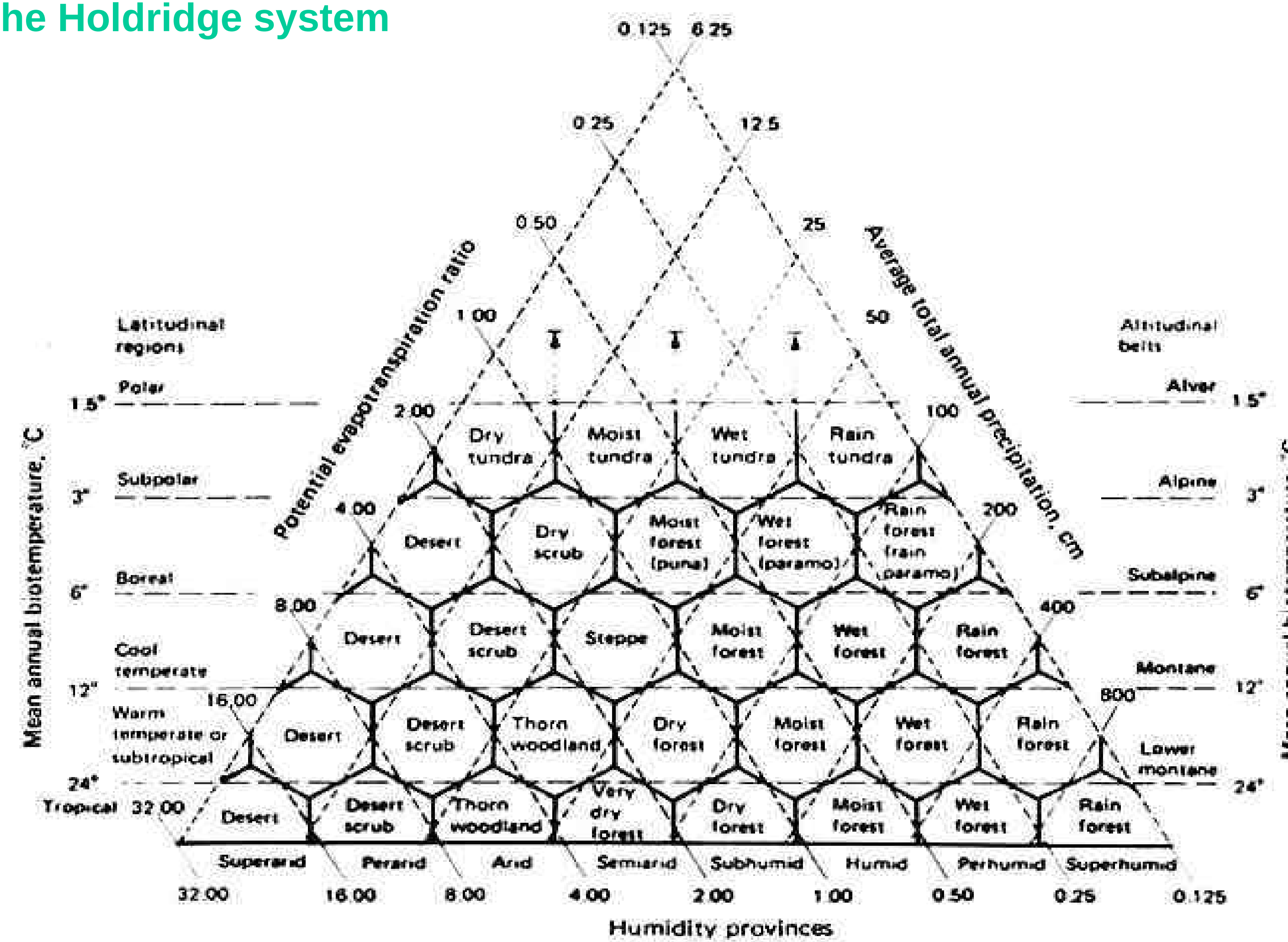
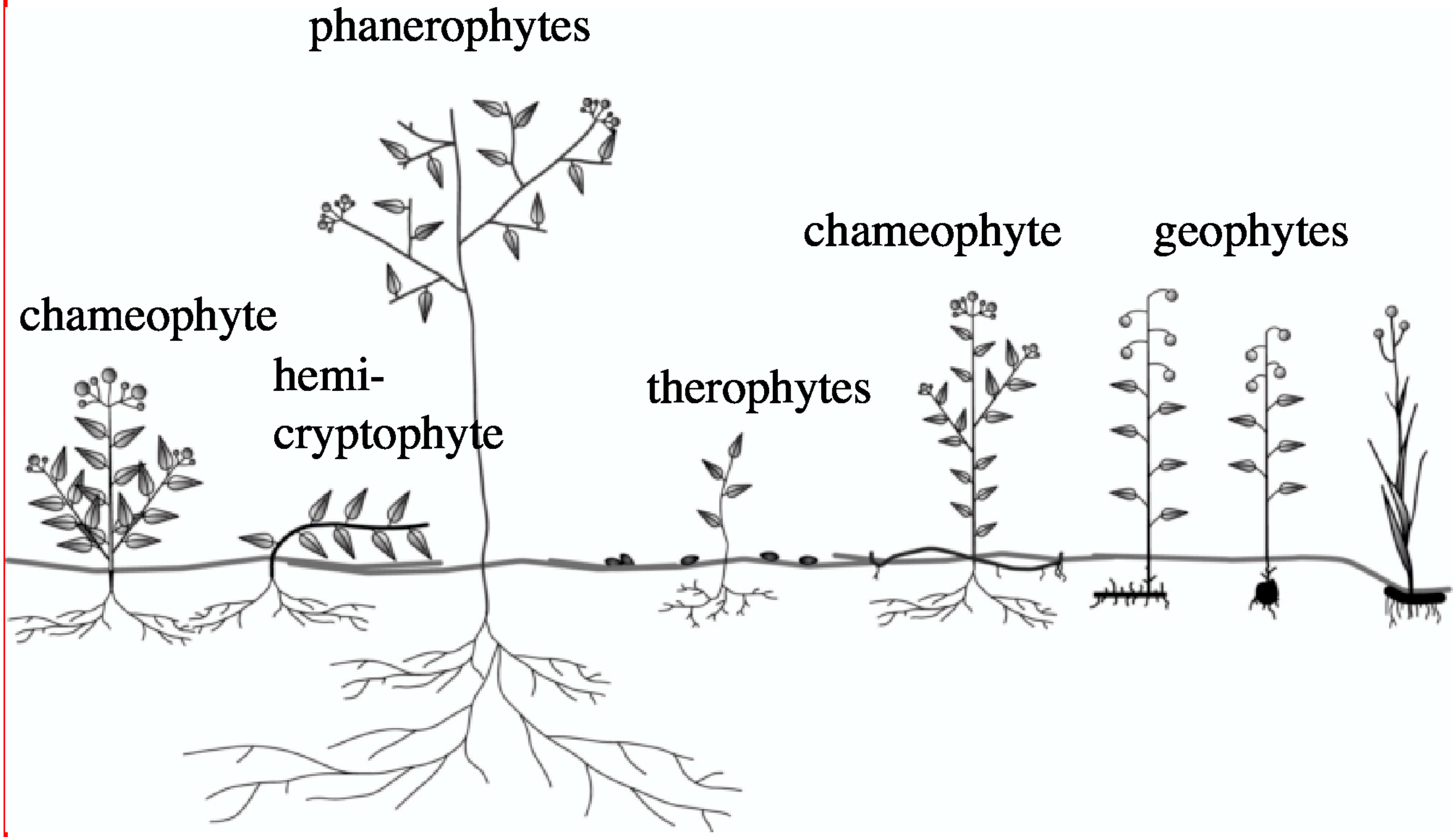
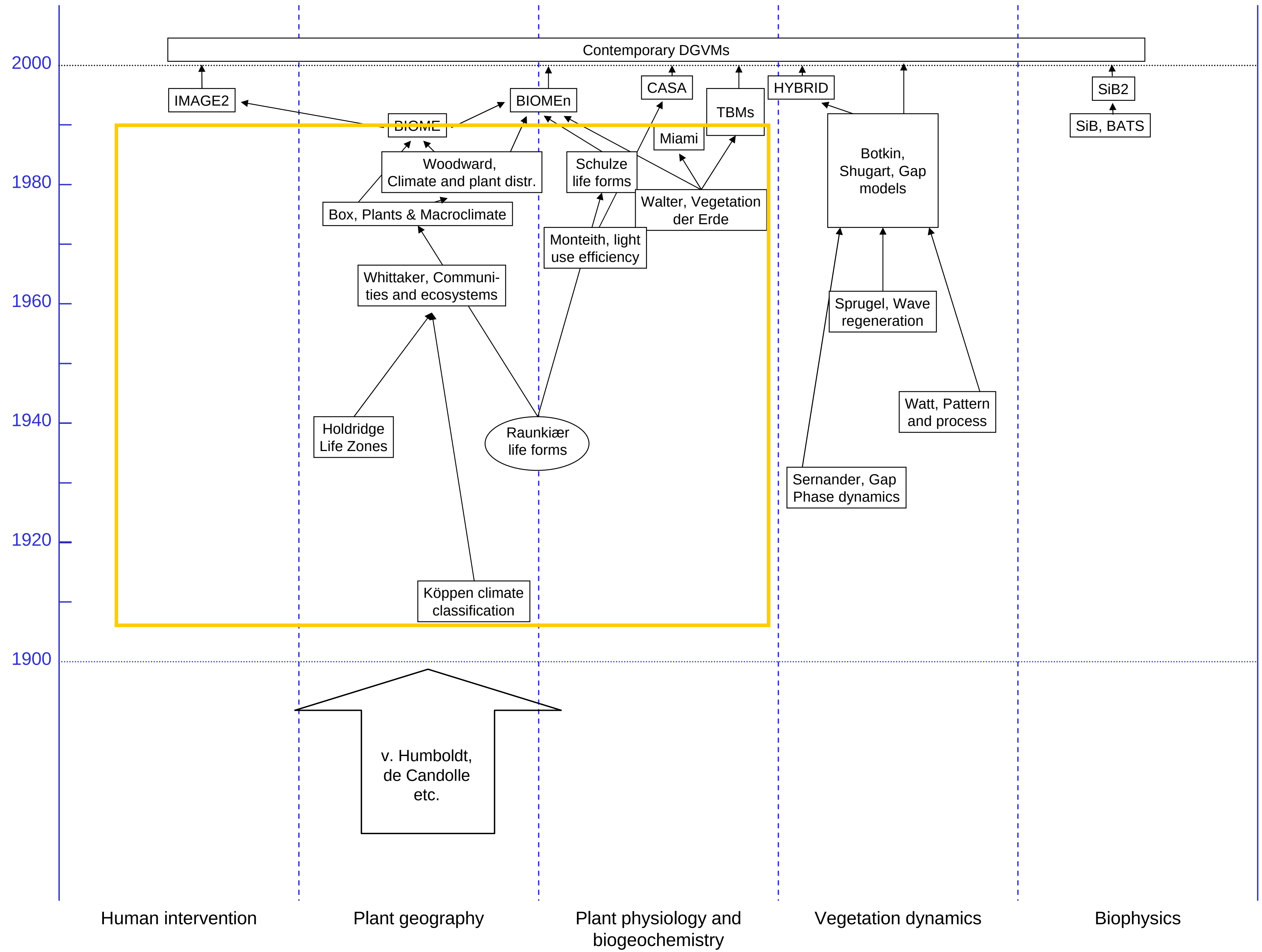
The Holdridge system



Life forms (Raunkiær)





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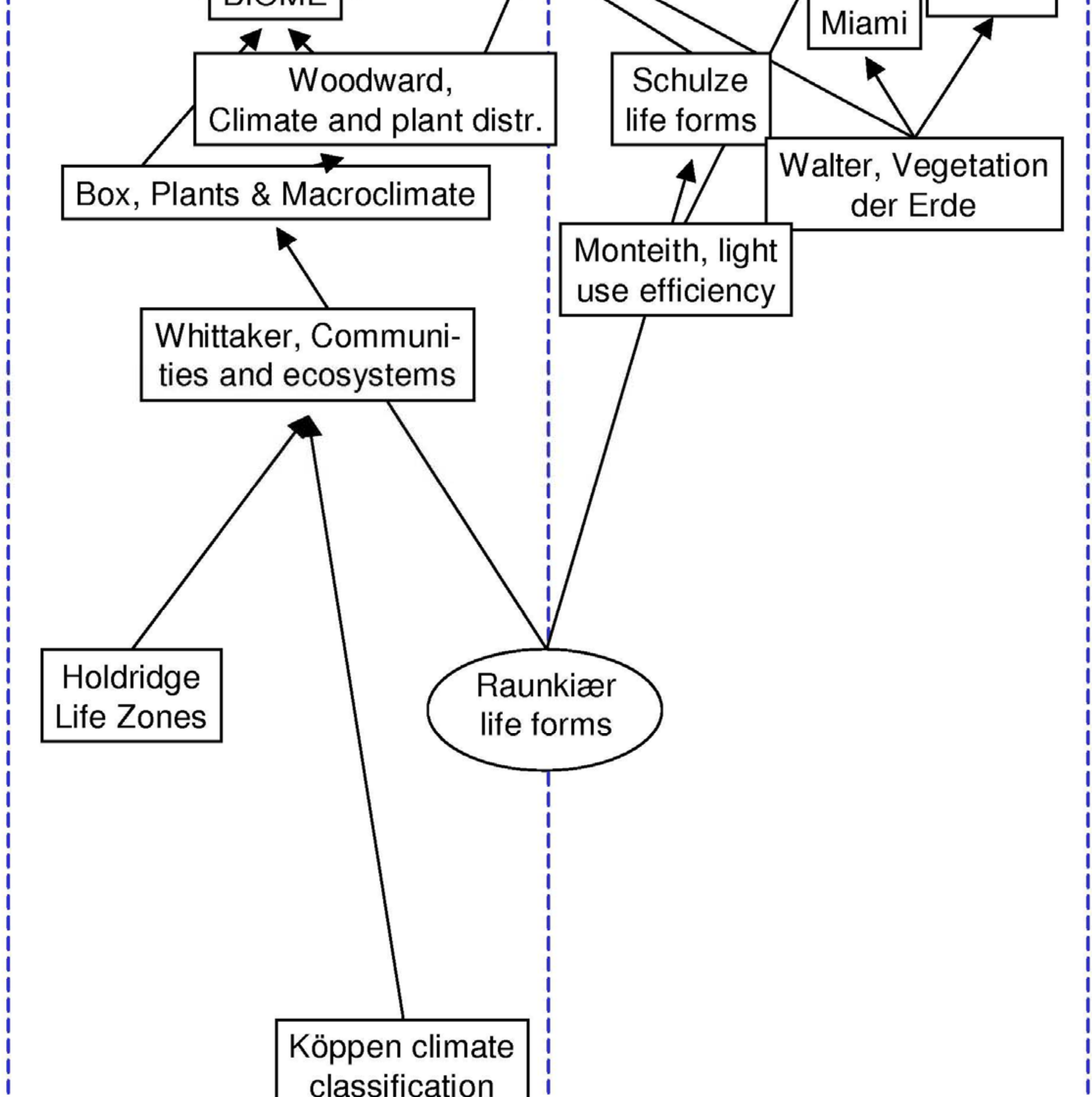

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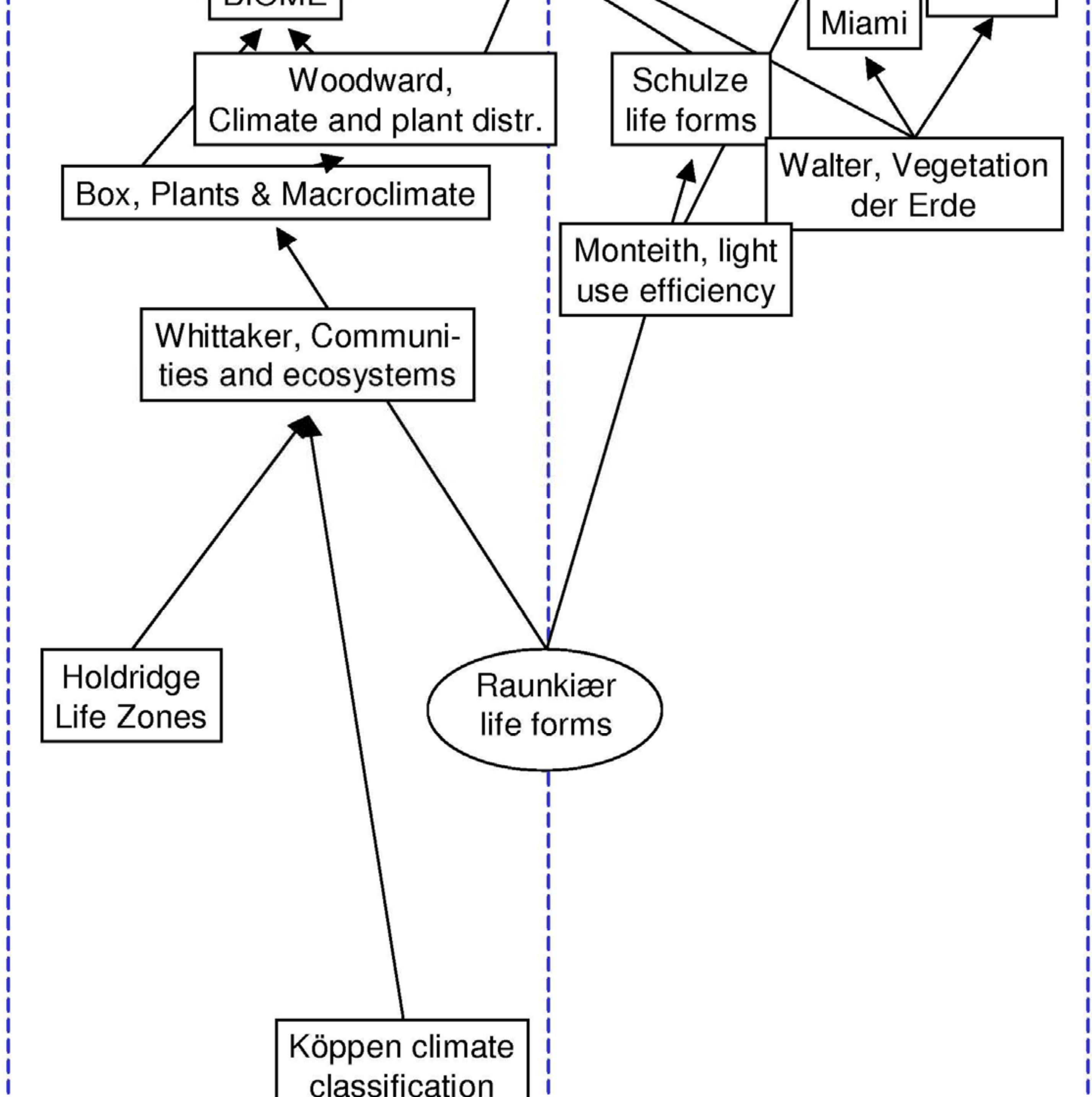
- Biogeography models:
  - limitation of plant and animal distribution in space and time
- Biogeochemistry models:
  - establishment, growth, survival and mortality of organisms in relation to essential resources

Bioclimatic variables (E. Box)

T_{max}	mean temperature of the warmest month (^oC)
T_{min}	mean temperature of the coldest month (^oC)
D_T	range between T_{min} and T_{max} (^oC)
P	mean total annual precipitation (mm)
MI	moisture index, defined as the ratio between P and annual potential evapotranspiration (Thornthwaite and Mather 1957)
P_{max}	mean total precipitation of the wettest month (mm)
P_{min}	mean total precipitation of the driest month (mm)
P_{Tmax}	mean total precipitation of the warmest month (mm)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The Miami Model (Lieth 1972)

$$NPP = \min(NPP_T, NPP_P)$$

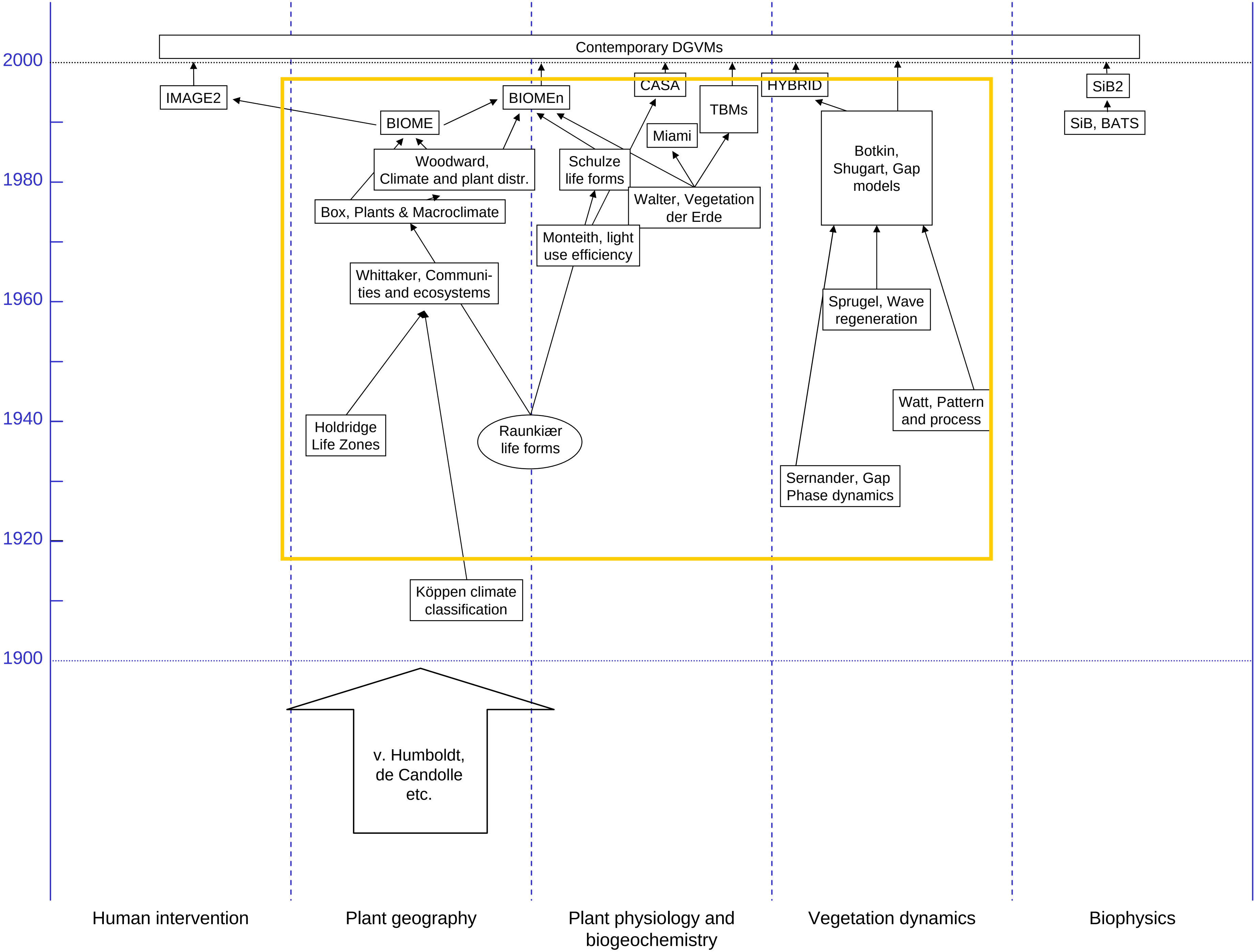
$$NPP_T = 3000\,(1 + \exp(1.315 - 0.119 * T))^{-1}$$

$$NPP_P = 3000\,(1 - \exp(-.000664 * P))$$

NPP – Net Primary Productivity (g DM m^{-2} yr^{-1})

P – Mean annual total precipitation

T – Mean annual temperature



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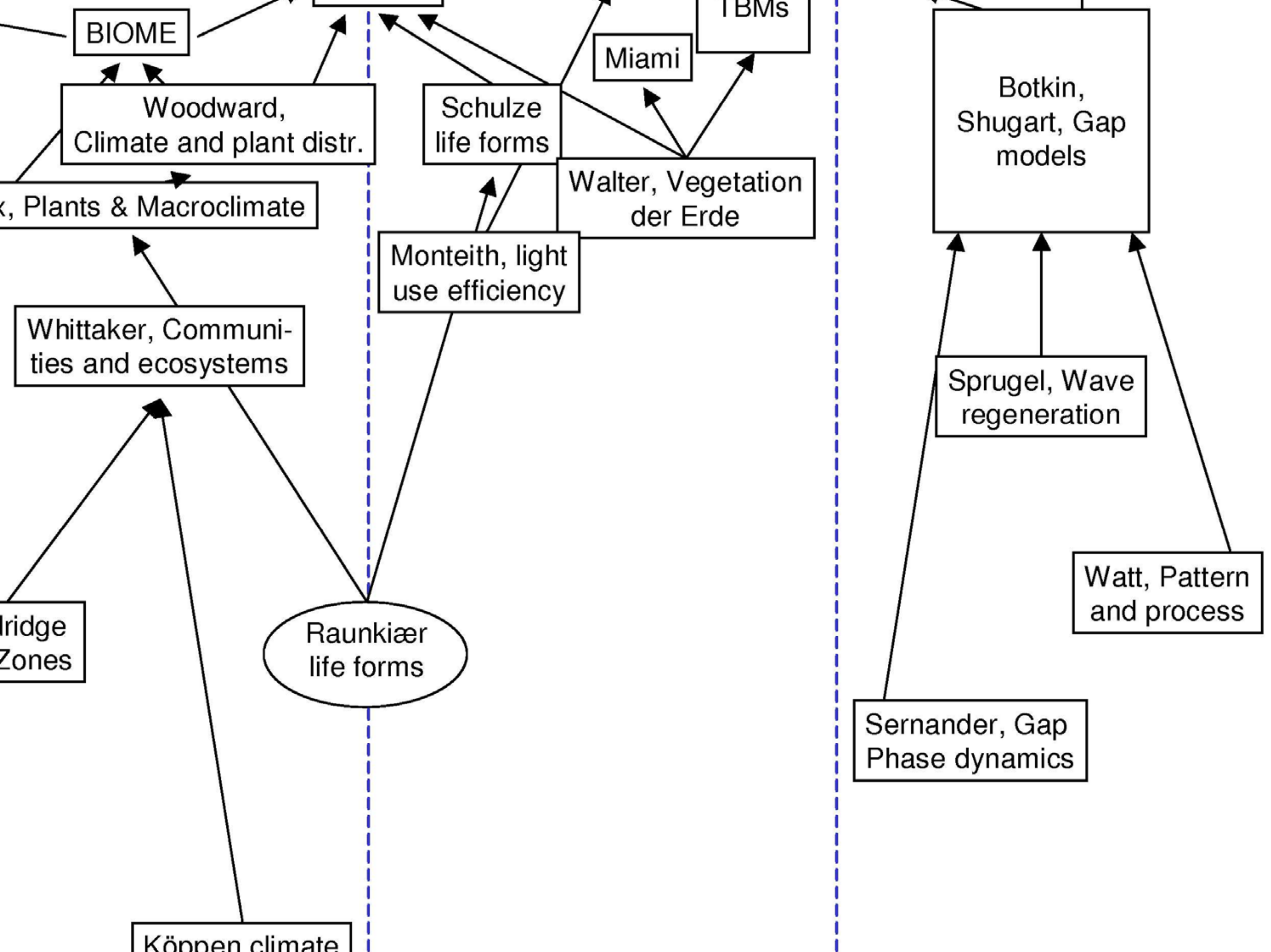

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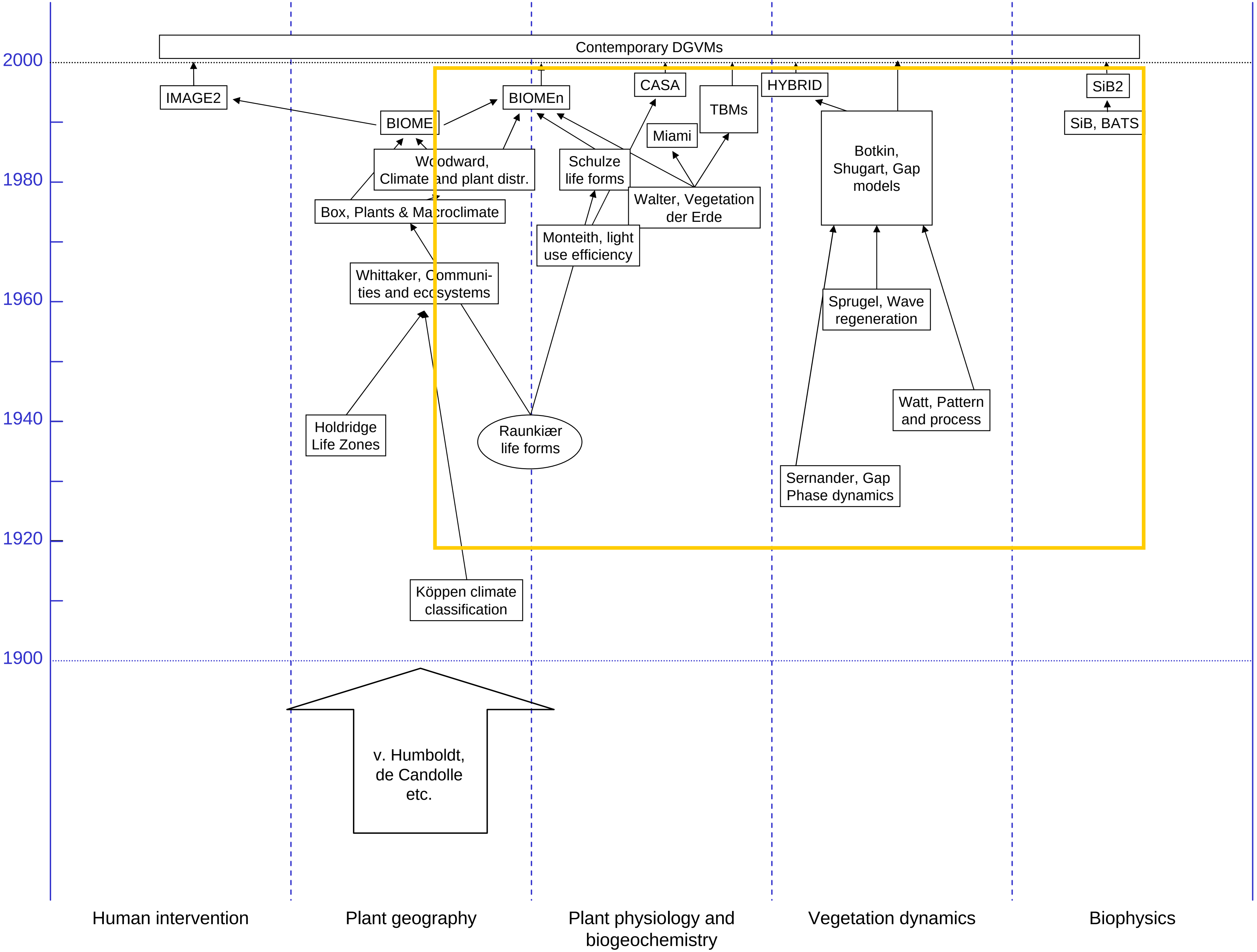
Rutger Sernander 1936 – Boreal forest gap dynamics



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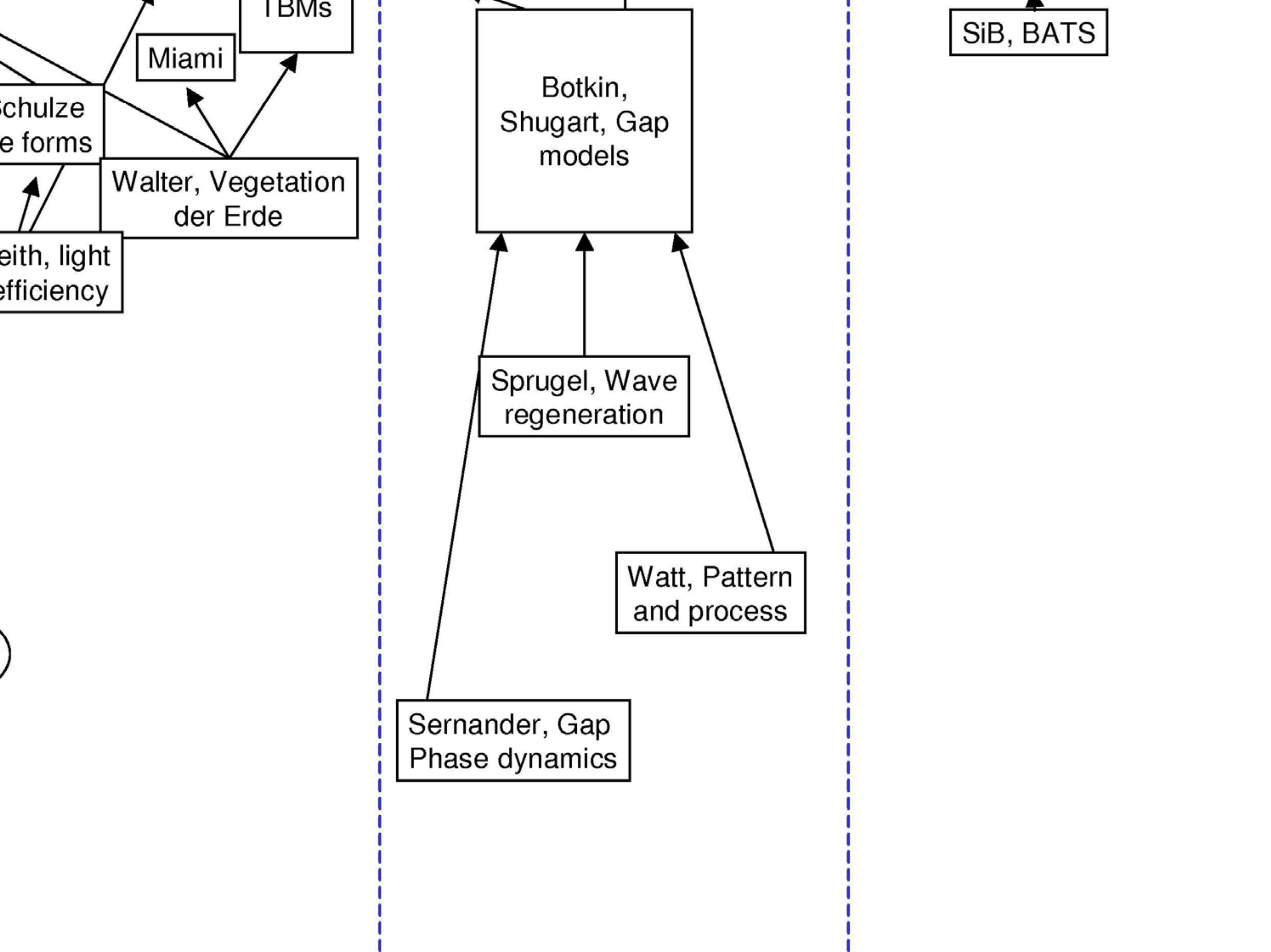

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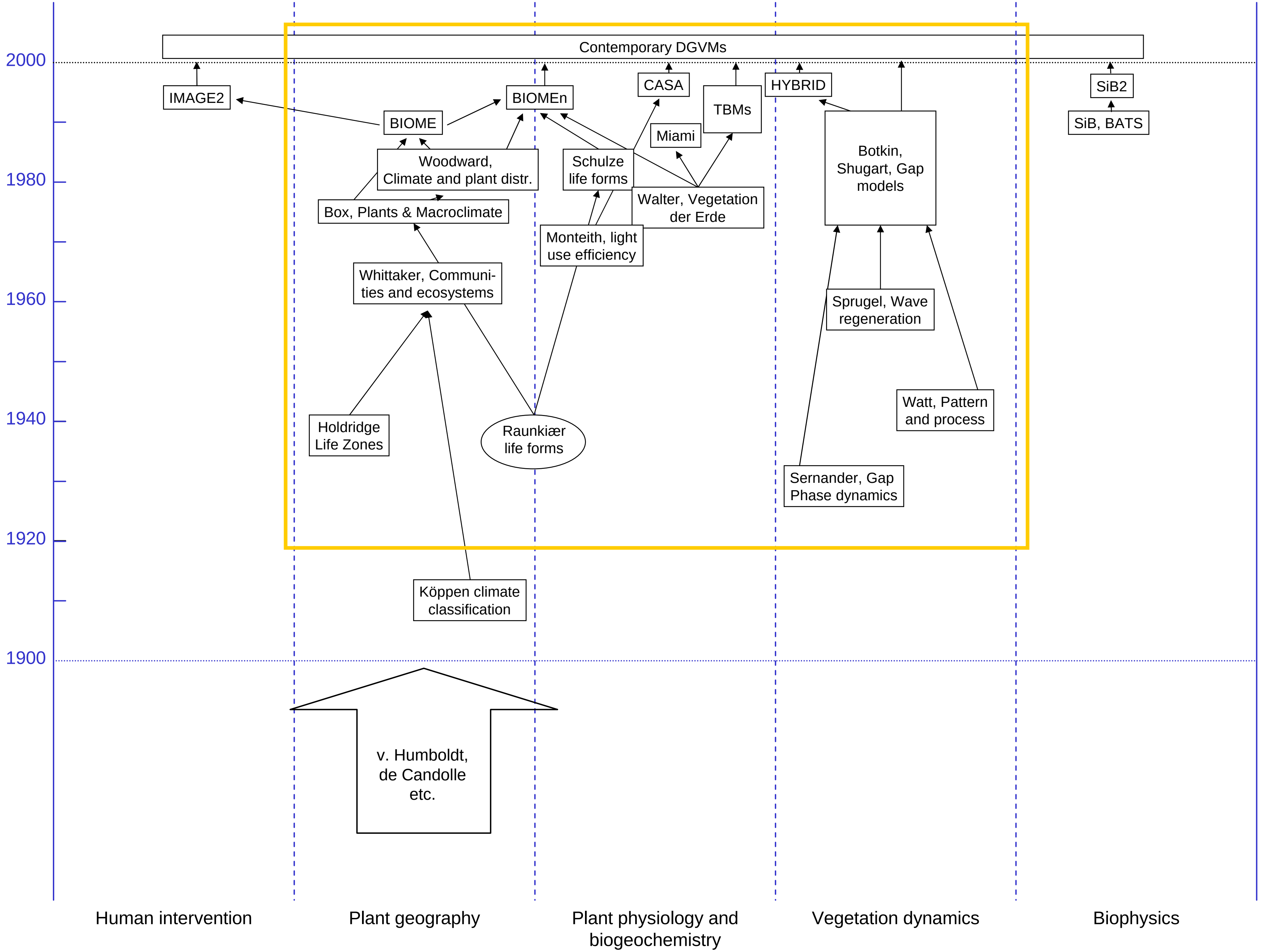
Simple Interactive Biosphere Model:

• initially a model of the energy balance at the land surface (for climate modelling), assuming a single „big leaf“

• later involving more complex physics and biogeochemistry



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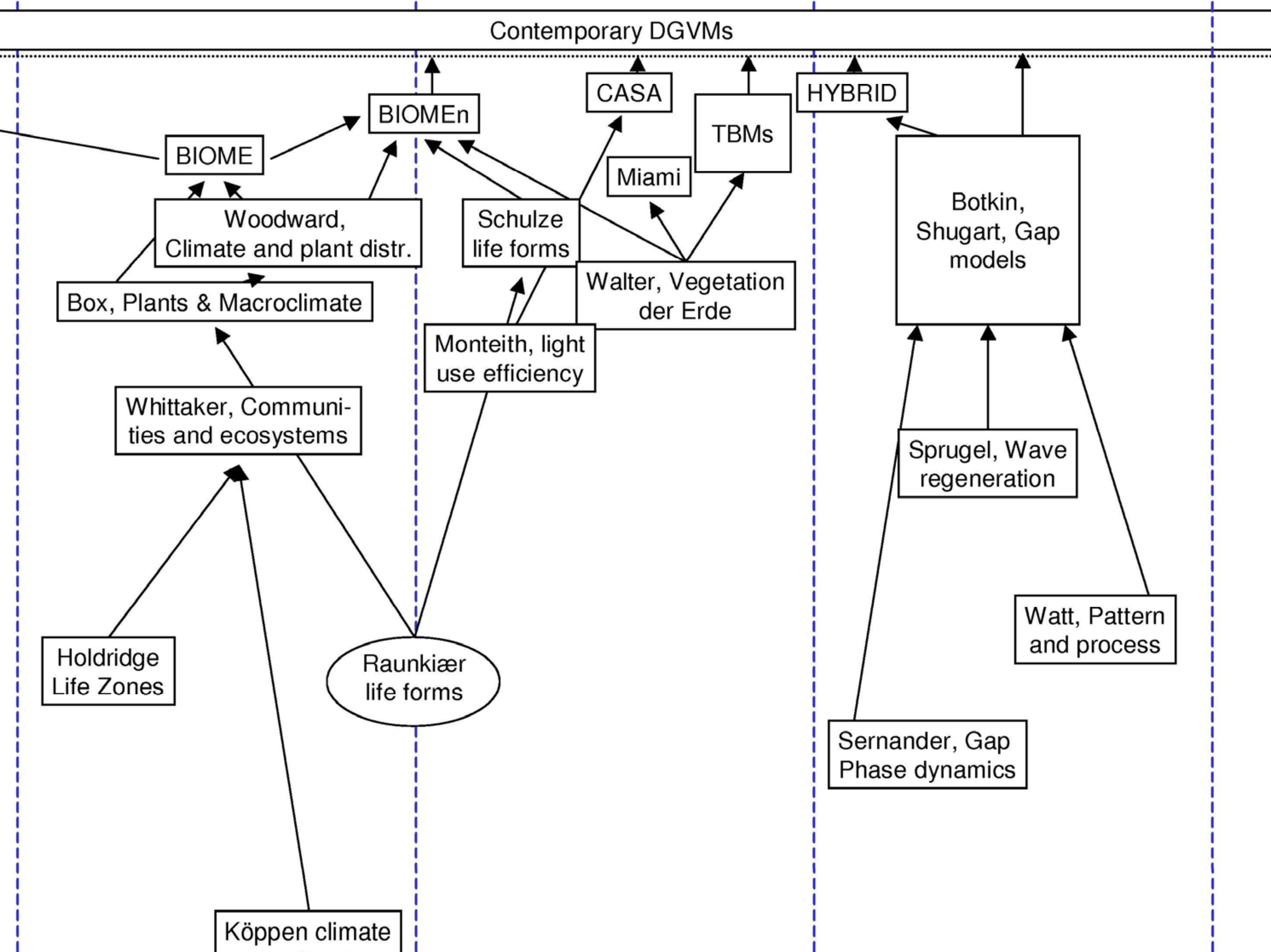

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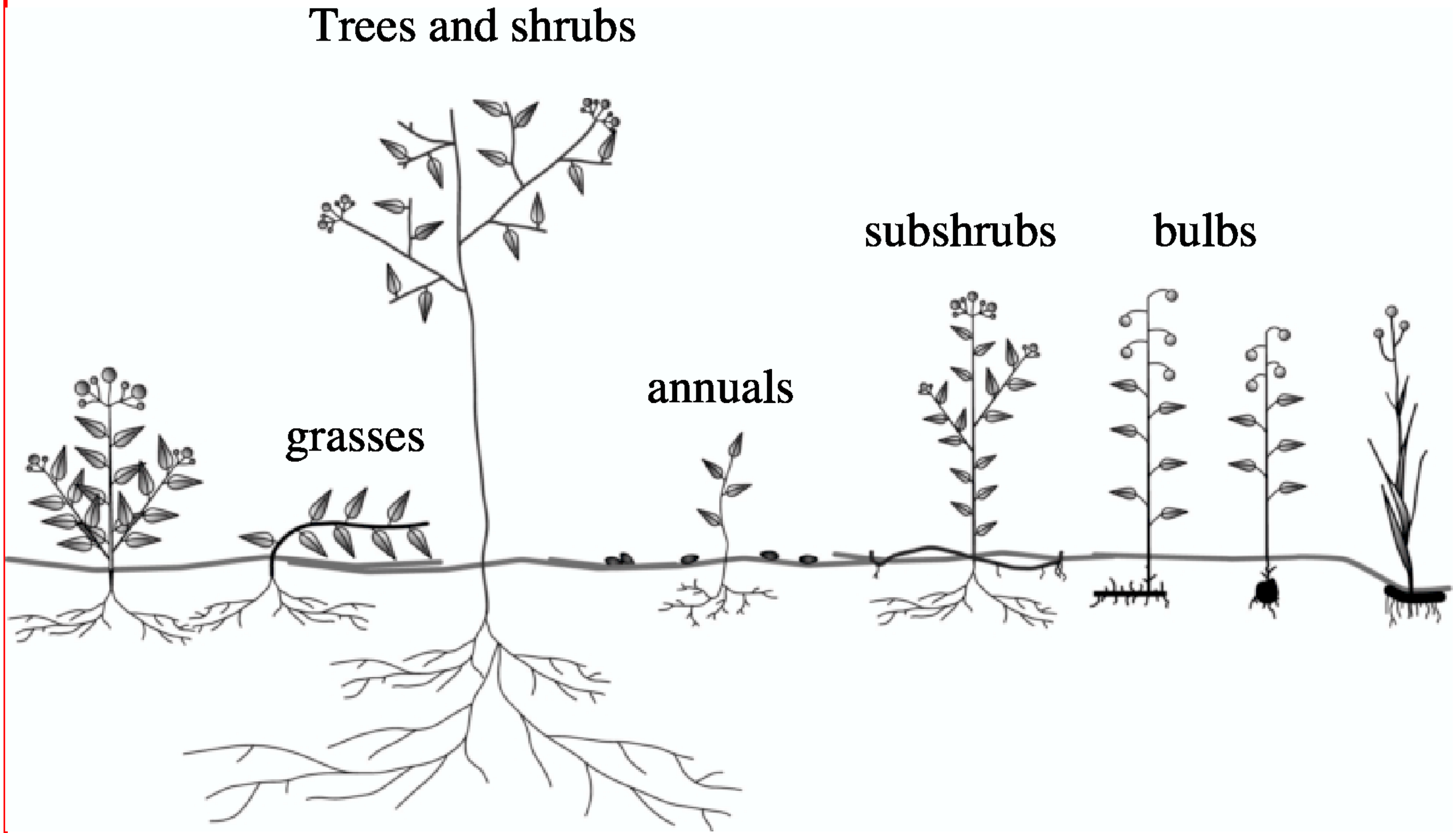
Combining biogeography and biogeochemistry

- Goal:
  - to predict biogeography from physiological and biophysical „principles“,
  - to predict biogeochemical fluxes from realistic biogeography
- Essential elements:
  - water balance estimation instead of rainfall measurements
  - basic plant types („functional types“)

Plant functional types



Mechanisms in BIOME

tolerance / requirement

cold tolerance

chilling requirement

heat requirement

moisture requirement / drought tolerance

Mechanisms in BIOME

tolerance / requirement	**ecophysiological mechanism**
cold tolerance	killing temperature during coldest period of the year
chilling re-quirement	winter chilling period required for budburst of woody plants
heat require-ment	annual growth respi-ration requirement
moisture requirement / drought tolerance	soil moisture avail-ability

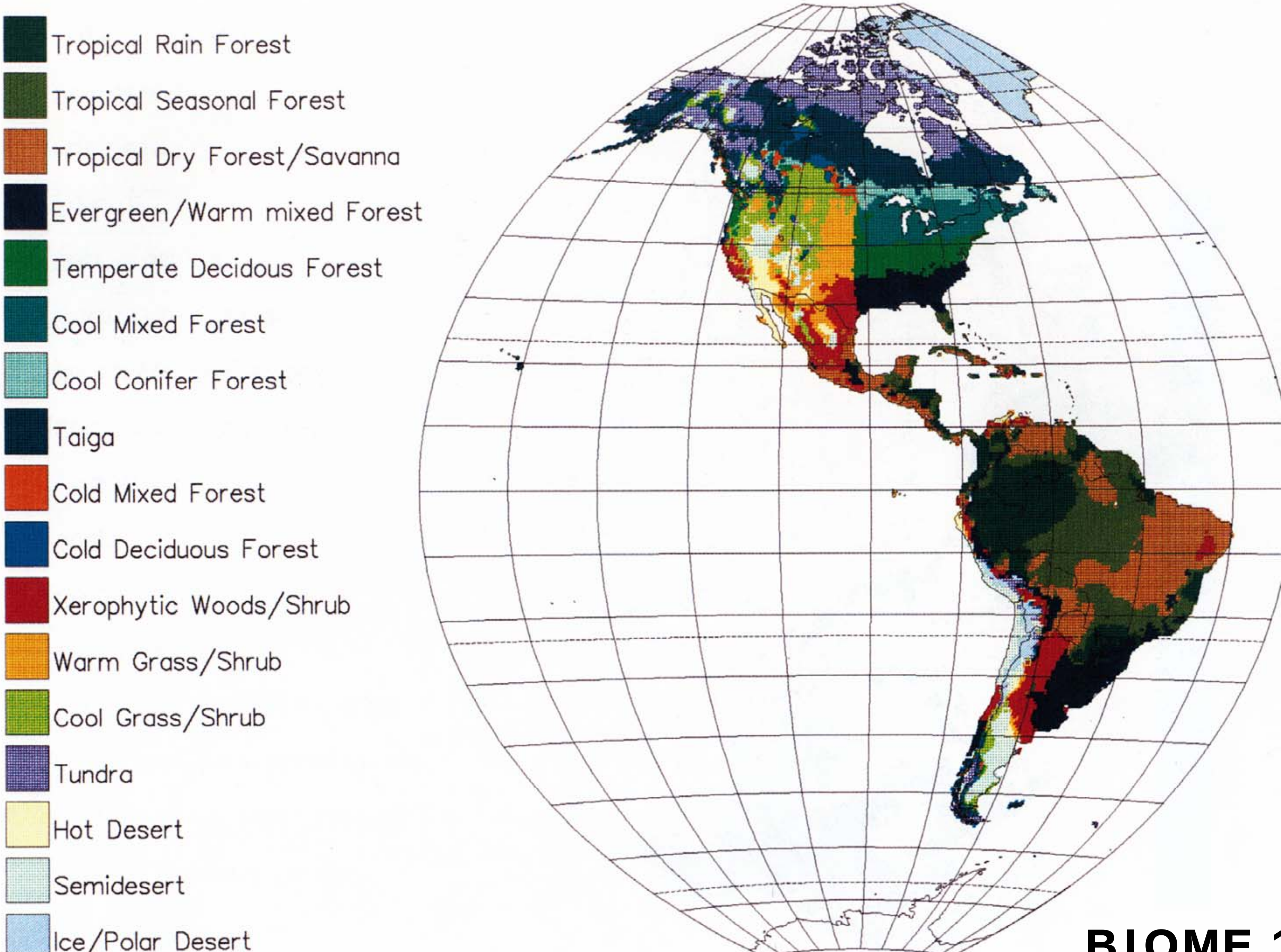
Mechanisms in BIOME

tolerance / requirement	ecophysiological mechanism	bioclimatic index
cold tolerance	killing temperature during coldest period of the year	T_{min} (temperature of the coldest month, lower limit)
chilling requirement	winter chilling period required for budburst of woody plants	T_{min} (temperature of the coldest month, upper limit)
heat requirement	annual growth respiration requirement	GDD (growing degree days above 0 °C and 5 °C)
moisture requirement / drought tolerance	soil moisture availability	AET/PET (annual actual evapotranspiration / annual potential evapotranspiration)

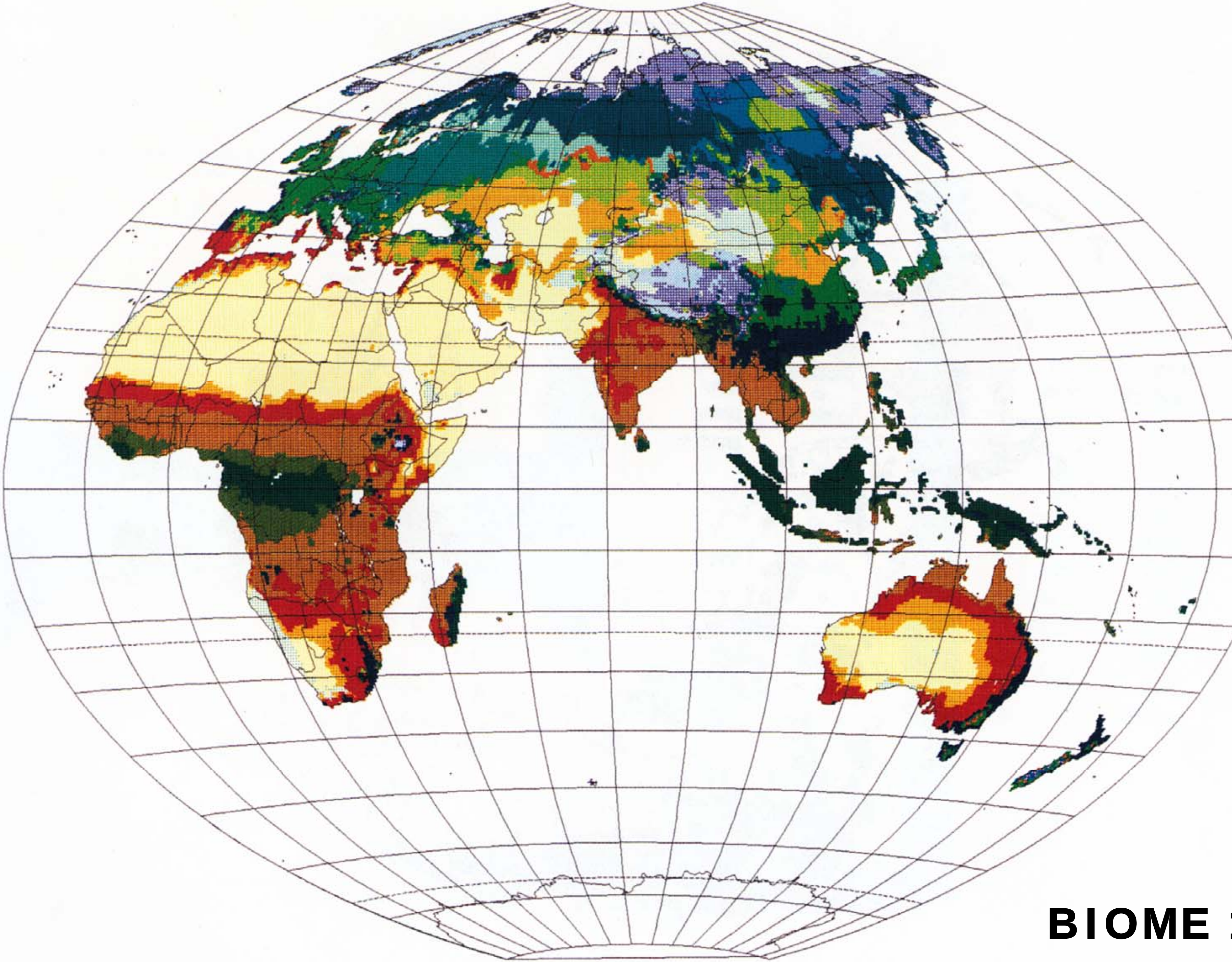
Mechanisms in BIOME

tolerance / requirement	ecophysiological mechanism	bioclimatic index	climatic variable (monthly means)
cold tolerance	killing temperature during coldest period of the year	T_{min} (temperature of the coldest month, lower limit)	temperature
chilling requirement	winter chilling period required for budburst of woody plants	T_{min} (temperature of the coldest month, upper limit)	temperature
heat requirement	annual growth respiration requirement	GDD (growing degree days above 0 °C and 5 °C)	temperature
moisture requirement / drought tolerance	soil moisture availability	AET/PET (annual actual evapotranspiration / annual potential evapotranspiration)	temperature precipitation cloudiness

	plant functional type	T_{min} min	T_{min} max	GDD_0 min	GDD_5 min	T_{max} min	AET/PET min	AET/PET max
trees	tropical evergreen	15.5					0.80	
	tropical raingreen	15.5					0.45	0.95
	warm-temperate ever-green	5.0					0.65	
	temperate summergreen	-15.0	15.5		1200		0.65	
	cool-temperate conifer	-19.0	5.0		900		0.65	
	boreal evergreen conifer	-35.0	-2.0		350		0.75	
	boreal summergreen		5.0		350		0.65	
non-trees	sclerophyll/succulent	5.0					0.28	
	warm grass/shrub					22.0	0.18	
	cool grass/shrub				500		0.33	
	cold grass/shrub			100			0.33	
	hot desert shrub					22.0		
	cold desert shrub			100				
no plants	(dummy type)							

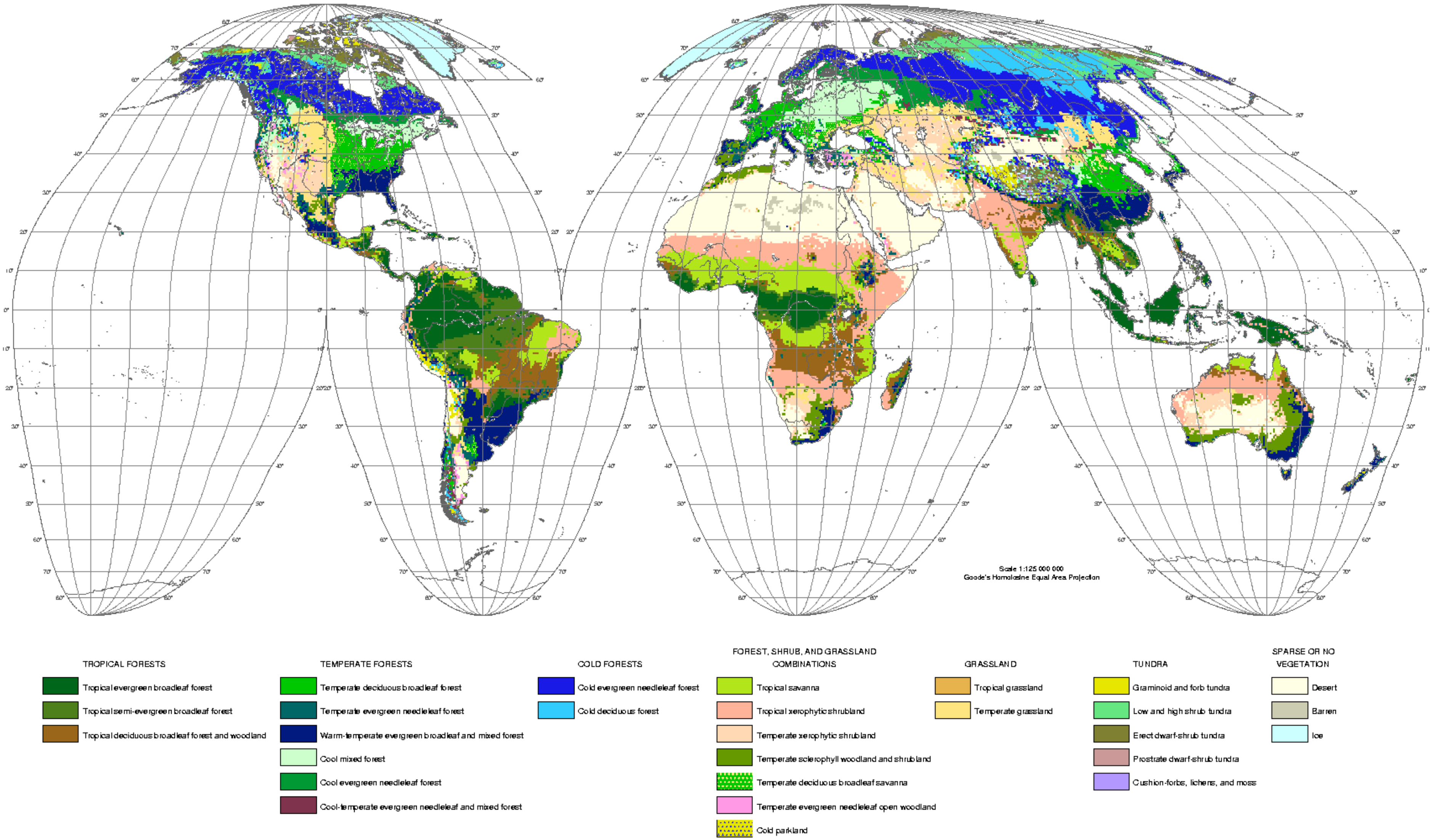

Tropical Rain Forest
Tropical Seasonal Forest
Tropical Dry Forest/Savanna
Evergreen/Warm mixed Forest
Temperate Decidous Forest
Cool Mixed Forest
Cool Conifer Forest
Taiga
Cold Mixed Forest
Cold Deciduous Forest
Xerophytic Woods/Shrub
Warm Grass/Shrub
Cool Grass/Shrub
Tundra
Hot Desert
Semidesert
Ice/Polar Desert

BIOME 1



BIOME 1

BIOME4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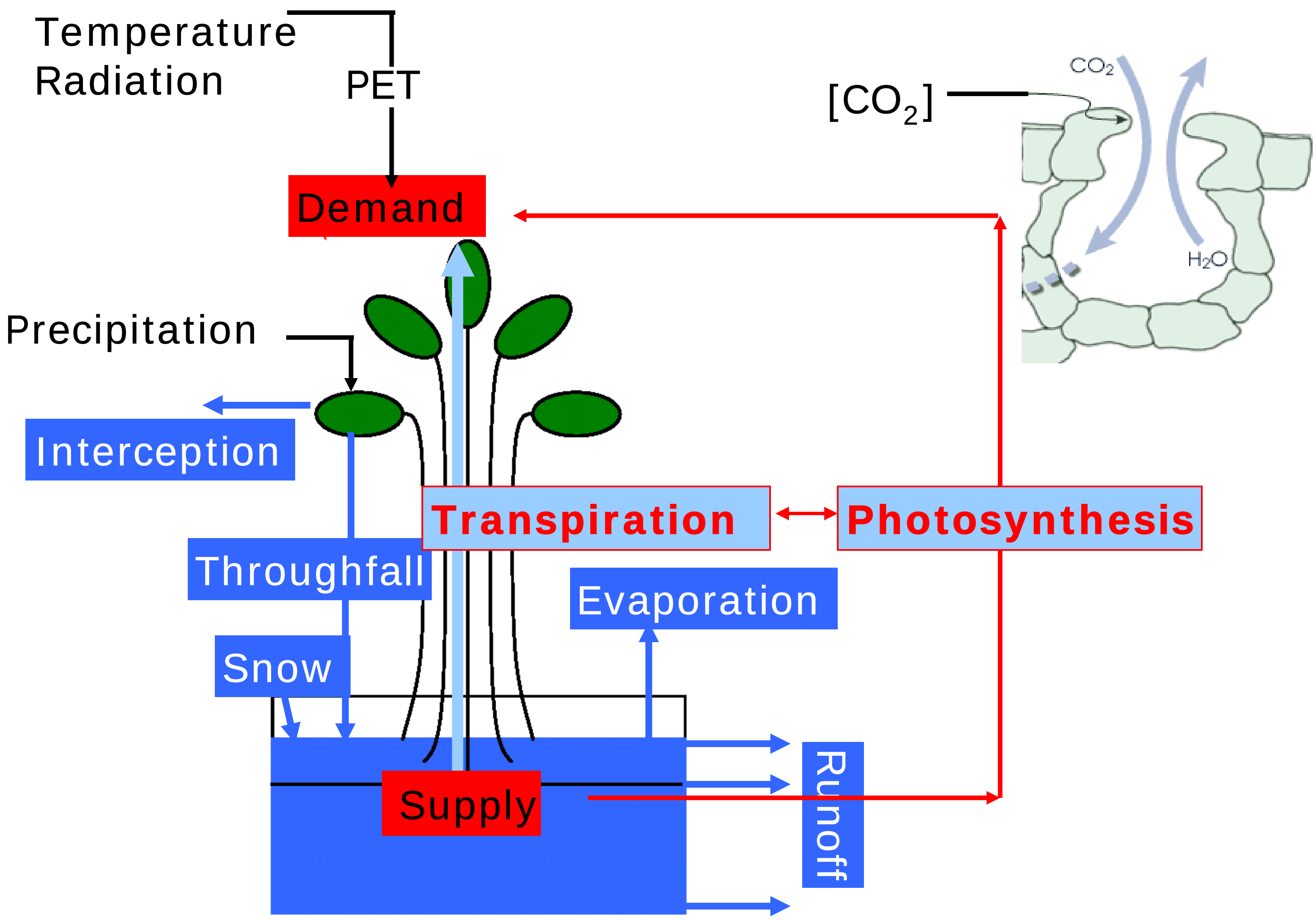
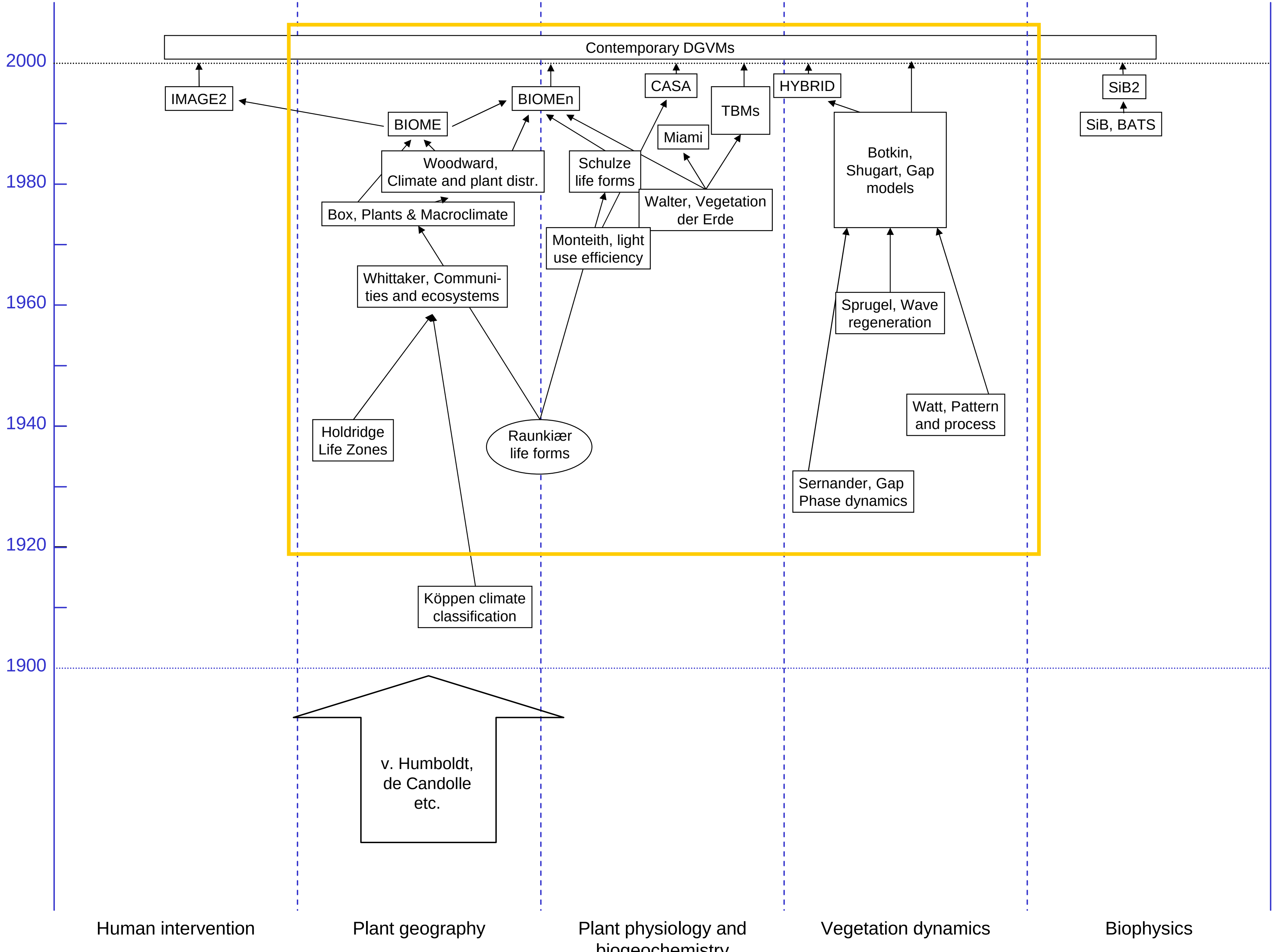
Goode's Homolosine Equal Area Projection
TROPICAL FORESTS
Tropical evergreen broadleaf forest
Tropical semi-evergreen broadleaf forest
Tropical deciduous broadleaf forest and woodland
TEMPERATE FORESTS
Temperate deciduous broadleaf forest
Temperate evergreen needleleaf forest
Warm-temperate evergreen broadleaf and mixed forest
Cool mixed forest
Cool evergreen needleleaf forest
Cool-temperate evergreen needleleaf and mixed forest
COLD FORESTS
Cold evergreen needleleaf forest
Cold deciduous forest
FOREST, SHRUB, AND GRASSLAND COMBINATIONS
Tropical savanna
Tropical xerophytic shrubland
Temperate xerophytic shrubland
Temperate sclerophyll woodland and shrubland
Temperate deciduous broadleaf savanna
Temperate evergreen needleleaf open woodland
Cold parkland
GRASSLAND
Tropical grassland
Temperate grassland
TUNDRA
Graminoid and forb tundra
Low and high shrub tundra
Erect dwarf-shrub tundra
Prostrate dwarf-shrub tundra
Cushion-forbs, lichens, and moss
SPARSE OR NO VEGETATION
Desert
Barren
Ice

H_2O and C fluxes





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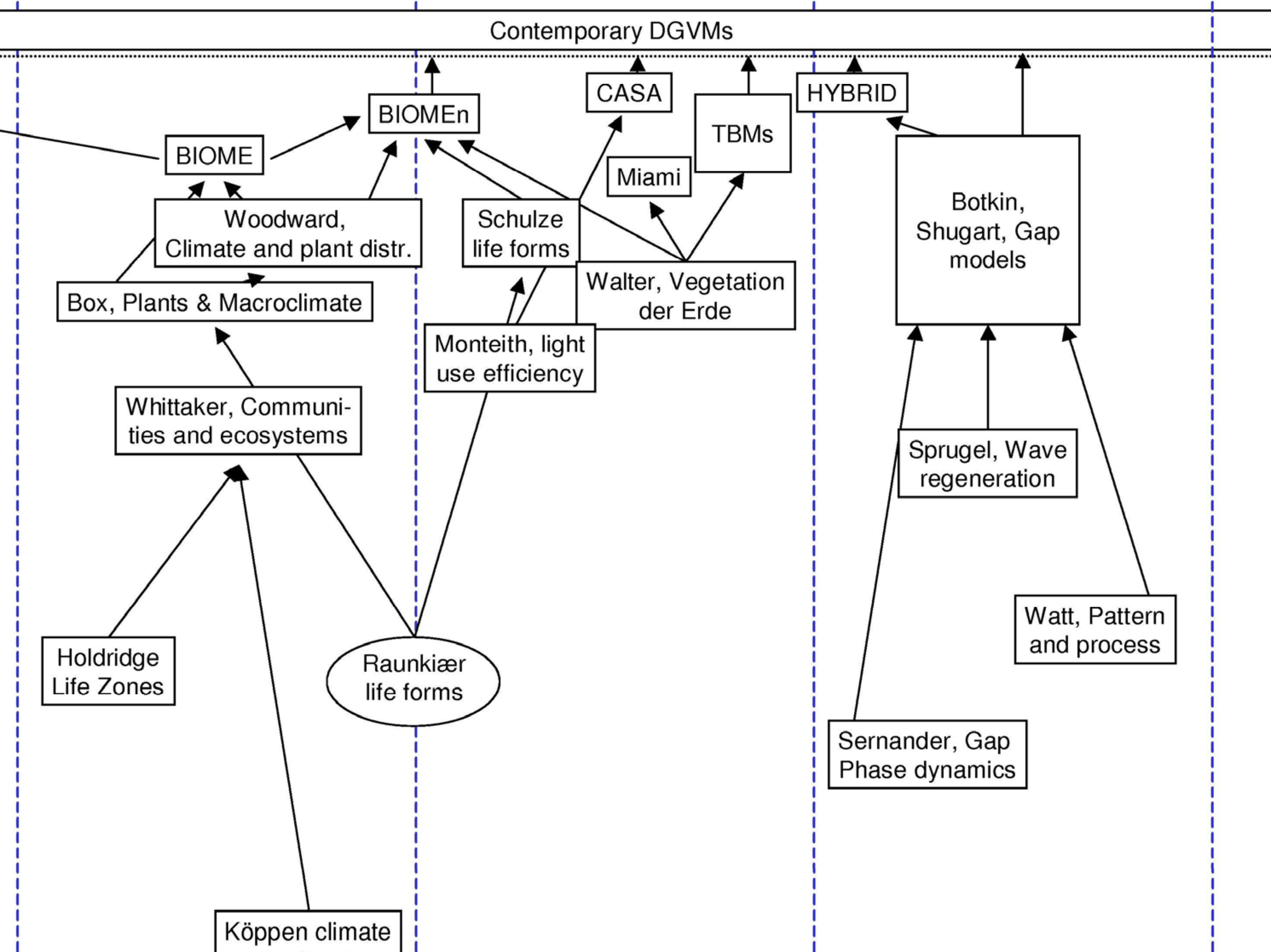
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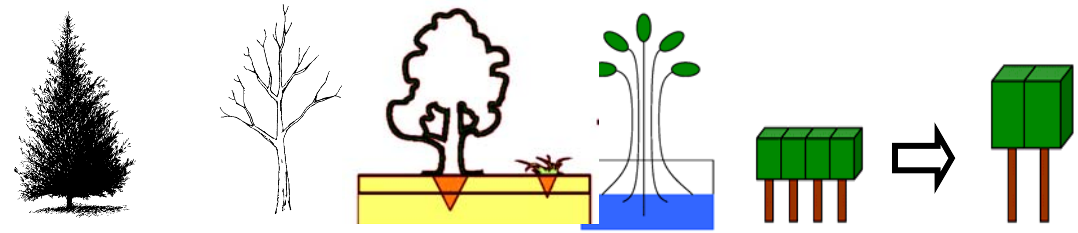
The LPJ Dynamic Global Vegetation Model (Sitch et al., GCB, 2003)

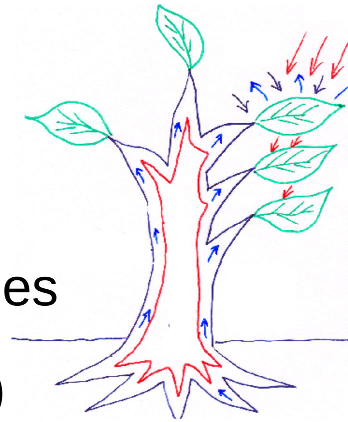
Climate, Soil, CO_2

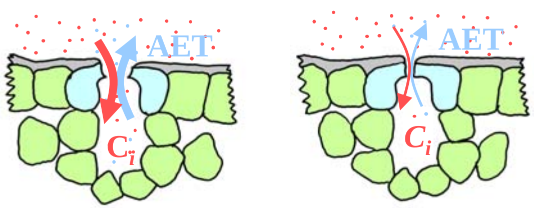
Space & Time Loops

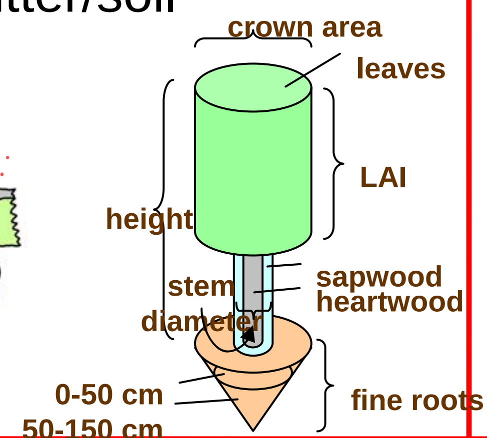
Transformed by process modules into



- 10 plant functional types
- competition, mortality, establishment
- fire, permafrost
- photosynthesis: coupled C and H_2O cycles
- C allocation (funct. and struct. relations)
- Carbon pools: 4 in vegetation, 4 in litter/soil
- Full hydrology

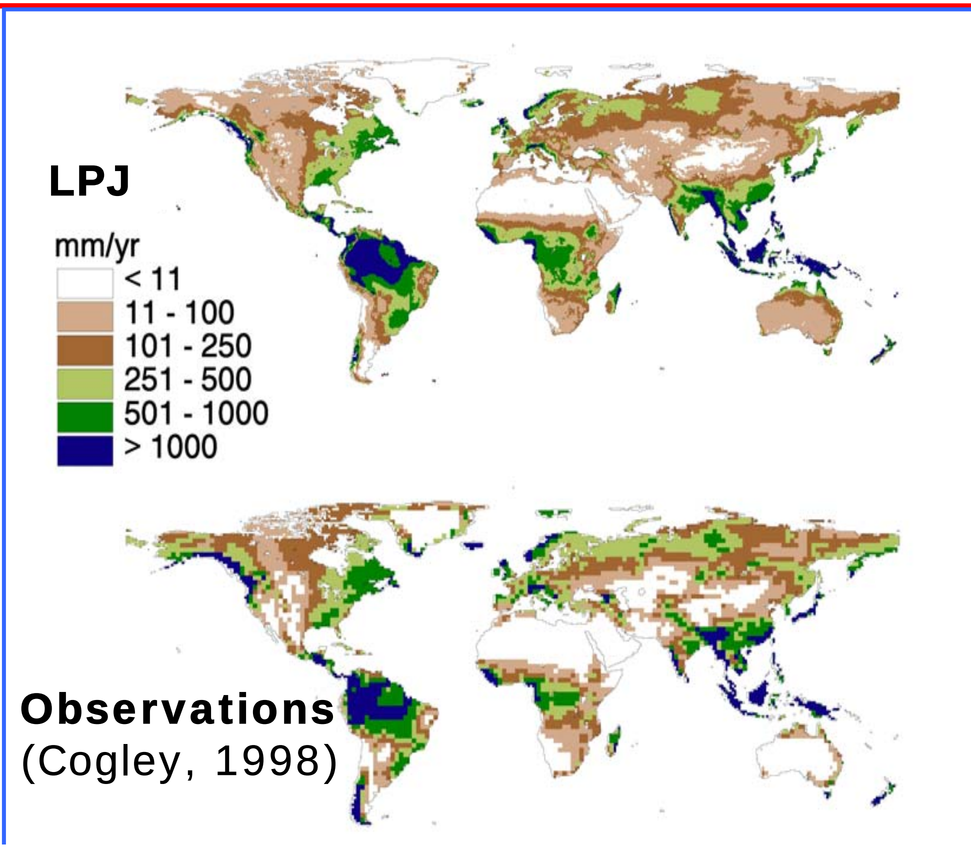






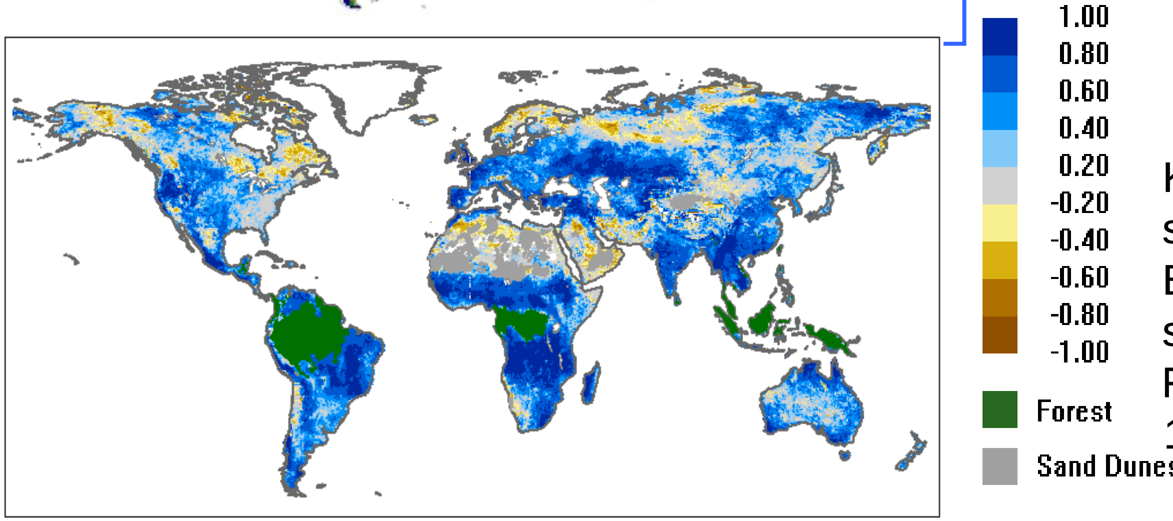
C budget, H_20 Budget, Vegetation Composition

Hydrological Validation



Runoff

Gerten et al. 2004



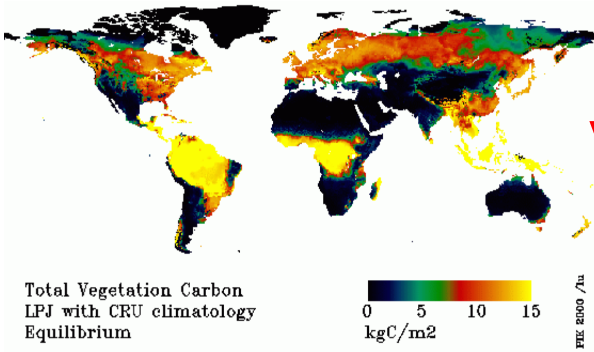
Soil moisture

Korrelationskoeffizient simulierte monatl. Bodenfeuchte vs. satellitengestützter Feuchteindex 1992–1998

Wagner et al. 2003

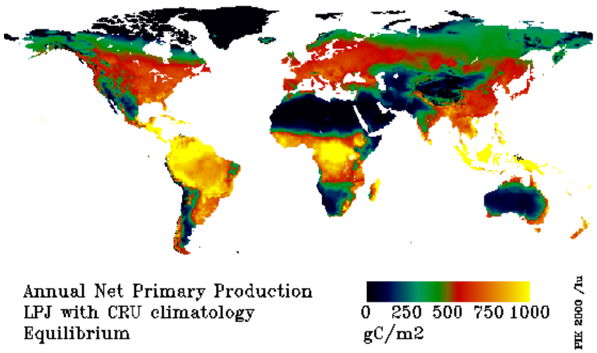
Biomass

Vegetation distribution



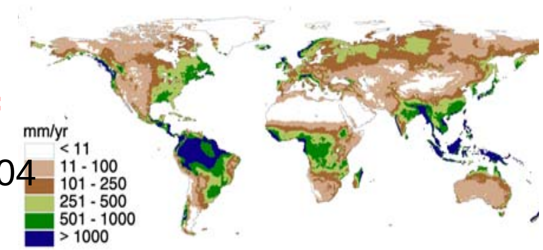
Sitch et al., GCB, 2003

NPP

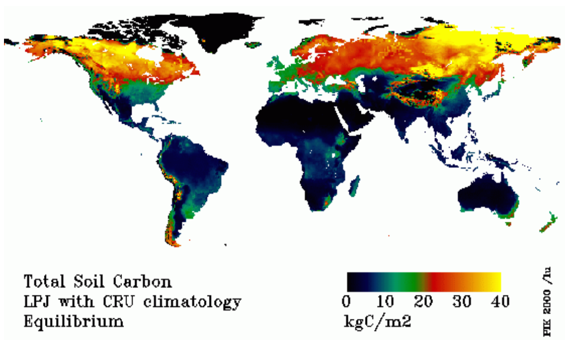


Runoff

Gerten et al., J. Hydrol., 2004

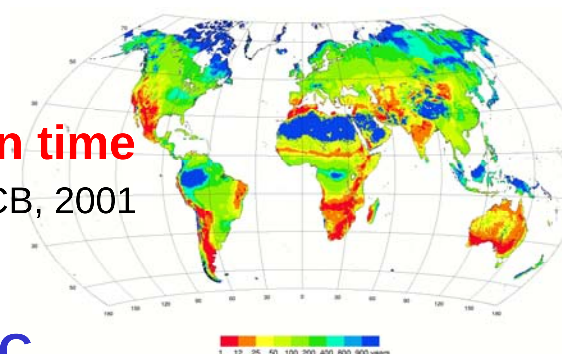


Soil C

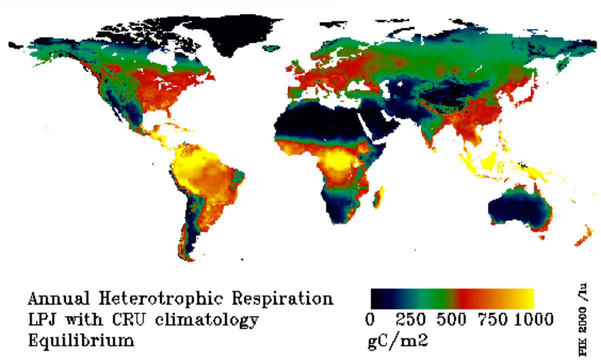


Fire return time

Thonicke et al., GCB, 2001

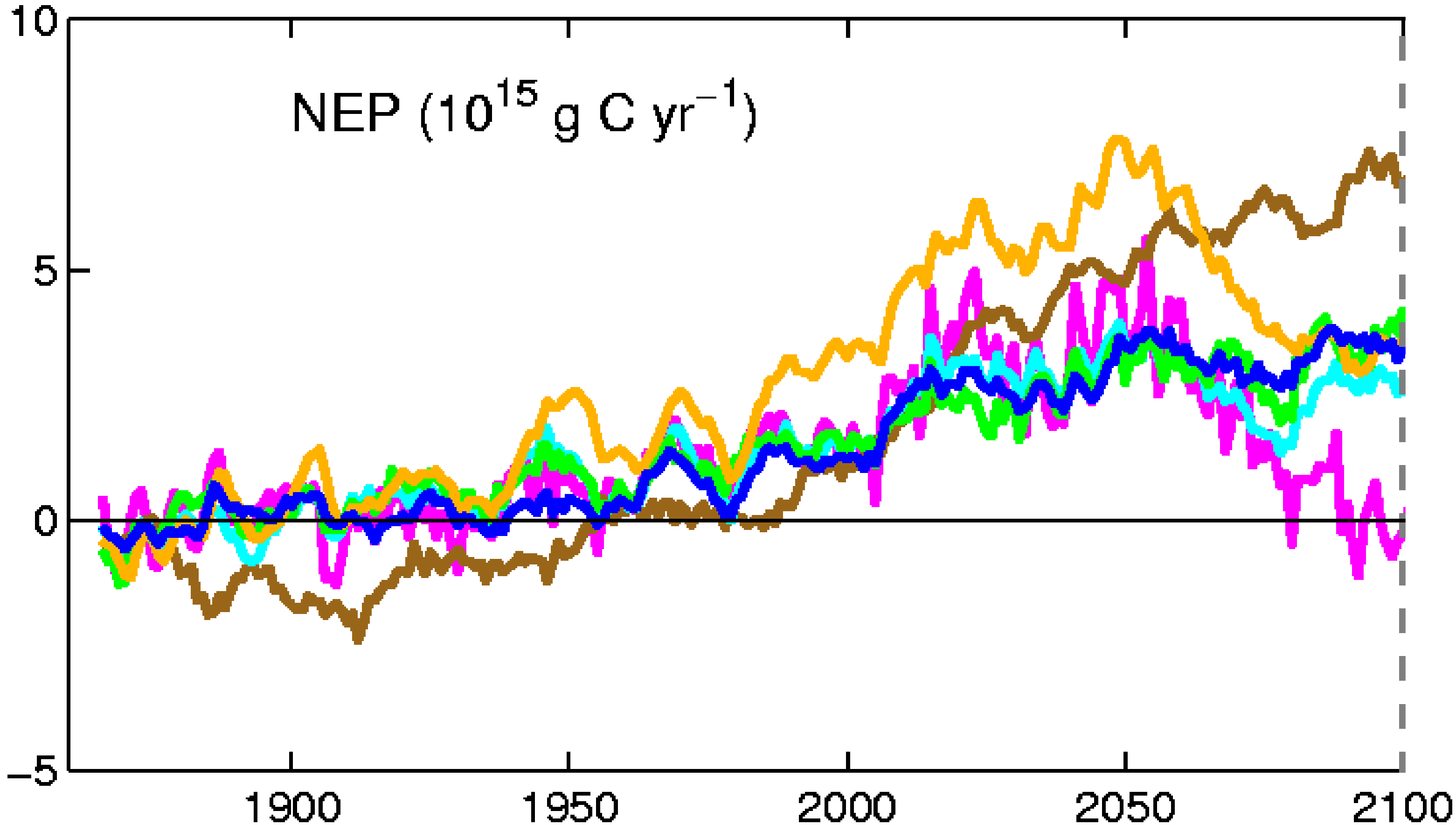


Soil C Dynamics



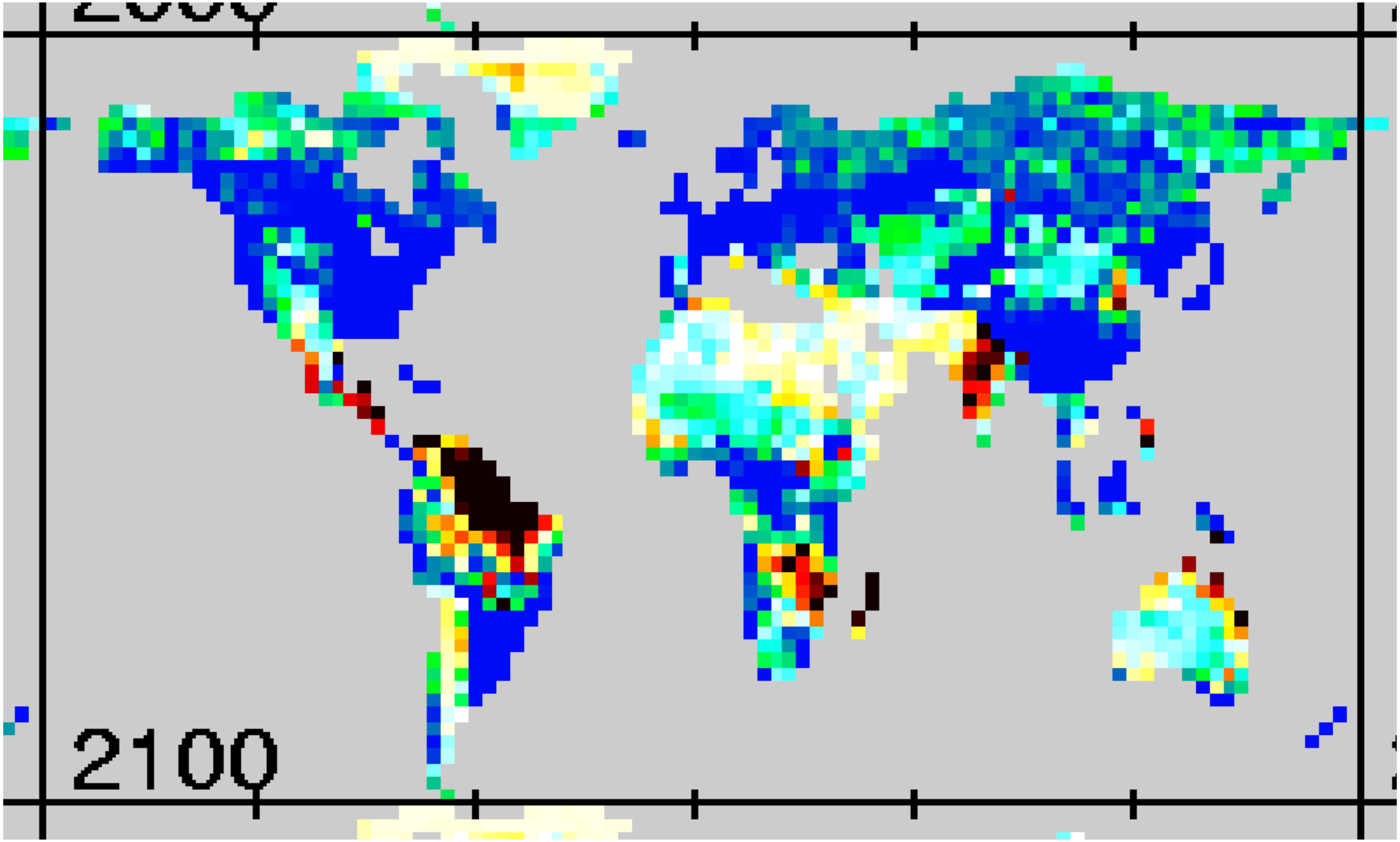
Sitch et al., GCB, 2003

Nettoökosystemproduktivität (NEP)



Nettoökosystemproduktivität

(g C m^{-2} y^{-2})

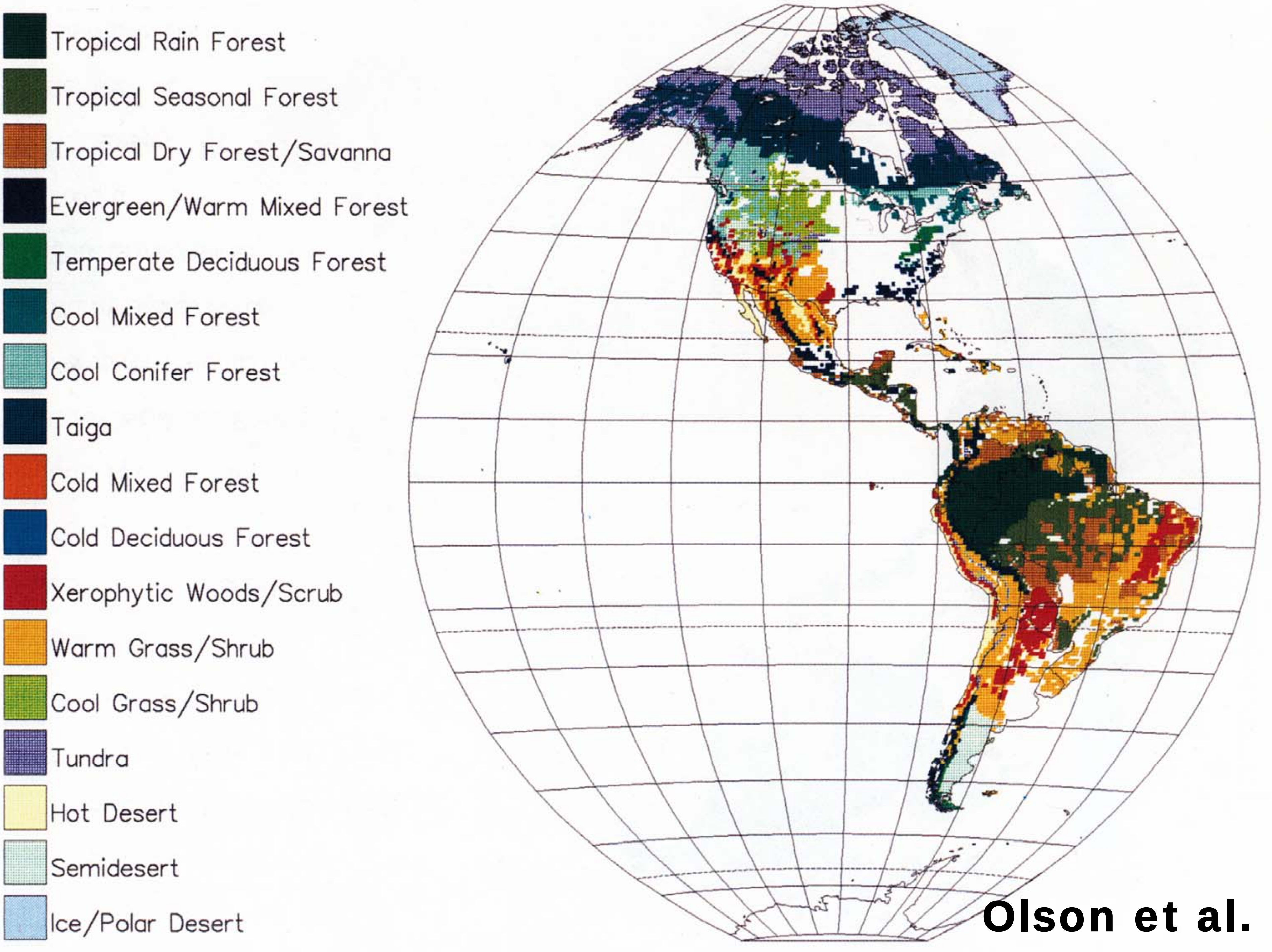


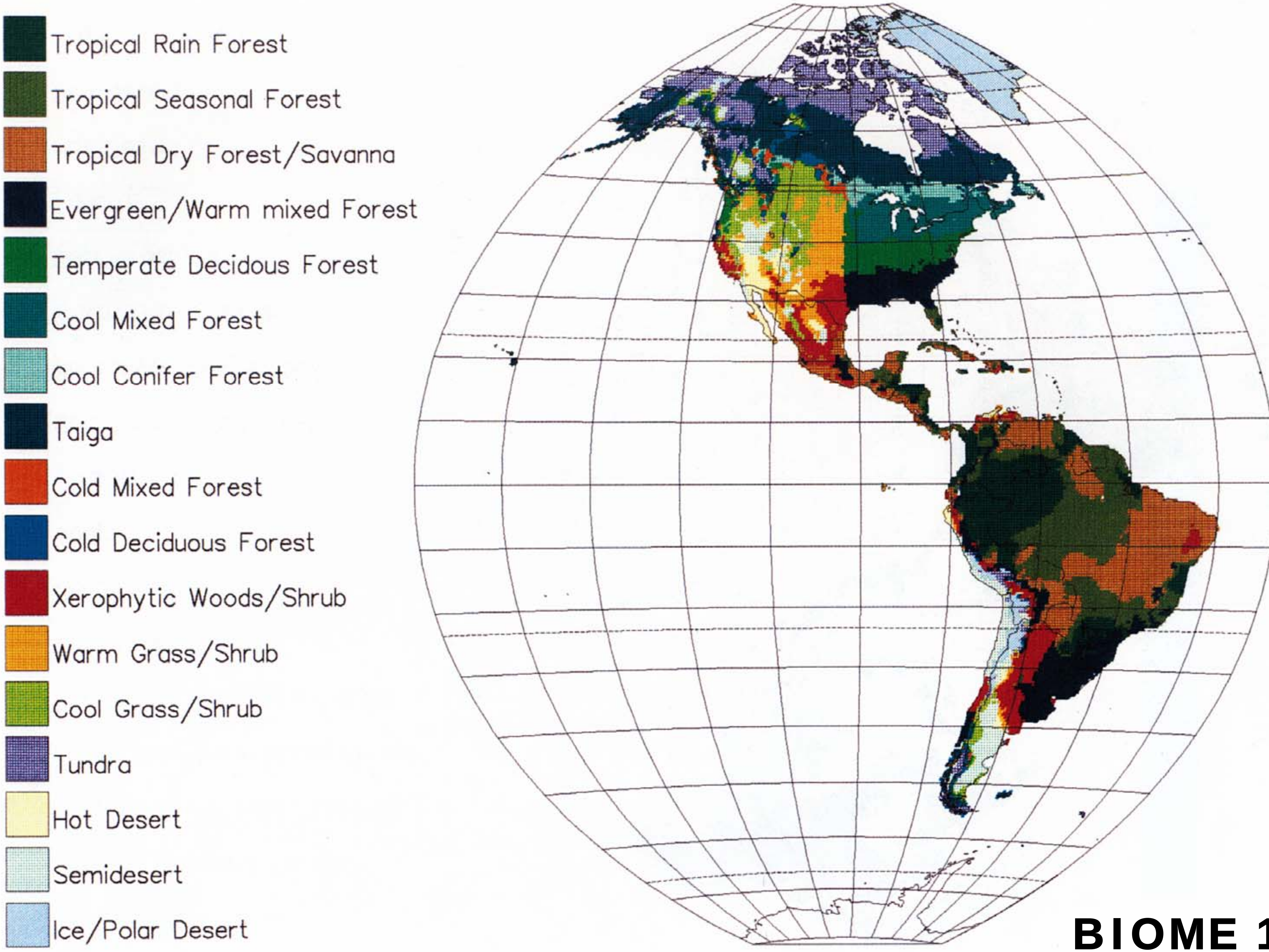
La modélisation des surfaces continentales en relation avec les changements climatiques

- Why *model* the (terrestrial) biosphere?
- A historical overview
- **Data issues**
- Critical gaps in understanding
- Intermediate complexity models
- Land use and land use change
- Recent and future applications

Data issues

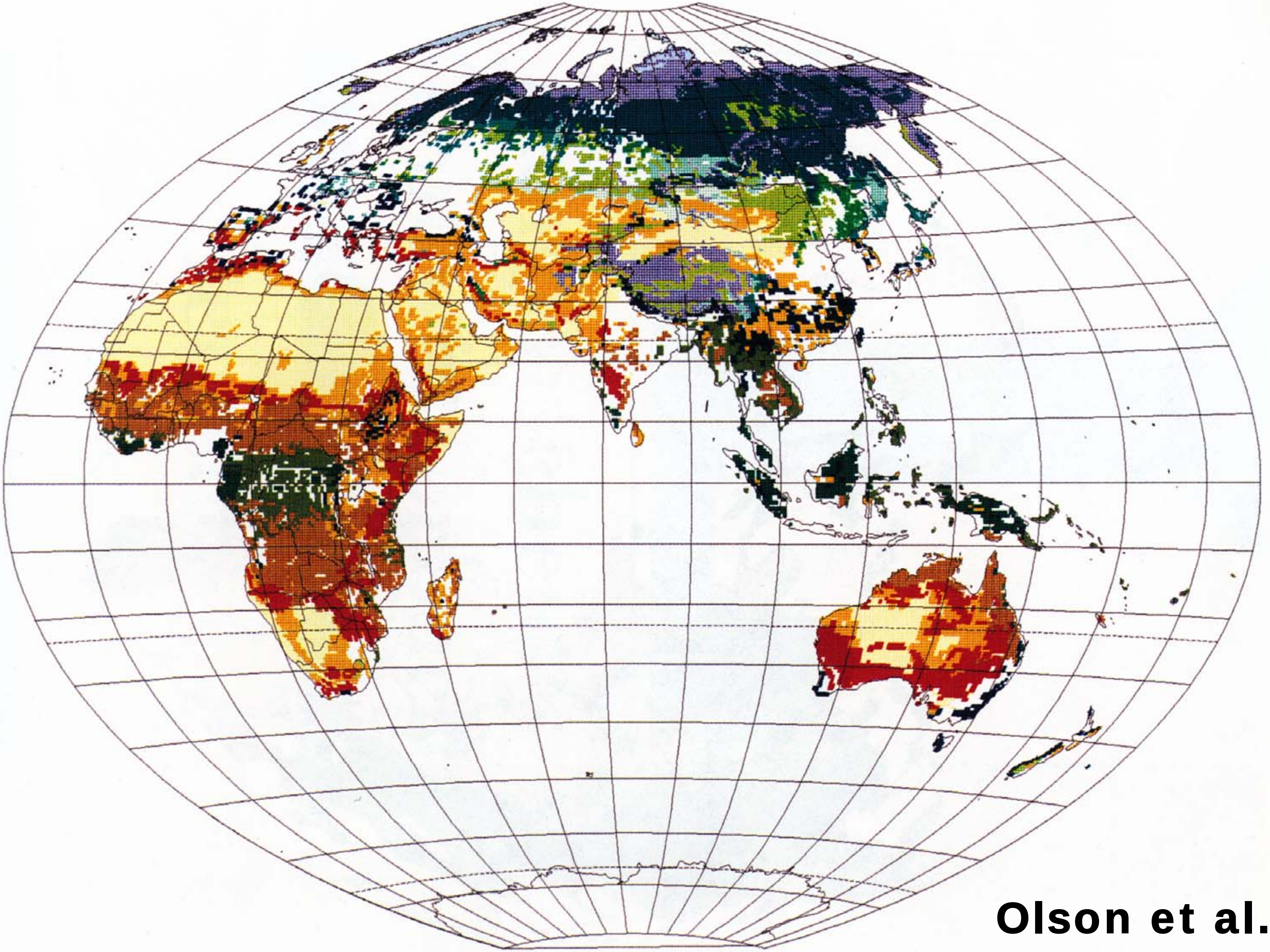
- „Driving“ data (climate, soils, CO_2, nutrients, etc.)
- Data for model testing (vegetation distribution, biogeochemical fluxes etc.)
- Appropriate spatial resolution


Tropical Rain Forest
Tropical Seasonal Forest
Tropical Dry Forest/Savanna
Evergreen/Warm Mixed Forest
Temperate Deciduous Forest
Cool Mixed Forest
Cool Conifer Forest
Taiga
Cold Mixed Forest
Cold Deciduous Forest
Xerophytic Woods/Scrub
Warm Grass/Shrub
Cool Grass/Shrub
Tundra
Hot Desert
Semidesert
Ice/Polar Desert
Olson et al.

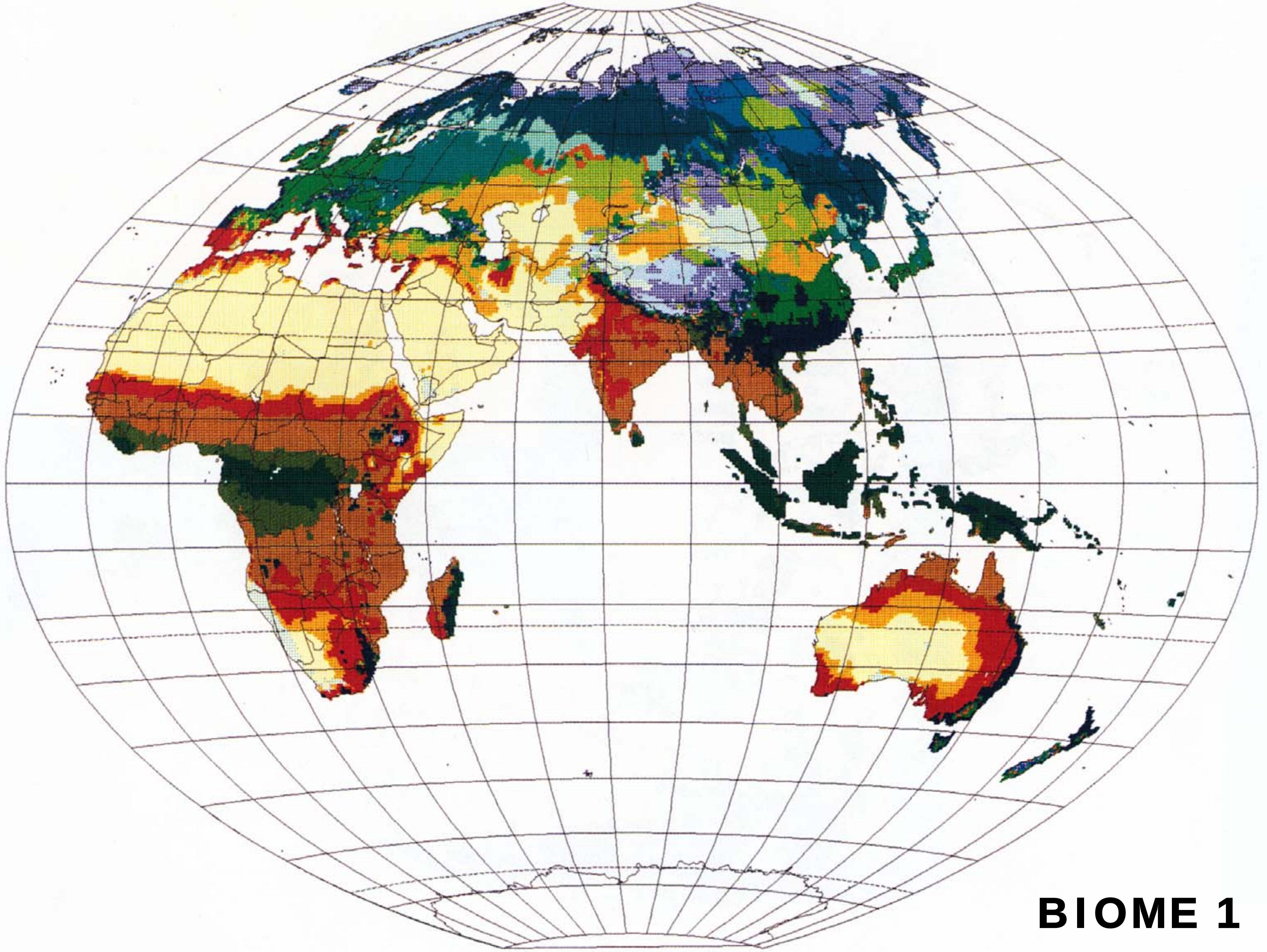


Tropical Rain Forest
Tropical Seasonal Forest
Tropical Dry Forest/Savanna
Evergreen/Warm mixed Forest
Temperate Decidous Forest
Cool Mixed Forest
Cool Conifer Forest
Taiga
Cold Mixed Forest
Cold Deciduous Forest
Xerophytic Woods/Shrub
Warm Grass/Shrub
Cool Grass/Shrub
Tundra
Hot Desert
Semidesert
Ice/Polar Desert

BIOME 1



Olson et al.


BIOME 1

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Critical gaps in understanding

- The importance of site history
- Soil carbon dynamics
- Ecosystem response to high atmospheric CO_2 concentrations
- Biodiversity (how many PFTs are sufficient?)
- Plant-animal interactions

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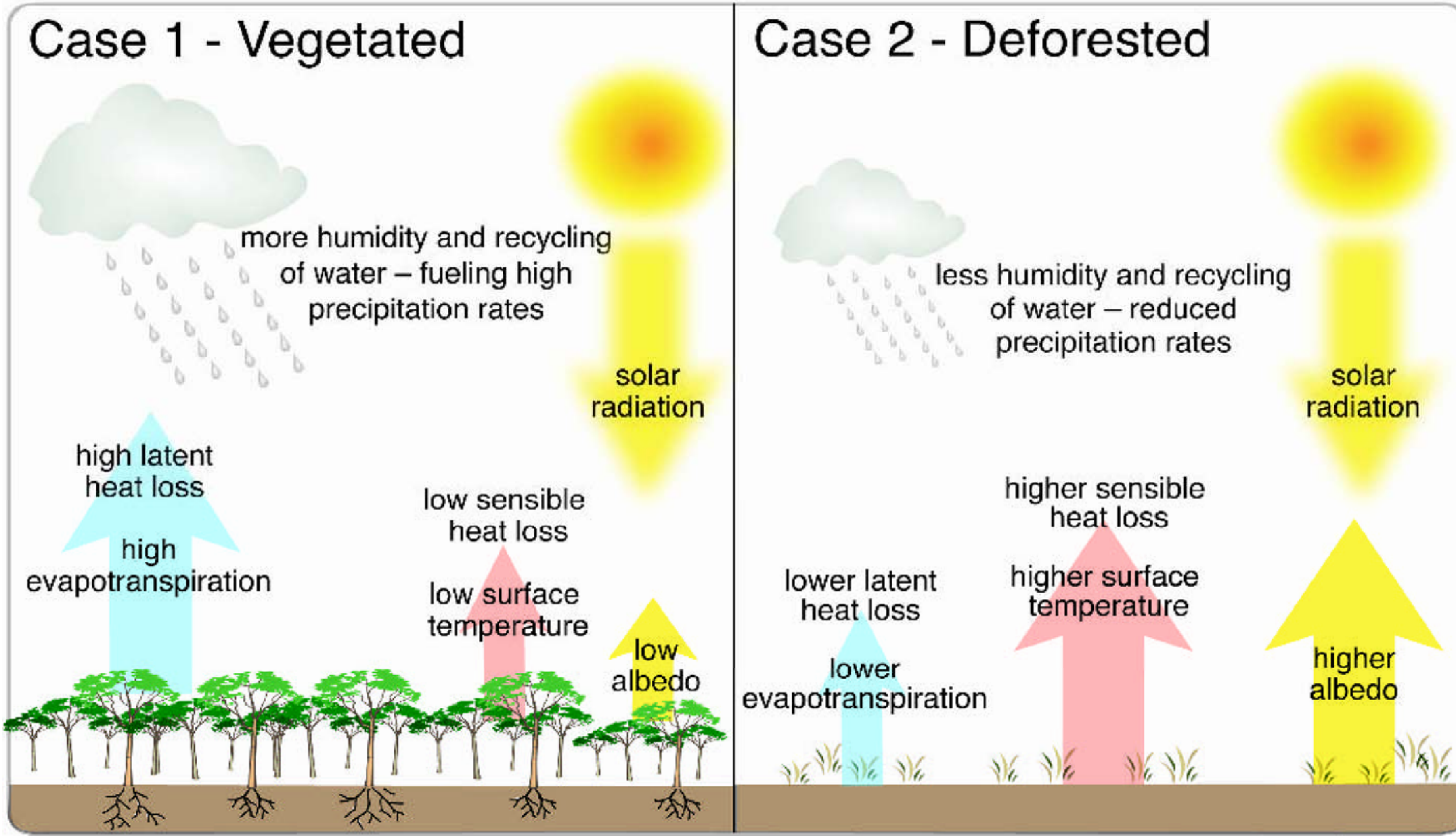
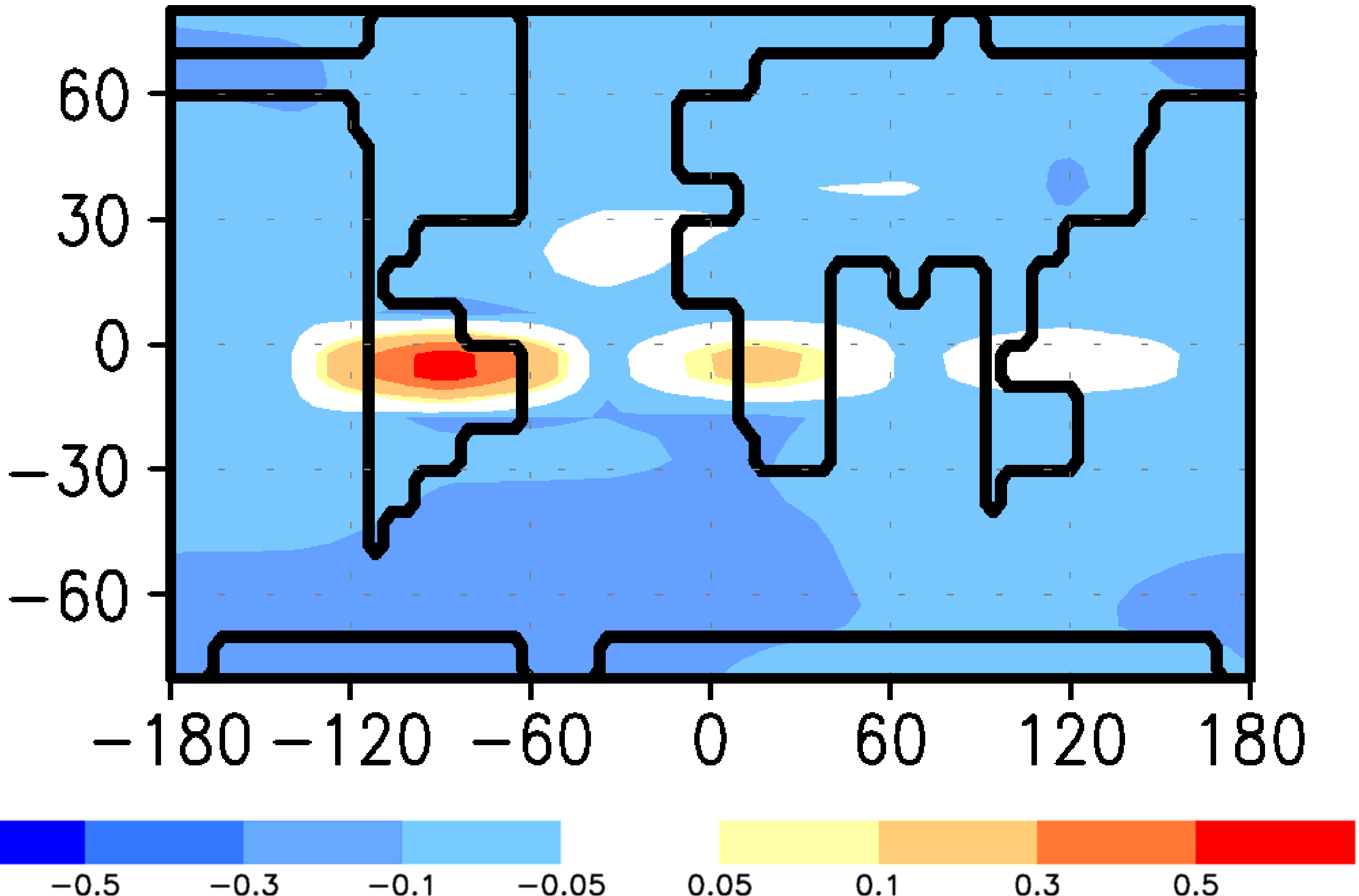
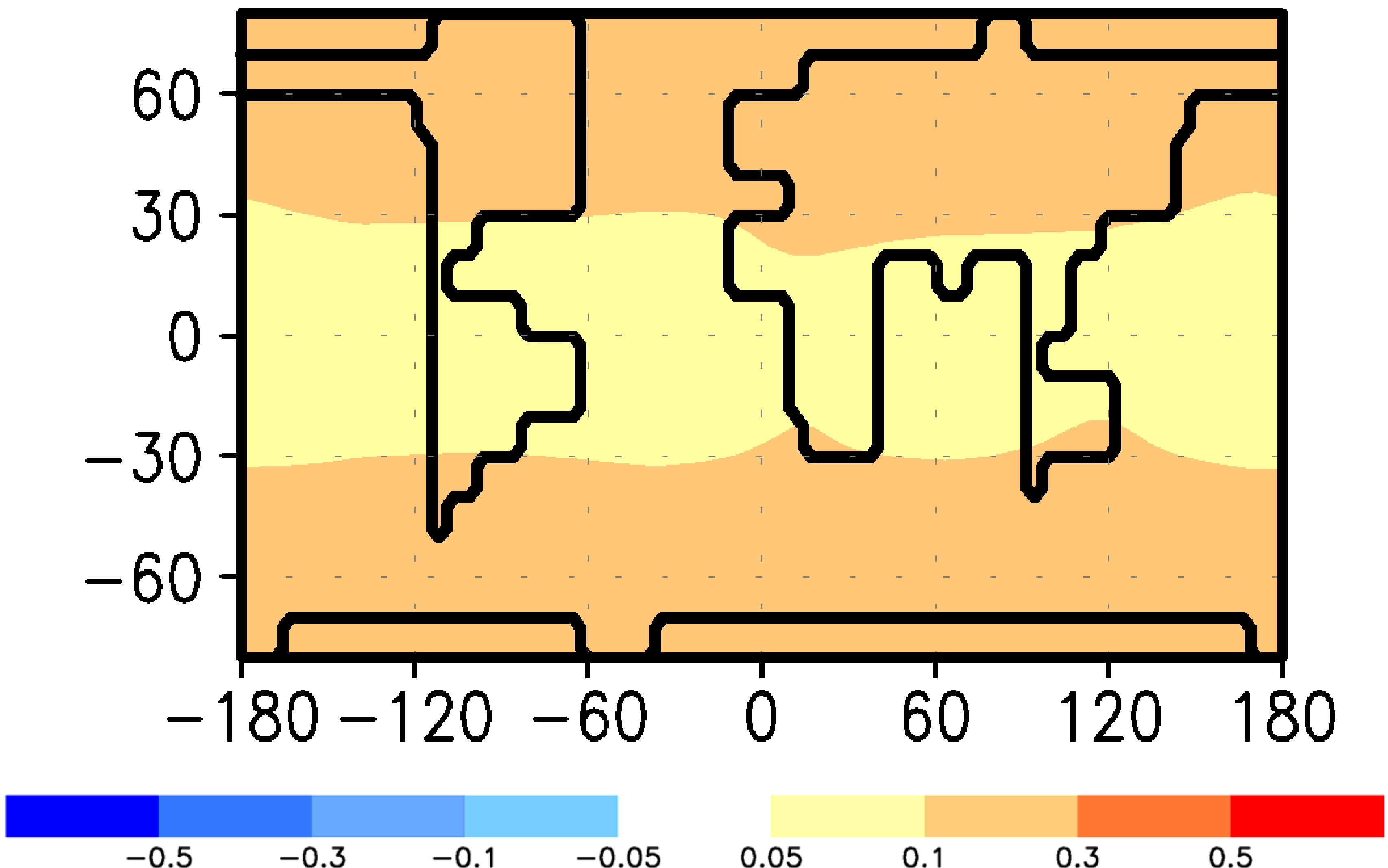

Case 1 - Vegetated
more humidity and recycling of water – fueling high precipitation rates
solar radiation
high latent heat loss
high evapotranspiration
low sensible heat loss
low surface temperature
low albedo
Case 2 - Deforested
less humidity and recycling of water – reduced precipitation rates
solar radiation
higher sensible heat loss
higher surface temperature
lower latent heat loss
lower evapotranspiration
higher albedo

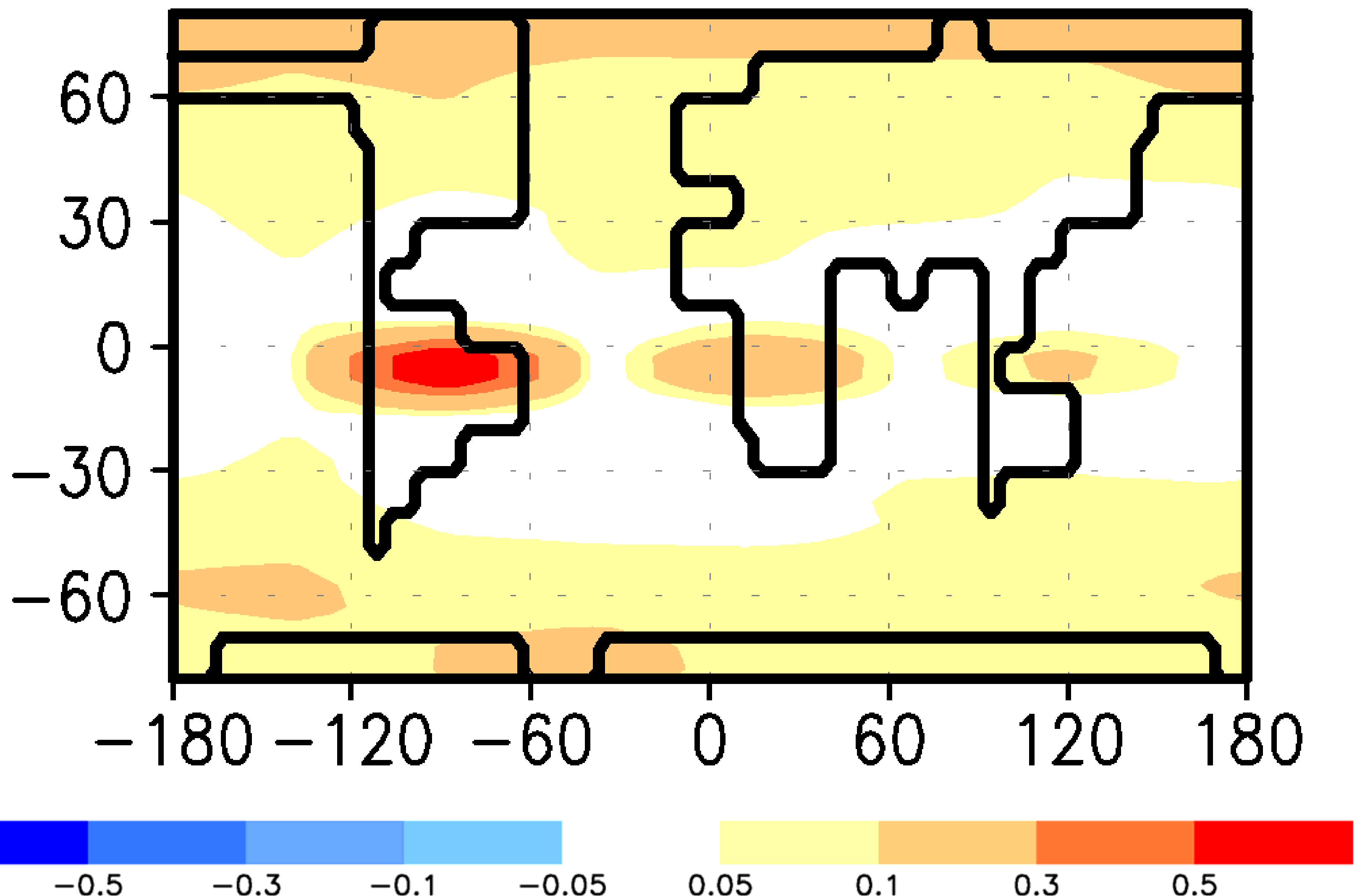
Tropical deforestation: physical impacts

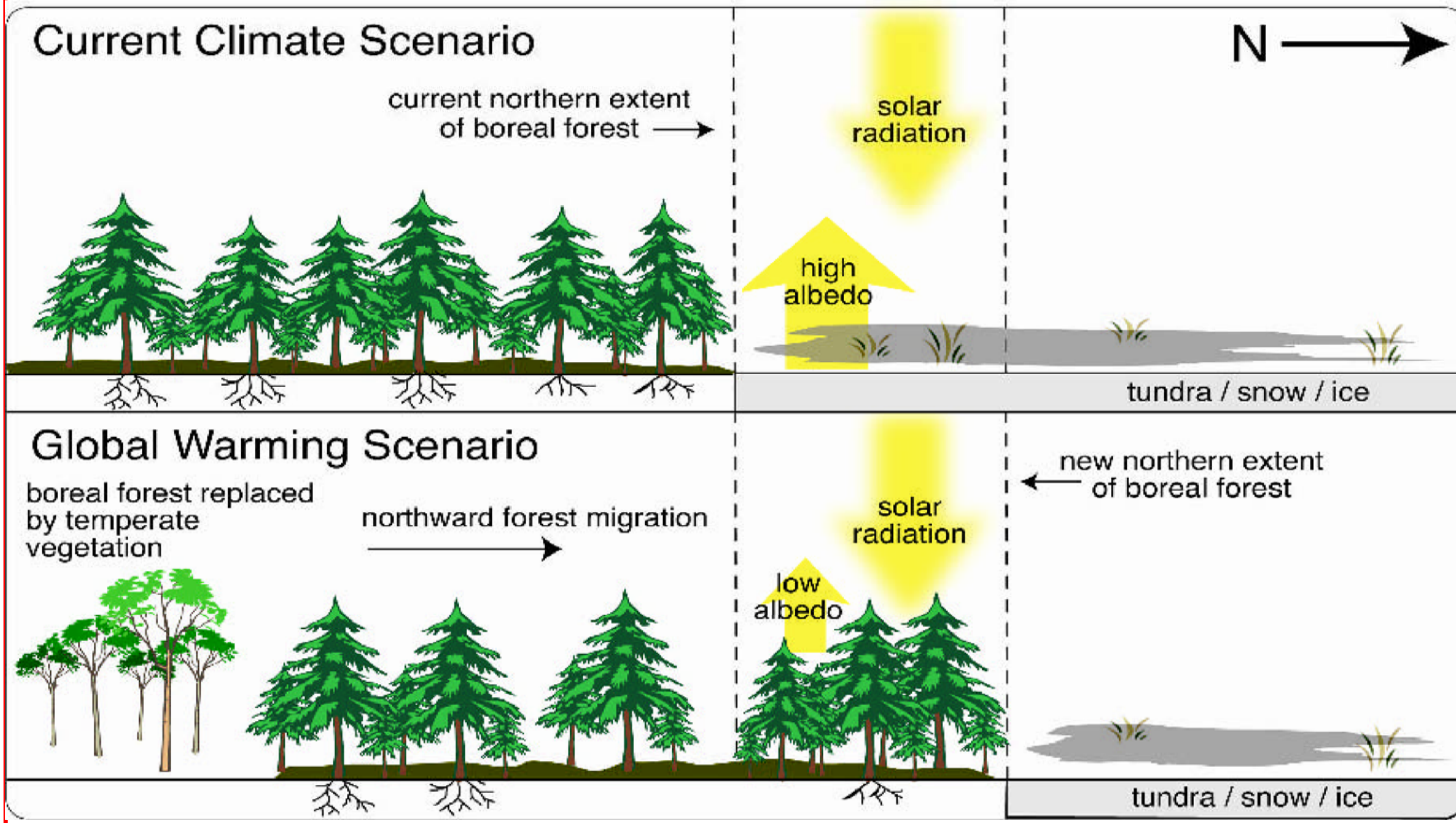


Tropical deforestation: biogeochemical impacts



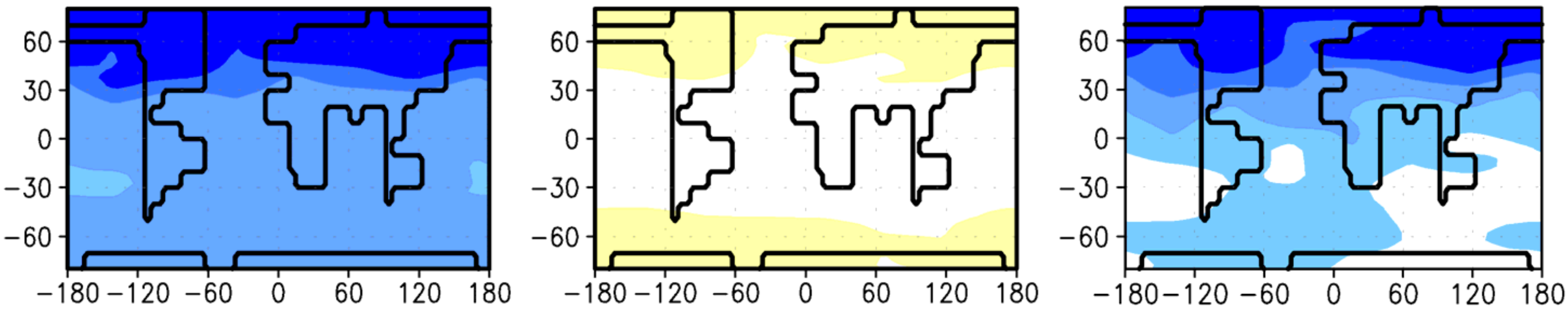
Tropical deforestation: combined impacts



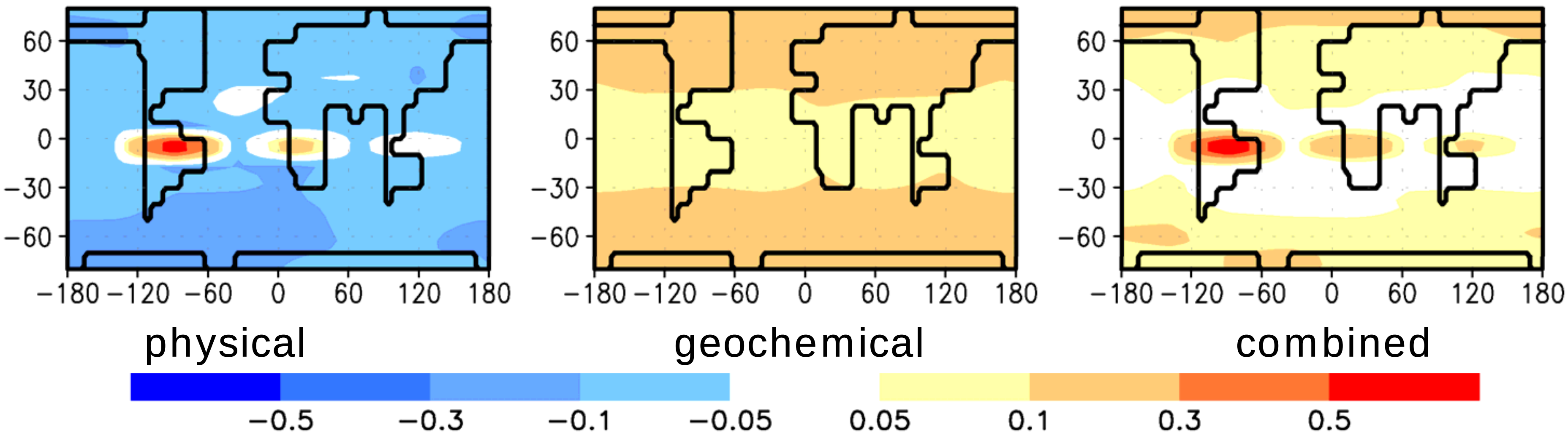

Current Climate Scenario
N
current northern extent
of boreal forest
solar
radiation
high
albedo
tundra / snow / ice
Global Warming Scenario
boreal forest replaced
by temperate
vegetation
northward forest migration
solar
radiation
low
albedo
new northern extent
of boreal forest
tundra / snow / ice

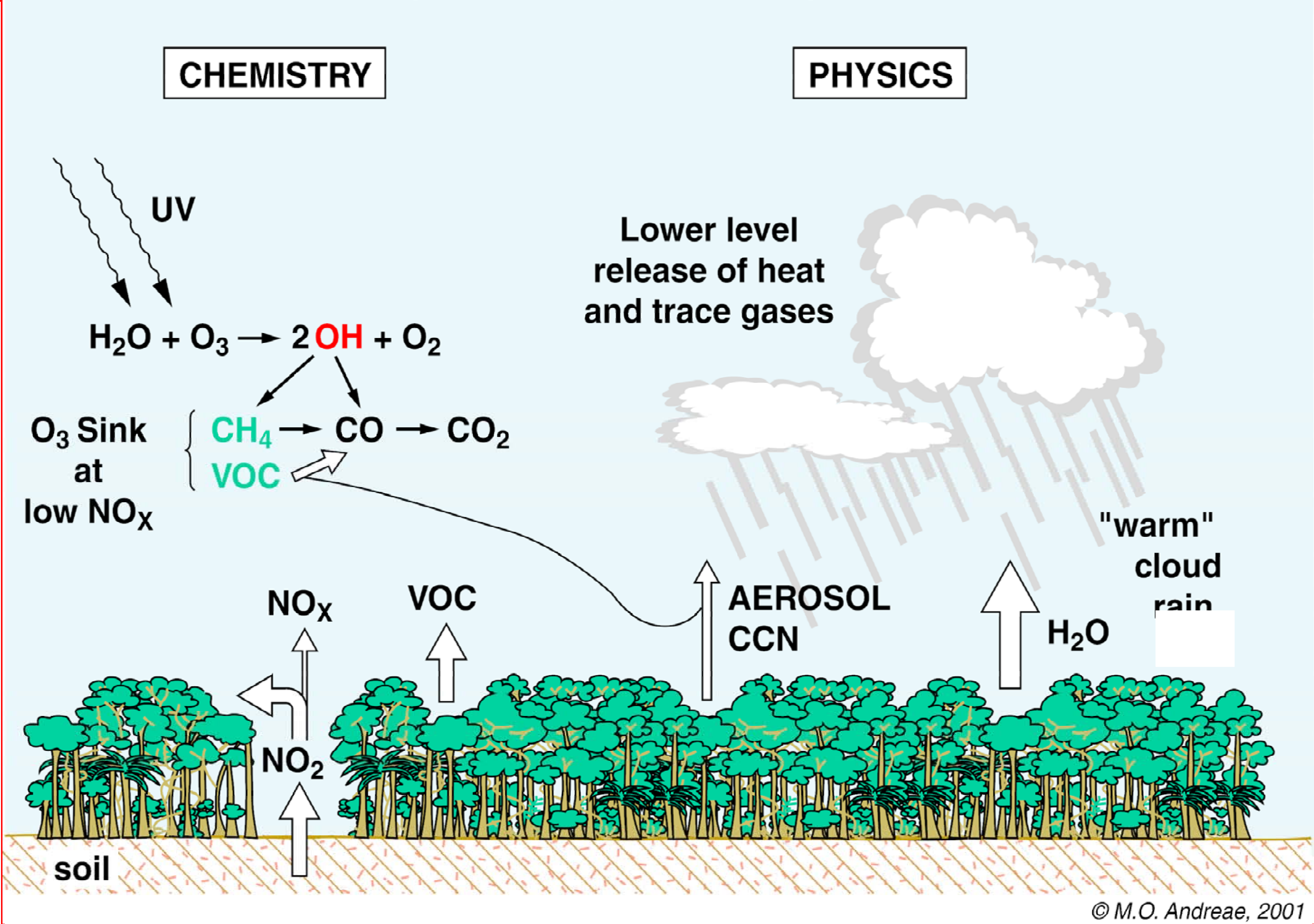
Impacts of deforestation on high and low latitudes

Total deforestation 50-60 °N:

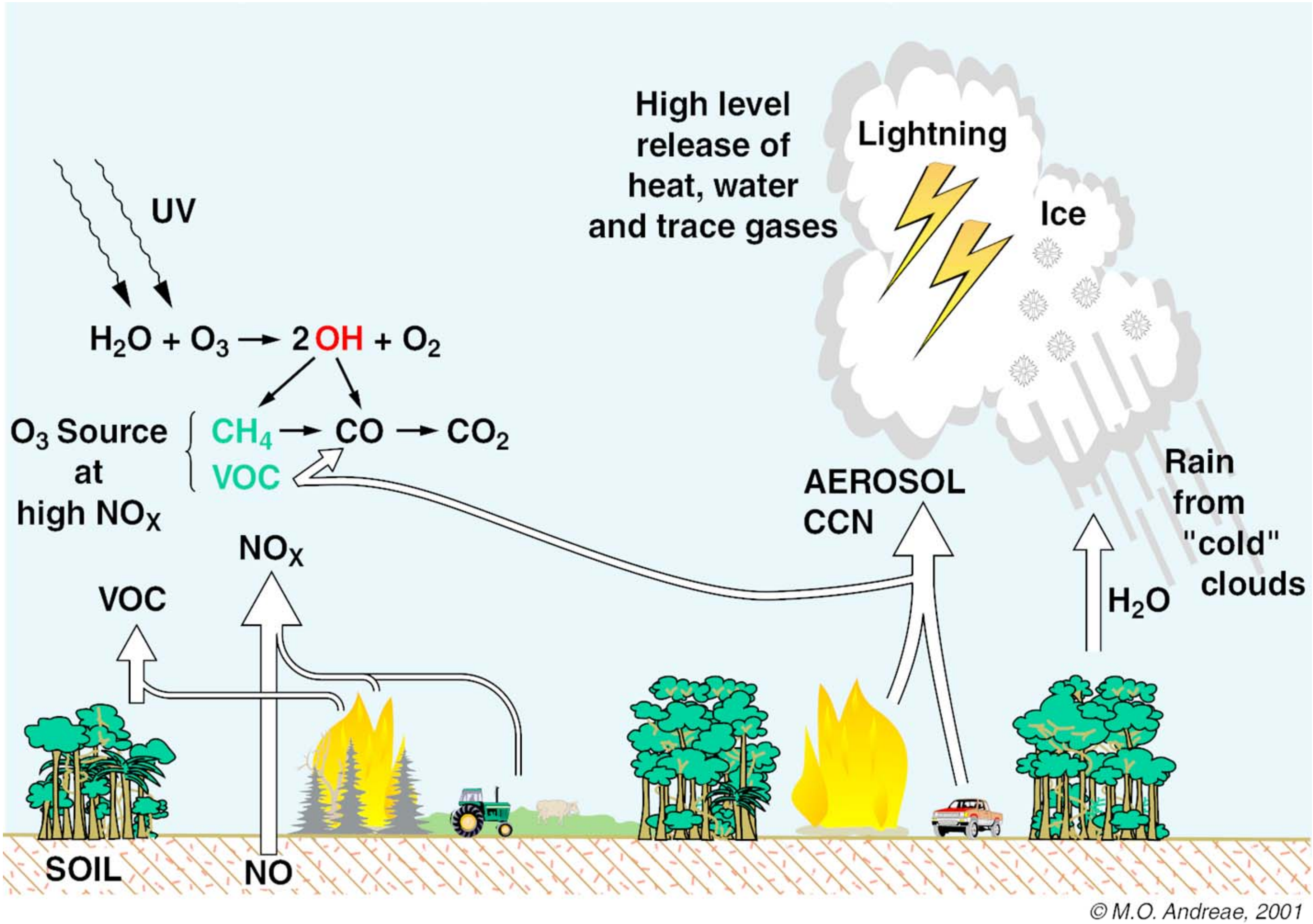


Total deforestation 0-10 °S:





CHEMISTRY
PHYSICS
UV
$H_2O + O_3 \rightarrow 2\,OH + O_2$
O_3 Sink at low NO_X
$CH_4 \rightarrow CO \rightarrow CO_2$
VOC
Lower level release of heat and trace gases
"warm" cloud rain
NO_X
VOC
AEROSOL
CCN
H_2O
NO_2
soil
© M.O. Andreae, 2001


UV
$H_2O + O_3 \rightarrow 2\,OH + O_2$
O_3 Source at high NO_X
$CH_4 \rightarrow CO \rightarrow CO_2$
VOC
NO_X
VOC
SOIL
NO
High level release of heat, water and trace gases
Lightning
Ice
AEROSOL CCN
Rain from "cold" clouds
H_2O
© M.O. Andreae, 2001

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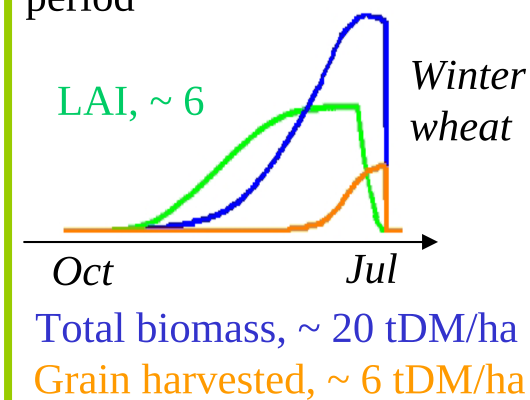
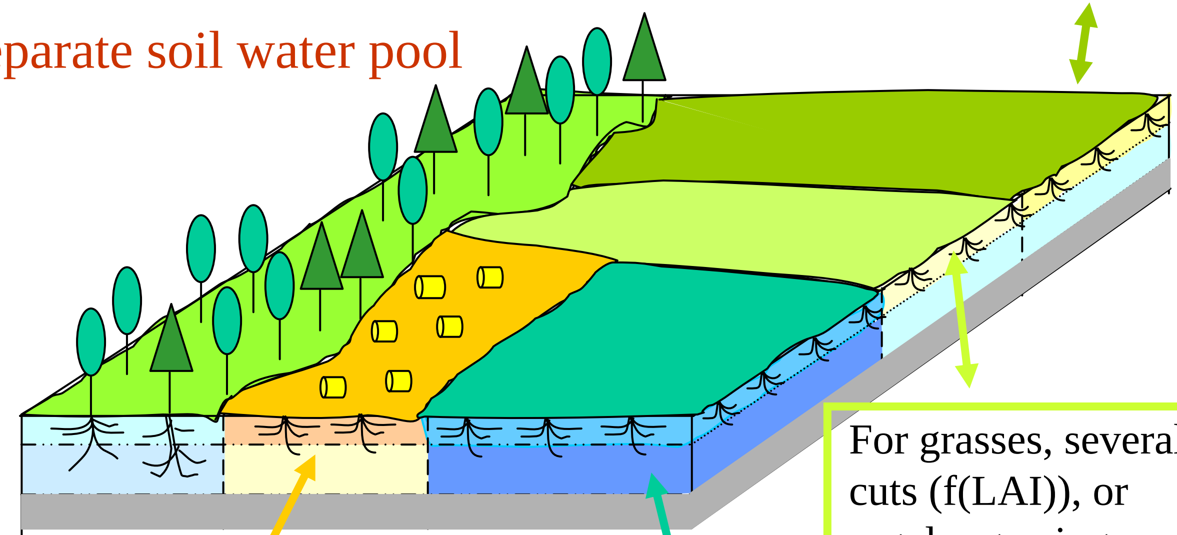
Implementation of agriculture within LPJ – how?

Adaptation of LPJ to simulate the carbon and water fluxes for crops: each CFT on a distinct stand with access to a separate soil water pool

Sowing date estimation:
for 4 temperate CFTs = f(T),
for 4 tropical CFTs = f(P)
Adaptation of heat sum and vernalization requirement

Daily coupled growth and development simulation:
Phenology, LAI change, carbon allocation to leaves, roots, storage organs, ...
Estimation of the harvesting period



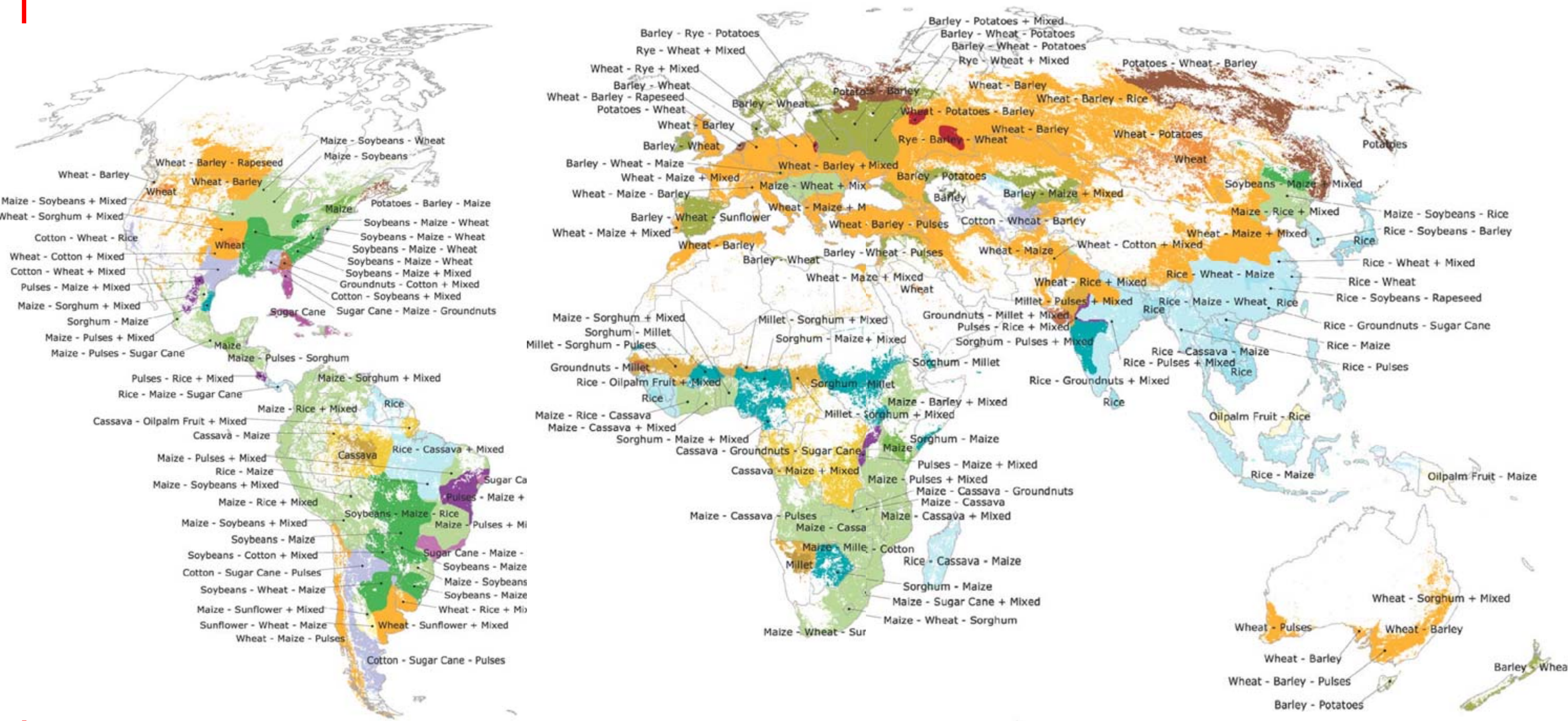


For grasses, several cuts (f(LAI)), or regular grazing

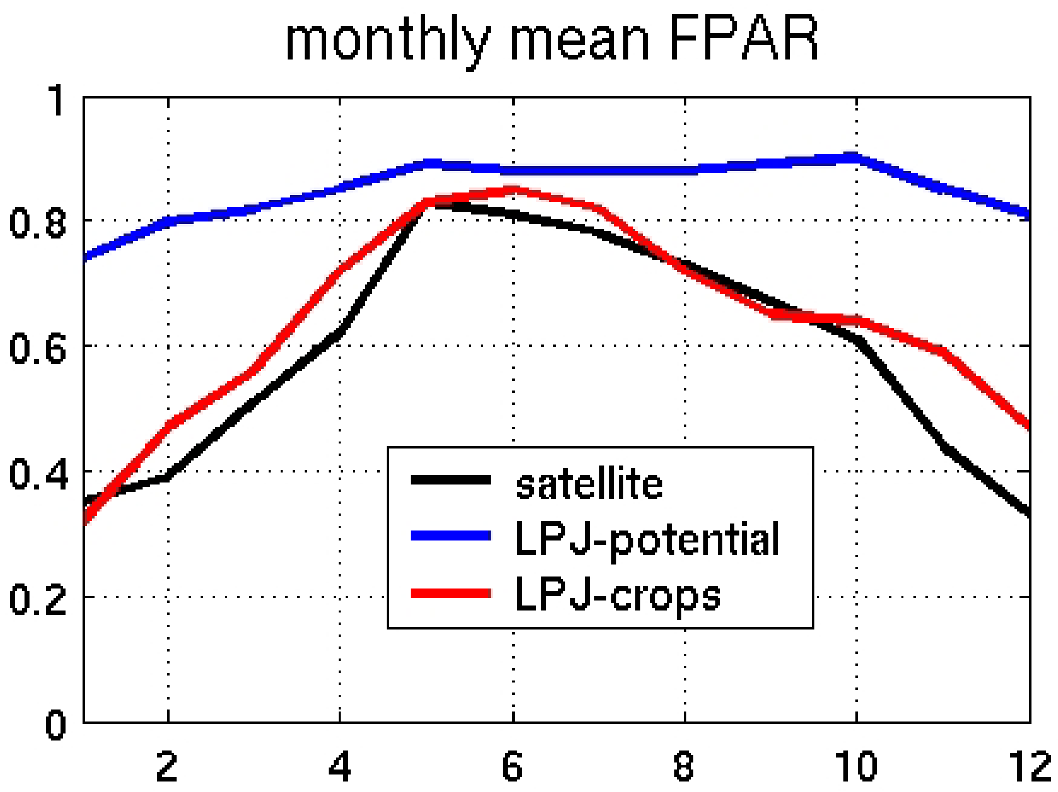
Harvested biomass removed, residues sent to the litter pool or removed (fodder, biofuel, ...)

No water stress for irrigated crops, computation of the water requirement and of the effective irrigation

Possibility of multiple cropping (e.g. rice)
Grass during the intercrop season otherwise



1b) Distribution of the major 19 crops types *(Leff et al. 2004)*



Phenological variations for the European temperate zone
[10°W-32°E; 34°N-72°N], period 1982-1998

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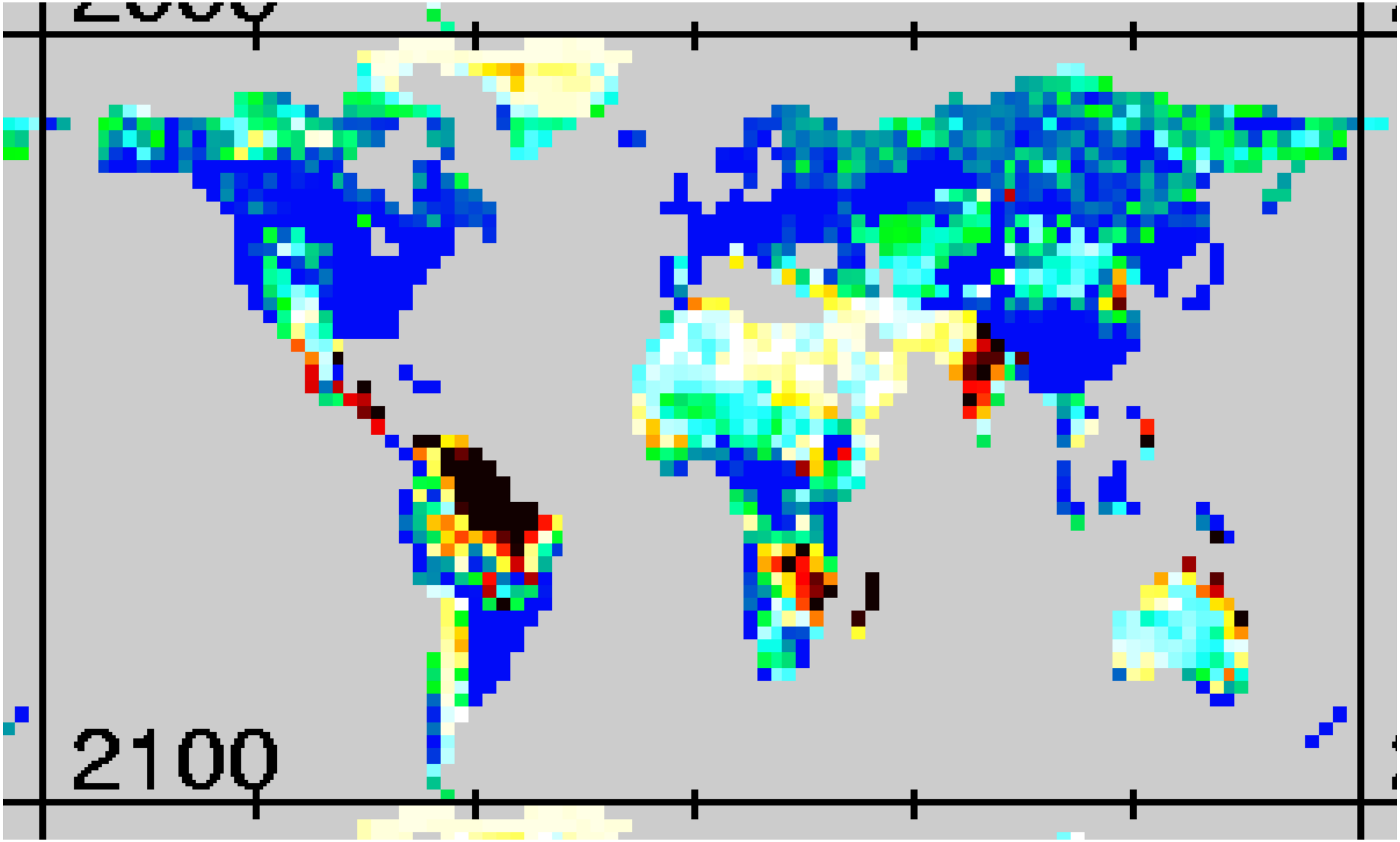
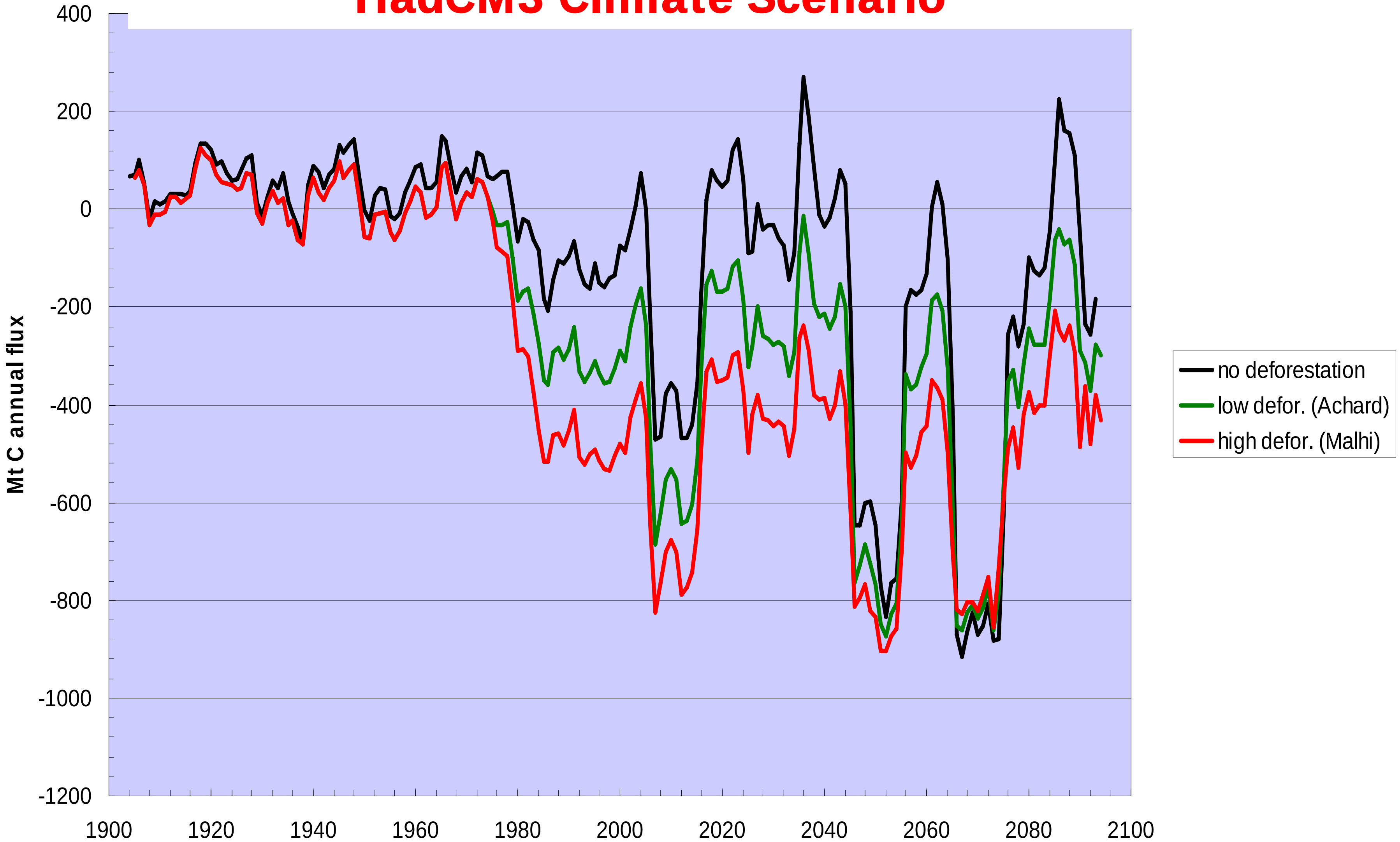
Nettoökosystemproduktivität

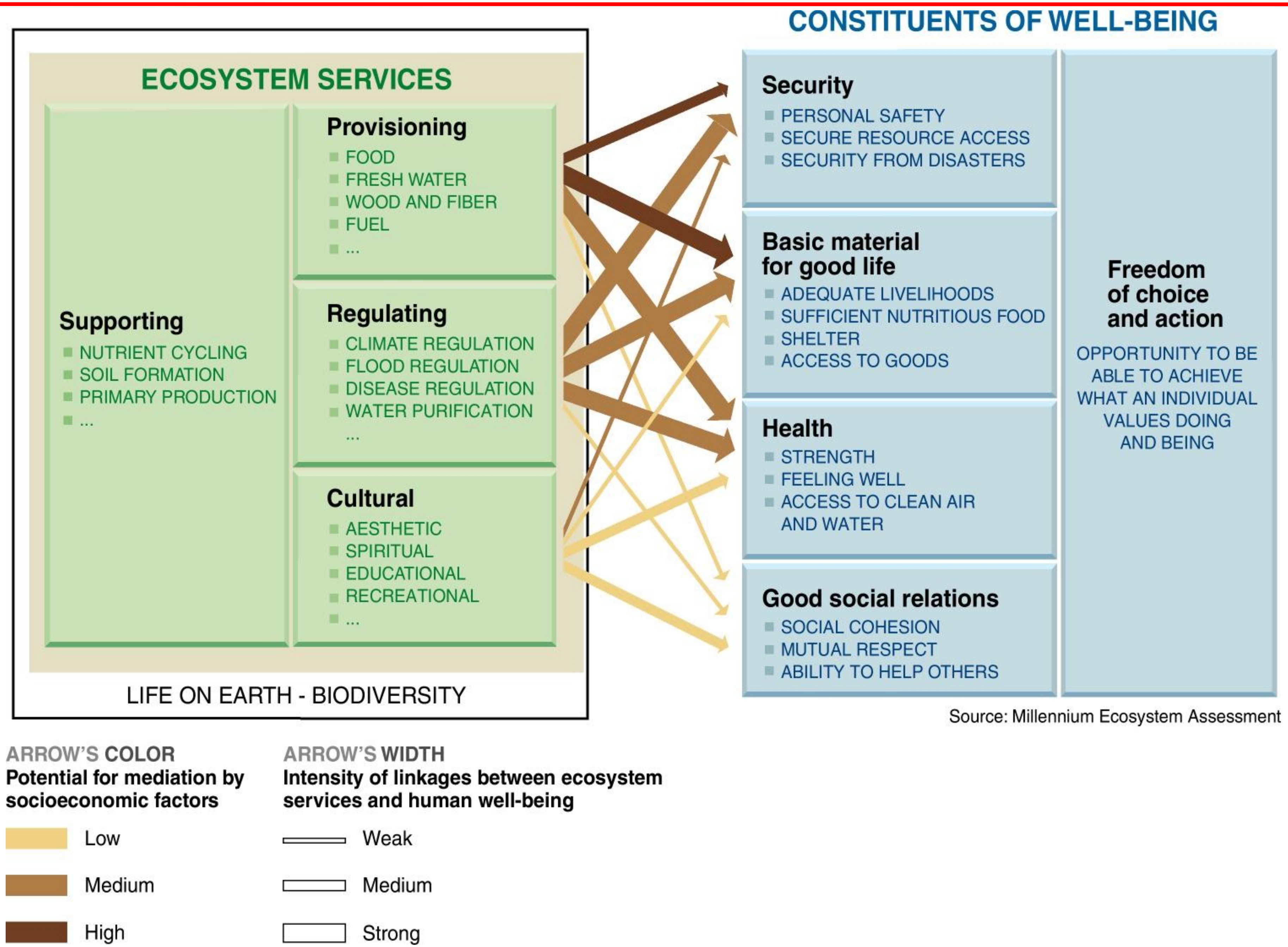
(g C m^{-2} y^{-2})



C balance of the Amazon for different rates of deforestation (10yr running means)

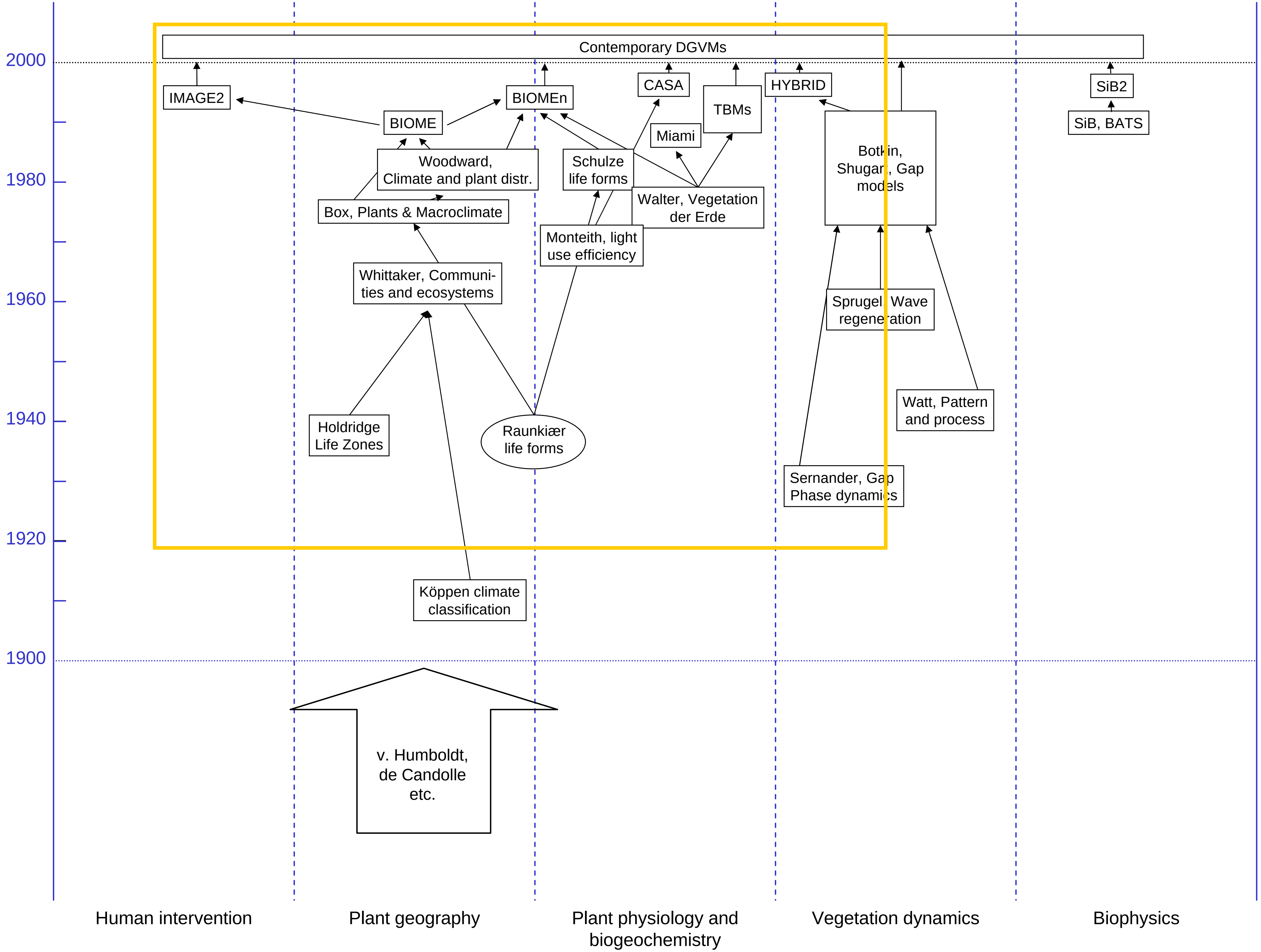
HadCM3 Climate Scenario



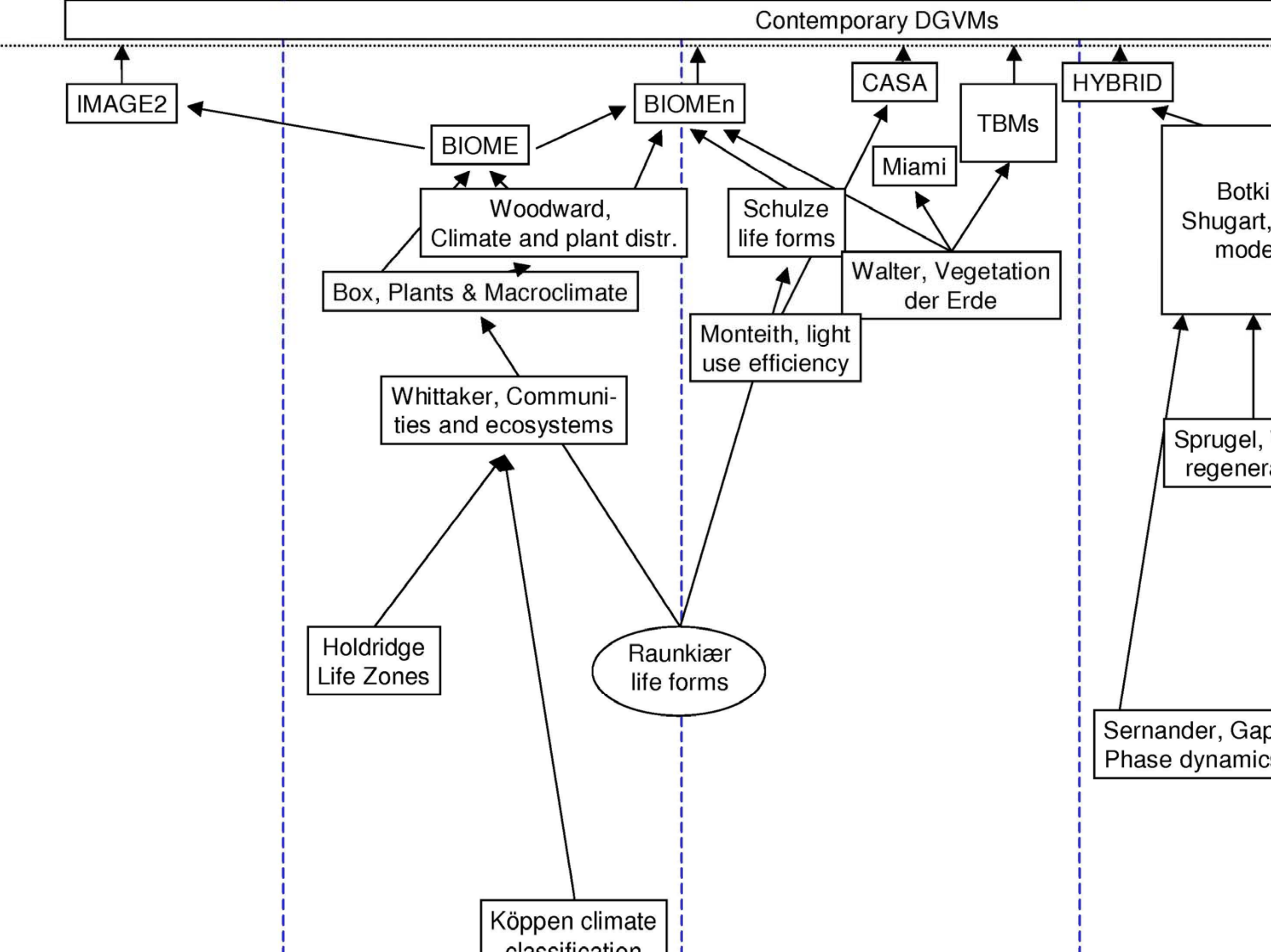

CONSTITUENTS OF WELL-BEING
ECOSYSTEM SERVICES
Provisioning
FOOD
FRESH WATER
WOOD AND FIBER
FUEL
...
Supporting
NUTRIENT CYCLING
SOIL FORMATION
PRIMARY PRODUCTION
...
Regulating
CLIMATE REGULATION
FLOOD REGULATION
DISEASE REGULATION
WATER PURIFICATION
...
Cultural
AESTHETIC
SPIRITUAL
EDUCATIONAL
RECREATIONAL
...
LIFE ON EARTH - BIODIVERSITY
Security
PERSONAL SAFETY
SECURE RESOURCE ACCESS
SECURITY FROM DISASTERS
Basic material for good life
ADEQUATE LIVELIHOODS
SUFFICIENT NUTRITIOUS FOOD
SHELTER
ACCESS TO GOODS
Health
STRENGTH
FEELING WELL
ACCESS TO CLEAN AIR AND WATER
Good social relations
SOCIAL COHESION
MUTUAL RESPECT
ABILITY TO HELP OTHERS
Freedom of choice and action
OPPORTUNITY TO BE ABLE TO ACHIEVE WHAT AN INDIVIDUAL VALUES DOING AND BEING
Source: Millennium Ecosystem Assessment
ARROW'S COLOR
Potential for mediation by socioeconomic factors
Low
Medium
High
ARROW'S WIDTH
Intensity of linkages between ecosystem services and human well-being
Weak
Medium
Strong

„Fully coupled“ Earth System models

- Biosphere coupled to atmosphere (physical and biogeochemical feedbacks) but also to anthroposphere (land use change and changed land use potential)
- Main problem: iterative modelling of climate & biosphere, optimization modelling of economic component (usually approximated through scenario analysis)



2000
1980
1960
1940
1920
1900
Contemporary DGVMs
IMAGE2
BIOME
BIOMEn
CASA
TBMs
HYBRID
SiB2
SiB, BATS
Miami
Woodward, Climate and plant distr.
Schulze life forms
Walter, Vegetation der Erde
Botkin, Shugart, Gap models
Box, Plants & Macroclimate
Monteith, light use efficiency
Whittaker, Communities and ecosystems
Sprugel, Wave regeneration
Watt, Pattern and process
Holdridge Life Zones
Raunkiær life forms
Sernander, Gap Phase dynamics
Köppen climate classification
v. Humboldt, de Candolle etc.
Human intervention
Plant geography
Plant physiology and biogeochemistry
Vegetation dynamics
Biophysics



Contemporary DGVMs
IMAGE2
BIOMEn
CASA
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TBMs
BIOME
Miami
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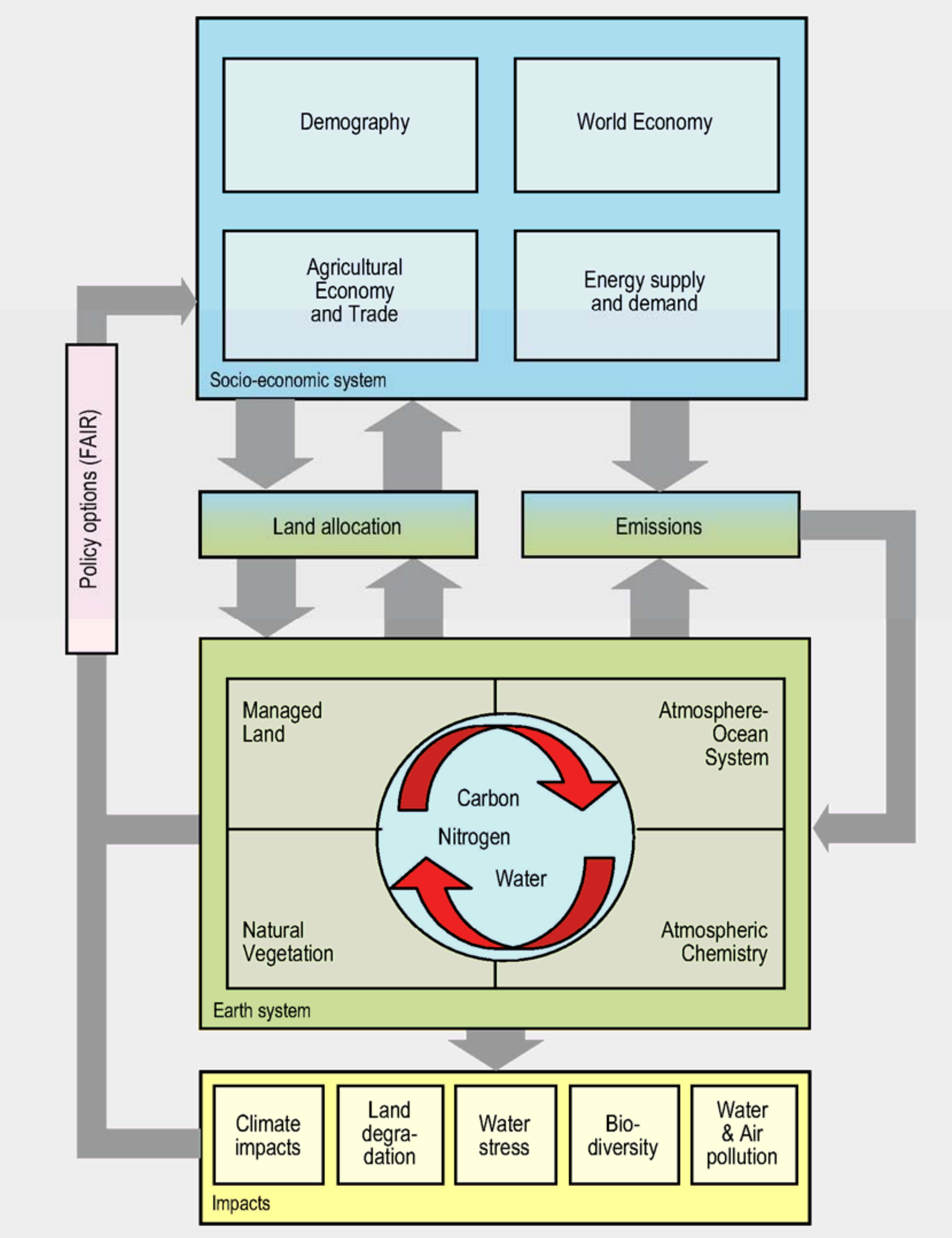
Shugart,
mode
Woodward,
Climate and plant distr.
Schulze
life forms
Walter, Vegetation
der Erde
Box, Plants & Macroclimate
Monteith, light
use efficiency
Whittaker, Communi-
ties and ecosystems
Sprugel,
regener
Holdridge
Life Zones
Raunkiær
life forms
Sernander, Gap
Phase dynamics
Köppen climate

The IMAGE Model 2.4



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Summary

- The land surface can be modelled for multiple purposes, requiring different methods
- Significant open questions remain about the carbon cycle and the potential future functioning of the land biosphere