SURFEX
The Carbon Options

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METEO FRANCE
Toujours un temps d'avance

The Carbon Options

- What?
  - Carbon fluxes
    - Photosynthesis ; Ecosystem respiration ; Net ecosystem exchange
  - Vegetation characteristics
    - LAI
    - Above-ground biomass ; Below-ground biomass
  - Carbon storage
    - Soil organic matter ; Litter ; Wood

The Carbon Options

- Why?
  - New applications
    - Kyoto protocol ; Climate modelling ; Environmental monitoring
  - Need to account for
    - CO_2 effet ; diverse responses to drought
    - C3 vs. C4 plants ; herbaceous vs. woody vegetation
  - LAI fully consistent with
    - Water and carbon fluxes ; soil moisture
  - More variables to validate/control the model
    - Assimilation of satellite data

The Carbon Options

- Where?
  - ISBA-A-gs
    - « AGS »: basic drought response, no interactive LAI, no a-g biomass
    - « LAI »: basic drought response, **interactive LAI**, no a-g biomass
    - « AST »: **drought-avoiding/tolerant**, no interactive LAI, no a-g biomass
    - « LST »: **drought-avoiding/tolerant**, **interactive LAI**, no a-g biomass
    - « NIT »: **drought-avoiding/tolerant**, **interactive LAI**, **a-g biomass**
  - ISBA-CC
    - **Below-ground biomass, wood, heterotrophic respiration**
    - Prototype SURFEX version
    - To be issued soon

The Carbon Options

- How?

  - The ISBA-A-gs model
    - Photosynthesis (Jacobs et al. 1996)
    - Meta-analysis of the response to drought (Calvet 2000, Calvet et al. 2004)
    - Plant growth (Calvet et al. 1998, Calvet and Soussana 2001, Gibelin et al. 2006)
  - The ISBA-CC model
    - Heterotrophic respiration and carbon storage (Gibelin et al. 2008)
  - Implementation/Verification
    - Field scale (Calvet et al. 1998, Calvet and Soussana 2001, Rivalland et al. 2005, Gibelin et al. 2008)
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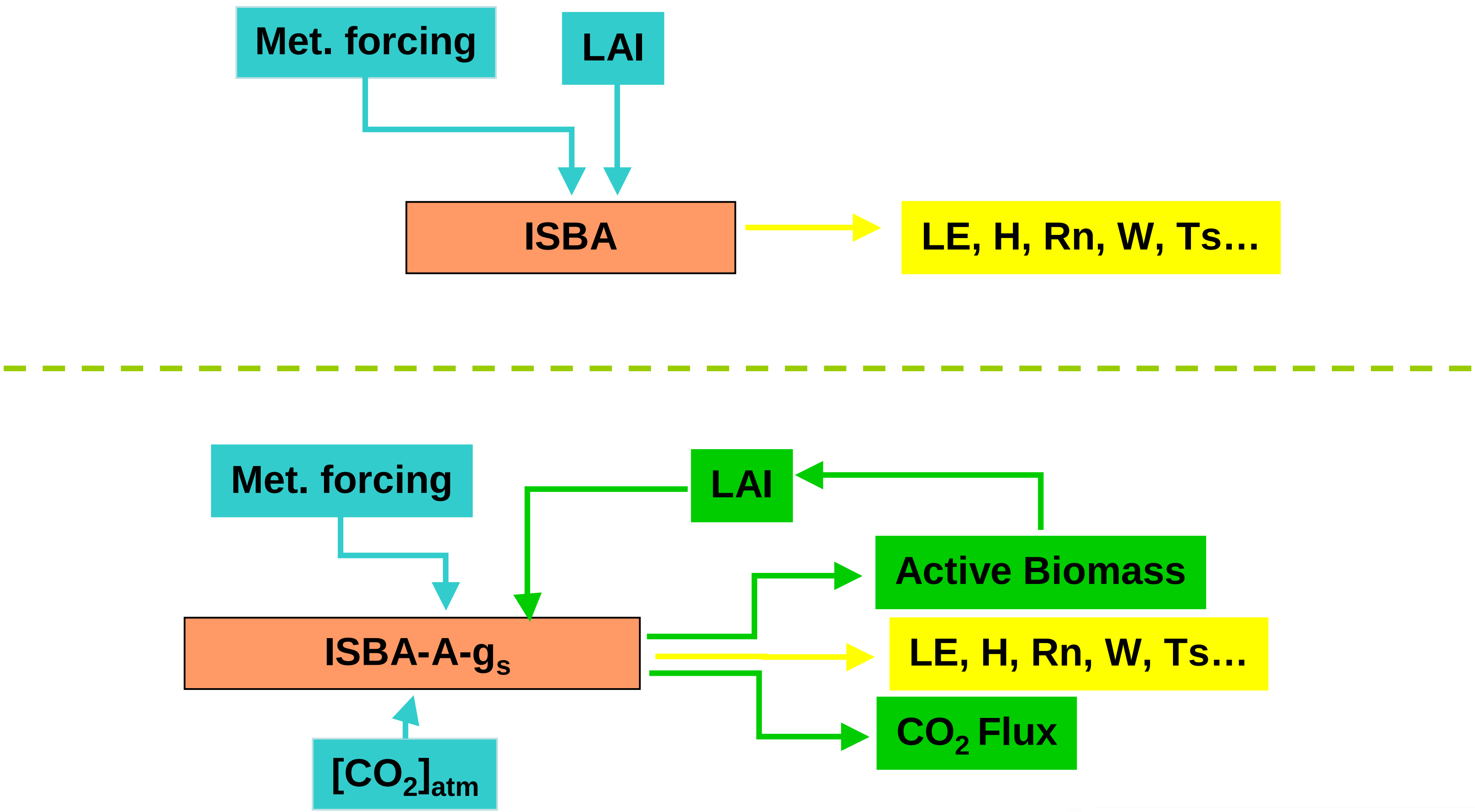
ISBA-A-gs

FIG. 1 – ISBA-A-gs vs. ISBA



The Carbon Options

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  - The ISBA-A-gs model
    - **Photosynthesis (Jacobs et al. 1996)**
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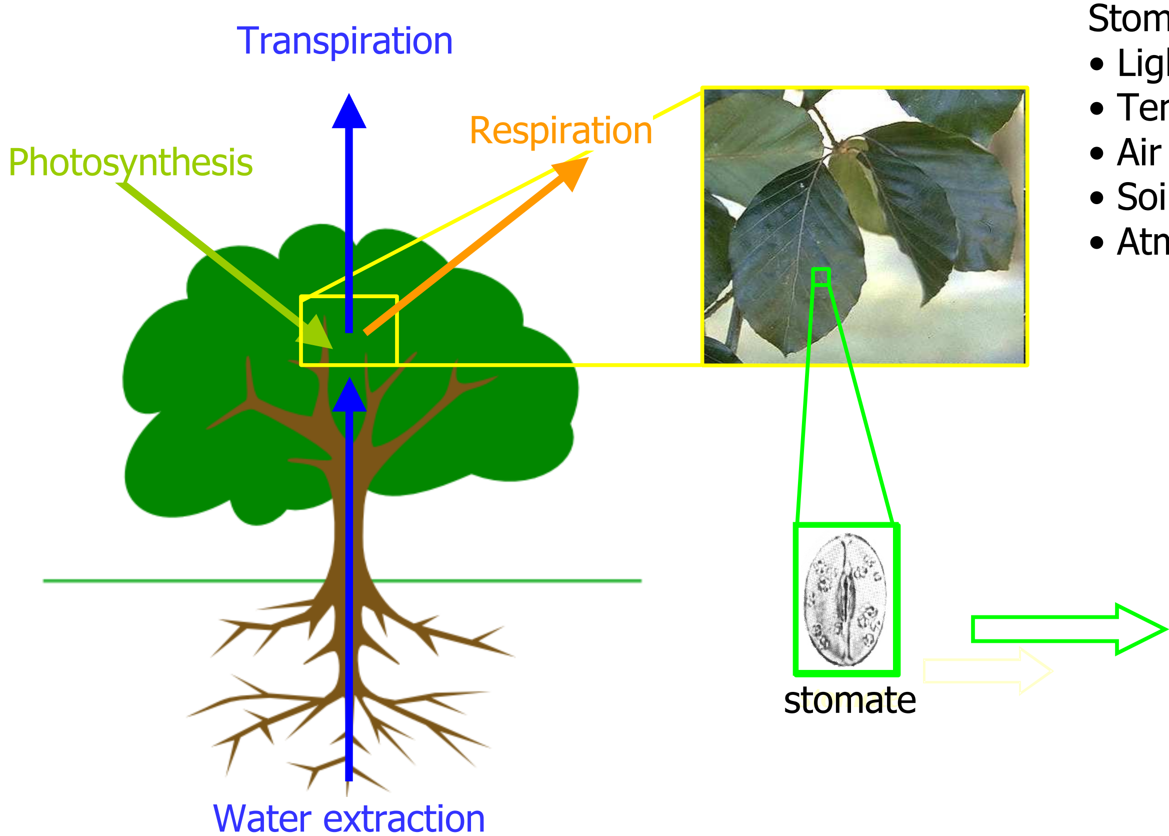
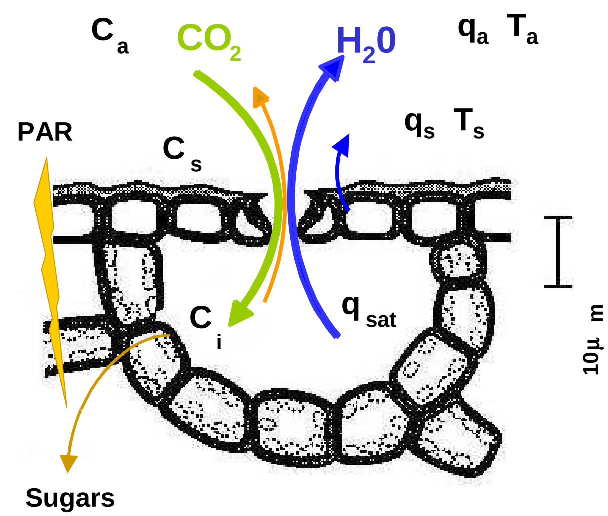
Photosynthesis

FIG. 2 – Photosynthesis and stomatal control are linked



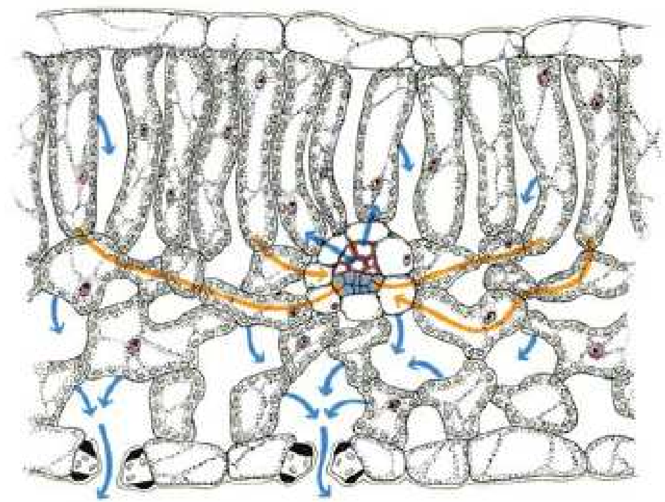
Stomatal opening (g_s) depends on:

- Light
- Temperature
- Air humidity
- Soil moisture
- Atmospheric [CO_2]



Photosynthesis

FIG. 3a – Modelling approach

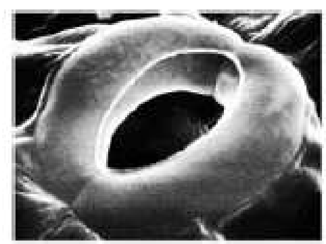


Photosynthesis

• SVAT approach (time step = minutes)

• Biochemical approach (explicit simulation of photosynthesis):

Jacobs et al. 1996

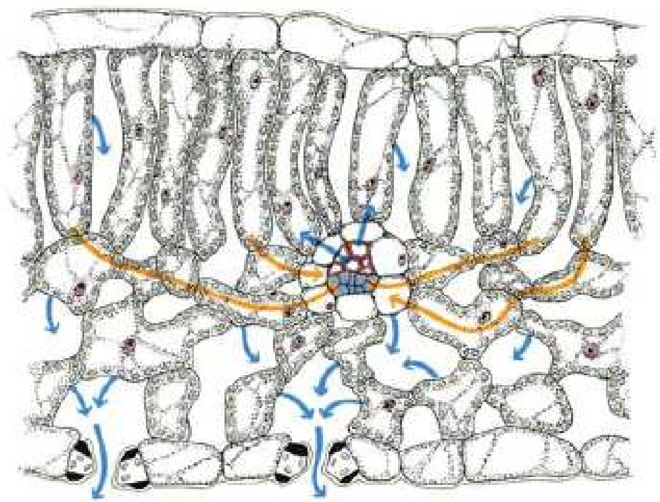


• Big-leaf but radiative transfer within the canopy for photosynthesis and stomatal conductance

Photosynthesis

FIG. 3b – Modelling approach

Photosynthesis



Other global models using
a biochemical approach:

SiB2 (Sellers et al. 1996)
IBIS (Foley et al. 1996)
BATS (Dickinson et al. 1998)
MOSES (Cox et al. 1998-2001)
BETHY (Knorr 2000)
ORCHIDEE (Krinner et al. 2005)

Photosynthesis

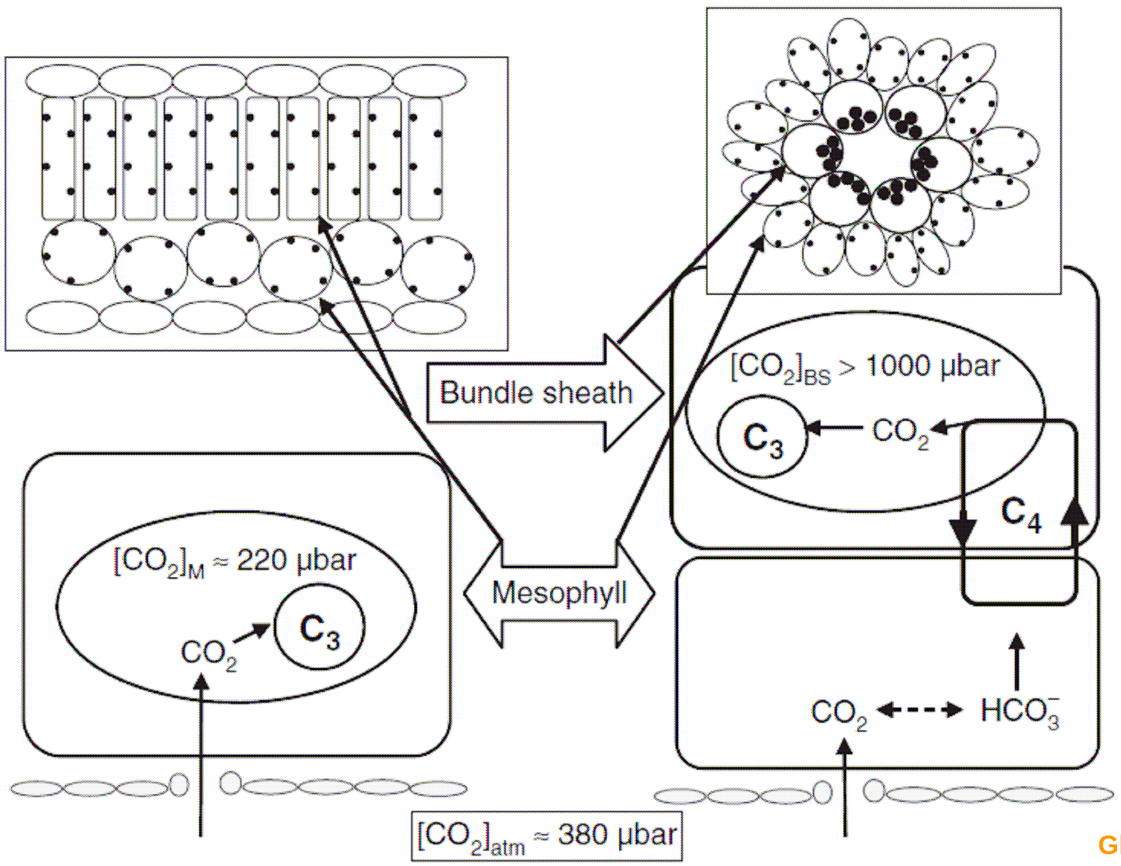
- Definitions
  - Photosynthesis is a process that converts CO_2 into organic compounds, especially sugars, using the energy from sunlight
    - C3 mechanism: Calvin cycle (Rubisco enzyme)
    - C4 mechanism : Calvin cycle (Rubisco enzyme) + Hatch & Slack cycle (PEP-carboxylase enzyme)
  - Environmental factors acting on photosynthesis and/or g_s
    - Solar radiation (PAR: 400-700 nm)
    - External CO_2 concentration (C_s)
    - Leaf temperature (T_s)
    - Leaf-to-air saturation deficit ($D_s = q_{sat}(T_s) - q_a$)
    - Drought (soil water deficit)

Photosynthesis

- C4 plants
  - ~20% of terrestrial CO_2-fixation on Earth
  - « Tropical grasses »
    - Tropical grasslands
    - Crops: maize, sugar cane, millet, …
  - Better use of high light intensities, especially at high temperatures
  - CO_2 concentration mechanism within the vascular bundle sheath
    - PEP-carboxylase enzyme
    - Enhances the photosynthesis yield (Rubisco)
    - Most « costly » in terms of energy than C3 mechanism

Photosynthesis

FIG. 4 – C3 vs. C4 photosynthesis



Ghannoum 2009

Photosynthesis

- The CO_2 effect

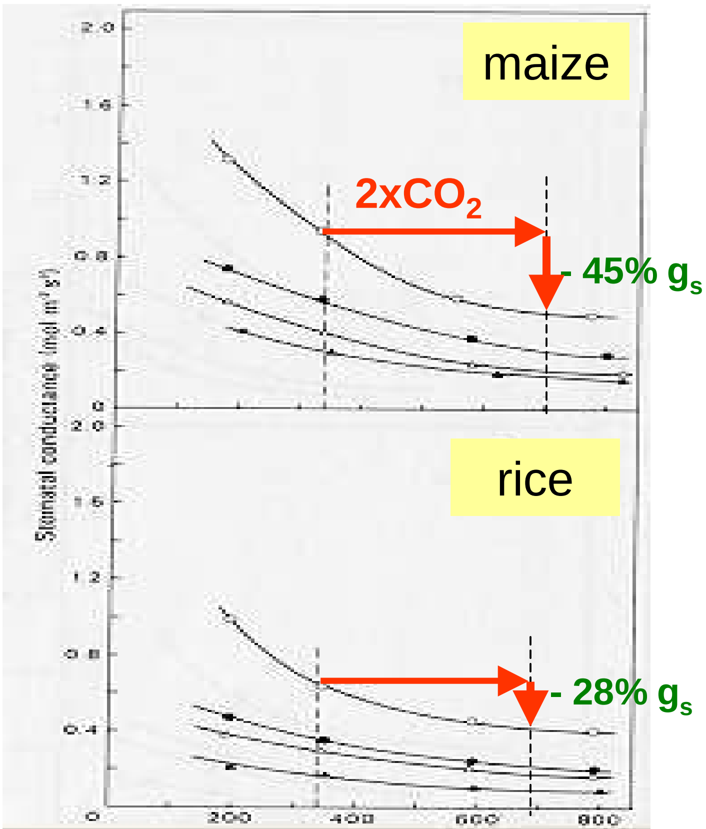
  - $[CO_2]$ is increasing
    - 320 ppm in the 60's
    - 371 ppm in 2000
    - 550 ppm in 2050 ?
    - 700 ppm in 2100 ?

  - $[CO_2]$ has a huge impact on photosynthesis and stomatal conductance
    - Favours photosynthesis (« Fertilisation »)
    - Reduces plant transpiration (« Antitranspirant effect »)
    - $\rightarrow$ Enhances the water use efficiency

  - Effect on ecosystems/crops still controversial

Photosynthesis

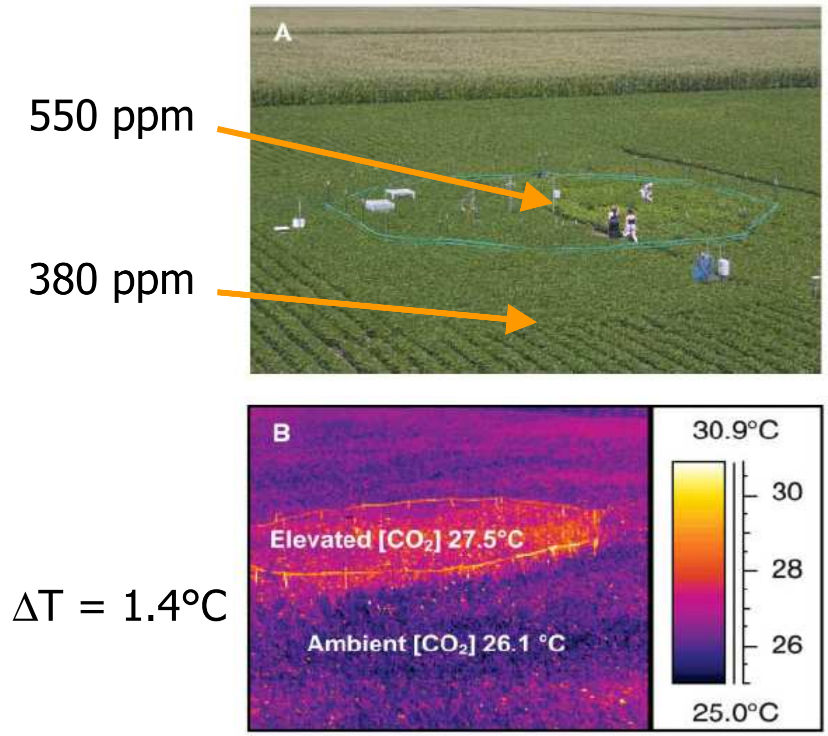
FIG. 5a – CO_2 effect: stomatal conductance



350 ppm 700 ppm

(Morison & Gifford, 1983)

CO_2 ↗ ⇒ E ↘

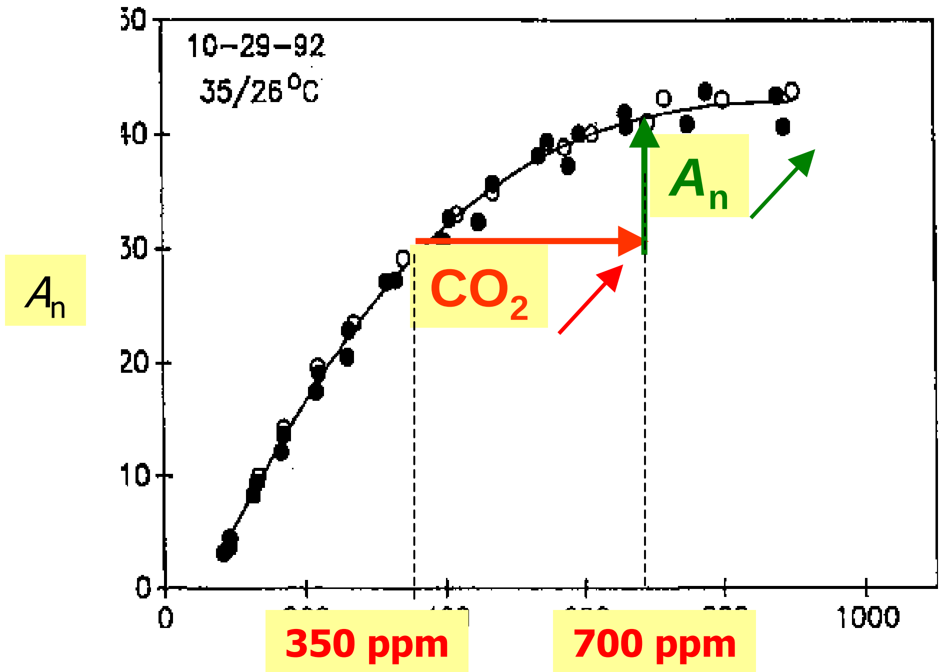


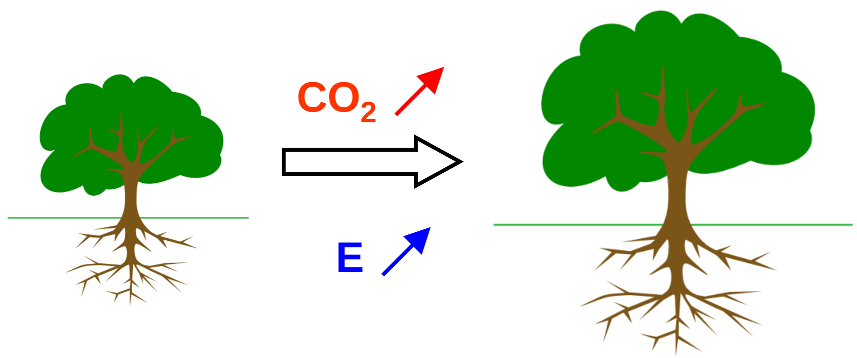
(Long et al. 2006, Science)

Photosynthesis

FIG. 5b – CO_2 effect: photosynthesis

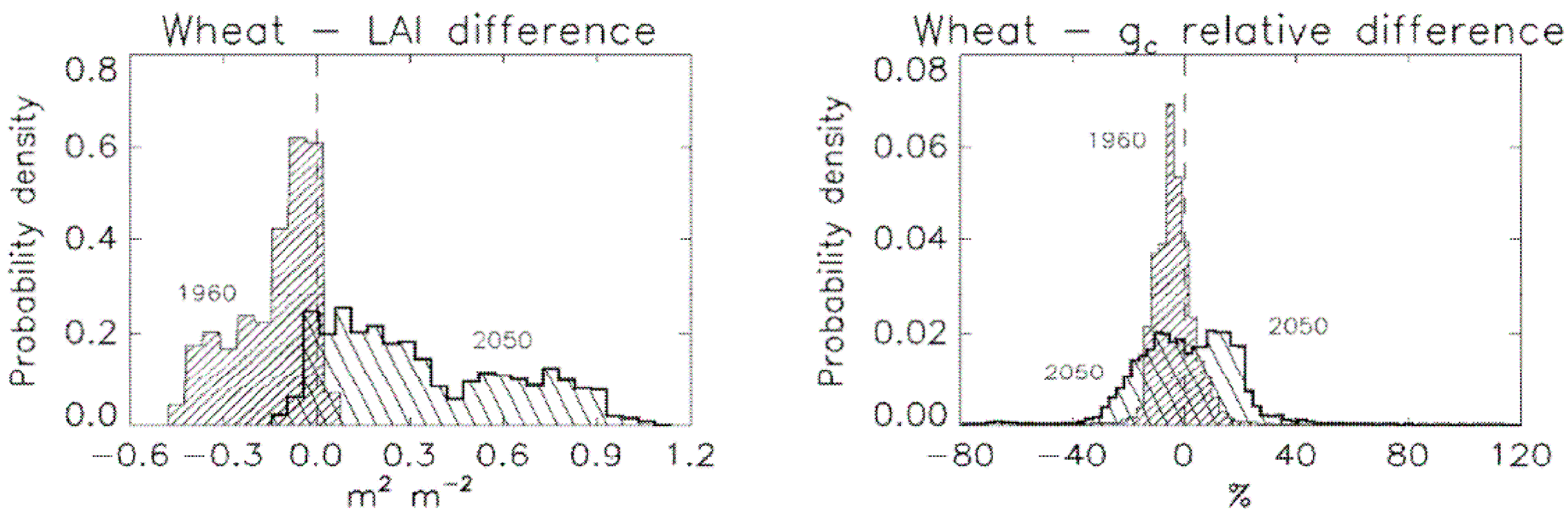
Net C assimilation





Photosynthesis

FIG. 6 – CO_2 effect: simulated by ISBA-A-gs



Calvet et al. 2008

Photosynthesis

- Parameters of the Jacobs model (leaf level)
  - Permanent and/or variable leaf properties
    - Leaf photosynthetic capacity ($A_{m,max}$, $mgCO_2\ m^{-2}\ s^{-1}$) at 25°C
    - Maximum quantum use efficiency (ε_0, $mgCO_2\ J^{-1}$ PAR)
    - CO_2 compensation concentration (Γ, µmol mol^{-1}) at 25°C
    - **Optimal scaled internal CO_2 concentration (C_i) at D_s=0 in well-watered conditions**
      ($f_0^* = (C_i - \Gamma)/(C_s - \Gamma)$, –)
    - **Maximum D_s in well-watered conditions (D_{max}^*, g kg^{-1})**
    - **Mesophyll conductance in well-watered conditions (g_m^*, mm s^{-1}) at 25°C**
    - Temperature parameters (T_1, T_2)
    - Cuticular conductance (g_c, mm s^{-1})
  - Hypothesis
    - **g_m^*, f_0^*, D_{max}^*:** depend on both plant species and growing conditions (soil moisture, climatic conditions, soil compaction, etc.)

Photosynthesis

- Parameters of the Jacobs model (leaf level)
  - Interpretation of the key parameters ***g_m*, f_0*, D_{max}*:***
    - Maximum gross photosynthesis rate (at D_s=0):

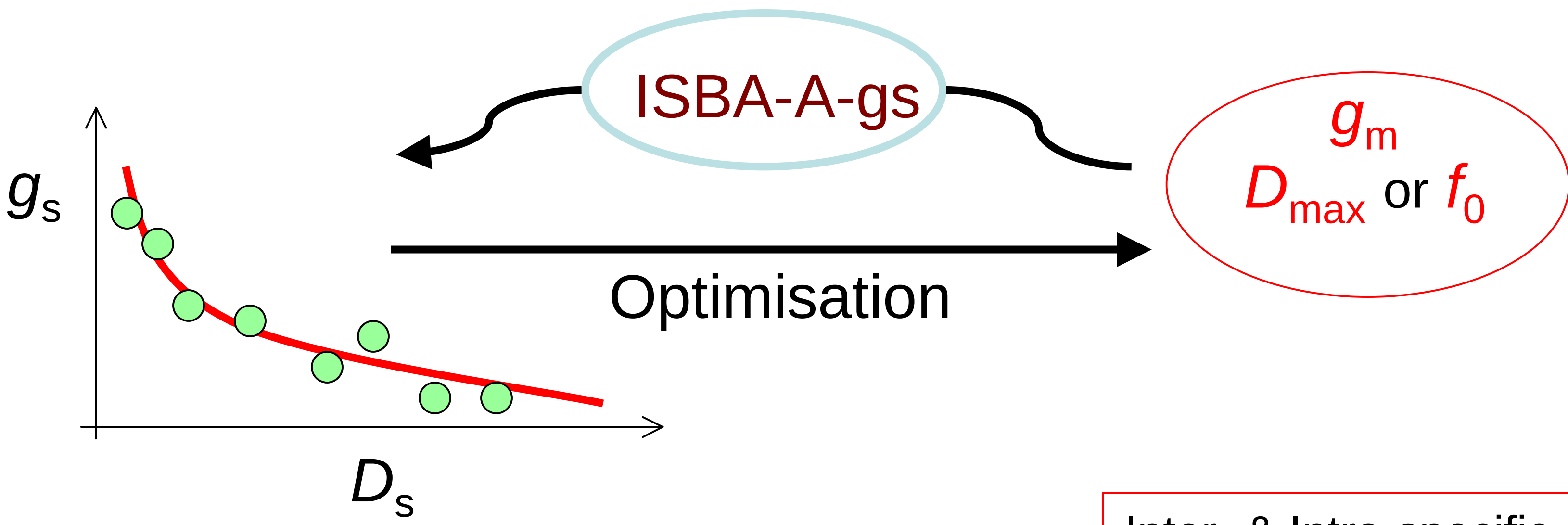
$$A_{\mathrm{m}} = A_{\mathrm{m,max}} \left[1 - \exp \left\{ \frac{-g_{\mathrm{m}}^* f_0^* (C_{\mathrm{s}} - \Gamma)}{A_{\mathrm{m,max}}} \right\} \right]$$

    - Water use efficiency (ratio of net photosynthesis rate / transpiration)

$$W_{\mathrm{UE}} = \frac{C_{\mathrm{s}} - \Gamma}{1.6 \rho_{\mathrm{a}}} \left[\frac{f_0^*}{D_{\mathrm{max}}^*} + \frac{1 - f_0^*}{D_{\mathrm{s}}} \right]$$

Photosynthesis

FIG. 7a – Parameter grouping



g_s-D_s relationships
at leaf and canopy scales
(meta-analysis)

Inter- & Intra-specific
g_m-D_{max} (herbaceous)
or
g_m-f_0 (woody)
relationships

Photosynthesis

- Parameter grouping

  - Herbaceous plants (meta-analysis)

    $\ln(g_m^*) = a_h - b_h \ln(D_{max}^*)$, $f_0^* = \text{constant}$

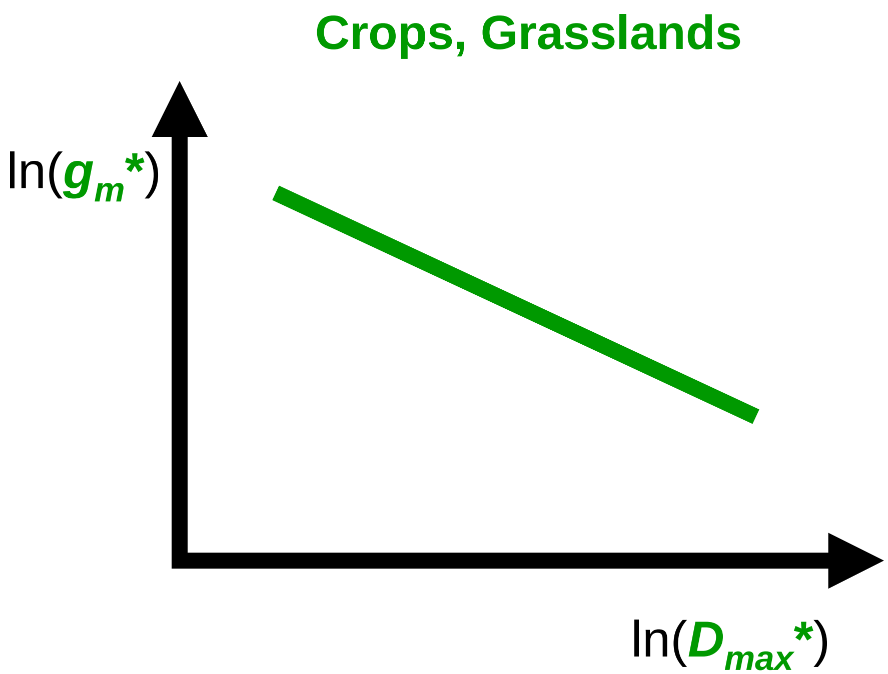
  - Woody plants (meta-analysis)

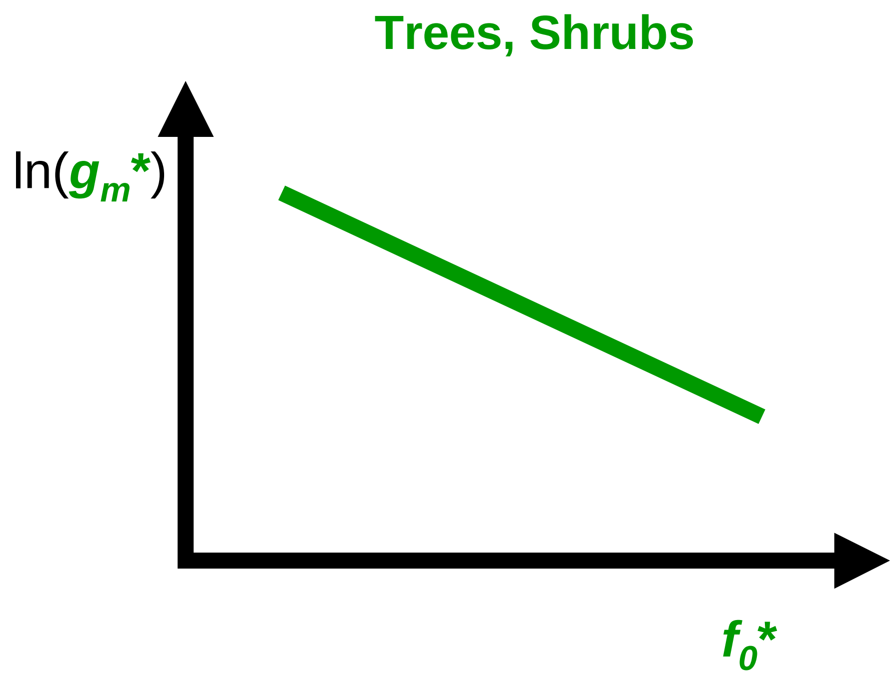
    $\ln(g_m^*) = a_w - b_w f_0^*$, $D_{max} = D_{max}^X - c_w \ln(g_m^*)$

  - C3 vs. C4 plants: contrasting values of
    - Leaf photosynthetic capacity ($A_{m,max}$ at 25°C)
    - Maximum quantum use efficiency (ε_0)
    - CO_2 compensation concentration (Γ at 25°C)
    - For herbaceous plants: a_h and b_h

Photosynthesis

FIG. 7b – Parameter grouping





Well-watered

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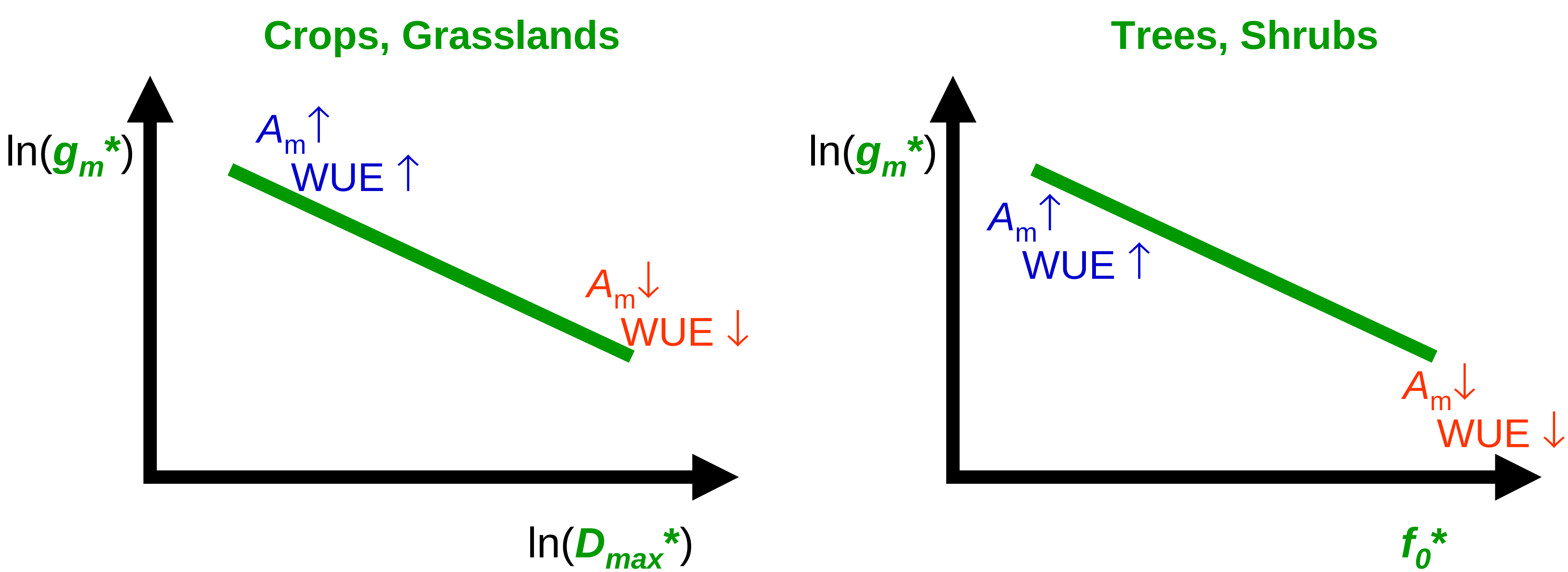
Response to drought

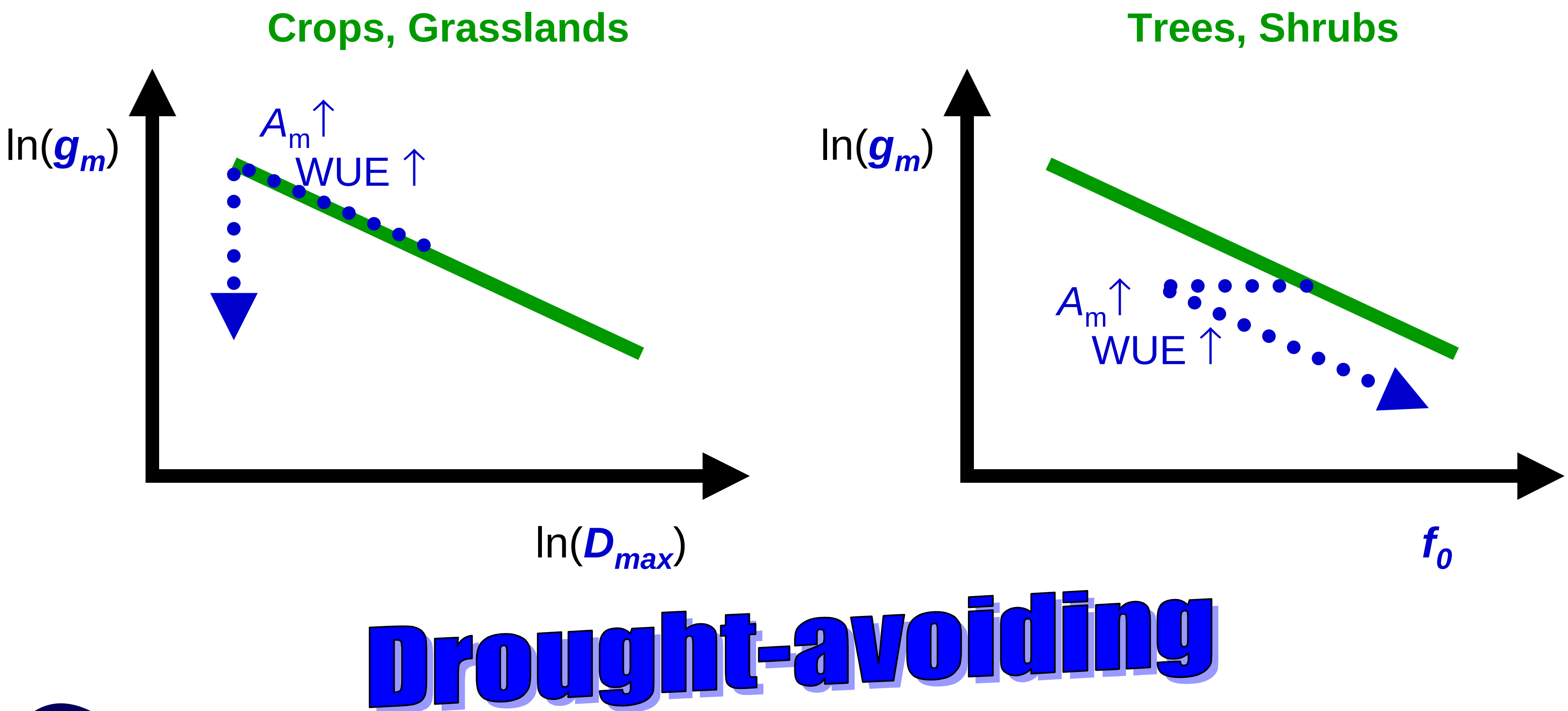
FIG. 7c – Parameter grouping



Well-watered

Response to drought

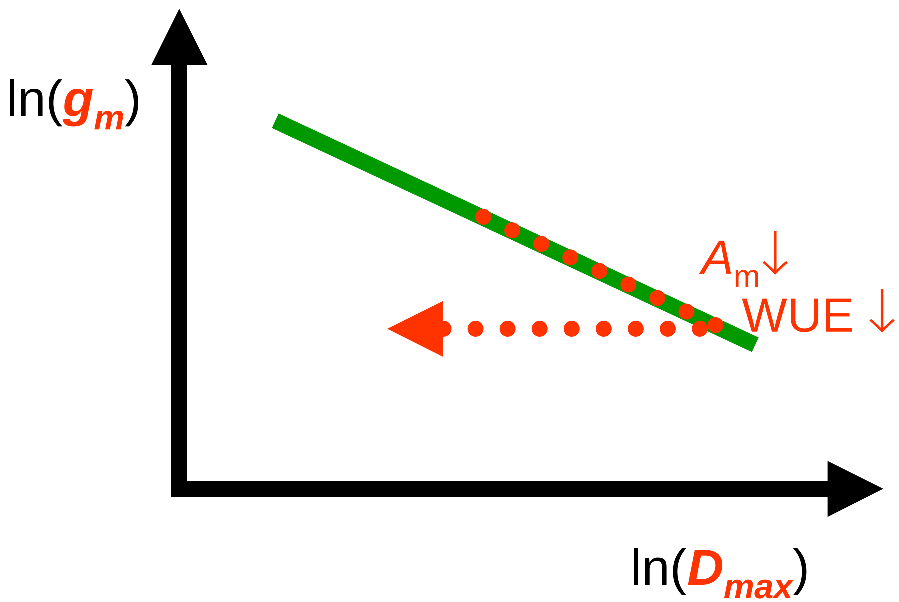
FIG. 7d – Tolerant or avoiding ? A meta-analysis



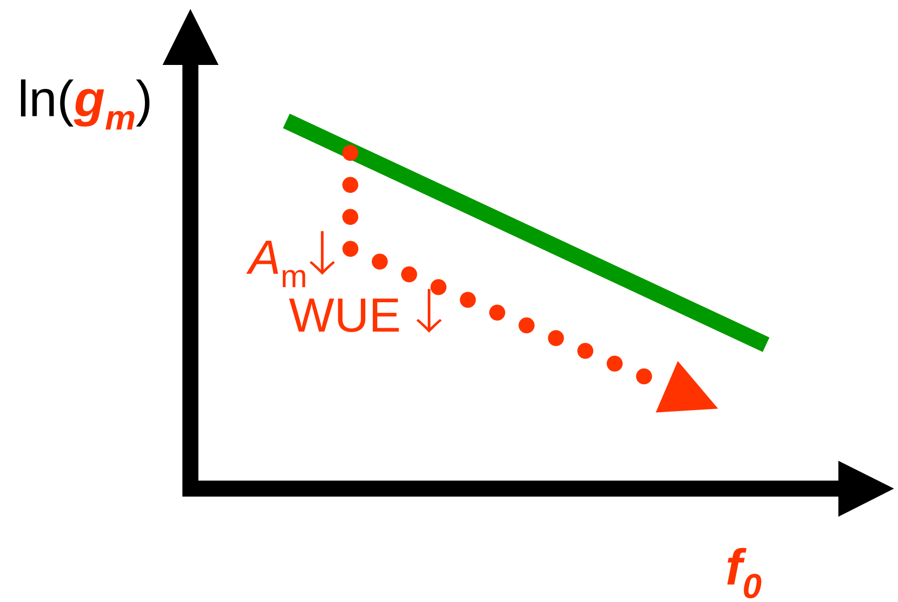
Response to drought

FIG. 7e – Tolerant or avoiding ? A meta-analysis

Crops, Grasslands



Trees, Shrubs



Drought-tolerant

Response to drought

FIG. 8a – Tolerant or avoiding ? Trees

Maritime pine

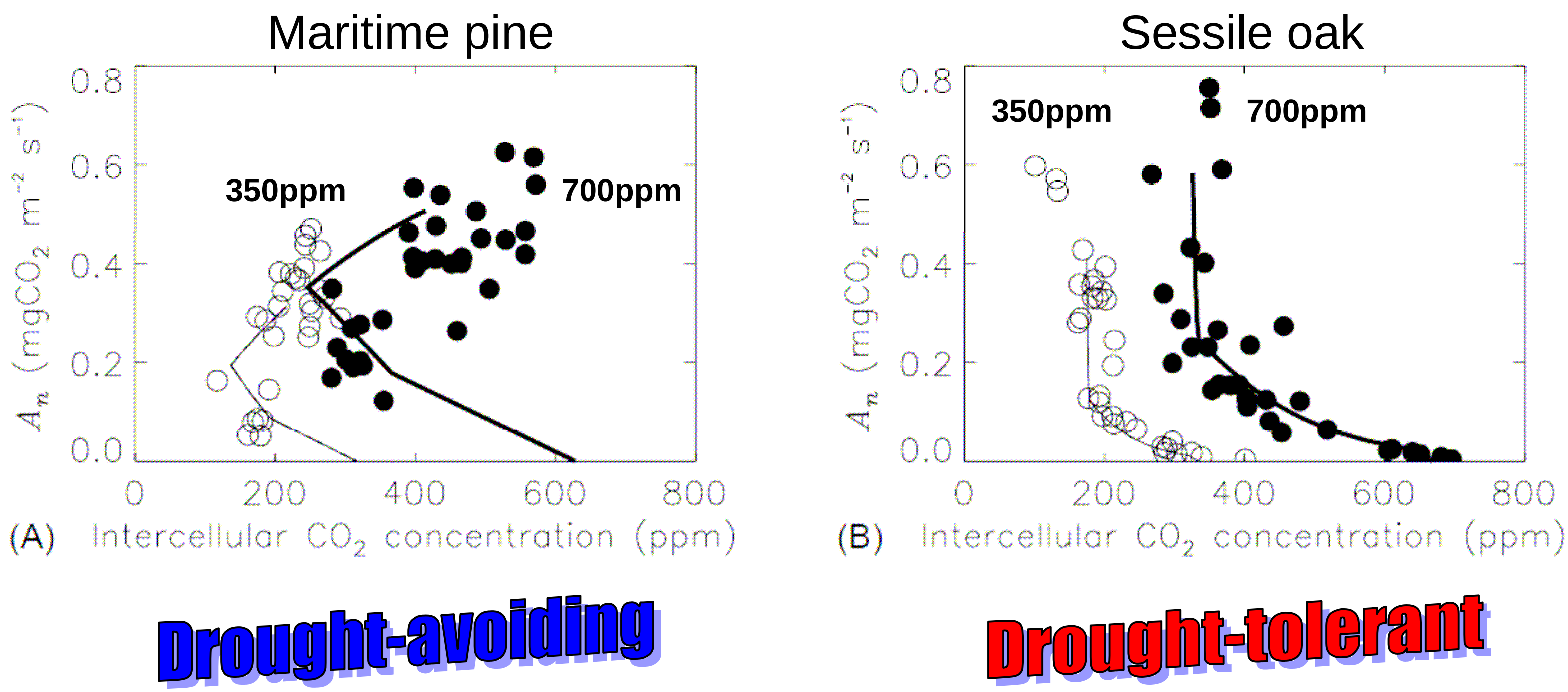
Drought-avoiding

Sessile oak

Drought-tolerant

Response to drought

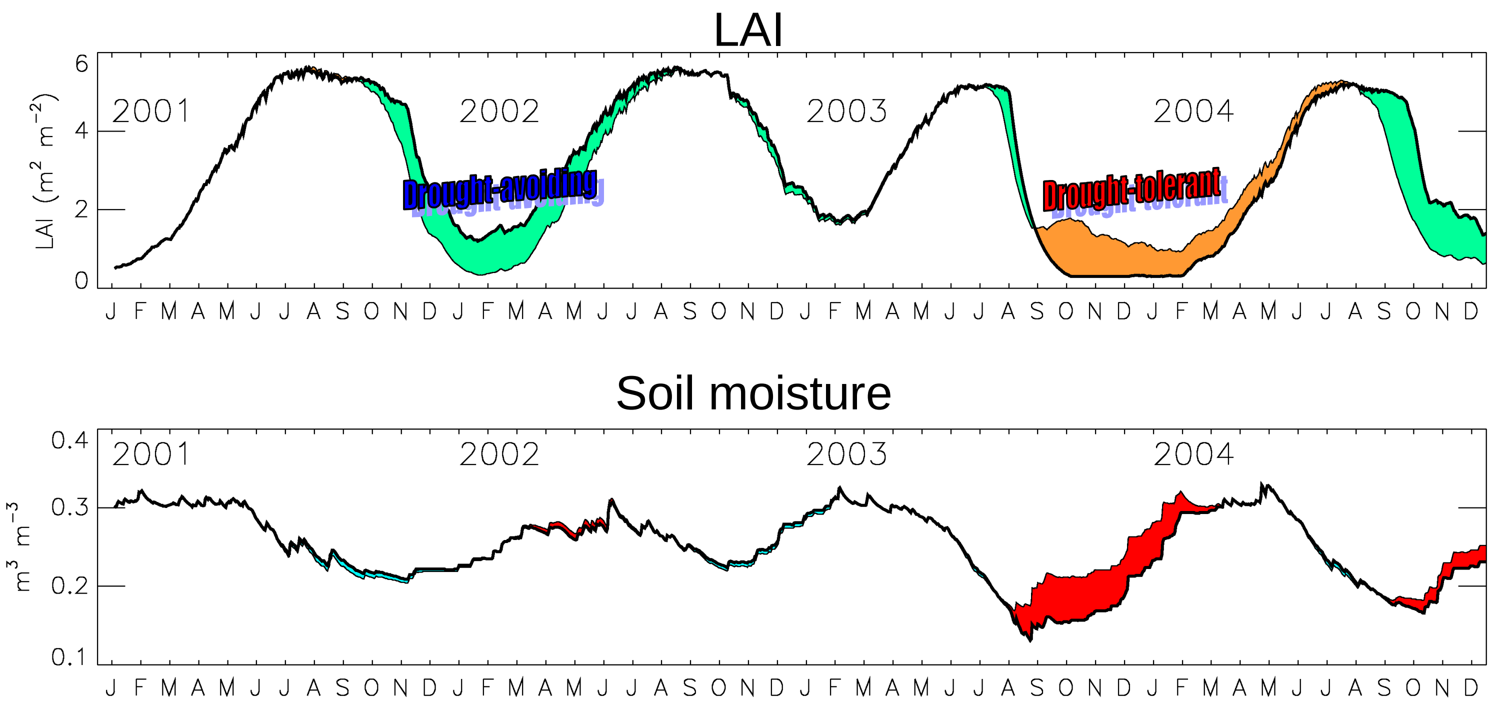
FIG. 8b – Tolerant or avoiding ? Trees



Calvet et al. 2004

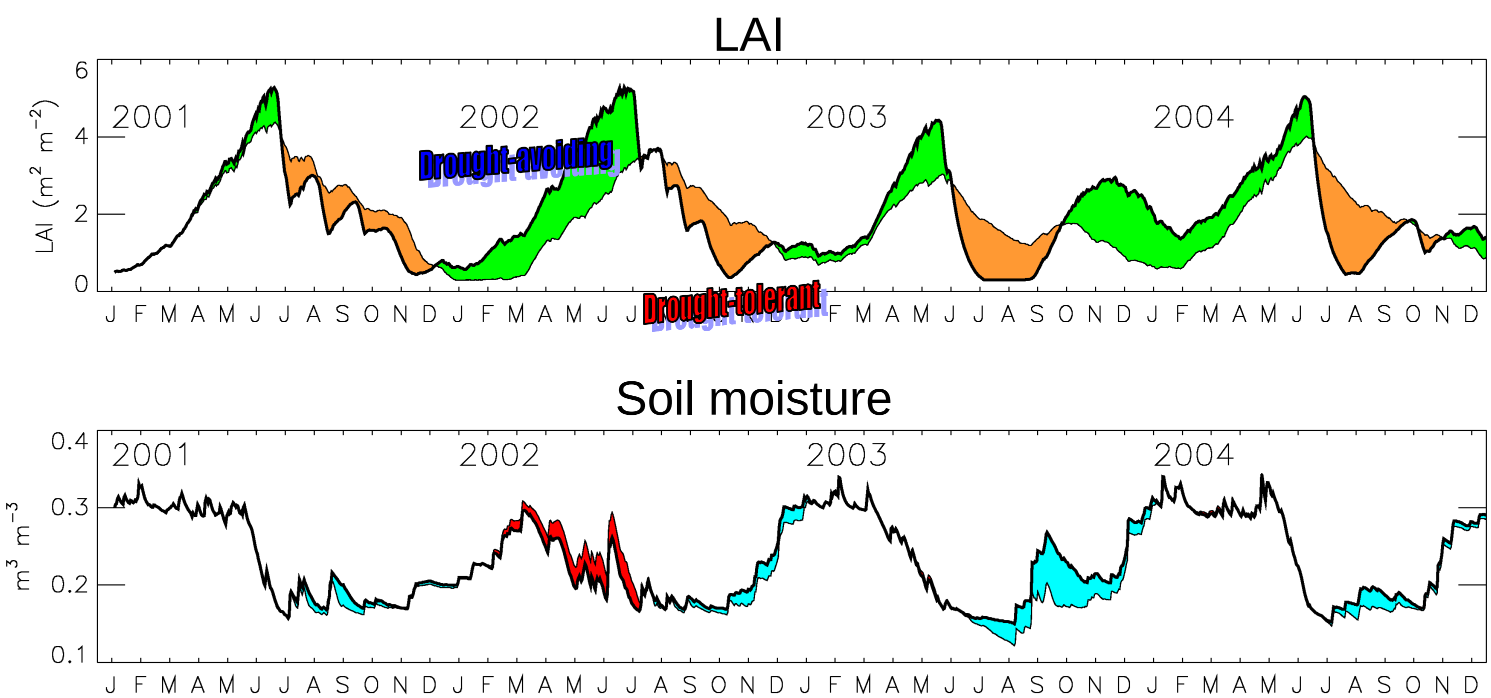
Response to drought

FIG. 8c – Tolerant or avoiding ? Deciduous broadleaf forest



Response to drought

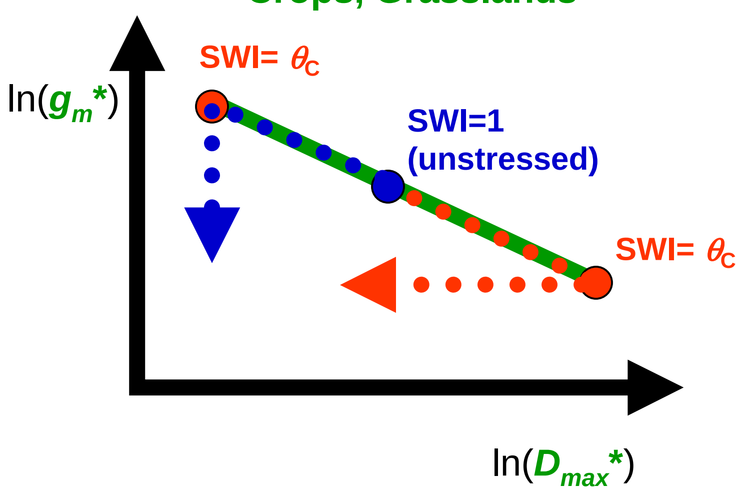
FIG. 8d – Tolerant or avoiding ? C3 crops



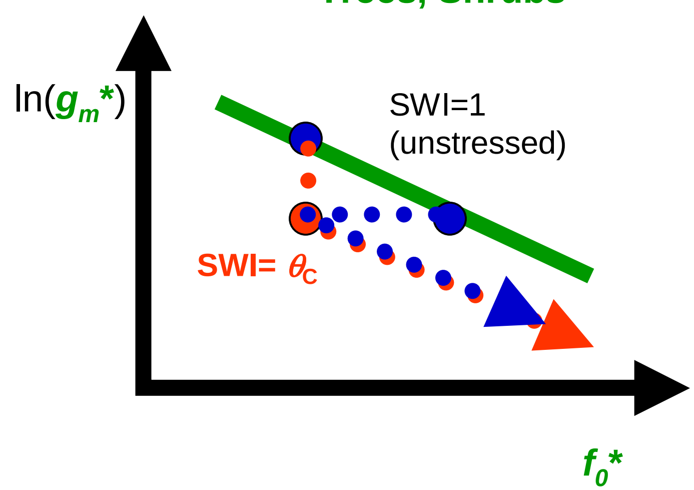
Response to drought

- Enhanced representation of drought: summary
  - Key parameters of the photosynthesis model are affected by drought:
    the well-watered value are adjusted by using the Soil Wetness Index (SWI)
  - Two possible strategies: drought-avoiding / drought-tolerant
  - Important parameter: θ_C critical extractable soil moisture content, below which severe soil moisture stress is observed

Crops, Grasslands



Trees, Shrubs



Calvet 2000, Calvet et al. 2004

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    - **Plant growth**
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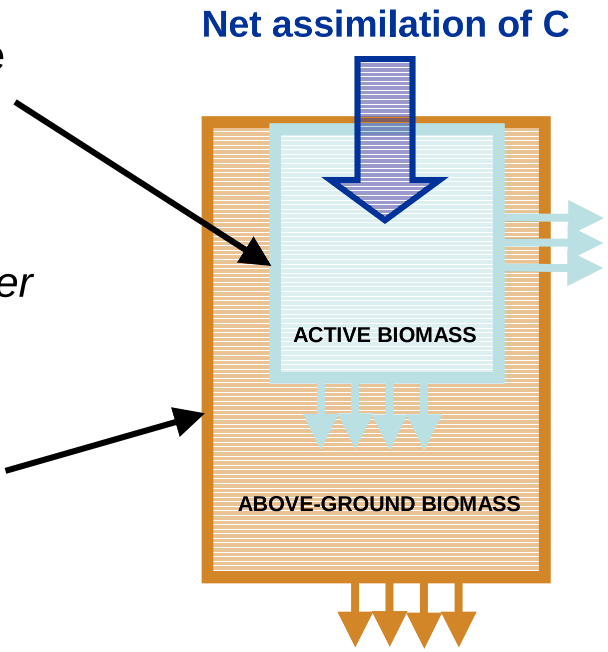
Plant growth

FIG. 9 – Active and structural biomass

Allocation

- The **active biomass** (= leaves) is a reservoir fed by the net CO_2 uptake by leaves
(i.e. *An* = Photosynthesis – Leaf respiration).
It looses carbon following an exponential law whose e-folding time depends on the daily maximum *An* (*parameter = max leaf span time* τ_m).
- The **above-ground biomass** (non-woody) is derived from the active biomass:
  - Growing period: a logarithmic nitrogen dilution equation is used
  - Senescence: respiration losses and exponential decline

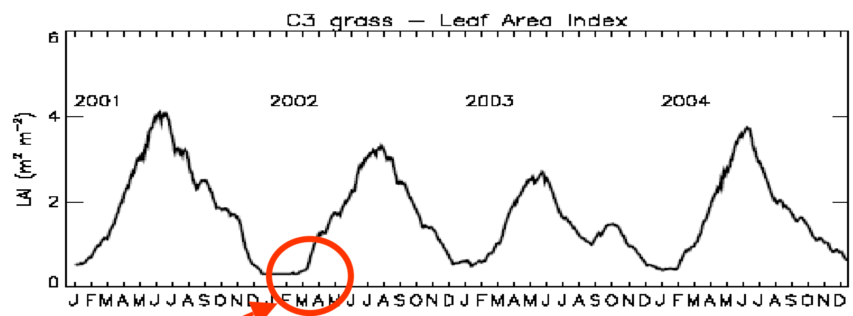


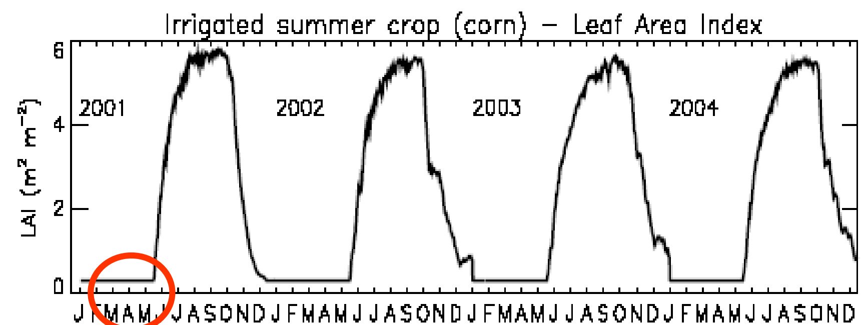
Plant growth

FIG. 10a – LAI simulations

(No)-Phenology ?

- LAI is linearly related to the **active biomass** (parameters = **SLA**, derived from leaf nitrogen concentration and 2 plasticity parameters)
- A minimum value of LAI, **LAI_{min}**, is prescribed (e.g. 0.3 for annual vegetation), permitting a self restart of the vegetation when photosynthesis becomes active
- Possibility to cut the vegetation or to maintain LAI at its minimum value, for agricultural applications





Plant growth

FIG. 10b – LAI simulations

(No)-Phenology ?

Merits of this methodology

• Simple

• Leaf onset and offset dates don‘t have to be prescribed

(permitting to simulate the interannual variability and climate change effects)

• No use of empirical degree-day sums

(all the factors are accounted for, not only temperature)

• Crop regrowth (autumn) is simulated

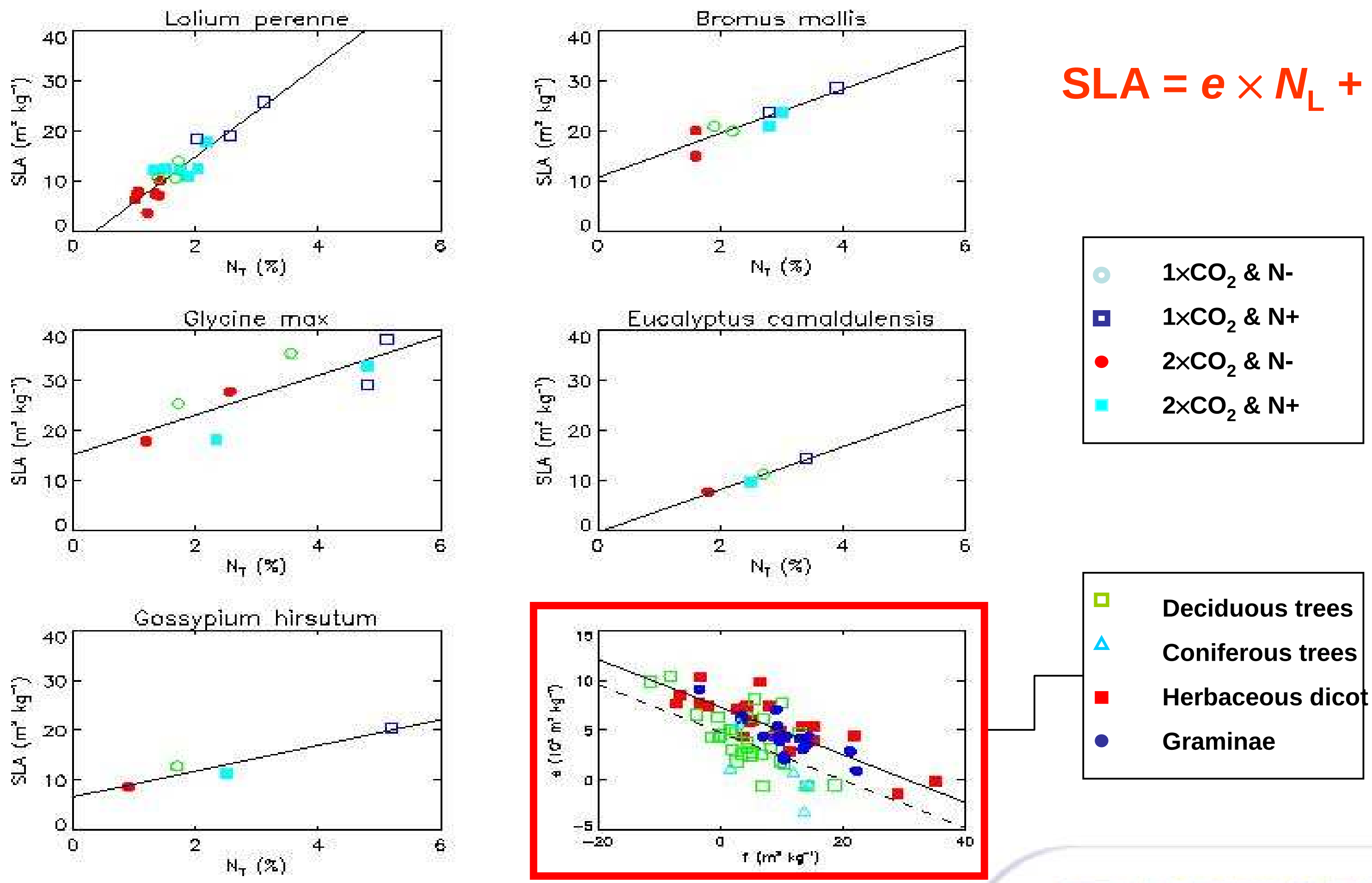
Other models using this approach

AVIM (Ji 1995, Dan et al. 2005)

STEP (Mougin et al. 1995)

Plant growth

FIG. 10c – LAI simulations: parameter grouping



$$SLA = e \times N_L + f$$

The Carbon Options

FIG. 11 – Key parameters of the « NIT » option

	Photosynthesis						Plant growth				
Vegetation type	*g_m * (mm s^{-1})*	*g_c (mm s^{-1})*	*f_0 * (-)*	*D_{max} * (gkg^{-1})*	*Drought response*	*θ_c (-)*	*τ_m (d)*	*LAI_{min} (m^2m^{-2})*	*e (m^2kg^{-1} $\%^{-1}$)*	*f (m^2kg^{-1})*	*N_L (%)*
C3 Crops	**1**	**0.25**	**0.95**	**50**	**Avoiding**	**0.3**	**150**	**0.3**	**3.79**	**9.84**	**1.3**
C4 crops	**9**	**0.15**	**0.60**	**33**	**Tolerant**	**0.3**	**150**	**0.3**	**7.68**	**-4.33**	**1.9**
C3 grasslands	**1**	**0.25**	**0.95**	**50**	**Tolerant**	**0.3**	**150**	**0.3**	**5.56**	**6.73**	**1.3**
C4 grasslands	**6**	**0.15**	**0.60**	**33**	**Tolerant**	**0.3**	**150**	**0.3**	**7.68**	**-4.33**	**1.3**
Coniferous forests	**2**	**0**	**0.57**	**124**	**Avoiding**	**0.3**	**365**	**1**	**4.85**	**-0.24**	**2.8**
Evergreen forests	**2**	**0.15**	**0.57**	**124**	**Tolerant**	**0.3**	**365**	**1**	**4.83**	**2.53**	**2.5**
Deciduous forests	**3**	**0.15**	**0.51**	**109**	**Tolerant**	**0.3**	**230**	**0.3**	**4.83**	**2.53**	**2**

Mesophyll conductance

Cuticular conductance

Critical SWI

Max leaf span time

N Plasticity parameters

Leaf N

Gibelin et al. 2006

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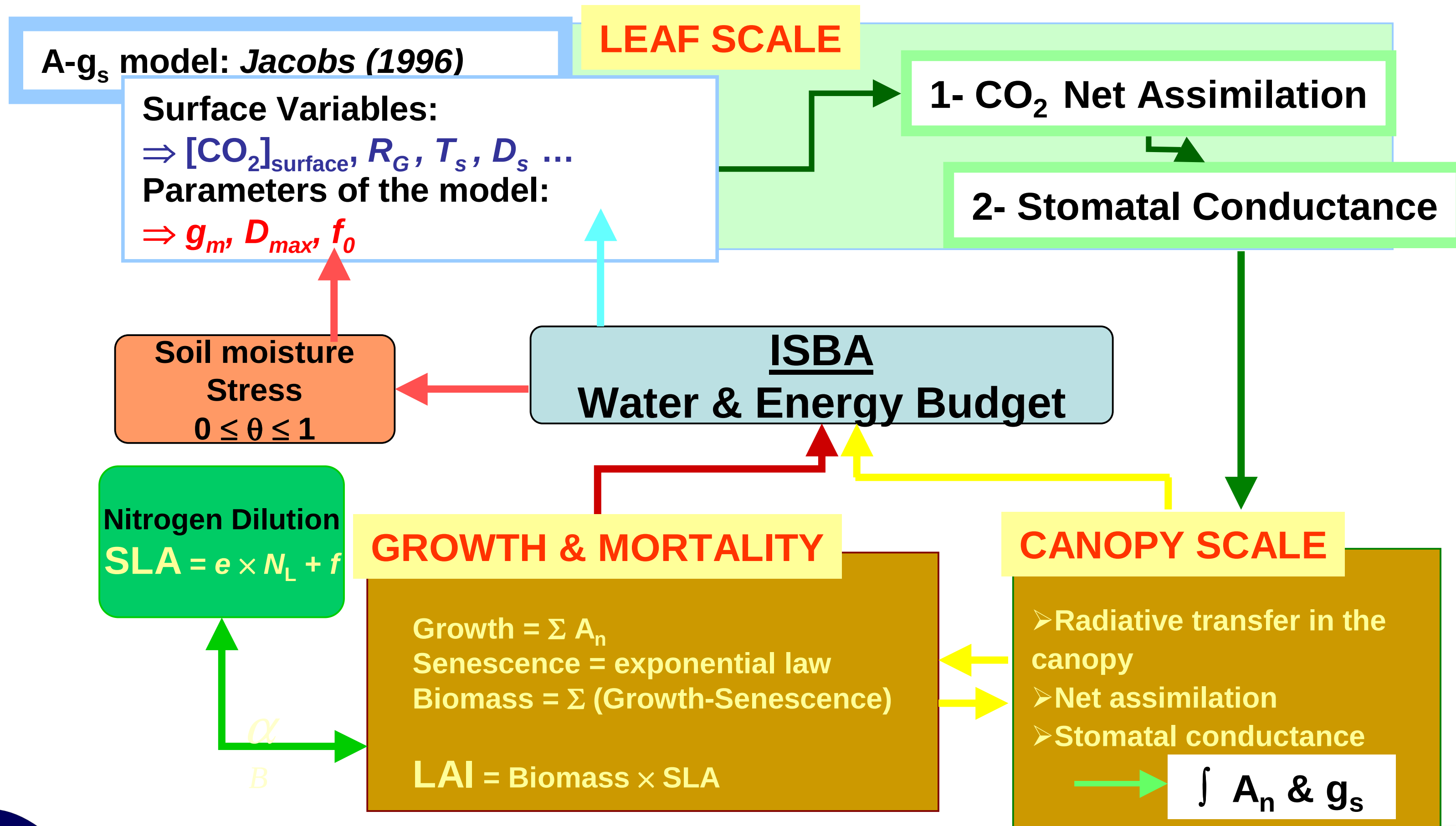
The Carbon Options

FIG. 12 – Summary of the « NIT » option



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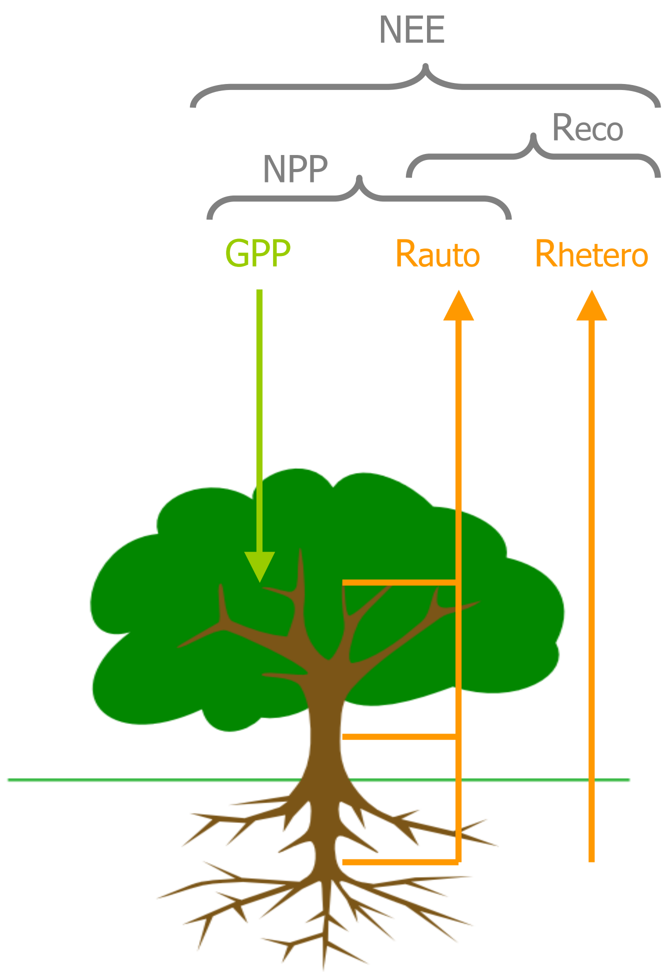
ISBA-CC

FIG. 13a – Different respiration terms



Photosynthesis (GPP)

Autotrophic Respiration (Rauto)

Heterotrophic Respiration (Rhetero)

NPP = GPP – Rauto

Reco = Rauto + Rhetero

NEE = GPP – Rauto – Rhetero

ISBA-CC

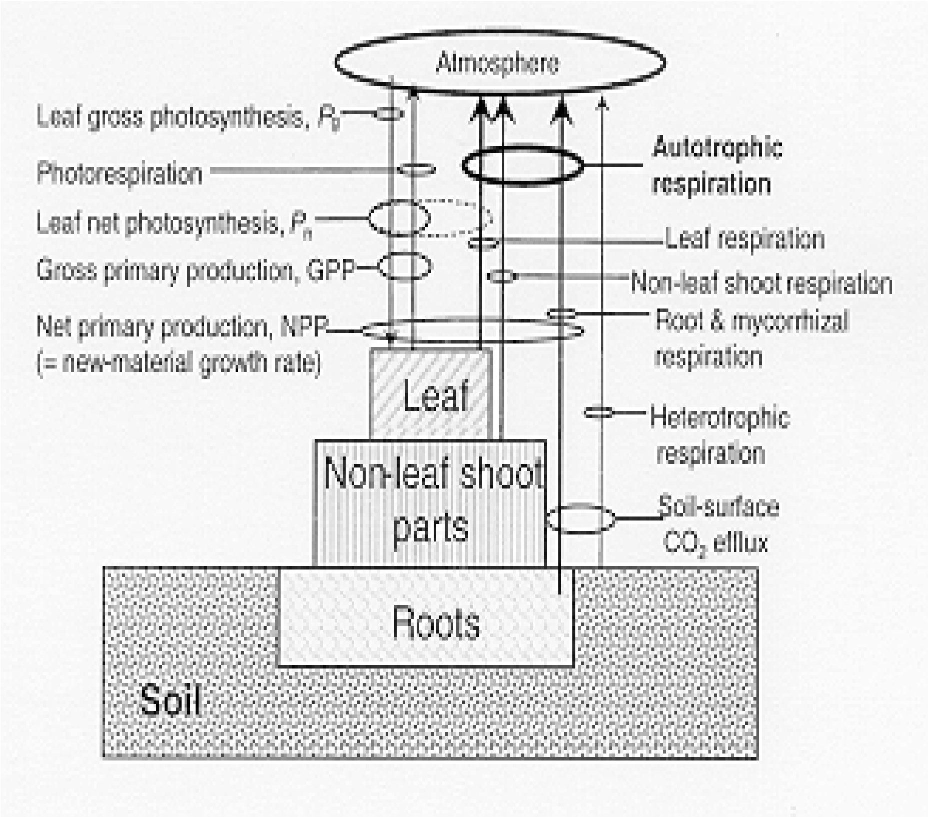
FIG. 13b – Different respiration terms

Respiration in ISBA-A-gs

- Ecosystem respiration is calculated by using a simple Q_{10} function depending on soil temperature (and soil moisture)

this is enough to calculate a net CO_2 flux but NPP cannot be simulated

- Autotrophic respiration is calculated for the above-ground biomass only
- Heterotrophic respiration is not explicitly calculated in ISBA-A-gs



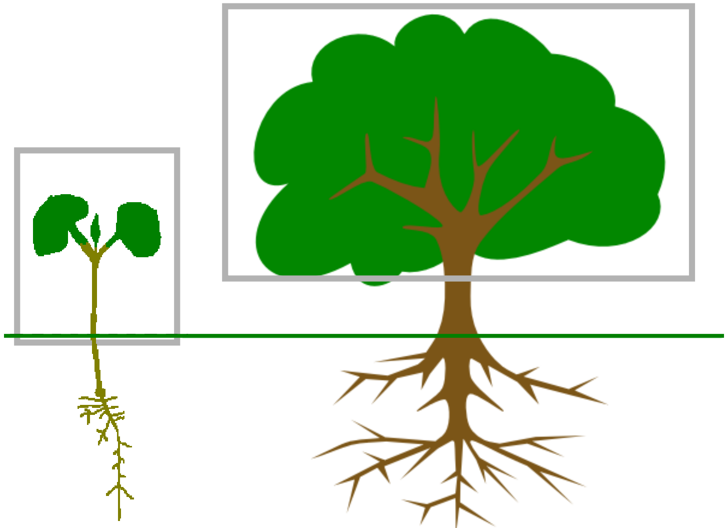
Gifford 2003

ISBA-CC

FIG. 14a – Upgrade of ISBA-A-gs: ISBA-CC

ISBA-A-g_s

(*Calvet et Soussana, 2001*)



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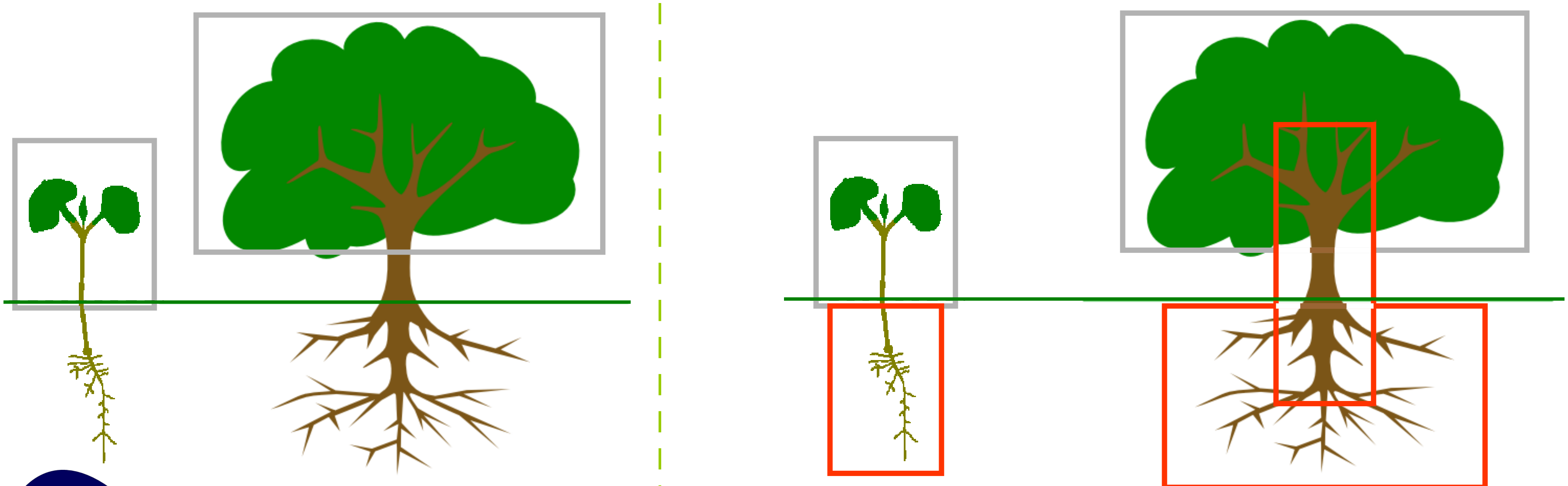
ISBA-CC

FIG. 14b – Upgrade of ISBA-A-gs: ISBA-CC

ISBA-A-g_s

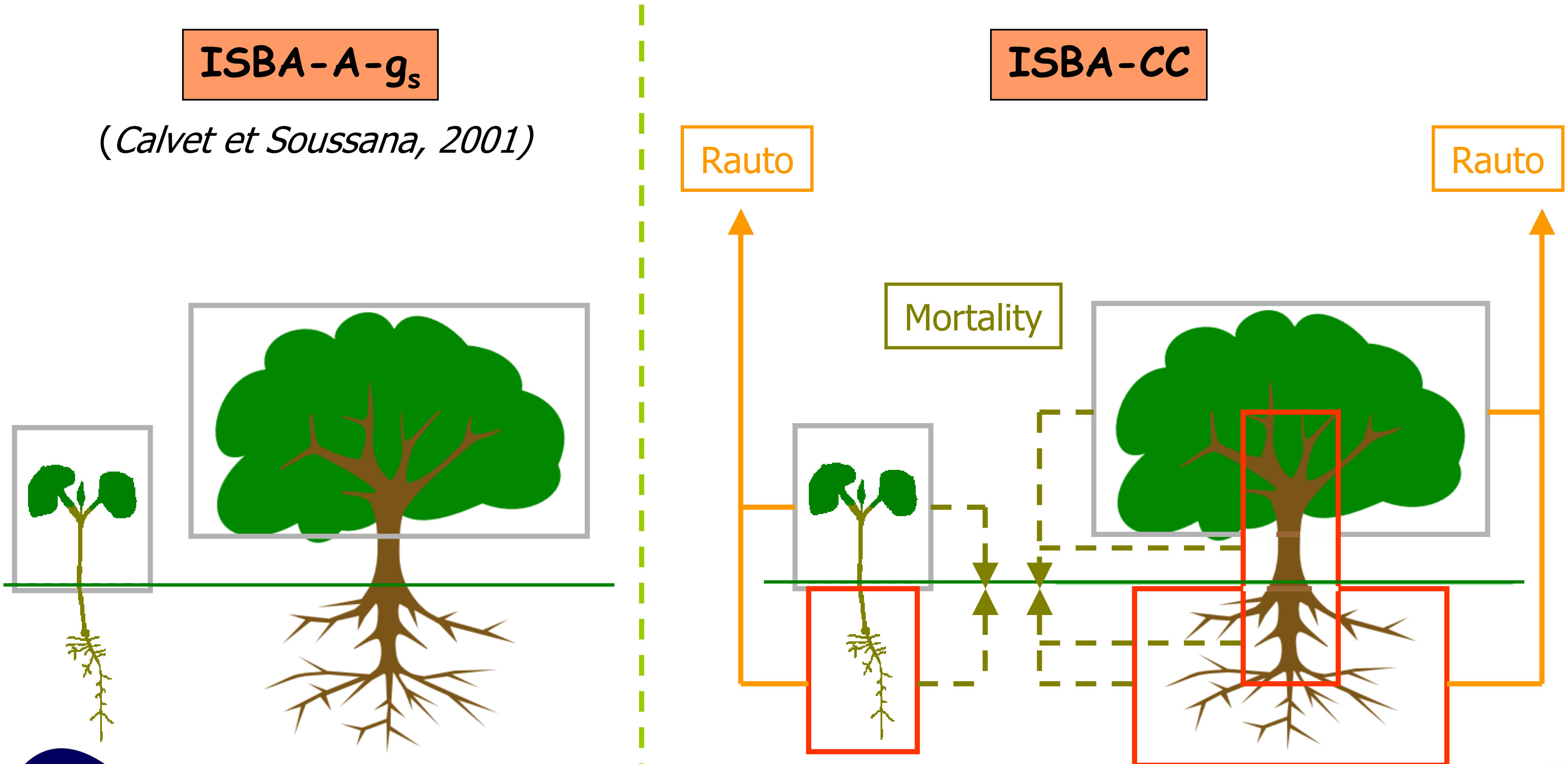
(*Calvet et Soussana, 2001*)

ISBA-CC



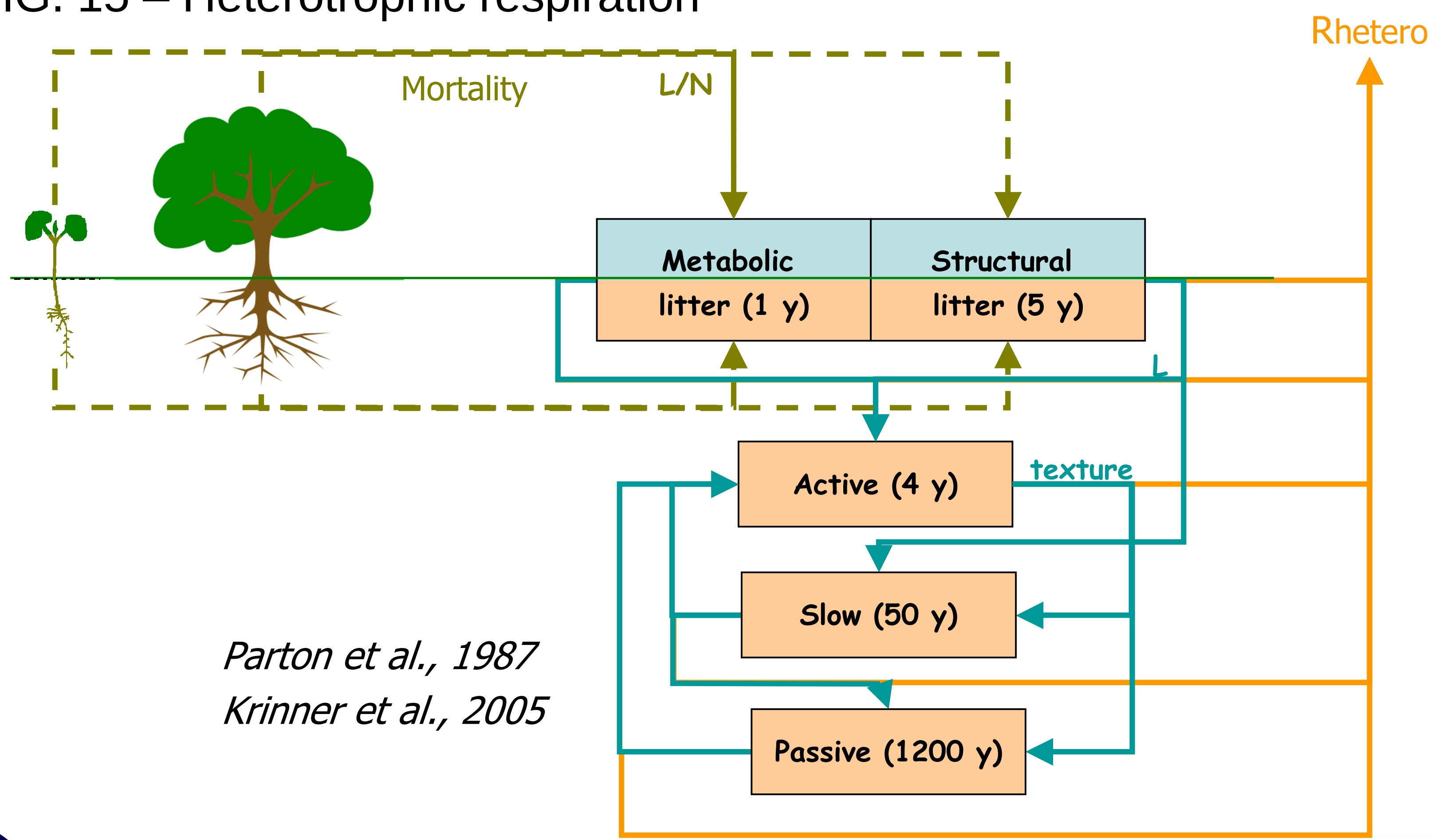
ISBA-CC

FIG. 14c – Upgrade of ISBA-A-gs: ISBA-CC



ISBA-CC

FIG. 15 – Heterotrophic respiration



Parton et al., 1987

Krinner et al., 2005

The Carbon Options

- How?
  - The ISBA-A-gs model
    - Photosynthesis (Jacobs et al. 1996)
    - Meta-analysis of the response to drought (Calvet 2000, Calvet et al. 2004)
    - Plant growth (Calvet et al. 1998, Calvet and Soussana 2001, Gibelin et al. 2006)
  - The ISBA-CC model
    - Heterotrophic respiration and carbon storage (Gibelin et al. 2008)
  - **Implementation/Verification**
    - Field scale (Calvet et al. 1998, Calvet and Soussana 2001, Rivalland et al. 2005, Gibelin et al. 2008)
    - Regional scale (Brut et al. 2009)
    - Global scale (Gibelin et al. 2006)

Implementation

- 2D implementation: usefulness of satellite data

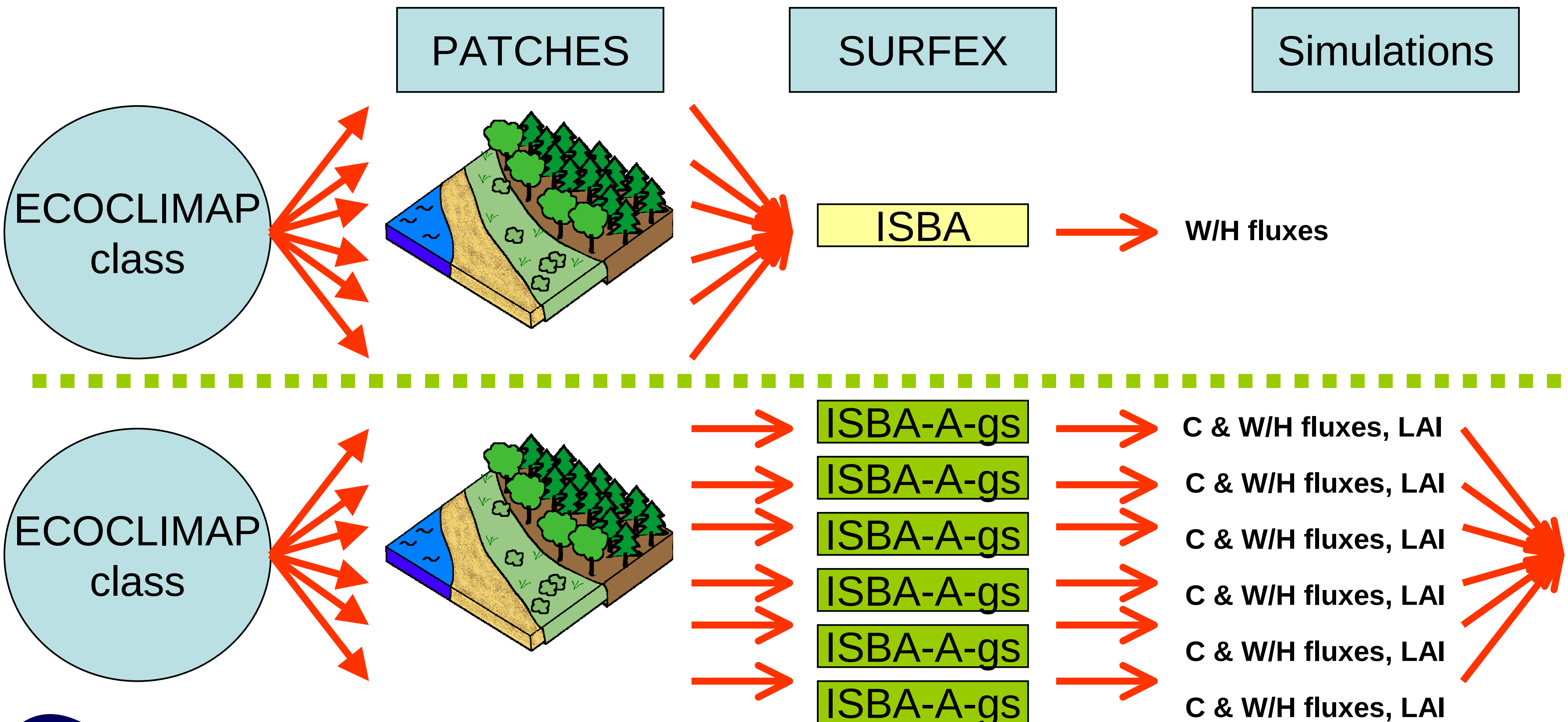
  - Integrate geographic information in SURFEX
    - Representing the spatial heterogeneity
    - Vegetation classes
    - Land cover: fractions of cover types (coniferous/deciduous/mixt forests, C3/C4-winter/summer crops, grasslands, irrigation…), bare soil fraction

  - Constrain the model: Assimilation
    - LAI
    - Surface soil moisture

  - Verification
    - Spatial distribution of biomass
    - LAI max
    - Leaf onset, senescence

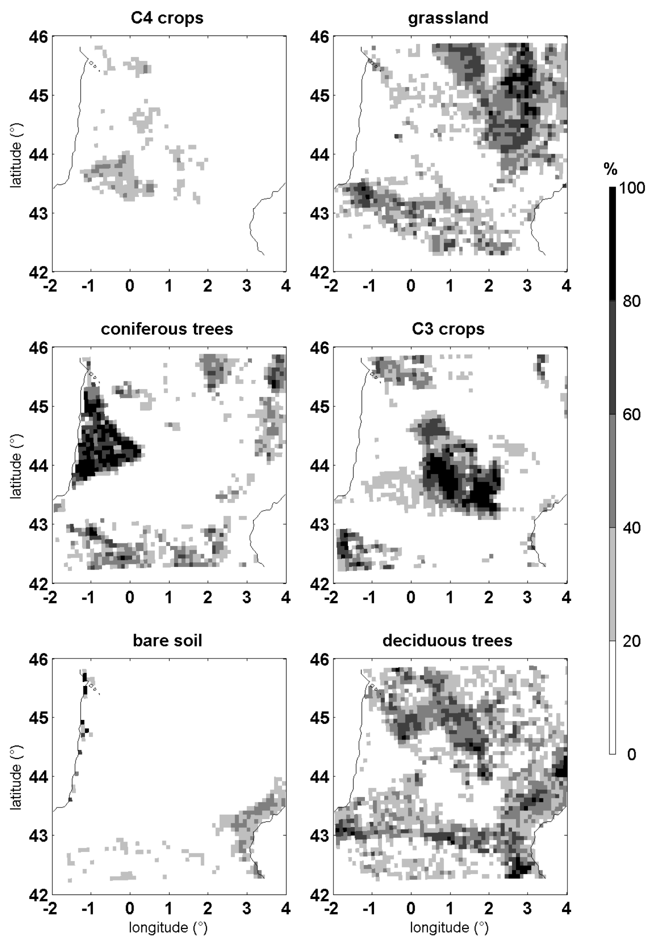
Implementation

FIG. 16 – Representation of heterogeneity: the patches



Implementation

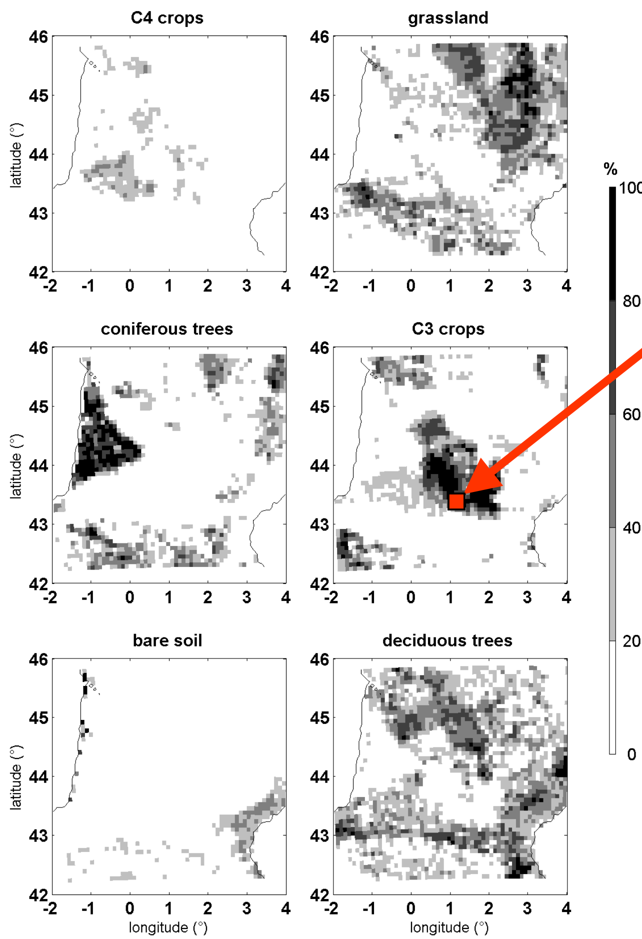
FIG. 17a – Representation of heterogeneity: example in SW France



Patch fractions over southwestern France
[Brut et al. 2009]

Implementation

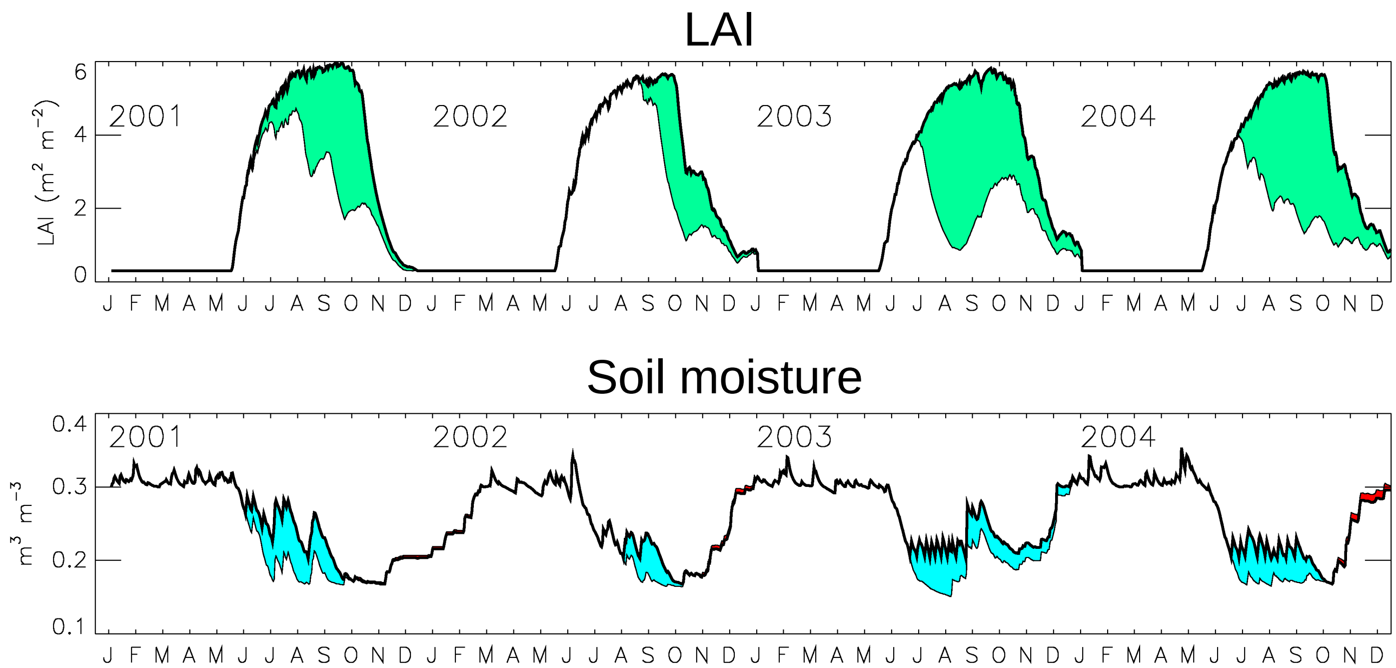
FIG. 17b – Representation of heterogeneity: example in SW France



Patch fractions over southwestern France
[Brut et al. 2009]

Implementation

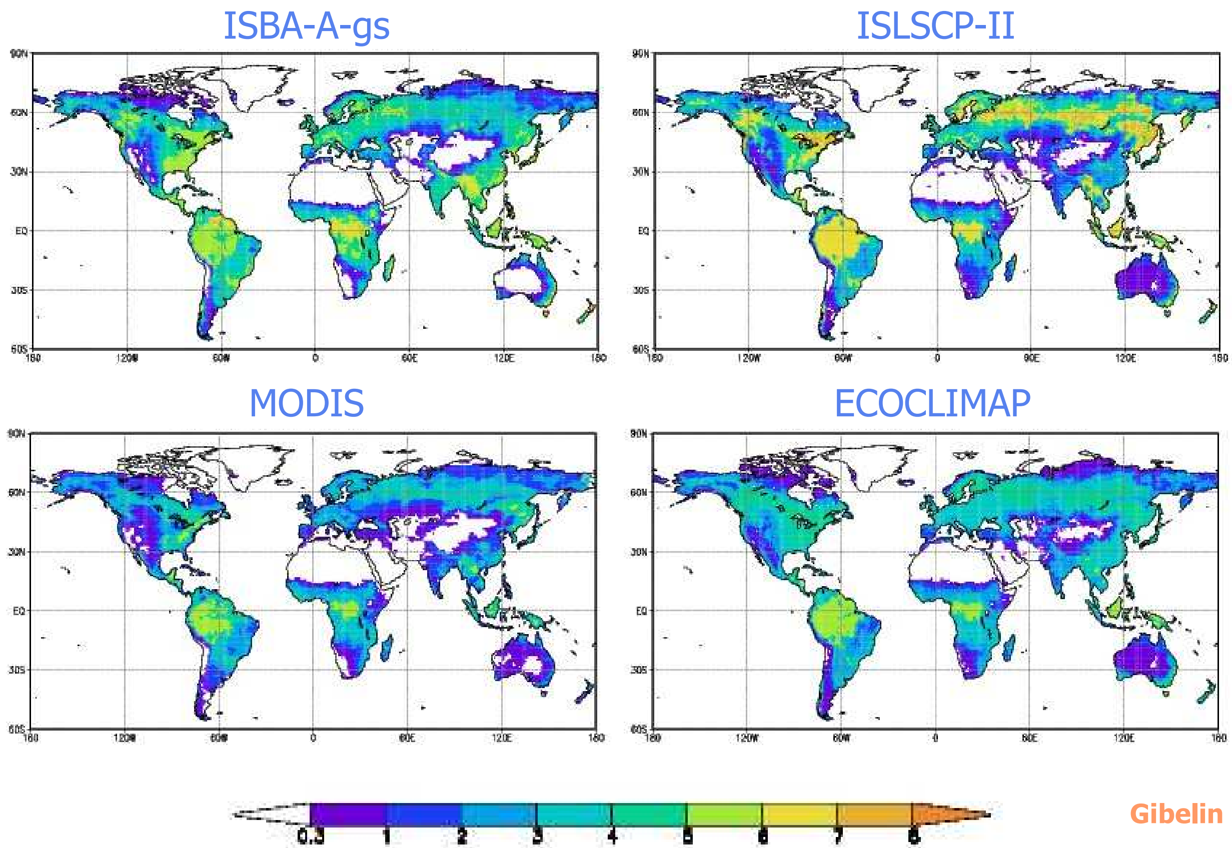
FIG. 18 – Representation of irrigation: maize (SW France)



Optimal Irrigation : 120mm 60mm 270mm 240mm

Verification

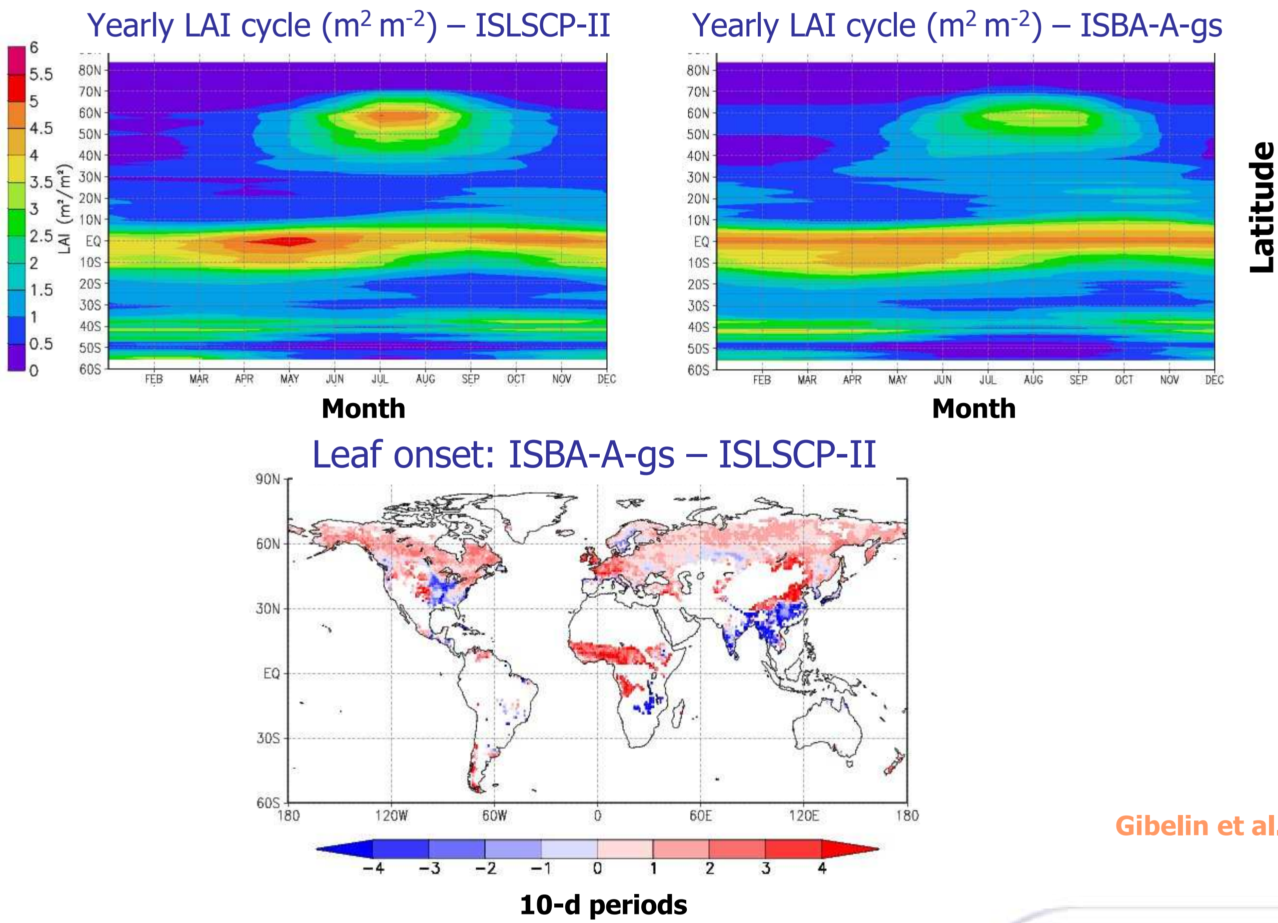
FIG. 19 – Yearly LAI_{max} ($m^2\ m^{-2}$)



Gibelin et al., 2006

Verification

FIG. 20 – Leaf onset: global scale



Gibelin et al., 2006

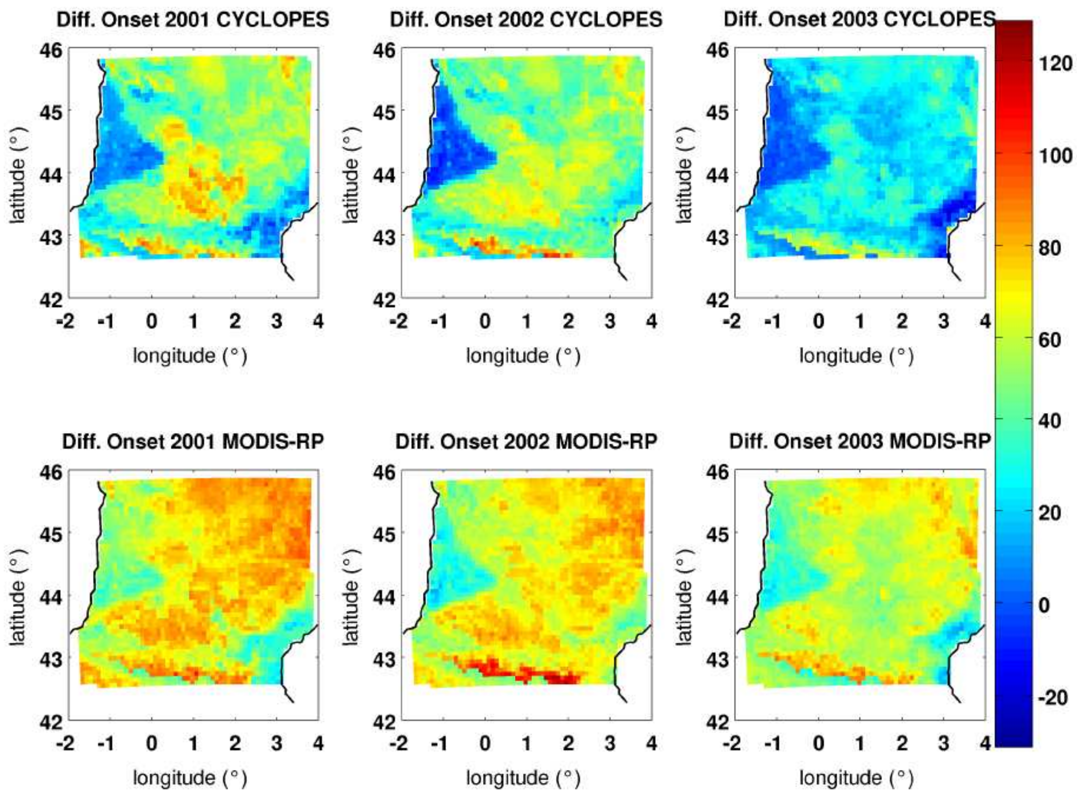
Verification

FIG. 21 – Leaf onset: regional scale (SW France)

2001 2002 2003

Difference with CYCLOPES

Difference with MODIS (reprocessed)



Brut et al., 2009

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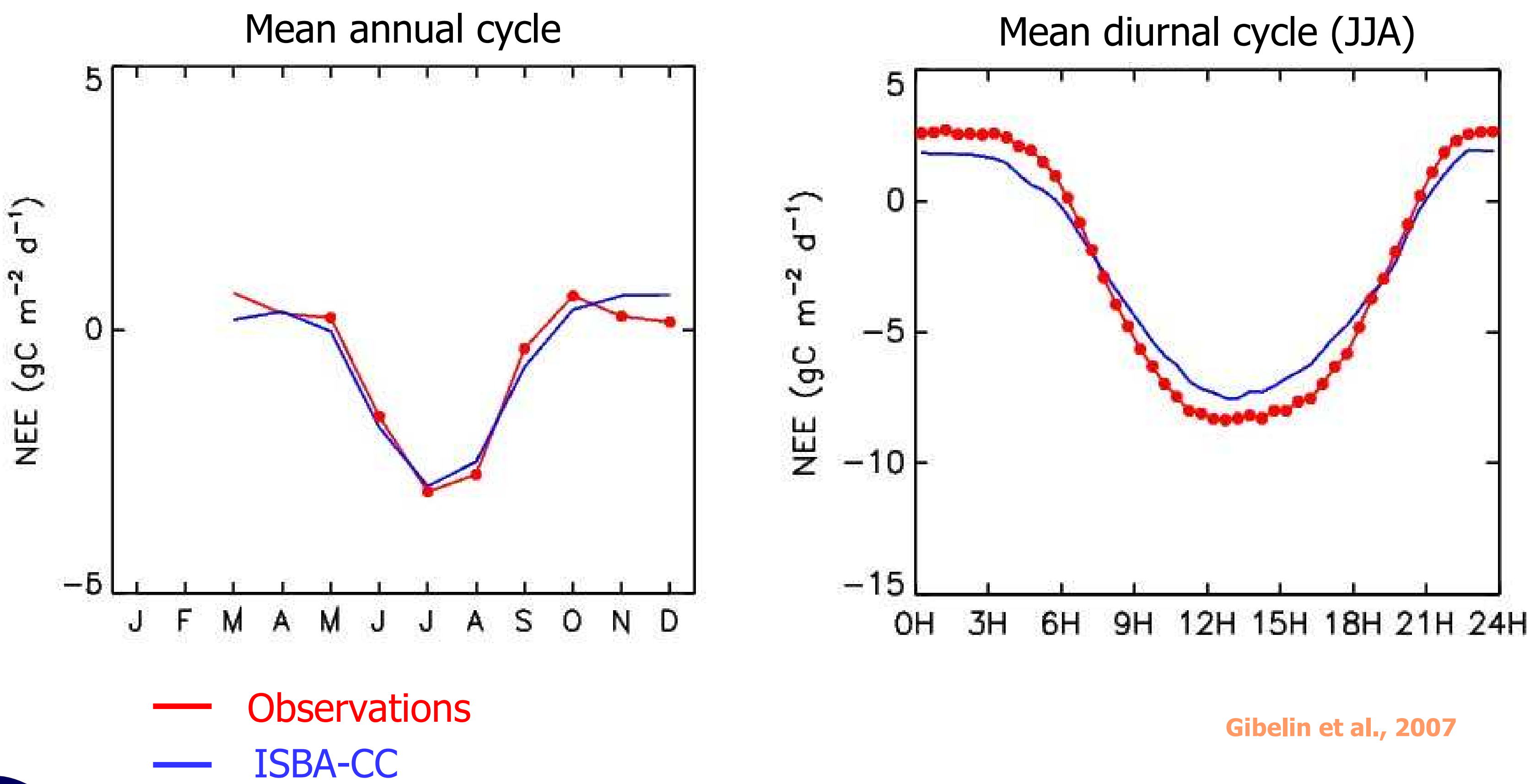
Verification

FIG. 22 – Fluxes: local scale (Gunnarsholt, Island, Deciduous broadleaf forest)



Gibelin et al., 2007

Conclusions

- « AST » option of SURFEX
  - Detailed photosynthesis model
  - Prescribed LAI
- « NIT » option of SURFEX
  - Interactive LAI (climatic simulations)
  - Used by ECMWF (CTESSEL)
- Forthcoming ISBA-CC option
- Representation of heterogeneity
  - Patches are compulsory
- Prospects
  - Improved parameterisations
    - radiative transfer within the vegetation canopy (link to double-source developments)
    - temperature responses
    - agricultural practices
  - Land data assimilation systems
  - Dynamic vegetation ?

THANK YOU FOR YOUR ATTENTION

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