SURFEX
The Carbon Options

Jean-Christophe Calvet,
Anne-Laure Gibelin, Patrick Le Moigne

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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
  - CO₂ effect; 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)
  - 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
  - Regional scale (Brut et al. 2009)
  - Global scale (Gibelin et al. 2006)
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- **Implementation/Verification**
  - Regional scale (Brut et al. 2009)
  - Global scale (Gibelin et al. 2006)
FIG. 1 – ISBA-A-gs vs. ISBA

Met. forcing → LAI → ISBA → LE, H, Rn, W, Ts...

Met. forcing → LAI → ISBA-A-gs → Active Biomass, CO₂ Flux → [CO₂]ₘₐₜ → LE, H, Rn, W, Ts...
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FIG. 2 – Photosynthesis and stomatal control are linked

Stomatal opening \( (g_s) \) depends on:
- Light
- Temperature
- Air humidity
- Soil moisture
- Atmospheric \([\text{CO}_2]\)

Photosynthesis

Transpiration

Respiration

Water extraction

Stomatal opening \( (g_s) \) depends on:
- Light
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Photosynthesis

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Transpiration

Respiration

Water extraction

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- Atmospheric \([\text{CO}_2]\)
Photosynthesis

FIG. 3a – Modelling approach

• 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

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
FIG. 4 – C3 vs. C4 photosynthesis

Ghannoum 2009
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 »)
  - → Enhances the water use efficiency

- Effect on ecosystems/crops still controversial
Photosynthesis

FIG. 5a – CO₂ effect: stomatal conductance

CO₂

550 ppm

ΔT = 1.4°C

507x178 ppm 700 ppm

350 ppm 380 ppm

(Long et al. 2006, Science)

(Morison & Gifford, 1983)
Photosynthesis

FIG. 5b – CO$_2$ effect: photosynthesis

Net C assimilation

$A_n$ 

350 ppm 700 ppm

CO$_2$ E
Photosynthesis

FIG. 6 – CO$_2$ effect: simulated by ISBA-A-gs
Photosynthesis

Parameters of the Jacobs model (leaf level)

- Permanent and/or variable leaf properties
  - Leaf photosynthetic capacity (\( A_{m,max} \), mg\( \text{CO}_2 \) m\(^{-2}\) s\(^{-1}\)) at 25°C
  - Maximum quantum use efficiency (\( \varepsilon_0 \), mg\( \text{CO}_2 \) J\(^{-1}\) PAR)
  - CO\(_2\) compensation concentration (\( I_c \), µmol mol\(^{-1}\)) at 25°C
  - Optimal scaled internal CO\(_2\) concentration (\( C_i \)) at \( D_s=0 \) in well-watered conditions
    \( f_0^* = (C_i - I)/(C_s - I) \)
  - 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 $D_s=0$):
      \[
      A_m = A_{m,\text{max}} \left[ 1 - \exp \left\{ \frac{g_m^* f_0^* (C_s - \Gamma)}{A_{m,\text{max}}} \right\} \right]
      \]
    - Water use efficiency (ratio of net photosynthesis rate / transpiration)
      \[
      W_{UE} = \frac{C_s - \Gamma}{1.6 \rho_a} \left[ \frac{f_0^*}{D_{\text{max}}^*} + \frac{1 - f_0^*}{D_s} \right]
      \]
FIG. 7a – Parameter grouping

\[ g_s - D_s \text{ relationships at leaf and canopy scales (meta-analysis)} \]

\[ ISBA-A-gs \]

\[ g_m \quad D_{\text{max}} \text{ or } f_0 \]

Inter- & Intra-specific
\[ g_m - D_{\text{max}} \text{ (herbaceous)} \]
or
\[ g_m - f_0 \text{ (woody)} \]
relationships
Photosynthesis

Parameter grouping

- Herbaceous plants (meta-analysis)

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

- Woody plants (meta-analysis)

\[ \ln (g_m^*) = a_w - b_w f_0^*, \quad D_{\text{max}} = D_{\text{max}}^x - c_w \ln (g_m^*) \]

- C3 vs. C4 plants: contrasting values of
  - Leaf photosynthetic capacity (\( A_{m,\text{max}} \) at 25°C)
  - Maximum quantum use efficiency (\( \varepsilon_0 \))
  - CO₂ compensation concentration (\( \Gamma \) at 25°C)
  - For herbaceous plants: \( a_h \) and \( b_h \)
Photosynthesis

FIG. 7b – Parameter grouping

Crops, Grasslands

Trees, Shrubs

\[ \ln(g_m^*) \]

\[ \ln(D_{max}^*) \]

\[ \ln(g_m^*) \]

\[ f_0^* \]

Well-watered
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
  • Regional scale (Brut et al. 2009)
  • Global scale (Gibelin et al. 2006)
Response to drought

FIG. 7c – Parameter grouping

Crops, Grasslands

Well-watered

Trees, Shrubs
Response to drought

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

Crops, Grasslands

\[ \ln(g_m) \]

\[ \ln(D_{\text{max}}) \]

Trees, Shrubs

\[ \ln(g_m) \]

\[ f_0 \]

\[ A_m \uparrow \quad \text{WUE} \uparrow \]

Drought-avoiding
Response to drought

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

Crops, Grasslands

Trees, Shrubs

\[
\ln(g_m) \quad \ln(D_{\text{max}})
\]

\[
\ln(g_m) \quad \ln(A_m) \quad \ln(WUE) \quad f_0
\]
Response to drought

FIG. 8a – Tolerant or avoiding? Trees

Maritime pine

Sessile oak

Drought-avoiding

Drought-tolerant
Response to drought

FIG. 8b – Tolerant or avoiding? Trees

Maritime pine

Sessile oak

Drought-avoiding

Drought-tolerant
Response to drought

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

**LAI**

![LAI graph showing LAI values over time from 2001 to 2004, with labels for drought-avoiding and drought-tolerant stages.]

**Soil moisture**

![Soil moisture graph showing soil moisture levels over time from 2001 to 2004.]

CNRM/GMME/VEGEO - October 2009
Response to drought

FIG. 8d – Tolerant or avoiding ? C3 crops
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: $\theta_c$ critical extractable soil moisture content, below which severe soil moisture stress is observed

\[ \ln(g_m^*) - \ln(D_{\text{max}}^*) \]

Crops, Grasslands

Trees, Shrubs

SWI = 1 (unstressed)

SWI = $\theta_c$

Calvet 2000, Calvet et al. 2004
The Carbon Options

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- The ISBA-A-gs model
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  - Plant growth
    (Calvet et al. 1998, Calvet and Soussana 2001, Gibelin et al. 2006)
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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. $A_n = \text{Photosynthesis} - \text{Leaf respiration}$).
  It looses carbon following an exponential law whose e-folding time depends on the daily maximum $A_n$ (*parameter* $= \text{max leaf span time } \tau_m$).

• 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, $LAI_{\text{min}}$, 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

\[ \text{SLA} = e \times N_L + f \]
FIG. 11 – Key parameters of the « NIT » option

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>(g_m) ((\text{mm s}^{-1}))</th>
<th>(g_c) ((\text{mm s}^{-1}))</th>
<th>(f_0) ((-))</th>
<th>(D_{\text{max}}) ((\text{g kg}^{-1}))</th>
<th>Drought response</th>
<th>(\theta_c) ((-))</th>
<th>(\tau_m) ((\text{d}))</th>
<th>LAI_{\text{min}} ((\text{m}^2\text{kg}^{-1}))</th>
<th>(e) ((\text{m}^2\text{kg}^{-1} \text{%}^{-1}))</th>
<th>(f) ((\text{m}^2\text{kg}^{-1}))</th>
<th>(N_L) ((%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3 Crops</td>
<td>1</td>
<td>0.25</td>
<td>0.95</td>
<td>50</td>
<td>Avoiding</td>
<td>0.3</td>
<td>150</td>
<td>0.3</td>
<td>3.79</td>
<td>9.84</td>
<td>1.3</td>
</tr>
<tr>
<td>C4 crops</td>
<td>9</td>
<td>0.15</td>
<td>0.60</td>
<td>33</td>
<td>Tolerant</td>
<td>0.3</td>
<td>150</td>
<td>0.3</td>
<td>7.68</td>
<td>-4.33</td>
<td>1.9</td>
</tr>
<tr>
<td>C3 grasslands</td>
<td>1</td>
<td>0.25</td>
<td>0.95</td>
<td>50</td>
<td>Tolerant</td>
<td>0.3</td>
<td>150</td>
<td>0.3</td>
<td>5.56</td>
<td>6.73</td>
<td>1.3</td>
</tr>
<tr>
<td>C4 grasslands</td>
<td>6</td>
<td>0.15</td>
<td>0.60</td>
<td>33</td>
<td>Tolerant</td>
<td>0.3</td>
<td>150</td>
<td>0.3</td>
<td>7.68</td>
<td>-4.33</td>
<td>1.3</td>
</tr>
<tr>
<td>Coniferous forests</td>
<td>2</td>
<td>0</td>
<td>0.57</td>
<td>124</td>
<td>Avoiding</td>
<td>0.3</td>
<td>365</td>
<td>1</td>
<td>4.85</td>
<td>-0.24</td>
<td>2.8</td>
</tr>
<tr>
<td>Evergreen forests</td>
<td>2</td>
<td>0.15</td>
<td>0.57</td>
<td>124</td>
<td>Tolerant</td>
<td>0.3</td>
<td>365</td>
<td>1</td>
<td>4.83</td>
<td>2.53</td>
<td>2.5</td>
</tr>
<tr>
<td>Deciduous forests</td>
<td>3</td>
<td>0.15</td>
<td>0.51</td>
<td>109</td>
<td>Tolerant</td>
<td>0.3</td>
<td>230</td>
<td>0.3</td>
<td>4.83</td>
<td>2.53</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Mesophyll conductance**
- **Cuticular conductance**
- **Max leaf span time**
- **Critical SWI**
- **N Plasticity parameters**
- **Leaf N**

Gibelin et al. 2006
FIG. 12 – Summary of the « NIT » option

A-gs model: Jacobs (1996)

Surface Variables:
⇒ $[CO_2]_{\text{surface}}$, $R_G$, $T_s$, $D_s$ …
Parameters of the model:
⇒ $g_m$, $D_{\text{max}}$, $f_0$

LEAF SCALE

1- CO$_2$ Net Assimilation

2- Stomatal Conductance

ISBA Water & Energy Budget

GROWTH & MORTALITY

Growth = $\sum A_n$
Senescence = exponential law
Biomass = $\sum (\text{Growth-Senescence})$

LAI = Biomass $\times$ SLA

Soil moisture Stress
$0 \leq \theta \leq 1$

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

CANOPY SCALE

Radiative transfer in the canopy
Net assimilation
Stomatal conductance

$\int A_n \& g_s$
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FIG. 13a – Different respiration terms

- Photosynthesis (GPP)
- Autotrophic Respiration (Rauto)
- Heterotrophic Respiration (Rhetero)

NPP = GPP – Rauto
Reco = Rauto + Rhetero
NEE = GPP – Rauto – Rhetero
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
FIG. 14a – Upgrade of ISBA-A-gs: ISBA-CC

ISBA-A-gs

(Calvet et Soussana, 2001)
FIG. 14b – Upgrade of ISBA-A-gs: ISBA-CC

(ISBA-A-gs) and (ISBA-CC) (Calvet et Soussana, 2001)
FIG. 14c – Upgrade of ISBA-A-gs: ISBA-CC

(ISBA-A-gs) (Calvet et Soussana, 2001)

(ISBA-CC)

Rauto

Mortality

Rauto
FIG. 15 – Heterotrophic respiration

Parton et al., 1987
Krinner et al., 2005
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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

ECOCLIMAP class

PATCHES

ECOCLIMAP class

SURFEX

Simulations

ISBA

W/H fluxes

ISBA-A-gs

C & W/H fluxes, LAI

C & W/H fluxes, LAI

C & W/H fluxes, LAI

C & W/H fluxes, LAI

C & W/H fluxes, LAI
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$_{\text{max}}$ ($m^2 m^{-2}$)

ISBA-A-gs
ISLSCP-II
MODIS
ECOCLIMAP

Gibelin et al., 2006
FIG. 20 – Leaf onset: global scale

Yearly LAI cycle (m² m⁻²) – ISLSCP-II

Yearly LAI cycle (m² m⁻²) – ISBA-A-gs

Leaf onset: ISBA-A-gs – ISLSCP-II

Gibelin et al., 2006
Verification

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

Difference with CYCLOPES

Difference with MODIS (reprocessed)

Brut et al., 2009
Verification

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

Mean annual cycle

Mean diurnal cycle (JJA)

Observations

ISBA-CC

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