Modeling of Water Stress in Crop Models: IBIS, BioCro and others

Fernando E. Miguez

Department of Agronomy
Iowa State University
femiguez@iastate.edu

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Outline

Education and Research

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- B.S. Agronomy (University of Buenos Aires, 2001)
- M.S. and PhD in Crop Sciences (University of Illinois, 2004, 2007)
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- Post-Doc at the Energy Sciences Institute (University of Illinois, 2008 – 2009)

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- Cover crops on Maize yield (Miguez and Bollero, 2005 and 2006)
- Miscanthus Production and Modeling (Miguez et al. 2008, 2009)
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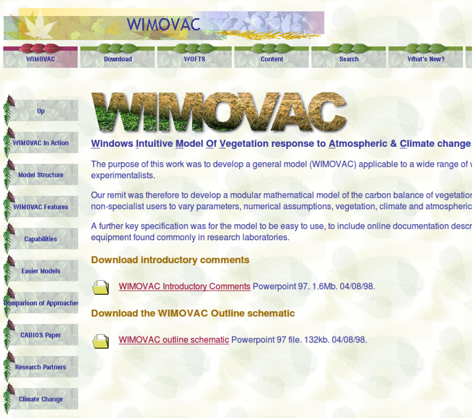
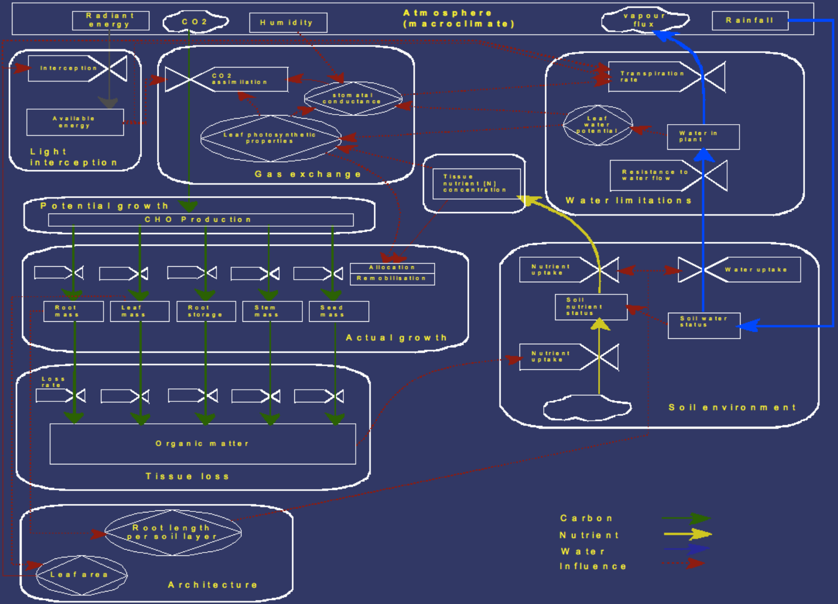
WIMOVAC



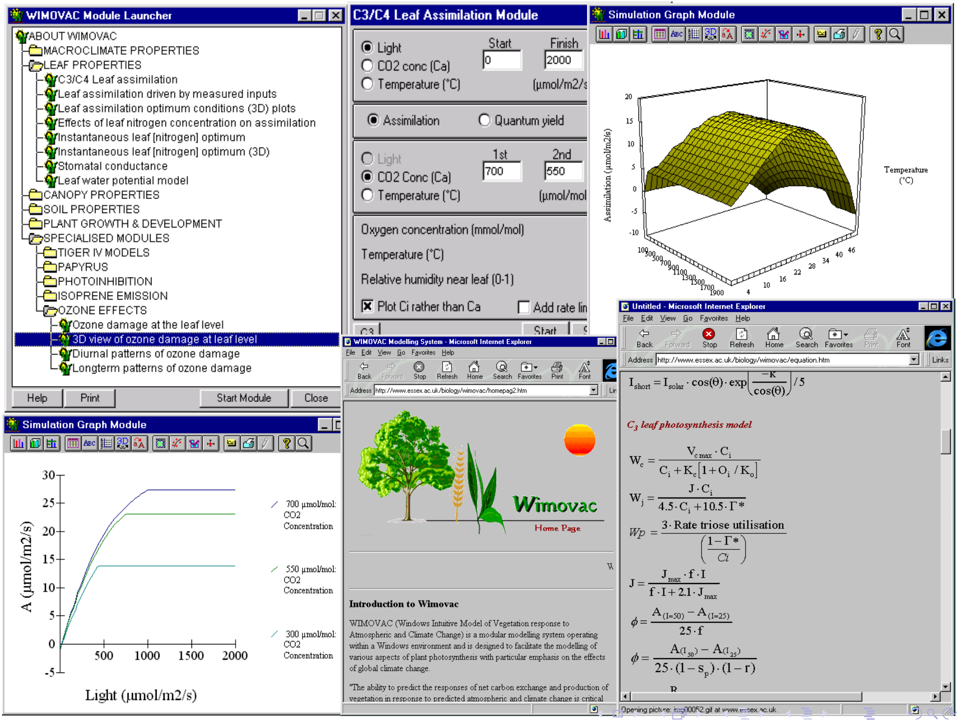
- Developed by Steve Humphries and Steve Long (UIUC)
- Created mainly 1994-1998
- User-friendly
- Written in Visual Basic
- On-line documentation and binary (Win XP)

http://www.life.illinois.edu/plantbio/wimovac/model.htm

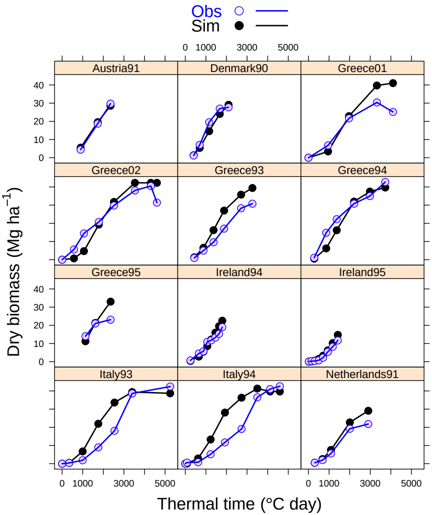


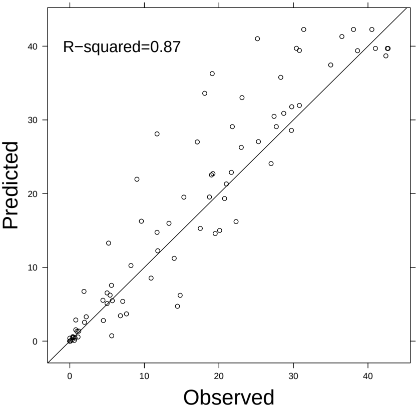
WIMOVAC Overview

Modified from Landsberg (1986)


WIMOVAC Module Launcher
ABOUT WIMOVAC
MACROCLIMATE PROPERTIES
LEAF PROPERTIES
C3/C4 Leaf assimilation
Leaf assimilation driven by measured inputs
Leaf assimilation optimum conditions (3D) plots
Effects of leaf nitrogen concentration on assimilation
Instantaneous leaf [nitrogen] optimum
Instantaneous leaf [nitrogen] optimum (3D)
Stomatal conductance
Leaf water potential model
CANOPY PROPERTIES
SOIL PROPERTIES
PLANT GROWTH & DEVELOPMENT
SPECIALISED MODULES
TIGER IV MODELS
PAPYRUS
PHOTOINHIBITION
ISOPRENE EMISSION
OZONE EFFECTS
Ozone damage at the leaf level
3D view of ozone damage at leaf level
Diurnal patterns of ozone damage
Longterm patterns of ozone damage
Help
Print
Start Module
Close
C3/C4 Leaf Assimilation Module
Light
CO2 conc (Ca)
Temperature (°C)
Start
Finish
0
2000
Assimilation
Quantum yield
1st
2nd
700
550
Oxygen concentration (mmol/mol)
Temperature (°C)
Relative humidity near leaf (0-1)
Plot Ci rather than Ca
Simulation Graph Module
Assimilation (µmol/m2/s)
Temperature (°C)
Simulation Graph Module
A (µmol/m2/s)
Light (µmol/m2/s)
700 µmol/mol: CO2 Concentration
550 µmol/mol: CO2 Concentration
300 µmol/mol: CO2 Concentration
WIMOVAC Modelling System - Microsoft Internet Explorer
http://www.essex.ac.uk/biology/wimovac/homepag2.htm
Wimovac
Home Page
Introduction to Wimovac
WIMOVAC (Windows Intuitive Model of Vegetation response to Atmospheric and Climate Change) is a modular modelling system operating within a Windows environment and is designed to facilitate the modelling of various aspects of plant photosynthesis with particular emphasis on the effects of global climate change.
"The ability to predict the responses of net carbon exchange and production of vegetation in response to predicted atmospheric and climate change is critical
Untitled - Microsoft Internet Explorer
http://www.essex.ac.uk/biology/wimovac/equation.htm
C3 leaf photosynthesis model
Wp = 3·Rate triose utilisation / ((1 − Γ*) / Ci)
Opening picture: img00052.gif at www.essex.ac.uk

Testing of Dry Biomass Production (Europe)





Miguez et al. (2009) GCB Bioenergy

Problems with WIMOVAC

- Written in old Visual Basic
- Computationally slow
- Only runs in Win XP (or older): obsolete
- GUI good for learning, not for research: reproducibility
- Not actively maintained or developed: bugs needed to be fixed

Outline

BioCro (R package): Miguez

Features

- **Statistics** Built-in algorithms for parameter estimation, model diagnostics and graphics
- **Interactive** Lets the user modify input and parameters and quickly plot the results
- **Documentation** Built-in documentation
- **Modular** Allows the user to directly test components of the model
- **Computational** Written in C/R
- **Flexibility** Easily coupled with other tools and software
- **Portability** Cross-platform and scalable
- **Maintenance** Currently under active development

Limitations

- **User-friendliness** Not as intuitive as WIMOVAC

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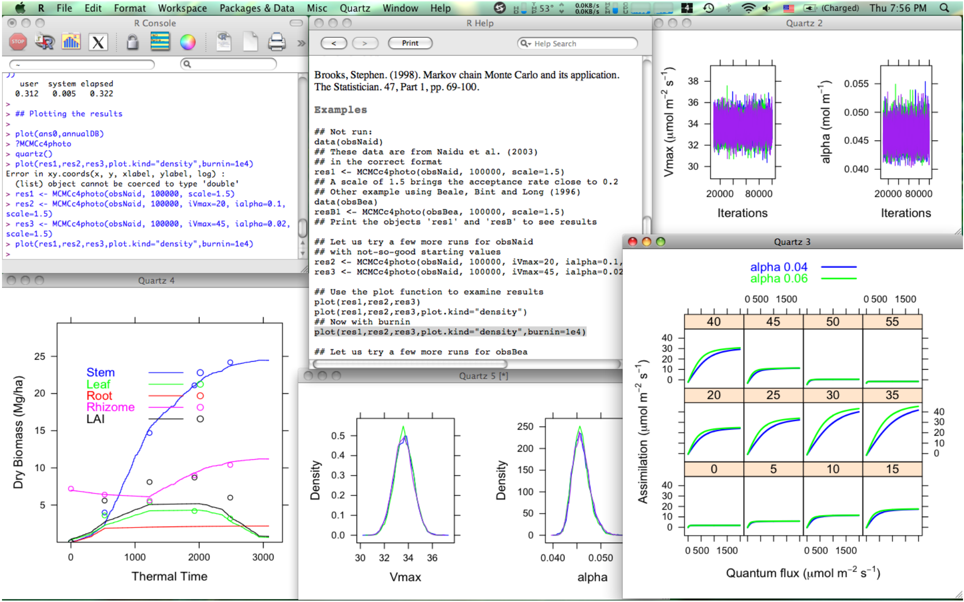
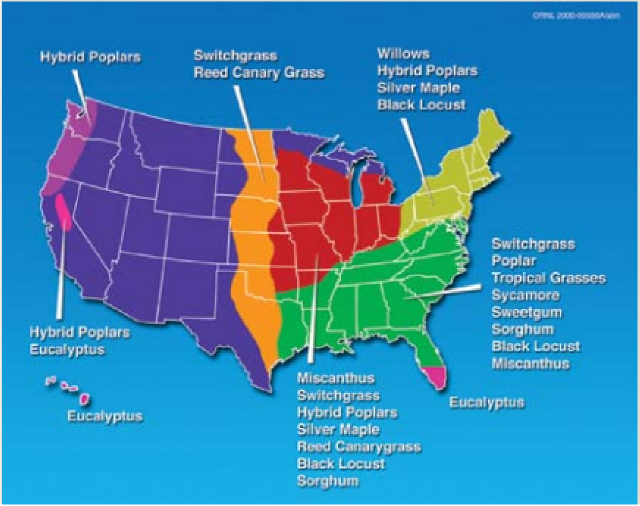

R File Edit Format Workspace Packages & Data Misc Quartz Window Help
Thu 7:56 PM
R Console
user system elapsed
0.312 0.005 0.322
> ## Plotting the results
> plot(ans0,annualDB)
> ?MCMCc4photo
> quartz()
> plot(res1,res2,res3,plot.kind="density",burnin=1e4)
Error in xy.coords(x, y, xlabel, ylabel, log) :
(list) object cannot be coerced to type 'double'
> res1 <- MCMCc4photo(obsNaid, 100000, scale=1.5)
> res2 <- MCMCc4photo(obsNaid, 100000, iVmax=20, ialpha=0.1, scale=1.5)
> res3 <- MCMCc4photo(obsNaid, 100000, iVmax=45, ialpha=0.02, scale=1.5)
> plot(res1,res2,res3,plot.kind="density",burnin=1e4)
R Help
Print
Help Search
Brooks, Stephen. (1998). Markov chain Monte Carlo and its application. The Statistician. 47, Part 1, pp. 69-100.
Examples
Not run:
data(obsNaid)
These data are from Naidu et al. (2003)
in the correct format
res1 <- MCMCc4photo(obsNaid, 100000, scale=1.5)
A scale of 1.5 brings the acceptance rate close to 0.2
Other example using Beale, Bint and Long (1996)
data(obsBea)
resB1 <- MCMCc4photo(obsBea, 100000, scale=1.5)
Print the objects 'res1' and 'resB' to see results
Let us try a few more runs for obsNaid
with not-so-good starting values
res2 <- MCMCc4photo(obsNaid, 100000, iVmax=20, ialpha=0.1,
res3 <- MCMCc4photo(obsNaid, 100000, iVmax=45, ialpha=0.02
Use the plot function to examine results
plot(res1,res2,res3)
plot(res1,res2,res3,plot.kind="density")
Now with burnin
plot(res1,res2,res3,plot.kind="density",burnin=1e4)
Let us try a few more runs for obsBea
Quartz 2
Vmax (μmol m−2 s−1)
alpha (mol m−1)
Iterations
Iterations
Quartz 3
alpha 0.04
alpha 0.06
Assimilation (μmol m−2 s−1)
Quantum flux (μmol m−2 s−1)
Quartz 4
Stem
Leaf
Root
Rhizome
LAI
Dry Biomass (Mg/ha)
Thermal Time
Quartz 5 [*]
Density
Vmax
Density
alpha

Estimating Dry Biomass Partitioning Coefficients

Developed Optimization Algorithms

- **Objective** Model carbon allocation to plant components
- **Harvestable Biomass** Mostly stems are harvested
- **Carbon Storage** How much carbon is stored belowground
- **Water and nutrient cycling** Dynamics during the growing season

Biomass Resources



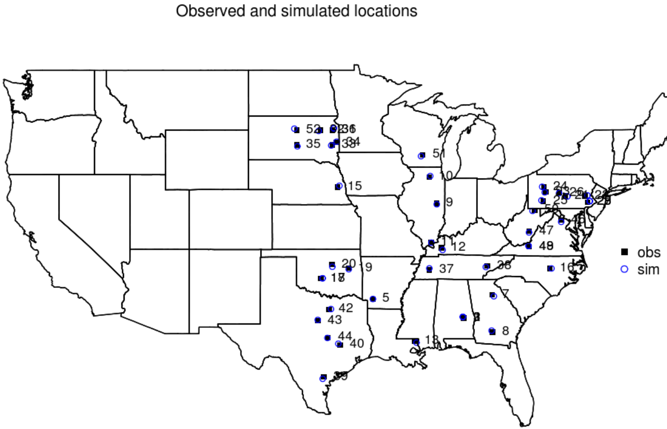
Source: Breaking the Biological Barriers to Cellulosic Ethanol. DOE/SC-0095. 2005

Crop Model Predictions for the US

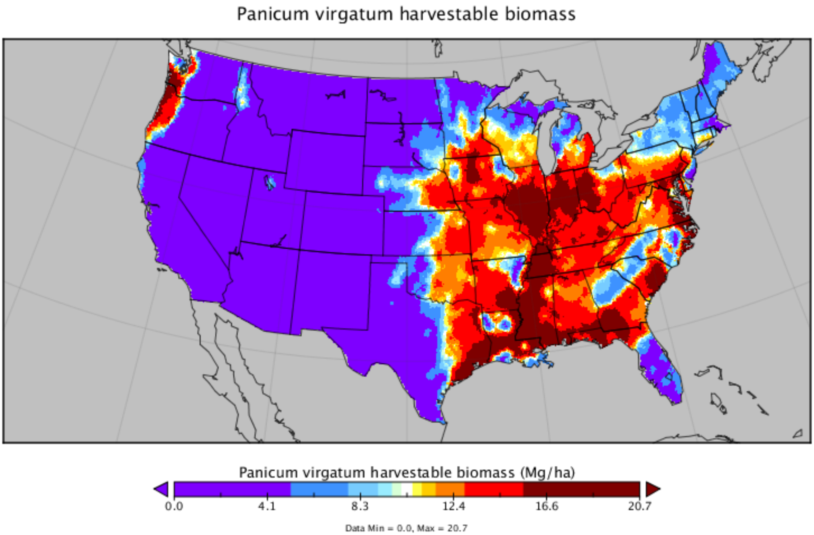
- Parameterized the model for Miscanthus and Switchgrass.
- Integrated BioCro with soil and weather databases
- Weather database obtained from NOAA (National Oceanographic and Atmospheric Administration) 32 by 32 km (1979-2008).
- Soil database obtained from USDA/NRCS (STATSGO2)

Testing locations (Switchgrass)

- Parameterized: one location, one cultivar (CiR)
- Data collected from 31 peer-reviewed studies.

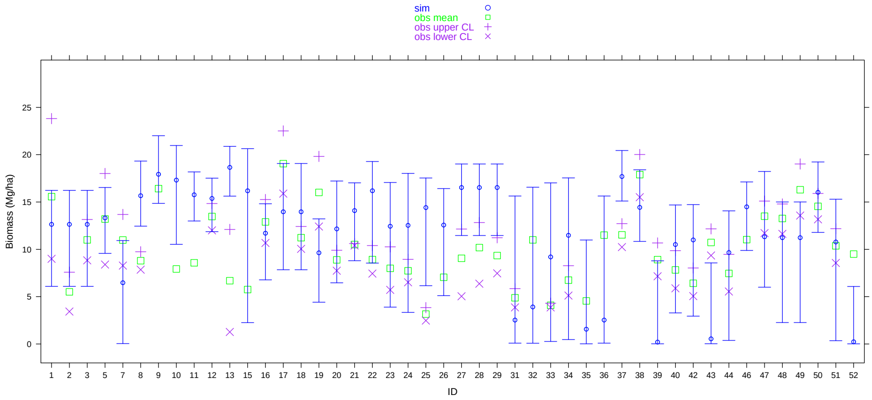


Switchgrass Harvestable Yield Predictions



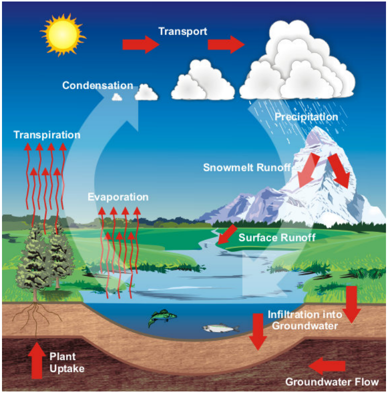
Testing of the model against Switchgrass yields

- Index of Agreement: 0.73
- Mean bias: -1.29 Mg/ha



Outline

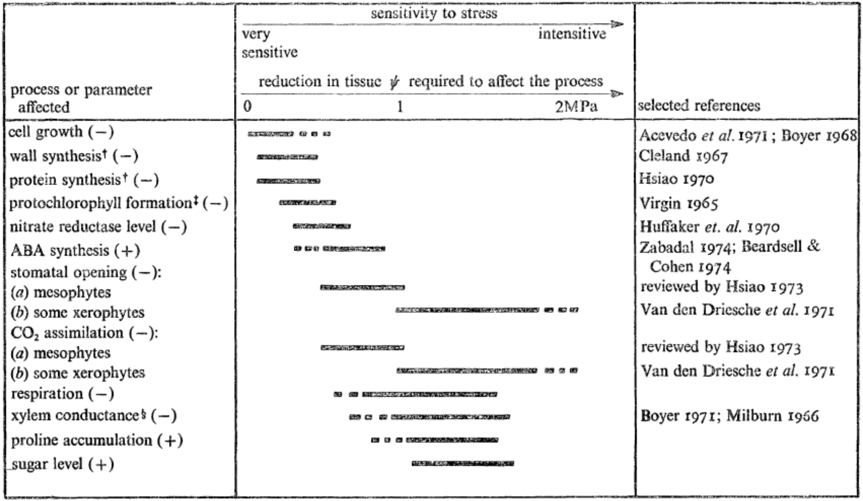
Why is modeling of water stress crucial?



It affects

- CO_2 uptake and thus productivity
- Soil water content and hydrology
- CO_2 and N_2O emissions
- Cannot model N stress independent of water stress
- Model response of crops to climate change
- Do crop models do a good job at modeling water stress?

What do we know about the physiology of water stress?



process or parameter affected	sensitivity to stress → very sensitive … intensitive; reduction in tissue ψ required to affect the process → 0 … 1 … 2MPa	selected references
cell growth (−)		Acevedo *et al.* 1971 ; Boyer 1968
wall synthesis† (−)		Cleland 1967
protein synthesis† (−)		Hsiao 1970
protochlorophyll formation‡ (−)		Virgin 1965
nitrate reductase level (−)		Huffaker *et. al.* 1970
ABA synthesis (+)		Zabadal 1974; Beardsell & Cohen 1974
stomatal opening (−):		
(*a*) mesophytes		reviewed by Hsiao 1973
(*b*) some xerophytes		Van den Driesche *et al.* 1971
CO_2 assimilation (−):		
(*a*) mesophytes		reviewed by Hsiao 1973
(*b*) some xerophytes		Van den Driesche *et al.* 1971
respiration (−)		
xylem conductance§ (−)		Boyer 1971; Milburn 1966
proline accumulation (+)		
sugar level (+)		

Hsiao et al. 1976

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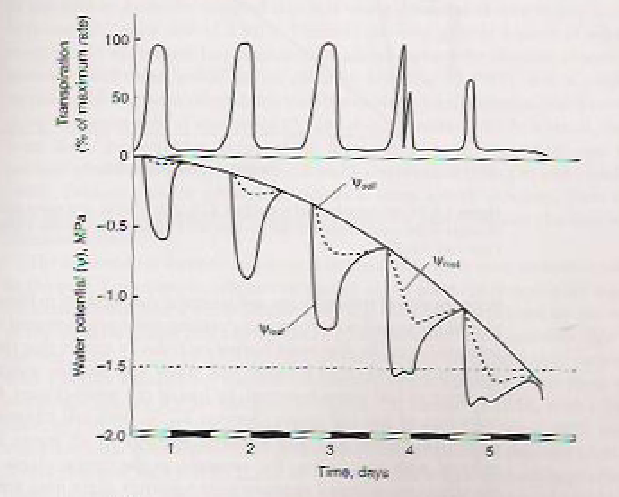


The Physiology of Crop Yield. Hay & Porter. 2006

Outline

RUE model

$$W_h = S_t \cdot e_i \cdot e_c \cdot \eta / k$$

- W_h is the dry matter at final harvest (g m^{-2})
- S_t is the cumulative incident solar radiation (MJ m^{-2})
- e_i is the efficiency of solar radiation interception
- e_c is the efficiency of solar radiation conversion into biomass
- η is the harvest index
- k is the energetic content of the biomass (MJ g^{-1})

Modeling Water Stress in RUE Crop Models

Switchgrass model: Grassini et al. 2009

Crop model based on RUE

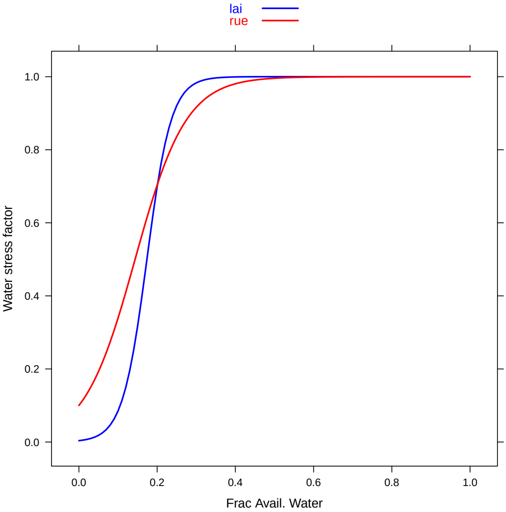
$$WSF_{LAI} = \frac{1}{1 + 270 \exp^{-32.2 \times FAWHC_{AVG}}}$$

$$WSF_{RUE} = \frac{1}{1 + 9 \exp^{-15.3 \times FAWHC_{AVG}}}$$

$FAWHC =$ fraction of soil available water holding capacity

Modeling Water Stress in RUE Crop Models

Switchgrass model: Grassini et al. 2009



Modeling Water Stress in IBIS

Documentation (Foley et al. 1996)

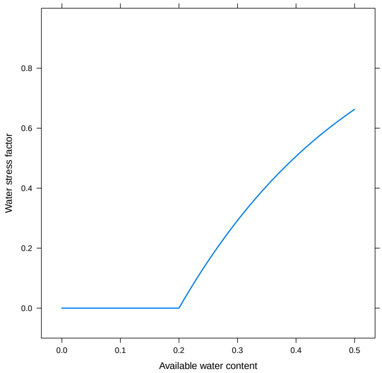
$$wsf = \frac{1 - \exp^{-2.5\frac{\theta - \theta_{wilt}}{1 - \theta_{wilt}}}}{1 - \exp^{-2.5}}$$

Source Code (physiology.f lines 989-1011, ibis 2.6b4)

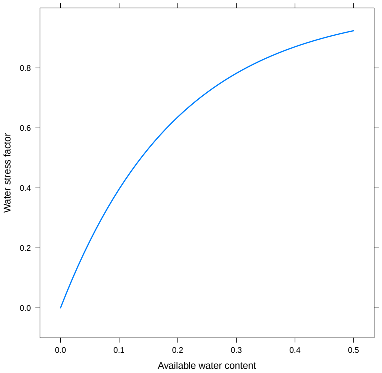
$$wsf = \frac{1 - \exp^{-5 * awc}}{1 - \exp^{-5}}$$

Modeling Water Stress in IBIS

Documentation



Source Code



Water Stress in GOTILWA

Keenan et al. 2010

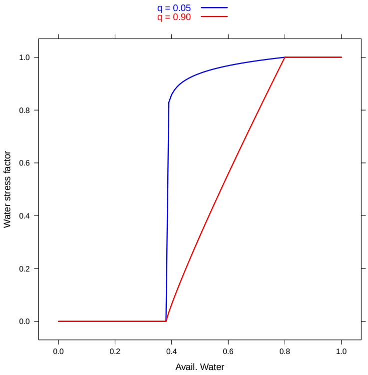
$$W_{fac} = \begin{cases} 1, & \text{if } S(t) \geq S_{max} \\ \left[\frac{s(t)-s_{min}}{s_{max}-s_{min}}\right]^q, & \text{if } S(t) < S_{max} \end{cases}$$

S = relative soil water content

$$S_{max} = 0.8$$

$$S_{min} = 0.38$$

q = non-linear effect



Modeling Water Stress in ED

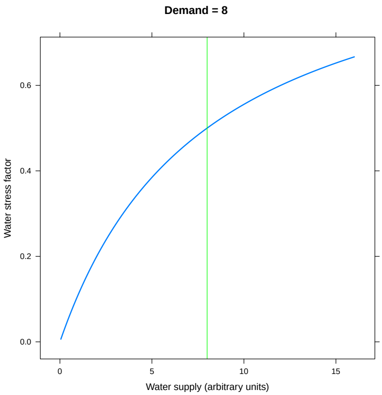
ED: Ecosystem Demography (Medvigy, Moorcroft, et al. 2009)

$$A_{net} = f_{o,w} A_o + (1 - f_{o,w}) A_c$$

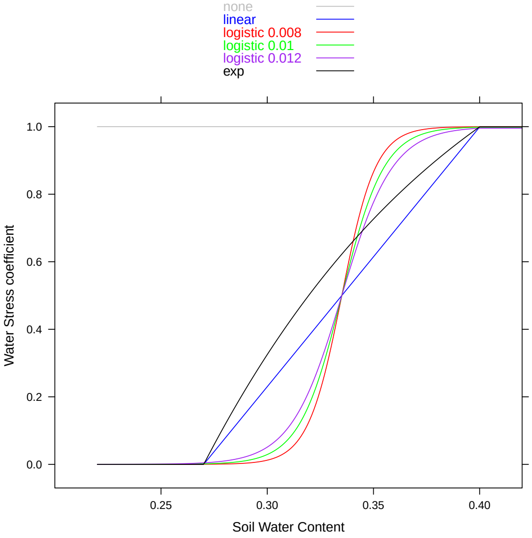
$$f_{o,w} = \frac{1}{1 + \frac{Demand}{Supply}}$$

A_o = open stomata

A_c = closed stomata



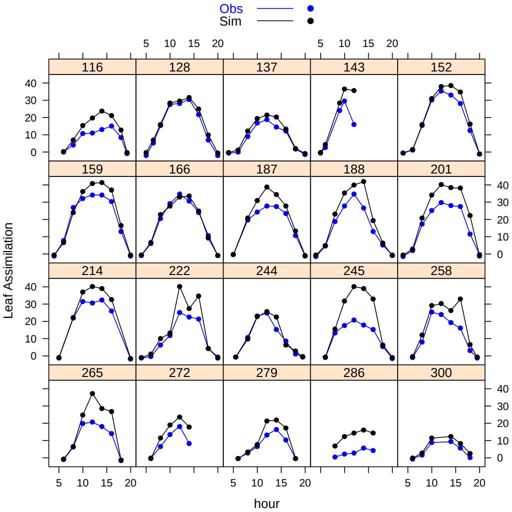
Modeling Water Stress in BioCro



- **silty clay soil**
- Field Cap. $= 0.4$
- Wilt. point $= 0.27$
- **loamy sand**
- Field Cap. $= 0.13$
- Wilt. point $= 0.06$

Outline

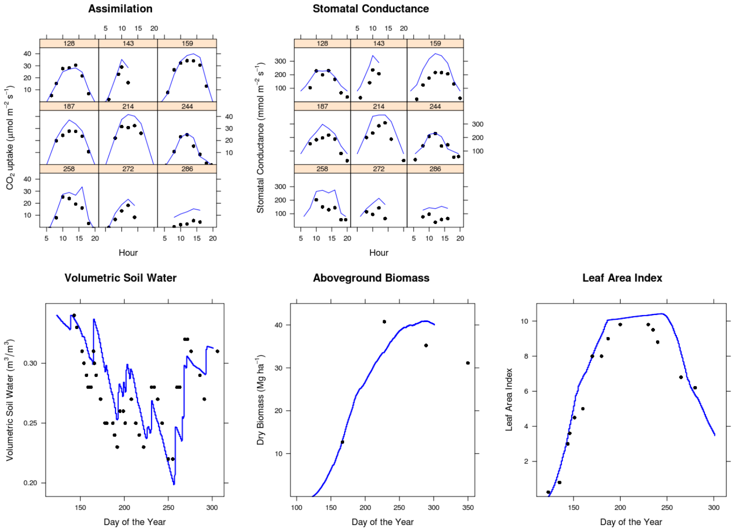
Modeling effect on Photosynthesis: Miscanthus data



Collatz et al. 1992 C_4 photosynthesis model.

- Largest difference at midday
- Water stress should not be a function of soil water...
- Should water stress should be a function of leaf water potential?
- What is the relationship between photosynthetic parameters and leaf water potential?

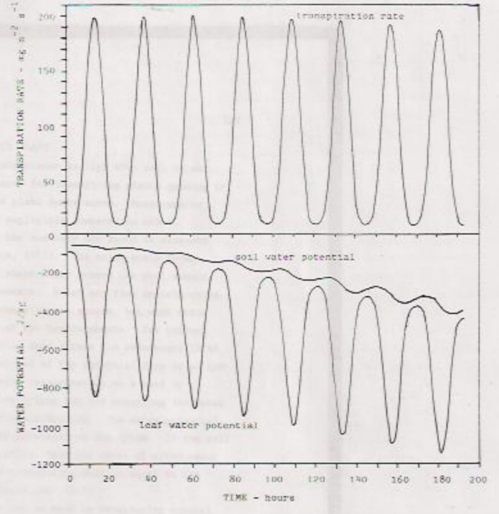
Testing in Illinois

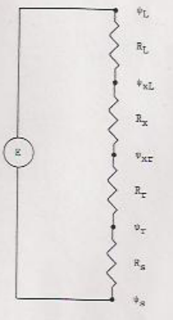


Heaton et al. (2008), Dohleman (2009), G. McIsaac

Simulating Leaf Water Potential

Campbell 1985, 1991 following Cowan (1965)



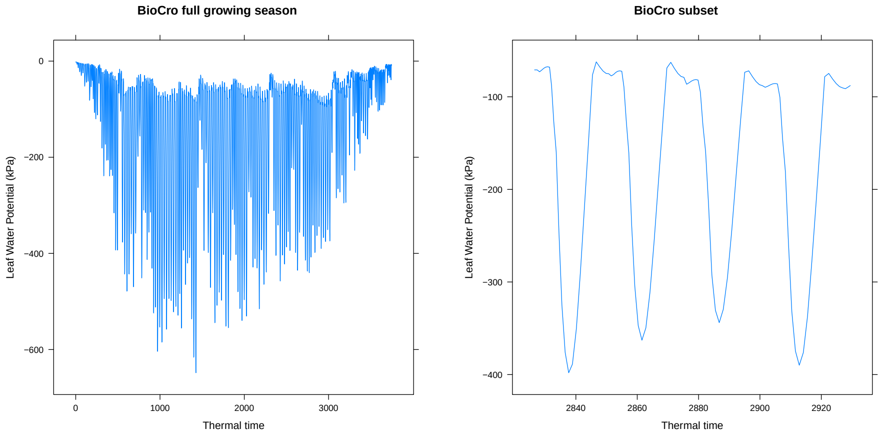


$$E = (\Psi_S - \Psi_L)/R$$

$$\Psi_L = \Psi_S - E \times R$$

Implementation of Campbell in BioCro

No effect of water stress



Outline

Now...

- How do we apply this to growth and transpiration reductions?
- WIMOVAC

$$g_{wmod} = \frac{\Psi_L - \Psi_{thresh}}{1000} \times g_{ws}$$

- Should the effect be applied on a biochemical limitation, stomatal limitation and/or mesophyll conductance?
- Possibly we can apply different type of stresses depending on the range of water potentials
- Mild stress: leaf expansion reduction and stomatal conductance
- Moderate stress: leaf + stomatal + biochemical

Challenges

- With a more complex model we need more data
- R: resistance assumed $5 \times 10^6\ m^4\ s^{-1}\ kg^{-1}$
- Is this constant throughout species and/or time?
- Need to validate leaf water potential
- Need to develop curves of relationship between stomatal and biochemical parameters and leaf water potential (**This is still an issue in all models!**)
- The computed leaf water potential is an average over all leaves, probably not realistic

Concluding Remarks

- Modeling of water stress on crops is the most important component of a model that simulates response of crops to changing climate
- "Despite many studies of the effects of water stress on basic photosynthetic metabolism, there is no generally accepted model of the process occurring in dehydrated leaves"
- Better (more complex) models might require additional experimentation and data

Questions ?