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Toward assimilation of hyperspectral reflectance data into field crop models: case of Monteith (RUE) and STICS models

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Introduction

The pressure on agro-ecosystems is increasing with the growing world population and its associated food and energy needs. Timely assessments of crop growth conditions are needed to forecast crop yield and support decision making. Optical remote sensing (RS), especially hyperspectral remote sensing, has been proven to be effective for quantitative estimation of crop canopy growth-status descriptors such as green leaf area index (LAI), crop cover fraction, canopy water content, leaf chlorophyll, and nitrogen content (e.g., Gitelson *et al*., 2005; Haboudane *et al*., 2002, 2004; Liu *et al*., 2008). Hyperspectral RS is capable of detecting canopy photosynthetic efficiency and environmental impacts on crop development (e.g., Gamon *et al*., 1992; Pattey *et al*., 2001; Strachan *et al*., 2002, 2008). However, these indices do not provide estimates of dry biomass, an important component of crop productivity and C cycle. In this study we tested two approaches for estimating dry biomass and yield. The first one consists in integrating crop stressors and descriptors derived from optical RS data with the Monteith's radiation use efficiency model. The second approach consists in optimizing unknown input parameters of a process-based crop model (STICS developed by INRA, Avignon, France) using multiple LAI images extracted from RS.

Materials & methods - Monteith's model

Multi-temporal remote sensing data were acquired by the Compact Airborne Spectrographic Imager and the Landsat-5/7 Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+) sensors to monitor the growth conditions. The modified triangular vegetation index (MTVI2) derived from the remote sensing data was used to estimate the fraction of absorbed photosynthetically active radiation (f_{APAR}). A canopy structure dynamics model was then used to simulate the seasonal variation of f_{APAR}. For Monteith RUE model, corn water stress was estimated from the near and shortwave infrared reflectance of the Landsat images for a dry period in the 2001 growing season. By estimating leaf chlorophyll content using the Transformed Chlorophyll Absorption in Reflectance Index (TCARI) in combination with the Optimized Soil Adjusted Vegetation Index (OSAVI), different levels of nitrogen content could be identified.

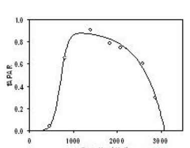
Radiation Use Efficiency Model (Monteith. 1972) $\Delta DM = \int_{t_0}^{t} PAR \times f_{APAR} \times (1-C) \times \varepsilon_c \, dt$

on a daily time step $\Delta DM(t_e) = \varepsilon_c \sum_{t=t_0}^{t_e} PAR(t) \times f_{APAR}(t) \times (1 - C(t))$

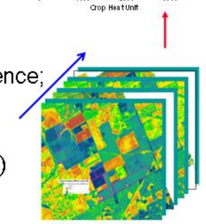
ΔDM: crop shoot dry biomass accumulated over a period
- t_0: day of emergence
- t_e: day of biomass estimation

PAR: incident photosynthetically active radiation (MJ m^{-2} d^{-1})
f_{APAR}: fractional PAR absorbed by the crop
C: crop stress index (heat, water, nutrient, etc.; 0 non-stressed)
ε_c: crop RUE (relatively constant)

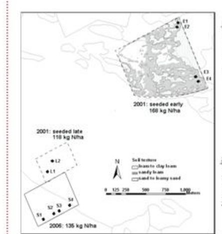
$$D = D_{\max}\left[1/(1+e^{-a(T-T_i)}) - e^{-b(T-T_s)}\right]$$ (Leblon *et al*., 1991)



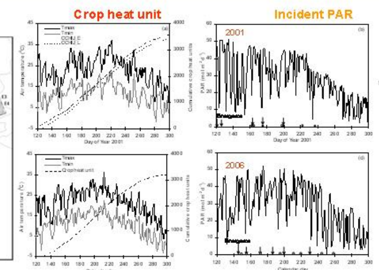
D: canopy structural descriptor (f_{APAR}) with a maximum achievable value D_{max};
- *T*: crop heat unit (CHU) accumulated since seeding date;
- T_i: inflection point during the growth phase;
- T_s: cumulative CHU at which D decreases to 0 due to senescence;
- *a*: relative growth rate at T_i & *b*: the rate of senescence.



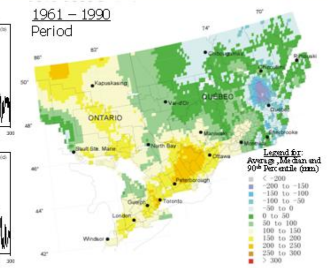
$$f_{APAR} = 1 - \left(\frac{VI - VI_\infty}{VI_0 - VI_\infty}\right)^{K2} \approx (MTVI2 - MTVI2_0)/(MTVI2_\infty - MTVI2_0)$$



Exp. Site (Ottawa, ON)



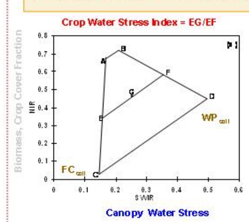
Meteorological data input

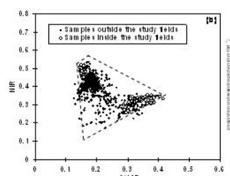


Mean water deficit

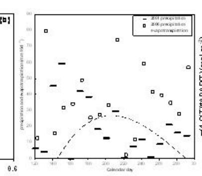
Bootsma, A., Anderson, D. and Gameda, S. 2004. Potential impacts of climate change on agro-climatic indices in southern regions of Ontario and Quebec. AAFC – ECORC Tech. Bulletin Contribution No. 03-284, Figure 16.

Results - Monteith's model

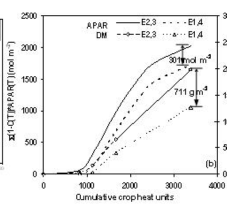




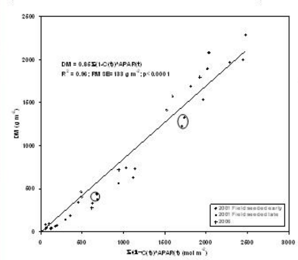
Detection of water stress (Moran *et al*., 1994; Ghulam *et al*., 2008)



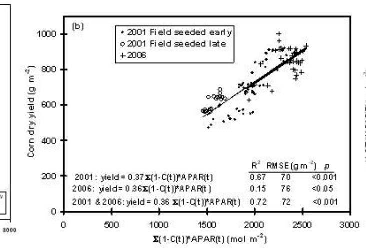
ET & Rainfall



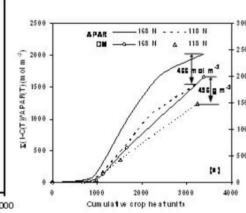
Impact of Water stress



Prediction of shoot biomass

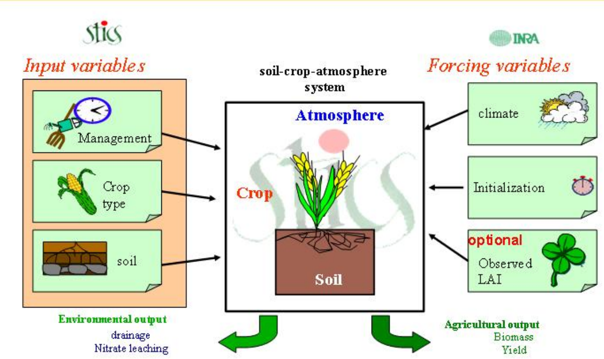


Prediction of yield (Liu *et al*., 2010)



Impact of N stress

Materials & methods - STICS crop growth model

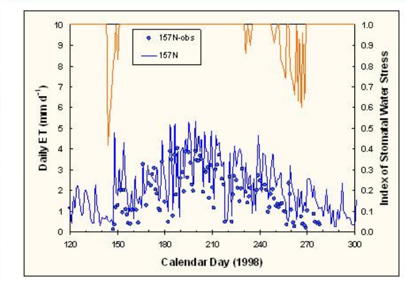


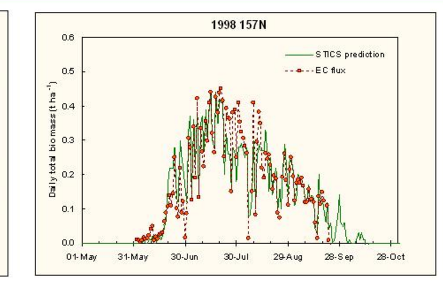
Schematic of STICS crop growth model (Brisson *et al*., 2003)

STICS was adapted to Eastern Canada by calibrating new generic cultivars of spring wheat, corn and soybean (Jégo *et al*., 2010, 2011). Validation of the new cultivars was done on 3 sites using 18 spring wheat datasets from 1993 to 2008, 23 soybean datasets from 1994 to 2008 and 40 corn datasets from 1994 to 2008.

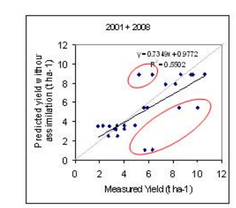
STICS daily predictions of evapotranspiration (ET) and biomass were evaluated using eddy fluxes measured in Ottawa area over 10 years (1996 à 2006). EC flux data were QC/QA for calibration, noise, wind speed and direction. The 30-min fluxes split into daytime and nighttime (Pattey *et al.* 2006), with daytime 30-min fluxes interpolated if gaps ≤3 h and nighttime 30-min fluxes **not** interpolated. The nighttime fluxes integrated if windy conditions for > 5 h (Pattey *et al.* 2002). Interpolation of 12-h fluxes using cumulative PPFD for daytime fluxes and relationship with Ta for nighttime fluxes (Pattey *et al.* 2001). Soil respiration chamber measurements were split between *Ra* and *Rh*. Assimilation of LAI derived from MTVI2 (Haboudane *et al.* 2004) was carried out to re-initialize seeding date & soil moisture at field capacity and run STICS using soil properties from Cansis (i.e., AAFC database) as input.

Results - STICS model

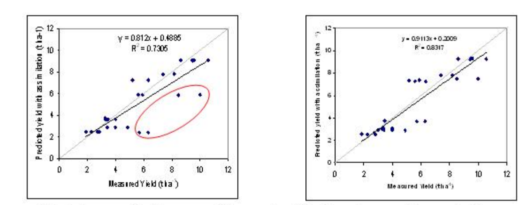




Prediction of daily corn evapotranspiration & total biomass compared to EC fluxes

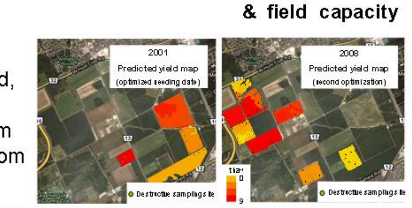


Yield predictions without assimilation recommended practices



Yield predictions with re-initialized seeding date & field capacity

With seeding date & field capacity re-initiated, better biomass and yield predictions were obtained. For Yield, RMSE was reduced from 19% to 12% with LAI assimilation and ME from 9% to 1%.



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