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Forcing a wheat crop model with LAI data to access agronomic variables: Evaluation of the impact of model and LAI uncertainties and comparison with an empirical approach

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ABSTRACT

The objective of this study is to evaluate the performances of estimating agronomic variables, such as total above ground biomass at key stages, or yield, from LAI data that could potentially be obtained from remote sensing observations. Approaches based either on empirical relationships or on forcing LAI within the STICS model (Brisson et al., 2009) are considered, with emphasis on the effect of the accuracy and frequency of LAI data used. Both actual and simulated case studies on wheat for Northern France conditions were investigated under several levels of knowledge of the model input parameters and initial conditions.

The results highlight the interest of using model based approaches for the estimation of agronomic variables. Forcing LAI data into the crop model allows compensating for the lack of detailed knowledge on management practices or soil characteristics. However, error and frequency of LAI observations may have an important impact on the estimation of agronomic variables, particularly for the early growth stages. In these conditions, an empirical approach, based on the calibration of a relationship between LAI at a given stage and the agronomic variable, provides an efficient alternative, though the validity of empirical relationships depends greatly on the database on which they have been obtained.

1. Introduction

Retrieval of vegetation canopy biophysical properties from remote sensing is gradually moving from research to operational contexts (Baret et al., 2007a; Weiss et al., 2007; Garrigues et al., 2008). Among all the canopy variables, leaf area index (LAI), defined as the one-sided green leaf area per unit horizontal soil area (Campbell and Norman, 1989), is the one on which most remote sensing algorithm development efforts have focused, mainly because LAI largely influences the spectral reflectance of vegetation canopies and has a key role in terrestrial ecosystem processes (Baret and Buis, 2007). Moreover recent efforts highlight the possibility of correcting for the typical saturation effect that affects the estimation of high LAI values that occur after canopy closure, effectively separating it from ground cover estimation (Duveiller et al., 2011).

The availability of remotely sensed LAI information at increasingly high spatial and temporal resolution, foreseeable in the next few years (see e.g. Martimort et al., 2007), opens up the possibility of developing several applications at a range of scales, from globe to field. Some of these applications rely on the possibility of deriving, from LAI, other variables of agronomic or environmental interest. Knowledge of these variables could allow improvements in agronomic and environmental management. At the field scale, decision support systems could be developed for farming operations such as sowing, fertilization and irrigation scheduling, forecasting of grain production in quantity and quality. At the regional scale, such information could assist in the minimization of negative side-effects of agriculture such as nitrogen (N) leaching and inefficient water use (Baret et al., 2007b) or in prospective studies of agro-environmental policies (Therond et al., 2011).

LAI is a good indicator of crop status and it is closely linked to several other crop and soil variables such as biomass, yield, crop nitrogen uptake, nutrition status and water stress occurrence. These variables have a more direct agronomic and environmental interest, but are not currently accessible to direct estimation from remote sensing. The use of LAI data in order to derive information on these variables is thus highly appealing.

For example, for wheat N fertilization management, knowledge of the above-ground biomass around the beginning of the

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rapid stem elongation phase allows the estimation of N uptake, an important term of the N balance (Houlès et al., 2007). Biomass is not directly amenable to estimation from remote sensing, since it is rather ground cover or LAI that influence canopy spectral reflectance. It is known that for a given LAI, the amount of shoot biomass may differ, mainly because of the influence of species, variety, light environment, water availability and mineral nutrition on specific leaf area (Dijkstra, 1990) and on the ratio between leaf and stem biomass.

Different approaches have been attempted for estimating biomass (or other variables) from LAI.

The simplest methods consist in directly relating observed LAI values to the agronomic variable of interest, e.g. biomass, by means of experimentally derived relationships (e.g. Baret et al., 1989). These methods will be referred to hereafter as "empirical approaches". For example, Houlès et al. (2007) use simple statistical relationships to derive biomass and N uptake from LAI, and to calculate the deficit of N absorption that has to be filled by N fertilization. A similar approach has been incorporated into the algorithm adopted in the Farmstar operational service (Blondlot et al., 2005) for nitrogen fertilization advice, based on LAI maps generated from SPOT satellite imagery. In the latter case, specific relationships between LAI and biomass for different wheat development stages and varieties have been obtained and calibrated using a large number of experimental trials, mostly carried out in the North of France (Blondlot et al., 2005). Empirical relationships are suitable in a specific operational context, although, given the complexity of the processes that link crop variables, they have a limited range of validity.

Other approaches rely on the coupling of remote sensing observation to process-based dynamic crop growth models. These approaches will be called hereafter "model based". The models take into account the main processes relating plants and environmental factors and are expected to have more general validity as compared to empirical approaches (Dorigo et al., 2007). LAI is a key state variable of crop models, thus LAI observations during the crop growth season can replace those calculated by the model, for example by simply "forcing" measured LAI data into the model, so that LAI effectively becomes a dynamic input of the model (Delécolle et al., 1992; Ripoche et al., 2001). For that purpose, LAI should be provided at the same time step of the model, so it typically needs to be interpolated into daily values. In this type of application the other parameters and driving variables of the model are not affected by LAI adjustment.

As an alternative, in data assimilation schemes, model parameters are updated and recalibrated, so that simulated LAI matches the observations. Different procedures for remote sensing data assimilation into canopy functioning models have been tried (Guérif and Duke, 2000; Weiss et al., 2001; Lauvernet, 2005; Launay and Guérif, 2005; Guérif et al., 2006; Dorigo et al., 2007). Reviews of the background and of examples of different assimilation techniques used for agronomic applications are provided by Lauvernet (2005) and Makowski et al. (2006).

For both approaches mentioned, the results achievable, in terms of accuracy of estimation of the variables of agronomic and environmental interest, greatly depend on the errors and uncertainties that occur during the different implementation steps. A primary source of error, for all the methods, stems from the error in LAI retrieval from remote sensing.

In empirical approaches, further errors could originate from the lack of general validity of the statistical relationships, in the case they are employed in situations differing from those in which they were originally obtained, or from the imperfect knowledge of other regressor variables.

In model based approaches, other sources of error and uncertainty come into play. These are due to the imperfect representation of agro-ecosystem processes by the model and to the uncertainties on the values of usually numerous model parameters and initialization variables. The frequency of availability of LAI observations is also a factor, since, for example, interpolation of sparse LAI data into daily values is needed for model forcing, introducing an error linked to the interpolation procedure.

The present work aims at investigating the effect of the accuracy and frequency of remotely sensed LAI on the estimation of variables of agronomic and environmental interest. There is great interest in clarifying the benefits of possible future improvements in the accuracy of LAI retrieval from remote sensing, through better sensors or algorithms (Martimort et al., 2007). Is the current accuracy of LAI derived from remote sensing adequate for agricultural applications? If we use LAI in order to infer other agronomic and environmental variables through forcing or assimilation into crop models, what would be the relative impact of the errors in the LAI and of the uncertainty in model parameters?

These issues are investigated in the present study, by means of an analysis of actual and simulated case studies on wheat for Northern France conditions. First, the crop growth model STICS (Brisson et al., 2009) is evaluated against wheat field data for different levels of knowledge of its input parameters. Then, a model based procedure for estimating biomass from LAI, involving forcing observed LAI into the STICS model, is tested in the same context. The impact of LAI error and LAI observation frequency on the estimation of agronomic variables from LAI forcing, is subsequently examined. For this purpose a more general simulation study based on a synthetic (virtual) wheat database is employed. Finally the impact of LAI error in an empirical approach to estimate biomass is evaluated and compared to the model based approach.

2. Measurements and tools

2.1. Field experiments

A database of winter wheat (*Triticum aestivum* L.) field trials carried out in Northern France is employed. It includes records from 2 sites, Grignon (lat. 48°50′ N, long. 01°55′ E, alt. 70 m) in 1994 with one single agronomic management sequence and Chambry (lat. 49°35′ N, long. 3°39′ E, alt. 110 m) for the years 1999 and 2000, with respectively 10 and 6 management modalities. Management differed for nitrogen fertilization and planting densities (Table 1). A silt soil prevailed in Grignon, whereas the trials in Chambry were carried out in two fields with different soil types, respectively a Calcosol over chalk and a Luvisol over frost-disturbed sand.

For each of the 17 field trials, all the agronomic practices were recorded. Above ground biomass, nitrogen concentration (%N) and LAI were measured between 6 and 15 times within the growth cycle. Plant samples were harvested from areas of 0.41 m^2 replicated twice or 3 times within each plot. Total above ground biomass was determined by drying at 80 °C for 48 h. LAI was measured destructively by means of a LICOR LI-3000A area meter. Total nitrogen was measured on sub-samples with an elemental analyser (NA 1500, Fisons). Soil moisture and soil mineral nitrogen content were measured at sowing and at harvest in all trials, whereas for five trials it was measured 6 times during the growth season. Finally grain yield and N content were measured at harvest. Further details on the field trials and the measurement protocols can be found in Houlès (2004).

The 1994–1995 growth season in Grignon was warmer as compared to the two other seasons in Chambry, with maxima reaching 37 °C. The coldest season was that recorded in Chambry for the year 1999–2000, reaching −8 °C at the end of January, whereas in the other years minima did not exceed −6 °C. Rainfall was higher at Chambry than at Grignon, with seasonal totals of more than 900 mm and about 600 mm, respectively.