Assimilation of short wavelength satellite observations into an agrometeorological model

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Abstract:
For given environmental and cultural conditions, the time profile of high spatial resolution satellite signal (SPOT HRV) was predicted at field scale through the link between a crop model and a canopy radiative transfer model. The interannual variations of the measured radiometric signal, due to known parameters variations, were reproduced. The impact of such parameters variations is significant for the estimation of canopy productivity. The use of SPOT HRV observations to constrain the modelling implies that the signal is well simulated. Synthetic observations were used to test the assimilation technique for many acquisition configurations. The quality of the productivity estimation depends on the quality of the inverted parameter adjustment. The merit function feature is very sensitive to the number and to the position of observations among the seasonal cycle. The low spatial resolution radiometric signal (NOAA AVHRR) was simulated at regional scale. The different components of the observed signal were obtained either with the crop model, or empirically.

INTRODUCTION

1. Objectives of the study
This article deals with the linkage between a vegetation model and satellite observations. It consists in the integration of satellite observations into a process model in order to estimate vegetation production. Due to the complexity of this issue, we focus on large temperate agricultural zones where parameters acting on the vegetation can be controlled. Thus, the study addresses both vegetation/climate interactions, and production forecasting over large agricultural areas. The linkage between satellite observations, acquired by either high or low spatial resolution sensors and allowing both field and region scales studies, and process models is used in order: (i) to develop methodologies in terms of satellite data integration ("assimilation") in controlled conditions. This is a prerequisite step before the extension to natural vegetation (more complex due to the mixing of various vegetation types), (ii) to estimate productions or production variations. Can the satellite observations, linked with process models, improve the crop production estimation along several years, without ground campaigns?

2. The approach
Fischer et al. (1995) have reviewed the studies combining remote sensing and crop process models to estimate crop yield. One of the approaches consists in simulating the observed radiometric signal by coupling a process model with a reflectance model, and in adjusting some process model parameters thanks to observations (Bouman, 1991a). Except in case of local experiments, the process model input parameters concerning cultural practices are unknown at the scale of an agricultural region. In the perspective of the yield forecasting for both a given field and a region, adjusting unknown parameters using satellite observations seems to be relevant. The agricultural landscape of temperate regions is mostly composed by a mixed agriculture (winter and summer crops). In general, the field size is smaller than the spatial resolution of sensors supplying daily acquisitions. But the use of high spatial resolution data is limited by the small scene number during the growing season. Thus, beside SPOT HRV high
spatial resolution data, we use daily acquisitions provided by NOAA AVHRR low spatial resolution sensor.

3. State of art

Productivity and satellite observations: Various types of models have been used in combination with remote sensing. Empirical models are for instance established between biomass production and a vegetation index (Tucker et al., 1986). Their validity range is limited to given site, vegetation type, and climatic conditions. One can not easily extend their use to other conditions. A semi-empirical model, the Monteith efficiency model (1977) was adapted to the use of radiometric data by Kumar and Monteith (1981). The production estimation of various crops was obtained with this model (Leblon et al., 1991; Guérif et al., 1993).

However, the model does not describe the physiological and biological mechanisms conditioning the growth and development, and then the biological efficiency. The agrometeorological models simulate the temporal evolution of various plant state variables: the leaf area index (LAI), the organs biomass, and the energy, water, carbon and nutrients fluxes between the plant, soil and atmosphere. The evolution of these variables along the growing season depends on meteorological and pedological conditions and on cultural practices. Satellite data are not used as input of such models. However, some radiative variables (e.g. reflectances) can be deduced from some model state variables (e.g. LAI) with a radiative transfer model.

Empirical or semi-empirical relations do not describe biophysical mechanisms, so in the context of this study, an agrometeorological model was used. The observations constrain the model by adjusting some initial conditions or some model parameters. The various existing strategies are displayed.

The inversion technique: The combined use of process models and radiometric observations (Seguin et al., 1992, Delécolle et al., 1992, et Fischer et al., 1995) was performed by Maas (1988a) using 3 different strategies (forcing, re-calibration and assimilation). The forcing strategy consists in retrieving biophysical variables from satellite observations, and then using them as model inputs. This approach was tested by Mass et al. (1985) with ground radiometric measurements, and by Delécolle and Guérif (1988) with SPOT HRV satellite observations. LAI values are derived from a vegetation index in order to obtain external control-variables to correct the flawed modelling. The re-calibration strategy consists in the inversion of biophysical variables that afterwards allow the re-adjustment or the re-initialisation of the process model: The comparison between ‘observed’ (derived from satellite data) and simulated LAI time profile allows the adjustment of parameters or initial conditions. This approach was tested with ground radiometric measurements (Maas et al. 1989, Maas 1988b et Maas 1991). The use of minimisation algorithms to reduce the simulation/observations difference induces larger computing time than for forcing strategy. The assimilation strategy consists in the direct use of radiometric observations (reflectances) to constrain the vegetation model. The time profile of canopy reflectances obtained from satellite remote sensing is reproduced by the linkage of a radiative transfer model with a process model (through LAI). The observed radiometric data are used without inverting any variable, to re-adjust or re-initialise a process model. Bouman (1991b) used this technique with ground radiometric data. In this study, we test the technique using high spatial resolution satellite observations, for a winter wheat canopy.

However, the low temporal resolution of high spatial resolution acquisitions leads to few available data during the crop growing period. All the parameters can not be adjusted thanks to these observations. But, the use of low spatial/high temporal resolution data depends on the possibility to interpret the signal.
The low spatial resolution signal: The combined use of models and satellite observations is interesting, providing that the radiometric signal allows the detection of some events strongly influencing the production estimation (beginning of the growth, climatic events). The daily acquisitions supplied by low spatial resolution sensors allow the monitoring of the vegetal cover growth and development conditions. Nevertheless, the signal measured for a pixel (roughly 1 km) results from many contributions, corresponding to many vegetation types. The problem consists in retrieving or simulating the spectral signature of every component. First approach consists in decomposing the mixed signal to extract temporal signals relative to each vegetation types. In case of spatial decomposition, we assume that the inter-variability observed between several AVHRR pixels is mainly due to difference in land use from one pixel to the other, the signature of a component being stable (Puyou-Lascassie et al., 1994; Kerdiles and Grondana, 1994; Faivre and Fischer, 1995). In case of a temporal decomposition, a semi-empirical model describes the time profile shape observed at regional scale along a seasonal cycle. Different sets of coefficient describe the seasonal profiles of the main components (Fischer, 1994). The spatial decomposition requires to know each pixel land use, whereas for temporal decomposition, having scenes along the whole seasonal cycle is necessary. The second approach is the rebuilding of the mixed signal observed by the sensor. The method consists in reproducing the observation. In the context of this study, we use a process model to simulate the region main crop contribution and empirical profiles for minority components.

The article consists in 3 sections. In the first one, time profiles of high spatial resolution canopy reflectances (field scale) were predicted in SPOT HRV wavelength bands. For several fields, the predicted reflectances were compared with remotely sensed reflectances for few dates of 2 cultural seasons. In the second step, the observations were used to constrain the model, according to the previously described assimilation technique. In the third section, to evaluate the interest of using the low spatial resolution (regional scale) in order to study the canopy seasonal development, the reflectances measured by NOAA AVHRR sensor were simulated.

I- DATA AND MODELS SENSITIVITY

I-1. Data and models

The main study site is located is Beauce region (winter cereals, 40x40km, France), the second site is located in Camargue region (France). Two SPOT HRV scenes in 1991 and 5 in 1992 are available. The data have been calibrated (Henry et al., 1995) and corrected for atmospheric effects (Rahman et Dedieu, 1994). The error on measured reflectances due to calibration and to atmospheric effects is about 0.02. The temporal archives of NOAA AVHRR (HRPT) daily afternoon measurements in visible and NIR channels for year 1992 have been acquired at Lannion CMS (France). Derrien et al., (1992) describe the reflectance pre-processing [calibration (Kaufman et Holben, 1993) and atmospheric corrections with 5S algorithm (Tanré et al., 1990)]. Aerosol effects are not taken into account in the correction. The agricultural services have performed a survey on 16 test-sites (700x700m) distributed over the Beauce site for 1991 and 1992. Survey supplies field size, crop type, cultivar, sowing date and yield estimation by farmer. A land use occupation map is available, as well as a weekly measured green LAI series for a winter wheat field sown on 17 October 1991 near Grignon town, in non-limiting nitrogen conditions (personal communication from M.H. Jeuffroy, INRA Grignon). Meteorological data coming from Grignon station are also available. Nine experimental winter wheat fields are located on Camargue site (Guérif et al., 1988; Jappiot, 1987). Measurements of LAI and of vertical view reflectances (radiometer having same wavelength bands as SPOT HRV) were performed on those fields.

AFRCWHEAT2 (Porter, 1993) crop process model daily predicts the net carbon dioxide assimilation, the respiration, the distribution of assimilates in plant organs, the phenological development, the organic matter net production and the grain yield. The input parameters are the daily meteorological data, environmental data, cultural practices and plant characteristics.
A water stress and a nitrogen submodels are integrated in the crop model. The model also predicts the canopy leaf area index (LAI) which is the link with the vegetation radiative transfer model. For reflectance models, we use one semi-empirical model (Baret, 1988) and 3 models which describe the radiative transfer in an homogeneous cover according to 3 different approaches: (i) SAIL model (Verhoef, 1984) uses the Kubelka and Munk theory (1931), (ii) discrete EXTRAD model (Goudriaan, 1977), and (iii) Nilson-Kuusk’s model (1989) in which the radiative transfer equation is solved. The SAIL model (Scattering by Arbitrarily Inclined Leaves) computes the reflectance in the sensor direction as a function of the canopy parameters and of sun and view angles. The used version (personal communication from F. Baret, INRA Avignon) accounts for the canopy hot-spot as described by Kuusk (1991a). The leaf optical properties come from literature (Bouman, 1992; Baret, 1986; Kuusk, 1991b), whereas soil optical properties are picked up from SPOT scenes. We assume the diffuse contribution of incoming radiation is 20%. The view and solar geometry includes zenith solar angle, view zenith angle and relative azimuth between sun and satellite at the satellite acquisition time.

I-2. The LAI prediction with a crop process model
The LAI time profile observed on the Grignon experimental field was compared to the AFRCWHEAT simulation. During the growing season, for a given day, the simulation underestimates the observations. The delay of simulation compared to observations is of few days (less than one week). Only one data set (LAI and reflectances) was available to estimate the reliability of the crop model simulations. Considering the results obtained for this data set, this LAI time delay may be systematically reproduced. In this case, the delay is reproduced on reflectances time profiles obtained from AFRCWHEAT simulated LAI. It is all the more important since the quality of parameters adjustment is strongly depending on the quality of the satellite observations direct way simulation.

I-3. The reflectance prediction with a radiative transfer model
The time profiles of ground radiometric measurements are reproduced for 9 Camargue fields. The LAI and soil reflectance measurements are used as inputs for the 4 reflectance models. The simulated reflectances are very sensitive to disturbing parameters such as the leaf angle distribution and the soil reflectances. The spherical leaf angle distribution is the best way to account for vegetation structure. The 4 models lead to close results, SAIL model will subsequently be used. The NDVI vegetation index reduces the error due to the ignorance of some parameters: for the set of field measurements (111 points), the correlation coefficient is 0.93, the rmse is 0.1 and the relative error is 18%. The large time variability of measured soil reflectances induces a large canopy reflectance variability at the beginning of the growth. Although the model values are often larger than for observations, values obtained for the 2 wavelengths are consistent. The simulation of the canopy reflectance time profiles is strongly sensitive to the soil optical properties time profiles. This conclusion raises the problem of the canopy reflectance simulation at regional scale, where soil spectral signature is not available. The impact of soil reflectance variability is however reduced by using NDVI.

I-4. Computing a surface reflectance from a satellite observation
The uncertainty giving the largest impact on the surface reflectance retrieval from satellite data, is due to the ignorance of the dynamics of water vapour and aerosol contents in the atmosphere. If the error on those parameters is large (larger than 50%), the relative error on reflectance is about 7% in NIR and 12% in visible (case of SPOT HRV data).

II- DIRECT SIMULATION - HIGH SPATIAL RESOLUTION
Method: The modelling of satellite measurements acquired in short wavelength above a crop cover is a prerequisite step before using data in the inversion process. The LAI, as predicted
daily by AFRCWHEAT, allows the link with SAIL model for simulating reflectances in SPOT HRV (or NOAA AVHRR) spectral bands, figure 1.

**Results:** For a given field, after calibration and atmospheric corrections, the measured reflectances in visible and in NIR are comparable with process/reflectance models simulation. The interannual variation of the SPOT HRV radiometric signal observed for 2 consecutive cultural seasons (Fig. 2) was simulated.

At the beginning of the growth, the NIR reflectance simulation almost systematically underestimates the observations. Two hypothesis may explain the model/measurements difference: (i) ignorance of soil reflectance time dynamics, (ii) bias in predicting the LAI temporal phasing with the crop model. However, we note an agreement between simulated and observed interannual variations. Results show that the impact of parameters acting on plant phenology and thus on production (sowing date, cultivar characteristics, and meteorological data) are reproduced.

**III- OBSERVATIONS ASSIMILATION - HIGH SPATIAL RESOLUTION**

**Method:** We assume the correction of the model initial state is obtained by minimising the difference between observed and simulated reflectances in adjusting initial conditions. The combined use of the process model and the reflectance model, with an initial conditions set, gives a reflectance time profile. Real or synthetic observations represent the reference set of reflectances. Since few acquisitions are available, we consider that only one parameter -the sowing date- is uncertain. This parameter drives the crop growth and development in given environment conditions, and influences the carbon fluxes. This is also an initial condition hardly controlled at regional scale, if we are interested in all the fields and not only surveyed fields. The sowing date minimising the merit function is obtained (i) either by scanning all the dates in a plausible range and by computing merit function in every cases, (ii) or in using a minimisation algorithm (interesting in the perspective of the adjustment of several parameters simultaneously). To prevent from retaining a solution corresponding to a local minimum, the algorithm is run with several initial dates. This method (Fig. 3) leads to the estimation of an adjusted sowing date.
Results: Results of the real data assimilation (visible and NIR reflectances coming from 4 SPOT HRV scenes) are satisfactory for an enquired field for which the direct simulation is in agreement with observations (Fig. 4). After adjustment, the retrieved date is 3 days later than the real sowing date. The production (NPP and yield) is estimated by using the retrieved sowing date as input in the process model. The retrieved/real sowing dates difference has no significant impact on the production estimation (error of 3%).

A reference set of simulation (synthetic observations) was used to discuss about the optimisation of observations temporal frequency, acquisition number, acquisition dates and observations accuracy. The estimation quality of variables such as carbon fluxes both depends on the acquisition number and on the acquisition temporal distribution. The best adjustments are obtained with early acquisition dates (during NIR signal increasing period). The less interesting acquisition periods for adjustment are the end of the vegetation cycle and the crop maximum activity period (NIR signal peak). A positive error >=10% on the observations has a significant impact on the production estimation.

IV- REGIONAL SIMULATION - HIGH AND LOW SPATIAL RESOLUTIONS  
Method: 1) Simulation of the reflectance time profiles of a crop at regional scale: For the site main crop, we assume that the dispersion of sowing dates and of cultivars over test sites is statistically representative of the region. For each sowing date/cultivar characteristics combination and for a given year, we simulated the reflectance time profiles in SPOT wavelength bands with the AFRCWHEAT2/SAIL coupled models, in nadir view conditions. These reflectances were weighted with the relative surface of each combination, to process reflectance and NDVI time profiles representative of all the region winter wheat fields.  
2) Simulation of the reflectance time profiles at low spatial resolution scale: To simulate reflectances at a coarse resolution (4 km), we combined every classes (classification) time profiles, weighted by their relative surface (Fig. 5). We assume that for a given spectral band, the resulting reflectance is the weighted average of individual reflectances. The winter cereal reflectances (2/3 of the total surface) were simulated by the method validated at field scale, whereas some empirical reflectances are used for other vegetation groups.
Results: 1) The SPOT HRV signal observed for the set of the region winter wheat fields was rebuilt for 2 successive years. The rebuilt signal roughly reproduces the SPOT HRV observations available for these 2 years.
2) Over the 220 km² selected zone (14 AVHRR pixels of 4 km x 4 km), winter cereals represent 65% of the surface. We use the reflectances averaged on those 14 pixels. Although an AVHRR pixel results from the combination of signals characterising several vegetation groups, we notice a global agreement between reflectances simulated and observed at NOAA AVHRR scale (Fig. 6). The high frequency of low resolution observations allow to check that the vegetation phenology is well reproduced. The difficulty consists in reproducing a signal resulting from various groups contributions. The interest in the rebuilding method is the use of a process model to predict the canopy production.

V-DISCUSSION-CONCLUSION

V-1. Advantages and limits of the proposed methods

Direct way simulation - High spatial resolution: The technique of process model/reflectance model linkage allows to reproduce the temporal dynamics of the satellite radiometric signal. In given conditions (sowing date/variety/climate), the main problem is the simulation of reflectances during the growing period. There is no difficulty to reproduce the radiometric signal interannual variation due to a change in one of the 3 groups of factors previously mentioned, provided that both models and real vegetation are sensitive to these factor variations. To improve the method, the process model has to be rigorously calibrated to reproduce the magnitude and the phase of the LAI temporal dynamics (ground measurements assimilation).

Satellite observations assimilation - High spatial resolution: In favourable conditions, i.e. when i) the radiometric profile is well reproduced and ii) at least one observation is available during the canopy growing beginning, the assimilation gives satisfactory results. The merit function feature is very sensitive to the number and to the position of acquisitions on the seasonal cycle. The more the merit function is marked, the less the uncertainty on the retrieved parameter is large. A more exhaustive study would consists in testing more combinations of observations and simulation (position, frequency, measurement error, simulation uncertainty, ...). Moreover, since the NDVI reduces the impact of disturbing effects such as the soil temporal variability and the directional effects, an interesting approach consists in evaluating the advantage and drawbacks of using a vegetation index instead of reflectances for the assimilation.

Towards the regional scale: the spatial resolution/temporal resolution compromise: The approach of region winter wheat fields radiometric signal rebuilding is interesting for
predicting the interannual variation of the reflectance profiles: the interannual lag obtained on the simulation is coherent with the lag observed on SPOT data. A land use map is required for using high spatial resolution observations. Besides, few acquisitions are available during a seasonal cycle due to the temporal frequency. The observed NOAA AVHRR sensor radiometric time profile was roughly reproduced. As a prerequisite step before using the assimilation approach with low spatial observations, we have to check that a variation of pertinent parameters (in term of adjustment) is observable on low resolution radiometric signal. Finally, the method of low resolution radiometric signal rebuilding has to be tested in various configurations (site, meteorology, crop type) to be validated.

The results obtained show the interest of the process model/satellite observations linkage, for the canopy production estimation. The satellite data assimilation strategy allows the estimation of some parameters required for a reliable modelling. This approach thus allows to assert the modelling quality over zones for which no ground information is available.

V-2. Perspectives: "regional" observations assimilation
The satellite data assimilation may lead to the up-scaling of matter and energy exchanges versus time. Can the data assimilation into models be performed with regional satellite observations, when crops dominate the landscape, to retrieve initial conditions representative of the main crop? Advantages and backwards of several approaches are summarised:

1) High spatial resolution: First, spatial resolution is tinny enough to allow working with only wheat pixels, provided that a land use classification is available. This also means one can work on a non-dominant crop. Second, view angles are small compared to those obtained with low spatial resolution sensors. The assimilation process is limited by the small number of available scenes during the growing period (low time frequency, cloudy days). However, if acquisition dates are judiciously distributed on the seasonal cycle, SPOT data allow the assimilation.

2) Low spatial resolution: Low spatial resolution data are acquired daily and thus allow the vegetation canopy monitoring. However, the view conditions induces more important directional effects than for high resolution. Moreover, to use low resolution, one has to simulate radiometric signal components for vegetation groups which he is a priori not interested in. It is preferable that the studied crop is dominant.

3) Combined use of high and low spatial resolution: In the future, combining high and low spatial resolution may be of great interest. The link of SPOT HRV data (high spatial resolution but low repetitivity) with NOAA AVHRR (low spatial resolution but high repetitivity) is limited by different acquisition conditions (date and geometry of acquisition, spectral bands). In the perspective of the establishment of assimilation methods when few informations are available (for extension to natural vegetation, and for production estimation), the future launch of SPOT4 satellite may be helpful. Two sensors will be on board: a high spatial resolution and low repetitivity sensor (HRVIR), and a low spatial resolution but high repetitivity sensor (VEGETATION). VEGETATION (about 1 x 1 km² resolution) has got the same spectral bands than HRVIR (20x20 m²). Besides, some of the acquisitions being performed in same conditions for the 2 sensors, the observations will be comparable (geometrically and spectrally superimposable).

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